"THE ECONOMIC UTILISATION OF STEELS IN ENGINEERING INDUSTRY"

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SUMMARY

Literature records considerable evidence of the irrelevance to product performance of materials data, traditionally used in the design of engineering components. That such data forms the basis of steel specification schedules against which selection in design is made, would suggest that the selection process satisfies apparent rather than real engineering requirements, a factor of economic concern when steel costs, by way of steel composition, are considered as an essential part of selection procedure.

The utilisation of heat-treatable steels in a major mass-producing industry has been observed by way of field studies. They have shown that while the above situation is widely recognised among materials and engineering design staff, the revision of "traditional" attitudes is slow to occur. While confused ideas relating responsibility to the customer with product cost support the retention of such an unrealistic approach to steel selection in design, the primary reason for the continuance of such practice is the difficulty of re-phrasing steel design data in more realistic terms more closely paralleling the design situation. Failure of existing standards to reflect technological advances in precision heat-treatment techniques, on mass-production scale, further increases the discrepancy often existing between planned product performance and that actually attainable by these means. Difficulty in effecting meaningful communication on all aspects of steel selction, purchasing, and processing, between the disciplines most concerned, contribute to the continued dependence on "traditional" materials and methods of manufacture.

The revision of engineering specifications is explored tentatively, using heat-treatment response as summarised for a given grade by a Jominy hardenability band. The flexibility of the method in meeting design requirements realistically is shown, although continuing to specify in terms of established strength criteria. For cost effectiveness in selection full exploitation of hardenability response in production heat-treatment systems is desirable and, to achieve this, the methods of calibrating quench severity are analysed, particularly for sealed-quench conditions. Limited experimental tests from one such procedure show the performance scatter among similar operational units. Analysis of heat-treatment data from the literature proved of limited use in the determination of expressions to describe heat treatment response in a given steel by means of compositional and microstructural factors. The results presented broadly support established qualitative principles, but the complexity of the equations obtained preclude their use at the present time, as a basis for the design of economic compositions.

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1. THE UTILISATION OF STEELS IN ENGINEERING INDUSTRY

Introduction:

For any engineering component, success in design - measured both in mechanical and commercial terms - must involve consideration and satisfaction of the following basic principles:

(a) That the final product of which the component forms part, shall function efficiently under service conditions. This implies that each component part shall meet minimum standards of durability under working conditions relevant to the operation of the whole, commensurate with an economic working "life".

(b) That the above requirements shall be met effectively by a combination of material selection and processing route at minimum overal cost.

The project has studied the bearing of the above factors on the utilisation of engineering steels. Technical and economical considerations governing steel selection in design and manufacture have been observed by means of a survey of major sectors of engineering industry where, if the magnitude of the steel user sector is considered together with the capital involved in all aspects of manufacture, it was felt that the critical interest of an impartial researcher could have significant economic repercussions.

To ensure reproducibility of product and its reliability when in use, component manufacture is covered by a series of specifications against which material selection, proving and acceptance checks are set as well as the control of subsequent processing and testing stages.

The technical basis of the present work considers the true nature of steel specifications and their effectiveness in presenting data of engineering and metallurgical relevance to design requirements. The economic importance of specifications becomes plain if material cost is accepted as a fundamental property. Deficiencies in materials data presentation foster over-design to ensure minimum performance requirements in a product; satisfying "factors of ignorance", whether these arise from short-comings either in design analysis or in material specification, implies uneconomic utilisation of raw materials which, in mass-production industries can contribute 40 to 70% of total manufacturing costs.

Prior experience of industry from both steel-producer and steel user viewpoints had shown the existence, almost universally, of steel mis-application of this kind with considerable scope for implementing raw material cost economics without detriment to the performance of the end products. It is suggested that such implementation requires no new ideas or theories (1). Steel compositions have become established at the dictates of steel-making traditions now lost to history and arising from obsolescent practices (2, 3). In particular, it may be suggested of heat-treatable alloy steels that the properties with which covering specifications endow them have been developed in response to apparent rather than real engineering requirements (4-6). Considered application of basic metallurgical principles, guided by economic considerations has already resulted in commercial manufacture of cheap, simple composition steels which can meet the property requirements attributed by specifications to "conventional" standard steels, with 50% saving on raw material costs (7). The same means, it is suggested, can be applied to steel selection enabling a product to meet in-service requirements adequately and at minimum cost, fully exploiting its mechanical properties by precision thermal and mechanical treatments of the kind already common to mass-producing industries. It remains to unify these approaches into realistic steel specifications, in terms of properties meaningful in design, obtainable in the most economic fashion by sensible use of thermo-mechanical treatments on cheap, simple compositions.

1.1 The Pattern of Steel Consumption in Engineering Industry

The mid-1968 level of steel consumption by all industries in this country was of the order of 330,000 tons/week (8), representing net home delivery figures of all qualities of finished steel. Table 1 lists the major end-users of alloy steels, some 20,000 tons/week being classed as such by the British Steel Corporation definition i.e. "...containing by weight at least 0.1 per cent of molybdenum or tungsten or vanadium, or 0.4 per cent of chromium or nickel, or 10 per cent of manganese" (8).

Annual production of alloy steels for the period 1962-67 is tabulated in the Year Book of the Corporation (9). Table 2 presents data from this on the areas of steel production of direct importance to engineering manufacture. Some three quarters of alloy steel production is accounted for in the categories listed, the balance comprising stainless steels (12 to 14.5% of annual tonnages) tool, die and magnet steels (2.5 to 3%) and high speed steels(0.9 to 1.2%). Where possible steel grades in common usage are matched to the B.S.C. compositional categories, together with mid-1968 basis prices.

A further source of information (10). volunteered percentaged data only on:

(a) The delivery of alloy grades in billet form for re-rolling to black bar.

(b) Black bar alloy steel deliveries to bright-drawers.

This data, presented in Table 3, accounts for about 40% of deliveries

FINISHED STEEL DELIVERIES

Average Weekly Tonnages - Mid 1968

Major Consumers	Alloy Steel	Non. Alloy Steel
Drop Forging	6,430	7,590
General Engineering	1,980	4,780
Motor Vehicles	1,880	31,770
Stockholders	1,100	57,770
Wire	1,030	22,780
Consumption (All Industries)	20,260	306,100
	326,360 tons/wk.	

TABLE 1.

Based on (8).

ANNUAL PRODUCTION OF ALLOY STEELS, 1962-67 (TONS x 10^{-3}).

	1962	1963	1964	1965	1966	1967	Eqviv. En Steels	Basis Prices*
Ni-Steels	20.1	23.2	30.6	29.1	21.4	20.3 (1.4%)	10, 12, 21, 22, 33, 37, 51	£76.5-£119.6
Cr $\leqslant \frac{3}{4}$C	126.2	132.3	131.1	150.6	152.1	110.1 (7.7%)	11, 18, 48, 206, 207	£72.0-£74.2
$> \frac{3}{4}$C	105.5	102.6	140.5	115.4	115.3	104.6 (7.3%)	31	£82.75
Mo-Steels	169.8	213.6	237.5	248.6	218.8	180.4 (12.5%)	16, 17	£79.1, £84.2
Ni-Cr $\leqslant 2\frac{1}{4}$Ni	49.0	66.3	86.0	74.1	59.2	57.9 (4.0%)	111, 351, 352	£78.7-£82.6
$> 2\frac{1}{4}$Ni	16.6	19.2	29.3	27.2	24.8	21.0 (1.4%)	23, 30A, 36A, 36B, 39A	£104.6-£123.75
Ni-Mo Steels	99.3	115.8	122.3	119.6	102.3	89.5 (6.5%)	13, 34, 35, 38, 160	£81.7-£141.75
Cr-Mo $\leqslant$ 0.4Mo	97.0	114.5	147.7	159.8	151.3	147.5 (10.2%)	19	£81.7
$>$ 0.4Mo	51.8	59.5	67.8	80.1	75.8	61.0 (4.3%)	20A, 20B, 29, 40A, 40B	£92.1-£110.3
Cr-V Steels	8.5	9.0	9.7	11.0	14.3	15.1 (1.1%)	47, 50	£82.8, £83.4
Ni-Cr-Mo $\leqslant 2\frac{1}{4}$Ni	169.3	216.8	275.5	265.6	230.3	215.5 (15.0%)	110, 325, 353-5, 361-3	£88.9-£105.8
$> 2\frac{1}{4}$Ni	49.7	64.0	79.5	76.7	61.5	54.5 (3.8%)	25-8, 30B, 36C, 39B	£118.6-£128.25
Totals:	958.8	1216.8	1357.5	1357.8	1227.1	1187.4 (75.2%)		*) Bar steels
Absolute Totals	1224.7	1444.7	1771.1	1786.1	1608.1	1435.7 (100%)		

TABLE 2.

Drawn from (9).

ALLOY STEEL DELIVERIES TO REROLLERS AND BRIGHT-DRAWERS

(Expressed as % of whole).

GRADE	Billets (a)		Black bar (b)	
	1966	1967	1966	1967
En 16	13	13	12	10
En 18	10	9	11	10
En 34, 35, 160	10	9	7	7
En 36	2	2	2	3
En 39A, B	0.5	0.5	0.5	0.5
En 351	2	3	4	4
En 353, 110	3	2	3	2
En 355	0.8	0.8	0.5	0.7
% Totals	41.3	39.3	40.0	37.2

(a) % of all deliveries of alloy steel billets to rerollers.

(b) % of all deliveries of black bar alloy steel to bright-drawers.

TABLE 3.

Drawn from (10)

in each category. Its more specific treatment by grade gives quantities of the same relative magnitude as Table 2 lists.

The figures do not reveal any significant trend in steel utilisation pattern, partly because of the method of classification employed and also because against the figures must be set the level of activity of steel user industries.

The largest single consumer industry in terms of delivery tonnage is motor vehicle manufacture, taking some 34,000 tons of finished steel per week (8), or rather more than 10% of the total direct delivery. In terms of carbon and alloy categories, the motor industry's share of each was again 10%, as Table 1 indicates. The drop-forging industry consumes almost a third of all alloy steel deliveries (6,430 tons/week as of mid-1968) together with 2½% of total non-alloy steel manufacture (7,600 tons/week). The average material utilisation commonly achieved in drop-forging is 75% and, over the past 10 years, the ratio by weight of carbon steel to alloy steel forging production has remained fairly constant at 55/45 (11). However, Table 4 shows that 75.5% of drop-forging production contributes to motor vehicle manufacture, representing a further 8 to 10 thousand tons of steel per week entering this industry; 98% of the production from the largest drop-forging producer is for the motor industry. Thus, if the average price of bought-in steel is assumed to be £80 to £90 per ton and the average cost of black forgings is £180 per ton (11), the weekly cost of steel to the motor industry as its basic material of construction is £4½ million.

A recent projection (12) has considered that British motor-vehicle population will rise to 15 million by 1970, and possibly to 22 million in 1980. At this latter level, allowing a 10 year vehicle life, the industry and its supporting component-manufacturing firms must maintain a replacement figure of 2.2 million vehicles or

DROP FORGING PRODUCTION, ANALYSIS % BY USER INDUSTRIES.

Year	Total Tonnage	Motor Industry	Mechanical Engineering	Mines	Aircraft	Railways	Ships	D.F. Own Needs	Others
1963	552,000	71.6	7.1	2.8	1.0	0.9	1.0	9.8	5.8
1964	643,000	77.2	6.0	2.6	1.0	1.2	0.6	5.8	5.6
1965	662,000	75.0	7.4	2.3	1.6	1.2	0.8	6.0	5.7
1966	621,000	75.5	7.7	2.5	1.2	0.8	1.2	5.0	6.1
1967	556,000	75.5	5.5	2.3	1.4	1.3	1.0	5.0	8.0

TABLE 4.

Drawn from (11).

vehicle sets per annum, or over 40,000 per week. This excludes production for export, routine servicing and spares. Thus it was estimated that output at 70,000 units per week, (as of Jan. 1966) would be required to rise to at least 100,000 units by 1980.

The automotive industry maintains its activity by manufacturing precision engineered components by the maximum utilisation of mass production techniques whereby materials contribute 40 to 70% of total production costs. Conventional approaches to the expansion in markets envisaged would be to enlarge factory capacity and increase the labour force employed. But such methods cannot be justified without overall improvement in productivity, which must make a major contribution to increased output if competitive manufacturers are to remain so. Such tactics must necessarily involve even further exploitation of mass-production methods, but the complete reappraisal of existing practices by means of value analysis and value engineering must supplement the gains from new investment. In all such areas of engineering manufacture, where raw material cost must be regarded as a material property equally as important to engineering design as the material specification itself, an analysis of the basis for material selection in design becomes a fundamentally important part of any such exercise.

1.2 Definition of Industrial Needs

Published statistics (8) summarising steel supplies to consumer industries record tonnages under general classifications, such as "non-alloy" and "alloy" which are again subdivided into descriptions of finished steel tonnages - for example, ingots, plates, wire rod, bright steel bars etc. The figures serve only to show the scale of the market and thus indicate, for example, the economic importance of motor vehicle manufacture in terms of steel consumption.

Attempts to secure more informative production figures for engineering steels, in terms of grades or qualities and the finished section sizes and weights of bar and forging steels on delivery, proved futile. It did not prove possible, therefore, to scrutinize patterns of steel manufacture and purchase by grade, which would reveal the more obvious areas of over-specification, e.g. mis-matching of through-hardening steel-composition to section size, or production of high alloy content heat-treatable steels which standard "economy" steels have tended to replace (En 33, Ni at £99.5 per ton as opposed to En 351, ¾% Ni Cr (£78.7 per ton) case hardening steels). Both Tables 2 and 3 show the "popularity" of En 16 (£79.1 per ton), a through-hardening manganese-molybdenum steel. It would be interesting to investigate the section sizes in which this is used, and to query why the similar, molybdenum-free En 15 (£45 per ton) could not adequately replace En 16 in lighter sections. Several "non-alloy", non-B.S. steels are marketed as replacements for En 16, up to £20 per ton cheaper than the latter (7).

The only reasonably complete source of quantitative information of the kind required was not open to detailed reference but it was learned that its acquisition was purely a by-product from the method of levy assessment on member companies of the association concerned! The assessment of industrial requirements was therefore reduced to:

(a) surveying the production and marketing of steel from maker/supplier aspects, and observing variation in steel buying patterns among consumers in a given industry.

(b) direct approaches to user companies to determine their individual patterns of steel selection and utilisation.

Approach (a) was pursued by circulating a description of the project and its aims to about 200 steel suppliers - primary producers, re-rollers, bright drawers and steel stockists. Replies from 50% of the circulation provided a general pattern of the principle sources and nature of supplies to industry, but quantitative information was withheld on grounds of "customer protection", thus rendering this form of survey ineffective. However, an introductory field study period in an electrical component manufacturing company had indicated that direct liaison would prove more informative in assessing existing steel utilisation patterns and in defining true industrial needs. Information of direct importance to the survey was <u>not</u> confidential in nature, and production details sought could have been determined by purchasing finished products on the open market and analysing their manufacture. Such is the admitted practice of competitors within industry, and can give rise to comparisons of the following kind:

The finished weight of alloy steel components in a small family car, - in current production and a consistent best seller -, is about $\frac{3}{4}$ cwt.; the number of alloy steel grades used is 19. Another British vehicle of similar size and performance, has a similar weight of steel shared among half the number of grades, including both carbon and alloy steels. In the former model a component is machined from alloy steel bar costing £90 per ton, while in the latter a plain-carbon steel extrusion answers the same purpose, at half the material cost and optimum material utilisation.

Such anomalies in the selection and utilisation of steels are incompatible with the projected growth characteristics of the motor industry (12). The purpose of this project has been to establish the technical and economic factors which govern the use of steel in engineering industry. While examples of steel diversification similar to those given are not exclusive to motor-vehicle manufacture, the very nature of the industry, its importance in the overall economy, its role as the largest user of alloy steel and its enforced interest in precise production methods, make it well-suited to survey. Extended field studies have been undertaken at the invitation of motor-vehicle and component manufacturing companies enabling discussion of steel selection in design and steel utilisation to be conducted with designers, buying office personnel, cost accountants, production engineers, metallurgists and materials engineers, value analysis and value engineering teams. In particular, the utilisation of heat-treatable steels was considered.

1.3 Synopsis of Field Studies in Engineering Industry

Introduction

Field studies concentrated on the selection and processing of engineering steels for motor vehicle manufacture and for the production of components almost exclusively for the industry.

Planning and execution of worthwhile study visits hinges on the availability of senior personnel for discussion, to some extent determined by immediate production demands. While such problems can be overcome, commercial secrecy may create difficulties of communication which cannot always be resolved. Where facilities were given for departmental discussions, it was found that the following itinerary took about a week to execute effectively:

(a) Summary of company structure, with particular reference to the standing of materials management.

(b) Buying office procedure, centres of supply, stock-holding, price negotiation, cost extras, etc.

(c) Materials acceptance and testing.

(d) Design office procedure, design criteria, company specifications, steel selection in design.

(e) Manufacturing processes, demands made on materials, efficiency of materials utilisation, costing of alternative processes or processing routes.

(f) Heat treatment and surface treatments - plant operation and control, quenching systems, costing of comparative treatments.

(g) Component testing.

(h) Developments in materials and processes, e.g. forgings v. castings, powder metallurgy, HERF etc.

It was not always possible to discuss all of these topics freely, nor were moves to do so always welcomed. Costing information of any kind was rarely given or permitted to generate discussion.

The manufacturing interests of companies visited and the scope of survey at each is outlined in Table 5. Ancillary studies included discussions with heat-treatment furnace manufacturers and industrial quenchant producers.

It is seen that extended surveys were possible at only a few of the major producers in the motor industry. Passenger car manufacturers alone number 32 in this country, not necessarily operating as independent companies. At the time of survey (late 1966 to mid 1967) the major grouping of British automotive interests had not occurred, but it was found that member-companies of the groupings then in existence maintained absolute autonomy over production matters, including material specifications and design criteria, purchasing and stockholding procedures to name the most

Code	Manufactures	Nature of Survey		Contact
		Duration	Extent	
A	Motor vehicle electrical components	2 weeks	Met. dept. Heat treatment	Chief metallurgist
B	Heavy diesel road vehicles, buses	1 week	Met. dept.	Chief metallurgist
C	Cars, vans, trucks	3 weeks	Departmental tour	Chief materials engineer
D	Cars, vans, trucks	3 days	Met. dept. Value analysis Heat treatment	Chief metallurgist
E	Brakes, suspensions, clutches etc.	1 week	Departmental tour	Value engineering
F	Cars	1 week	Materials dept. Buying office	Chief metallurgist
G	Gear boxes, transmissions	Day	-	Chief metallurgist
H	Diesel engines	Day	-	Chief metallurgist
I	Cars, vans, trucks	Day	-	Materials engineer

TABLE 5.

obvious. Thus, not only were divergencies of steel selection and processing decisions found among the major manufacturing groups, but equally marked contrasts were observed among member companies of a group.

The use of alloy steels was the prime objective. Initially, the production of components from bar was considered, being the extent of interest with Companies A and B. In the event, it proved that Company B was possibly a major user of bar steel among vehicle manufacturers. Car producers, having larger vehicle outputs to sustain than do commercial vehicle builders, buy-in most components of bar steel origin; bar steels represent almost the total alloy steel consumption of Company E. Forgings constitute the major part of alloy steel usage and were considered in addition to bar steel on all other visits.

Also of interest, were areas of manufacture where "traditional" materials and manufacturing methods were being challenged e.g. the replacement of alloy steels by malleable irons, sintered powders etc.

1.3-1 Steel Specifications

The survey covered those sectors of industry for whom BS 970 (13) was originally drawn up, as a specification for the purchase and application of steels "for automobile and general engineering purposes". Adherence to BS 970 specifications predominated in the majority of companies visited, but the adoption of SAE specifications (14) is growing. Company specifications with comprehensive coverage was rarely found; those of Company A were drawn up to meet the needs of component manufacture, involving small ruling section in heat-treatment and requiring good machinability and formability etc., while Companies C and H had adopted, with little modification, parts of BS 970 and SMMT data sheets (15).

Company C standards refer back directly to BS 970 for details of manufacture, heat treatment definitions, test procedures and chemical composition, but detail minor descriptive and property differences e.g. fracture appearance on "selected" En 1A, condition of material as supplied, yield stress requirements for En 3A, En 32 variants, En 35, En 36A, En 351 and 352, En 361, while all orders and drawings for alloy case-hardening steels must be endorsed "to be fine grain size 6-8, and to be single quenching quality". One SAE steel is included with En-case-hardening steels - its detailed specification is not referred to. Recently, company specifications have been introduced to cover CMn "economy" steels (7). A price order listing of heat treatable steels is given, based on ultimate tensile properties and limiting ruling section.

Official usage of BS. 970 throughout member firms in company C dated from the merging of manufacturing interests in 1951. While one of the firms involved had worked from BS. 970 since its inception, specifications of another were based on wartime "WV" steels. The WV numbering system was retained, modified by symbols indicating mechanical properties, until rationalisation brought BS. 970 into general use. Schedules revised in 1962 provide cross-references to the obsolete nomenclature and drawing revisions still include transfers from the earlier, pre-merger coding to En-numbers. Elsewhere in the same organisation, a member firm has retained its own specifications for bodywork and chassis materials.

Company H's Materials Standard No.1, covers wrought steels under the headings Type (e.g. soft mild, carburising, steels for localised hardening by flame or induction etc.), Specification (British Standards without exception) and Properties and Uses (to act as a guide to material selection and summarising mechanical property features of British Standards). Again, reference to the relevant British Standard is necessary for detailed description of composition or properties. A "best buy" guide for a given section size and tensile range is taken directly from SMMT Standard 79.

Company D works to both BS 970 and SAE compositional standards. For En-steels, minimum acceptable sulphur levels are defined where desirable in assisting machinability, and grain sizes are specified. SAE-specifications are used because of the closer carbon control they ensure. While hardenability requirements do not appear on specifications, they are used as acceptance checks on cast-by-cast purchases of forging steels. Company B also works to BS 970, - indeed, this specification was proferred when a copy of the company's steel standards was asked for - with closer compositional tolerances on some heat-treatable steels to "ensure hardenability". No SAE-steels are used. Reference was made here to interest in a "controlled residual levels" steel, but it seemed that no company specification was held for this. Component manufacturer E adheres to BS. 970 steels almost entirely, while claiming to be fully aware of the Standards' inconsistencies and weaknesses. Company specifications exist for steels for critical components, notably for an induction hardening En 8D type, to control surface quality and cleanliness, carbon and sulphur segregation, and to detail the preparation of mechanical test-pieces. The company is considering wholesale adoption of company specifications for steel, if only to cover the "uncertainty" period which the introduction of the BS. 970 revision is likely to cause. These would simply ensure that the present ordering system could continue until the new BS. 970 format had been adequately assessed against company needs. At Company F, there are no comprehensive company specifications, British Standards being used wherever possible. But the move is away from BS. 970 to SAE steels for forgings, while bar materials remain on En-standards. Modifications to BS. 970 specifications cover compositional tolerances in particular, e.g. carbon control in induction hardening steels, and <u>minimum</u> sulphur requirements of 0.025% as information implicit to BS. 970 ordering. Forging steels are being rationalised on SAE 4620 and 8620, specified by composition only; no hardenability response SAE-H specifications are used.

Company G has adopted SAE specifications for high-volume areas of production, and the bulk of heat-treatable steels are specified by hardenability standards, but not necessarily to SAE-H bands. Where steel consumption is low, BS. 970 En-steels are used, specified by composition alone. To ensure machinability consistency, maximum and minimum sulphur levels are quoted for all steels.

1.3-2 Steel Selection in Design

In addition to satisfying engineering requirements of a component, the selection of steel for mass-production manufacture must involve consideration of steel cost as an important design parameter. The component is required to perform efficiently and effectively at minimum overall cost. However, it soon became clear that this is not always considered important, and that the attitude to raw material costs is modified to some extent by the nature of the end product. There exists in some design offices and purchasing departments confusion over what really constitutes "quality" in the end product. The erroneous view is heard that, to cheapen component costs in manufacture by the utilisation of more economic manufacturing materials and processes, is to deny the customer "quality", even though performance of the end product remains unaffected.

Thus, manufacturers of commercial vehicles, coaches etc. argue that they offer to their customers a capital investment from which considerable returns are possible over a number of years. The situation generates the attitude that material and production costs are secondary to the maintenance of a reputation for reliable, well-proven products, whether or not materials are overspecified in the light of continuous improvement in the efficiency of processing methods. The fallacy of this argument is illustrated most clearly by the experiences of a company manufacturing heavy earth-moving vehicles (16, 17) where material cost reductions have been made to the benefit of the customer financially, without detriment to vehicle life or performance. Compare the American attitude: "...it's just smart engineering to add quality and hold down costs at the same time." (1).

It would be expected that the converse of the commercial vehicle builder's attitude would exist among producers of motor cars. The car has a high rate of depreciation, and yields no direct monetary gain from use by the major part of the consumer market. In such an area of manufacture, supplying to a very cost-conscious market, it would be expected that interest in materials economies would be high. While this is reputedly so, cost conscious evolution of materials selection methods may remain restricted by the same "traditionalisms" and misguided "quality" arguments. The dependence in material selection on specifications which are in themselves "traditional" in property designation maintains this situation. As well as being questioned on the design criteria to which they worked, designers and materials staff were also asked to suggest how steel specifications could be improved to increase their effectiveness from both engineering and economic viewpoints. It should be mentioned that direct access to design staff was very limited - only at companies C and E was this possible to any extent - and that discussion of selection in design was predominantly held with metallurgical staff, either operating as such or forming part of a general materials engineering section.

1.3-3 Design Criteria

General engineering practice employs ultimate tensile strength as the primary design criterion. This is so in the British and European motor industries at least; UTS is the basis of most material specifications, including the BS. 970, En-specifications.

UTS represents stress characteristics of a steel after large amounts of plastic strain have taken place. Stresses imposed in the majority of engineering situations confine strains to the elastic range and plastic yielding would render components useless; "service failure" does not necessarily mean ultimate disintegration of a component. Recognition of the limited significance of UTS as a design criterion has led a minority of design offices to apply yield stress or proof stress criteria to steel selection in design, but a general adoption of such criteria is thwarted by their omission from the contractual parts of standard steel specifications (13). Their omission from <u>company</u> specifications was commonly found, also.

The adoption of the yield criterion is a more realistic approach to <u>static</u> loading, but the majority of practical situations involve complex combinations of static and super-imposed alternating loads, leading to failure by fatigue. UTS or yield strength is used in the construction of variants of Goodman diagrams (18) which indicate significant strength for design purposes. While such a procedure was discussed in a design office, and illustrated by reference to the design of a crankshaft, an independent but interested authority considered this "an exceptional case" for the industry in question, where Achbach's "evolved techniques" (19) remains the most usual approach!

At the same company, design staff pointed out there are definite limits to originality of design around the basic 4-stroke engine. Thus any new design was 90% dependent on previous experience with earlier designs and such was the case with the selection and processing of materials of construction also, it was maintained.

Attempts to design on fatigue data were under active consideration at two companies visited. Company E had consulted with Motor Industries Research Association on the comparative fatigue performance of steels shortlisted for a critical design and was itself engaged in generating specification data strictly relevant to component service conditions, from "simulated ride" test rigs.

Mechanical properties such as elongation and impact values which, in BS 970, are contractually binding on the steel supplier are also strictly insisted upon by most design offices, although on the significance of Izod value for a particular motor vehicle component - classified "critical", because its failure would mean loss of control of the vehicle - complete divergence of opinion was found in the same design office. The opponents of high Izod values based their objections not so much on the validity or otherwise of the test itself, but on the experiences of American manufacturers. A steel commonly used for a particular component in the States has a fatigue strength superior to that of a BS steel used here, but its adoption here is rejected on the grounds of its poor impact strength (3-5 ft. lbs.), the British design specifying 30-40 ft. lbs. While the absolute rightness of their case is debatable in the context of such a component, it stands as an example of inexact or artificial requirements being placed on the choice of materials leading to the selection of unnecessarily expensive materials and also, in this instance, unnecessary restrictions on the manufacturing process (5).

Design considerations of wear resistance in service may be accommodated by empirical means in design stress analysis (20, 21). Recommendations on corrosion resistance may be passed over entirely to materials personnel.

The use of BS and company standards has already been outlined. In addition, materials engineers or metallurgists may furnish the designer with general guides to steel usage, in terms of typical end-products, or in cost terms (15). In some quarters it was found on survey that design staff considered such schedules more useful to them in making material selection decisions than either British Standard Specifications or company specifications, which were termed "collections of metallurgical jargon". Constructive criticism of existing BS schedules where given called for proof stress data and guidance to notch sensitivity characteristics of steels in preference to Izod figures. For the most part however, BS 970 criticisms were metallurgical in nature and echoed the numerous papers which have discussed this aspect (17, 22, 23).

1.3-4 The Selection Decision.

Material selection in design remains the designer's prerogative and total responsibility. Ideally, his decision is made in accordance with the design criteria adopted for a given component, and the stress calculations arising from the application of the criteria to the engineering situation. This would imply comprehensive stress analysis for every prototype or re-designed component, and for every situation involving additional loading on existing components. As had already been mentioned, this is not always so and reference is often made to what has gone before, transferring material specifications from one drawing to the next, with only a cursory treatment of modified loading detail. An exact "fit" is rarely aimed for. Over-specification and safety factors in design calculations accommodate the likelihood of design "stretching" and the increased in-service loading of critical components, which such development brings. This practice is found in all sectors of the automotive industry and multiple utilisation of parts and assembling over a "range" of models is particularly common in commercial vehicle design. Up-grading to higher UTS steels is regarded as a more expedient solution than accurate design reassessment; the efficiency of such a solution is is debatable where fatigue resistance is the true measure of component performance (figure 1.) (24).

There is an increasing tendency for materials' staff, metallurgical or otherwise, to exercise some measure of control over material selection, however. All drawings from the design office bear a material specification given by the designer, but it is common practice for this to require the approval of either the Chief Materials Engineer or the Chief Metallurgist. It is thus possible in theory to question and suggest amendments to the designer's decision; in practice, the procedure can be little more than a "rubber stamp" operation, it being easier to refer to prior proven selections than to consider each design recommendation anew. No revision of a specified material can be made without design office approval.

The influence of the materials engineer or metallurgical staff on the selection decision is largely determined by the respect in which they are held by the design office. Inter-disciplinary suspicion was found in all quarters and can constitute a barrier to efficient, economic operation. Thus, the title Chief Materials Engineer promises more effective liaison than would be possible under the title Chief Metallurgist! Company organisation and management structure may also influence design office opinion of the standing of metallurgical staff, who may be regarded (often correctly) purely as quality control personnel. The so-called research laboratory may be required to fulfil this function only and, with its associated personnel, be ranked as a service department in the management structure, alongside fire and ambulance services, and canteens! In such conditions, it is more likely to be the chief buyer who holds the designer's attention on material selection decisions more effectively than can materials staff, and on occasions his word is based on more informed and contemporary opinion. The expression that "steels have been with us a long time", was heard from several materials men who, although of metallurgical training, are having to contend with the application to manufacture of plastics, rubbers, paints, adhesives etc.; preoccupation with problems of the unfamiliar tends therefore to lead to neglect of the familiar.

Designer/materials engineer liaison is most effective in companies employing value analysis techniques, where round-table discussions at the early stages of design conception bring together designers, production engineers, cost accountants and materials staff. Within the limitations that traditional means of material specification impose, the closest match of design to material and processing route can be made, with overall cost the guiding criterion. But again, the rationalisation in materials that such action can produce at the start of a new design is rarely carried through to consider established designs which have been in quantity production for some time, partly for reasons of "reliability" heard elsewhere. However, it was from such interdisciplinary environments that most criticism of data presentation in existing steel specifications came. Meaningful scheduling of data for design would require the fullest co-operation between engineers and metallurgists (6); it is perhaps significant that the shortcomings of existing specifications are more likely to be recognised where this is already effective.

1.3-5 Amendments to Material Selection

Resistance to change is understood more clearly by taking a broad appreciation of the cumulative effect of altering one or more factors in the manufacture of an established product. Reasons (21) for requiring a material change include:

(a) The need to reduce basic material costs.
(b) The need to reduce production costs.
(c) The need to solve materials processing problems arising

in production.

(d) The need to make a functional change, or improvement in service performance, reliability or life.

(e) The need to take every advantage of a new material or new processing development.

All of these should be the working brief of every materials engineer; all are the obvious aims of value analysis teams, where this technique is used. But they emphasize that material selection is not a simple single-stage process, and it is necessary to consider the co-relation between the material and the means on hand for processing it in order to use a material effectively or to replace it for any of the reaons quoted. To do this requires the co-operation of not only designers and materials staff, but also that of production engineers and cost estimators among others. The decision to effect a material change may depend on the costing system employed. It may be found that reassessment of rates for production operatives working on the revised form, at contemporary labour costs, can result in higher costs in the short term, diminishing only comparatively as other allied costs rise. For example, a materials team combining design, engineering and metallurgical experience of steel selection were able to effect raw material economies by the rationalisation of heat treatable steels in a new engine and gearbox design, to SAE 4620 and 8620. To carry the exercise over to other models which had remained virtually unchanged in design for some seven years was prevented by the revision of job rates which this would require, which could not be accommodated in the current vehicle price.

Where materials or metallurgical staff have difficulty in convincing designers on the economic advantages of alternative materials or processing routes, it is common for them to run their own processing and rig- or service-testing trials. While such tacics can pointedly demonstrate material over-specification or mis-application, design office rejection may conclude successful trials of this kind. Even within organisations having well-developed costing-economics sections, covering all materials of construction and finishing, a sense of frustration was evident due to design office inertia and misunderstanding of the true meaning of material or process substitution or replacement, although the record of such sections more than justified their existence. From one such group came the following case histories:

(a) En 34 (2% Ni, Mo) was "traditionally" selected for rear-axle gear forgings for commercial vehicle manufacture. A 20% material cost saving was made by changing to SAE 8617 forgings, without impairment of production rates or of properties in the gear assembly. It was accepted by the design office. In a subsequent design, for no apparent technical reason, the design office reverted to En 34 specification.

(b) It was found that by using En 355 peeled black bar, instead of bright-drawn En 355 bar, a cost saving of £3,000 per annum was possible on lorry rear axle production. It was later shown that replacing En 355 by a proprietory CMn steel (7) would realise a further £3,000 saving. Trials showed that this economy steel would give 3 to 4 times the life of En 355, but the design office retained the latter specification.

Yet, the activities of the same cost economies group, of which the steel interests formed but a part, were able to effect savings worth £$\frac{1}{4}$ million per annum.

It is interesting to follow material changes effected by a major U.S. producer in manufacturing motor vehicles rear axle crown wheels and pinions, yielding material costs savings without loss of performance:

Originally, SAE 4820 ($3\frac{1}{2}$% Ni, Mo steel) was employed. Changing to SAE 6420 (2% Ni, Mo) gave savings of \$$2\frac{1}{4}$/100 lb. steel. Now, the same gears are forged from SAE 4020, carbon molybdenum steel saving a further \$$1\frac{1}{4}$/100 lb. steel. The adoption of progressively leaner alloy steels has only been possible by close heat treatment control to utilise the 20-points carbon common to all these steels, effectively leaving engineering "requirements" unaltered. The company attributes direct material cost savings of \$ 1 million per annum to precision process control, enabling lean alloy steels to be exploited. (25). A wider appreciation of American practices and attitudes can be gained by reference to the numerous case histories reported in (1).

1.3-6 Purchasing and stockholding.

Steel scarcity, once due to the inability of manufacturers to meet the needs of expanding industrial activity, no longer affects the motor industry, - although special orders may incur delays of, for example, up to a year (for cold-drawn stainless steel tubing). Yet in spite of the general opinion that steel purchases had never been easier, and that it is "a buyer's market", a reluctance was found to rationalise sources of supply. While buyers will deal with three or four sources of steel for forgings, and commonly with only one, bar steel purchases may involve twenty or more suppliers.

Forging steels can be more readily controlled from purchase at the steel-maker, through stock-holders and on to the forgers, company G for example retaining steel cast identity on gear forgings through heat-treatment to final gear-cutting. Coding systems relating forging blanks to steel cast origin are widely used to plan production sequences, particularly where hardenability response on heat treatment is important (23) and to cover test or in-service failures. But few manufacturers exert any control at all on the origins of bar material, purchased from re-rollers, bright-drawers or stock-holding intermediaries. Consumption of bar material rarely merits the buying of steel by the cast, except possibly by component manufacturers; motor vehicle manufacturers buy-in ready made the majority of components of bar steel origin.

The complexity of bar steel purchasing and stockholdings to maintain cast identity can be imagined from the following:-

(a) At the works of company E, a component manufacturer, the automatic lathe shop takes some 200 tons of bar steel per week, in 600 steel grade/bar size combinations, to produce 3 to 4 million parts. 55% of the bar used has free machining additions. 100% acceptance testing of bar stock is claimed, rejects averaging 6% of total purchases.

(b) Motor vehicle manufacturer C uses 200 tons of bar steel per week, bought in from 20 different sources of supply, in 128 steel grade/bar size combinations.

Reluctance to reduce the number of bar steel suppliers stems from times of steel shortage, when it was often difficult to maintain day-to-day production without relying upon several sources. Retaining this attitude precludes the adoption of proprietary steels, for example, the various forms of carbon-manganese "economy" steels. These are as yet outside British Standards; their uniqueness of supply is an excuse frequently used to explain their limited exploitation to date by industry. While supporting this attitude, company F relies exclusively on a single forging supplier, who uses forging steels from one source within the same engineering group! Yet company G limits all its steel purchases to three sources and, by rationalising the number of grades used, is able to order steel by casts which are held in stock by their re-rollers, bright drawers and forgers at no extra cost to themselves. At the same firm, all "economy" steels are investigated and assessed in production; at least one such steel has been adopted successfully, its uniqueness of source being of no concern to the company.

The traditional aim in motor vehicle production is that finished vehicles shall pay for the materials that have gone into them, implying that stock-holding time and costs are kept to a minimum. Up to three weeks stock is held by most companies, the startling exception being company B, where bar steels stocks for nine months production was quoted, re-ordering at intervals of eight weeks. It is believed that this practice has now been discontinued in favour of the three week cycle, under the guidance of buying office and stock control personnel from another works in the same combine.

Iron and Steel Board price schedules, which controlled the purchasing of steel at the time of survey, were discontinued on the nationalisation of the industry (July 1967). Pricing schedules are now produced by each steel supplier, but the groupings within the British Steel Corporation framework prevent price undercutting. However, the survey revealed that ISB schedules were regarded more as a guide to steel prices, and never rigidly applied. Scheduled cost extras were avoided by private agreement, and by specification "intent" (26). Rebate on scrap returns and discount schemes were in general operation.

Steel buyers were found to interest themselves in steel selection, maintaining non-technical liaison between designers and laboratory staff, questioning material costs and drawing attention to cheaper alternatives - but usually with the proviso that standard steels only were considered.

1.3-7 Production Processes

The primary metal-forming processes applicable to engineering steels are reviewed under the following headings:

(a) Manufacture of components from bar by metal removal methods, (i.e. machining).

(b) Component manufacture from forgings, with or without finish machining (i.e. dropforging, extrusion and precision for ming processes).

In certain sectors of industry, such conventional forms of manufacture are being challenged by other processes, substituting bar products and forgings by:

(c) castings,

(d) powder metallurgy products.

a. Manufacture from Bar Material.

Bar steels are used in quantity primarily by component manufacturers supplying to the motor trade. Thus, company E takes 200 tons of bar steel per week, in over 600 grade/bar size combinations to maintain production of 3 million component pieces. About 200 five and six-station automatic lathes are used to produce 2,000 different components. At motor vehicle producer C, 200 tons/week bar stock consumption compares with 700-800 tons/week of rough forgings and 700-800 tons/week of steel for pressings; bar steel consumption at B amounts to 80-100 tons/week, the company tending to make components in its own works rather than buying in from such firms as E.

British Steel Corporation statistics (8) are not sufficiently detailed to indicate percentages of black bar and bright bar used by engineering industry. The black bar figure is incorporated with a total for hot-rolled sections but for the motor manufacturers visited it appears that no more than 5% of bar material was used in the as-rolled condition. Bright drawing is said to enhance machinability but the "work-hardened surface layer is only 0.025" deep on average, and quite ineffective on realistic machining practice (27). Its prime value is in providing size tolerances necessary for auto-lathe handling. Except on hexagonal sections, it was found that the bright drawn finish was rarely retained as part of the component surface. Table 6 shows the cost differentials for black bars and bright drawn bar.

By purchasing En 355 as black bar and peeling this at the works, company D claimed savings of £3,000 per annum on lorry rear-axle manufacture. Yet, by contrast, Company B specifies turned bar for the manufacture of fulcrum pins, shackle pins etc in order to guarantee a seam-free surface, although it was admitted here that this reasoning is probably inapplicable to present day rolling practice. It is known that close-tolerance black bar is being produced for auto-lathe machining but its adoption was not recorded.

For auto-lathe production, high output rates are achieved by the use of leaded or re-sulphurised steels; 55% of the bar steels used by Company E have free-machining additives. Small gears are hobbed from leaded bars e.g. differential pinions up to 2½ inches in diameter. Forging blanks requiring considerable machining, as with larger motor vehicle gears, are also of leaded steels. The assessment of the effects of machining additives can only be done with any certainty with high production rates of a limited range of components, where machine tool variables may be optimised for each machined shape.

	B.S.-Type	Forging billets	Black bar	Bright bar
0.5-1.0 Ni	En 10, 12	£54.13.0	£ 77.13.0	£110.19.0
2.75/3.5 Ni, 0.5/1.1 Cr	En 23	£80.3.0	£109.12.0	£151.8.0
3.0/3.75 Ni, 0.5/1.25 Cr, 0.2/0.4 Mo	En 27	£96.4.0	£128.2.0	£172.15.0

Forging billets: 75-50 tons. One size & quality. 3"-10" section. Random lengths, 5' and over.

Black bar: 50-25 tons. One size, quality & finish. 2" dia. or over. Random lengths.

Bright bar: 50-25 tons. One size, quality & finish. 2"-3" dia.

TABLE 6.

Basis prices (£/ton) for alloy steels (1st October 1968).

From "Foundry Trade Journal".

That no comments were heard concerning machinability variations from cast-to-cast of these steels tended to confirm the theory that machines are rarely geared to take optimum advantage of free machining additions. The wish was expressed that suppliers would indicate in some way sulphide type and distribution in all resulphurised bar stock! What such detailed control would in fact achieve is open to question in view of the above situation.

Where no-free cutting steels are machined, the complaints on machinability did not concern dirtiness of steels as might have been expected, but rather that sulphur levels could be so low as to render steel "unmachinable". Through the ISO standards committee, the motor industry is advocating adoption of maximum and minimum sulphur levels, the upper figure generally being higher than continental practice. For example, Company C specifies a sulphur range of 0.055% to 0.030% in En 15, to guarantee established machining rates. It was noted that all companies visited were able to purchase steels to maximum and minimum sulphur levels without incurring cost penalties.

Where rationalisation of bar steel grades to BS En-specifications has been attempted, the pattern of steel selection is generally as follows:-

En - 1A mass-production on automatic lathes of small, low strength components which do not require subsequent welding operations in assembly, or heat- or surface- treatments.

En 3, 3B - mass-production on autolathes, of components in the same strength category as above but requiring welds in assembly.

En 32, 32B - machined low strength components, requiring case hardening by carburising or cyaniding.

En 8 variants - for components requiring R properties (or
35 tons yield strength) after heat treatment, and
possibly induction hardening.

En 16 variants - for components requiring T properties (or
45 tons yield strength) after heat treatment, and
possibly induction hardening.

b. Component Manufacture from Forgings.

The importance of the drop-forging industry as the major processor of alloy steels has already been noted (see Table 1), as has the predominance of forgings over bar steel manufacture by tonnage in the motor industry. Of the 100,000 tons of wrought steels used per annum in the manufacture of gearbox, steering and rear axle components for automotive production Smith (27) estimates that 90% consist of forgings, the remainder being in bar form. In addition, the majority of vehicle builders use forged crankshafts and connecting rods, although the upsurge of interest in castings is making inroads into this area of manufacture, influenced by years of successful application in the States (28). 75% of drop-forging production enters the automotive industry (11), some sectors of which have their own forging capacity which must, however, produce in commercial competition with outside suppliers. Approximately a third of Company C's forging requirements (200 to 250 tons per week) are met by internal production.

Table 7 details some of the manufacture of a drop-forging company, whose output is almost entirely for the automotive industry. It shows comparisons of customer requirements in terms of raw material and forging quality control, and heat treatments. Such an analysis, on a larger sample size could indicate effectiveness of steel utilisation interpreted by the drop-forger on behalf of customers.

DROP FORGING MANUFACTURE

Summary: Grades of steel processed - "Practically all specifications of BS 970. Additionally selected range of U.S. and Continental specifications."

Tonnages handled (1 year) - Plain carbon steel 68,389 tons
including (11,076 tons resulphurised
(1,589 tons leaded.
Alloy steel 91,596 tons
including 7,213 tons leaded.

Component	Raw Material			Max. Ruling Section	Heat Treatment	Finishing and Test Requirements	
	Grade	Cost	Form				
Crankshaft (Company C)	En 16T .025S	164	2 " sq. billet. 24 lbs.wt. Step turn test per cast	2.687"	Harden 850°C/Oil Temper 600°C/Air	Descale	Check hardness 255/302 B_H
Crankshaft (I)	En 9T	100	$2\frac{3}{4}$" sq. billet. 24 lbs.wt. Step turn test per cast	3.5"	Harden 860°C/Oil Temper 550-660°C	Descale	Check hardness 255/286B_H (10% sample)
Crankshaft (D)	En 8D .025S	100	Up-ending quality. Cast segregation. Grain size above 2 ASTM	2.812"	Harden 850°C/Water Temper 550-660°C	Descale Pickle	Check hardness 213/285B_H (10% sample) (H.t. fracture test bar with cranks)
Crankshaft	En 25	245	$45\frac{1}{4}$ lbs. Step turn test per cast. Cast segregation.	4.0"	Norm. 880°C/Air Harden 840°C/Oil Temper 660°C/Air	Descale Balance & centre	Check hardness 293/321 B_H (100% testing)
Crankshaft (H)	En 19C .8/1.1Cr .15/.25Mo .025S	178	$3\frac{1}{4}$" sq. billet. 53 lbs.wt. Analysis and mechanical tests certified. Casts colour coded. Step turn test per cast.	4.25"	Harden 870°C/Oil Temper 660°C/Air	Descale Cold set	Check hardness 248/285 B_H (10% sample)

TABLE 7.

Component	Raw Material			Max. Ruling Section	Heat Treatment	Finishing and Test Requirements	
	Grade	Cost	Form				
Mainshaft gear (C)	En 361	178	1 "dia. 1.56 lbs. wt. Cast code and segregation	1.3"	Norm. 900°C/Air	Descale	Check hardness 143/179 B_H
Layshaft gear	En 36C .025S	228	2" sq. 4 lbs.wt. Analysis, fine grain size. Step turn test per cast.	1.0"	Norm. 900°C/Air Temper 625°C/Air	Descale	Check hardness 225 B_H. Microsection.
Crown wheel (I)	En 352	180	3" sq. 8.5 lbs.wt. Cast coding, segregation Analysis, mech. tests,g.s. Jominy tests.	1.3"		-	As forged
Spur wheel	En 34 .025S	191	3½" sq. 18.25 lbs.wt. Analysis, fine grain size.	1.9"	Norm. 900°C/Air	-	Check hardness 241 B_H max.
Crown wheel (C)	En 352	180	4½" sq. 30 lbs.wt.	1.5"	Norm. 900°C/Air	Descale	Check hardness 229 B_H max.
Crown wheel	En 353	200	6" sq. 73.5 lbs.wt. Cast segregation. Test bars to customer.	2.2"		-	As forged
Axle shaft (C)	En 17T	173	1" dia. 7.62 lbs.wt.	1.25"	Harden 850°C/Oil Temper 600°C/Air	Cold set	Check hardness 248/302 B_H (10% sample)
Axle shaft (D)	En 8A (modified)	100	Analysis. SAC-H test. 6 pickle bars) to customer 2 micros)	1.7"	Norm. 900°C/Air	Descale	Check hardness 163/217 B_H. (10% sample).

TABLE 7 (continued).

Component	Raw Material			Max. Ruling Section	Heat Treatment	Finishing and Test Requirements	
	Grade	Cost	Form				
Connecting rod (F)	En 8R	100	2" x ¾" bar. 1.09 lbs.wt. Forging quality. Decarburisation check.	0.95"	Harden 860°C/Oil Temper 550-660°C	Descale	Check hardness 201/255B_H(10% sample) Magnetic crack detection.
Connecting rod (C)	En 16U	164	1¾" sq. bar. 2.125 lbs.wt.	1.25"	Harden 860°C/Oil Temper 550-660°C	Descale Pickle	Check hardness 269/321 B_H (100% testing)
Connecting rod (I)	En 15S	108	1 " sq. bar. 2.74 lbs.wt. UTS 55 t.s.i. Izod 25 ft.lbs.	1.5"	Harden 850°C/Oil Temper 550-660°C	Descale Pickle	Check hardness 229/285 B_H (100% testing)
Connecting rod (H)	En 18T	160	2 " sq. billet. 4.25 lbs.wt. Analysis and mechanical tests certified. Cast segregation. Step turn test per cast.	1.6"	Harden 850°C/Oil Temper 550-700°C	Descale Cold coin.	Check hardness 248/302 B_H (10% sample) Magnetic crack detection.
Connecting rod	En 16T	164	2" sq. billet. 4.5 lbs.wt.	1.7"	Harden 850°C/Oil Temper 550-660°C	Descale	- ditto -
Connecting rod	En 19 .025S	178	3" sq. billet. 13.7 lbs.wt. Single slag, vac. degassed casts. Lloyds test standards. 2 step turns, 3 pickle bars/cast.	2.7"	Harden 870°C/Oil Temper 550-720°C	Descale Pickle	Check hardness 248/302 B_H (100% testing).

TABLE 7 (continued).

The "cost" figures refer to the cost index scale appearing in SMMT Standard No 79 (15), where the basis price of black bar, machining quality steel En 8 is taken as 100. This simple analysis alone shows selection "inconsistencies" e.g. En 16 T and En 9 T for similarly sized and loaded crankshafts. Direct analysis of steel tonnages by grade and section size to weight and ruling section of resulting forgings was not possible, according to the manufacturer.

Considering the machining aspects of forgings, Smith (27) summarises the primary grades of steel thus formed for automobile end-usage as:-

1. Plain-carbon grades e.g.: En 5, En 8 are normalised at 870°C prior to machining, and the finished components probably induction hardened.

2. Carburising grades, e.g.: Nickel-molybdenum steels En 34, En 35, SAE 4620, usually finished-machined after high temperature annealing (950°C for 2 hrs.) and controlled furnace cooling.
   Nickel-chrome-molybdenum steels En 354, En 355, SAE 8620 finish-machined after normalising heat treatment.

3. Medium carbon, low alloy grades for through-hardening or induction hardening, e.g. En 16, En 17, En 18, En 19, which require a high temperature anneal with controlled cooling prior to machining.

Ideally, pre-machining heat treatments are carried out by the user, on acceptance of forgings "in the black". In practice, while the majority of companies apply such treatments to all incoming forgings regardless of prior treatment, in order to minimise and standardise distortion patterns induced by subsequent machining operations, others accept pre-machining treatments applied by the forger as being adequate to consistency of machining.

Table 8 lists the forging weights for a mass-produced family car, while Table 9 gives the total weights of alloy steel in two vehicles of similar engine capacity but differing engine and drive layouts.

c. Cold Forming Applications.

Cold forming has attained economic viability in highly specialised areas of application only. Of the firms visited, three had staff actively engaged in the development and application of these techniques. Cold forming of gear blanks for example can effect considerable material savings over conventional forging by giving close-tolerance blanks and leading in turn to a reduction in finish-machining, provided that traditional machining attitudes can be overcome. By tradition, all-over machining is insisted upon for gears, with a stipulated minimum depth of first cut "to clear forging defects and scale". The conditions applied are such that good conventional forging practice can attain to tolerances closer than the specified first cut merits!

Cold forming equipment installed by Company C several years ago is of low loading capacity, uneconomically slow in operation and without ancillary plant for billet preparation and lubrication, but at Company E, cold forming has been successfully applied to the manufacture of hydraulic cylinder barrels from En 2 rod. It was noted, however, that cost savings on this operation are equivalent only to the value of the material lost when cylinders are machined from bar.

The principle component-manufacturing processes making inroads on "conventional" methods are:

d. Casting

Alloy steel forgings - finished weights per vehicle

Steel		Weight
En 16	Crankshaft	22¾ lbs.
	Connecting rods (4) Connecting rod caps (4)	5¾ lbs.
	Steering levers (2)	2 lbs.
	Upper suspension levers (2)	10½ lbs.
En 18	Sliding coupling	½ lb.
	Reverse gear	¾ lb.
En 352	Laygear	2½ lbs.
	1st speed gear	1 lb.
	Final drive gear	4½ lbs.
En 352 leaded	Drive shaft and wheel (2)	2¼ lbs.
En 353	Final drive pinion	¼ lb.
SAE 8615	1st motion shaft	1¼ lbs.
	3rd motion shaft	1¾ lbs.
	Drive gear	1 lb.
	Crankshaft primary gear	1¼ lbs.
	Synchro hub	¾ lb.
	3rd speed gear	1 lb.
	2nd speed gear	¾ lb.
	2nd speed synchro	¾ lb.

TABLE 8.

	'CAR X'	'CAR Y'
En 12	10 oz.	$2\frac{1}{4}$ lbs.
En 16	$42\frac{1}{2}$ lbs.	$41\frac{3}{4}$ lbs.
En 18	$1\frac{1}{4}$ lbs.	$< \frac{1}{2}$ lb.
En 19	6 lbs.	-
En 31	$7\frac{3}{4}$ lbs.	$6\frac{3}{4}$ lbs.
En 34	$\frac{1}{2}$ lb.	-
En 36	$< \frac{1}{2}$ lb.	-
En 52	$< \frac{1}{2}$ lb.	$< \frac{1}{2}$ lb.
En 206	$< \frac{1}{2}$ lb.	-
En 207	$5\frac{1}{4}$ lbs.	-
En 351	$< \frac{1}{2}$ lb.	$1\frac{1}{2}$ lbs.
En 352	$8\frac{1}{4}$ lbs.	$3\frac{3}{4}$ lbs.
En 352 leaded	$2\frac{1}{4}$ lbs.	-
En 353	$< \frac{1}{2}$ lb.	-
En 355 leaded	$< \frac{1}{2}$ lb.	$< \frac{1}{2}$ lb.
SAE 8615	8 lbs.	$8\frac{1}{4}$ lbs.
214 NS	$< \frac{1}{2}$ lb.	$< \frac{1}{2}$ lb.
En 35	-	$5\frac{3}{4}$ lbs.
En 353 leaded.	-	1 lb.

NOTE:
'CAR X' Front-wheel drive, 1098c.cs.
'CAR Y' Conventional drive, 1098c.cs.

TABLE 9. Alloy steels- finished weights per vehicle.

Adoption of cast crankshafts for new passenger cars is increasing, having taken some ten years for the innovation to cross the Atlantic (28). Cast connecting rods have yet to arrive.

Forged crankshafts are produced in En 16 or En 18 grades, induction hardened at bearing journals. While it has been established that replacing an En 18 crankshaft in a diesel engine, by one in nodular iron resulted in a material cost saving of 30/- per vehicle, comparable figures for a car are not available but variously estimated at 15/- to 20/-. But the adoption of the cast crankshaft is unlikely, as yet, to be universal. It was maintained by one materials group that the serviceability of the cast crankshaft has yet to be proved in a sports car. For a company with such interests as well as more conventional manufacture the cost of duplicating finish-machining to accommodate both saloon car castings and sports car forgings would outweigh any material cost savings, although no cost figures were produced to support this argument.

e. Components by Powder Metallurgy.

Suspicion of powder metallurgical methods throughout the motor industry originated in disappointing results from earlier interest and support for the technique. Advances in sintering technology to give consistent products have been rapid, but few firms have retained interest or have followed developments. Also, there is the growing realisation that sintering must be designed for and that an exact copy of the component to be replaced is rarely the ideal form for the sintered product. Eventually, the technique is likely to make considerable inroads into the manufacture of components hitherto machined or forged from steel, but as yet the contrast between companies regarding the adoption of sintered parts is very marked.

Cost savings of 50% basic price of a simple forging can be achieved readily on a component redesigned for powder metallurgical manufacture; a materials group estimated that savings of £5. per vehicle could be realised on a small car, by wider adoption of sintered components,

e.g. 1. Reverse wheel operating lever - 2/7½ as a forging, 1/4 as a sinter.

2. Rocker brackets - four per vehicle give cost saving of 2/- over forged brackets.

Self-lubricating gears, rated at 55 tons tensile strength, can be produced although resistance to wear especially on helical gears constitutes a major problem yet to be overcome to make their manufacture competitive with forged gear-box gears.

1.3-8 Heat Treatment

Mass production has enforced the adoption of continuous heat treatment plant or at least its consideration to replace batch-type plant, throughout the motor industry as a whole. Thus, normalising and pre-machining treatment of forgings, carburising, hardening and tempering operations are carried out predominantly on semi- or fully automatic plant, where production capacity merits its use, e.g. high volume production of gears - normalising forged gear blanks on acceptance, case carbusising after finish-machining and finally, stress-relieving or tempering.

(a) Surface Treatments

For surface treatments to improve wear properties, resistance to fatigue etc., successful adoption of gaseous processes has been governed by the ability to monitor and control furnace atmospheres accurately, to ensure consistency of product. In continuous furnaces, as opposed to batch operations, atmosphere control is complicated by temperature gradients through the length of the furnace - determining the rate of chemical reaction at the steel surface and the decomposition of the atmosphere into its active components - , together with turbulence caused by entry and exit of the charge. Rapidity and reproducibility of atmosphere composition recording has been a prime factor in achieving consistency of case properties on large volumes of work handled round-the-clock. For carburising treatments this has progressed by way of dew-point control (Dewtronik and Foxborough), electrical resistance and infra-red absorption carbon dioxide determination. While the former methods may take ten minutes to detect compositional change, the infra red techneque will record atmosphere condition every twelve seconds. While continuous furnaces for case-hardening treatments were in operation or in process of installation at the major factories visited, adoption of infra-red atmosphere control was limited. Such equipment is unlikely to replace existing control methods, but appears to be the firstchoice for new furnace installations.

Where production does not merit the continuous plant for surface treatments, batch sealed-quench furnaces are now in widespread use. Here the sophistication of infra-red atmosphere control is not so necessary and dew-point methods predominate. Although continuous furnaces can accommodate carbo-nitriding treatments, batch furnaces are generally used for this surface treatment depending on the relative demand for it in preference to carburising. Salt bath treatments are retained in some form by all companies reviewed, but the tendency is to transfer work from these to gaseous treatments in batch furnaces, as these are released for such work by the introduction of continuous furnace plant. Pack carburising plant is virtually non-existent, an extensive semi-automated plant being phased-out by one motor car manufacturer at the end of 1966.

Surface treatment processing schedules were generally comprehensive in detailing furnace conditions necessary to produce standard case-depths on carburising, for example, although it was felt that surface carbon level control aimed at was often optimistic rather than practical in view of the lack of sensitivity of atmosphere analysis methods employed. Company E uses processing schedules covering batch furnace carburising and carbo-nitriding operation, to give case depths in the range 0.003" to 0.004", which quote cycle times, temperatures and throughput per hour, but make no reference to atmosphere composition or control. At Company F, heat treatment schedules for both batch and continuous furnace operation detailed test-piece tolerances on case depth, composition and hardness for given steel grades (see also (29)). Rationalisation of case-hardening steels to two SAE grades had resulted partly from the installation of continuous carburising plant. Such equipment requires to be "fed" continuously with steel for treatment and, once set up, is inflexible in operation, working to fixed carburising conditions applicable to a limited steel composition range. Processing SAE 4620 and 8620 gears for which designs specify a surface carbon of 0.90 - 0.95% with a depth of 0.020-0.030 ins, the furnace is run at the optimum through-put rate consistent with the automatic interlocks of the loading-to-unloading circuit. The SAE-steels were replacing En.355 for gear manufacture, and some designs retained this specification. As these require 0.65% surface carbon for optimum wear resistance and fatigue life, they are accommodated by batch furnace treatments. New designs will phase out the use of En 355 in favour of the SAE grades.

In general, surface carbon levels in case hardened steels were in close agreement for similar steel grades from company to company but the definition of case depth, and consequently its value on complex cross-sections (e.g. gear-teeth) was not consistent. It was not always clear whether deliberate attempts were made to relate case depth to design loading requirements. Where this was so, empirical means based on prior operating experience were used rather than exact design.

High temperature carburising (from 1000°C) is not extensively used; one company at present carburising at 900°C have estimated that the extra cost break-even point is well above the standard practice case-depth range. Break-even is estimated at 0.06" case depth, at which a time saving of approximately forty minutes would be achieved on a 5½-6 hr. cycle.

(b) Quench Hardening.

The motor industry at large purchases practically all its heat-treatable steel in the grain-refined condition. Adversely, fine grain size reduces the hardenability potential of a given composition (30); beneficially, it is held synonymous with steel "toughness" and is said to enhance fatigue performance (17, 30, 31) and to reduce distortion and tendencies to cracking on heat treatment (17). A reasoned analysis of the "benefits" obtained from grain refined steels (29) considers consistency of raw material, and attention to heat treatment detail of greater importance in distortion control.

Accent on sealed-quench facilities in heat treatment has brought about the rejection of "traditional" grain-refining reheat and quench treatments. Direct quench from the carburising temperature for example is followed by a light tempering or stress relieving operation, in sequence on continuous furnace installations. Work at the Motor Industries Research Association has recommended that gears should be left untempered after single quenching, for good bending strength (32).

However, while direct quenching is standard practice virtually everywhere, it is as yet featured only in an appendix to BS970, all contractual properties being based on test results from specimens which have undergone a double quenching treatment. This inconsistency may be reflected in company heat treatment specifications; all working drawings examined at Company B carried double quenching heat treatment instructions, although the firm has issued its own direct quench specification. Deliberate usage of double quench treatment was recorded in one instance only when material was not bought to a controlled grain size because of the "doubtful" characteristics of obsolescent pit furnaces used for carburising; direct quenching from a pit furnace is both difficult and potentially hazardous.

Companies showing little interest in the effectiveness of quenchants were in a minority, a notable exception being a major motor car producer completely dependent on one quench oil for <u>all</u> quench hardening purposes, whose specification dated from 1939! But elsewhere, from works to works, inconsistency in choice and application of quench oils of differing characteristics was found without there being any attempt to optimise or to calibrate quenching variables - "sustained mediocrity is to be preferred to intermittent perfection" (33).

Ideally, a quenchant should be capable of rapid heat removal in the initial stage of quenching (as with water) to bring the steel down to the martensite transformation temperature, without the possibility of other austenite decomposition products being formed. Thereafter, a slow cool through the range of martensite transformation is considered preferable, and is characteristic of mineral oil quenching. But the rate of heat removal is dependent not only on the physical and chemical characteristics of the quenchant but also upon its temperature, and the effectiveness of its agitation and circulation past the components being quenched.

Visits to three producers of quench-oils revealed that quenchant technology was developing in three ways

(1) Accelerated quench-oil development, attempting to speed up the initial stages of quenching, to approach the speed of a water quench, yet retaining a slow-cooling rate through the martensitic range, particularly useful

in promoting depth of hardening in lean-alloy steels without the risk of quench-cracking.

(2) "Marquench" oil development - hot quenching oils, working temperature between 100 and 200°C, are coming into increasing use where the minimising of distortion on quenching is a major factor. The quenchant operates at about the martensite transformation temperature, down to which its quenching action is fast; at the bath temperature, surface and core temperatures equilibrate reducing the residual stresses induced by transformation volume changes.

(3) Water additive development - work aims to produce quenchant properties intermediate to water and conventional oil, slowing down the later cooling stage by extending the period of vapour blanket stability.

The accelerated oils are held to be particularly useful in exploiting optimum hardenability properties in low alloy economy steels. Apart from within the works of component manufacturer A, adoption of such quenchants was found at Company B only - where the added expense was in all probability not warranted because of the suspicion there of lean alloy steels! Accelerated oils are best suited to mass-production of small, bar-machined components of up to 2" ruling section. Opposition to accelerated quench oils was based on fears of the variability of quenching characteristics which drag-out and oxidation of the accelerating additives were said to cause. But, an oil research group responsible for the developing of accelerated quench oils, now in industrial use was convinced that the general disinterest in them was due to their cost and in consequence, further development work had been dropped in favour of research into water-additive quenchants. It was later learned that water-additive quenchants now available commercially are no cheaper than accelerated oils to instal and as yet, require careful control and maintenance by the supplier.

Marquench oils are coming into favour for sealed-quenching of carburised gears, where gear tooth distortion is a factor contributing to noise generation, rear axle crown wheel and pinion assemblies being particularly critical in this respect. Tooth movement is a consequence of residual stresses resulting from machining operations and from differential volume changes between case and core on quenching, due to differing transformation rates arising from extreme carbon levels. It has always been regarded as a factor "to be lived with", one which can be tolerated and largely corrected for at the machining stage, when gear teeth distort into the correct profile, provided that consistency of distortion from heat-treatment can be sustained.

Company F follows the school of thought that the presence of a small fraction of retained austenite in the otherwise martensitic case of a carburised gear induces a residual stress pattern contributing to fatigue resistance of the gear under service loads. It has been reported that retained austenite up to 15% is not detrimental to pitting fatigue strength, when it is finely dispersed. Its presence allows mating surfaces to conform more readily, reducing local areas of high stress - in effect, running-in the gears (34). The firm carries out extensive fatigue-life testing of gear assemblies and, although undertaking martempering oil trials in conjunction with a quenchant supplier, the feeling expressed is that without the residual stress pattern resulting from distortion on quenching, fatigue life will be impaired! Elsewhere, it was found that attention to tray-loading or jigging of components could minimise distortion difficulties.

Murray (35) has concluded that the adoption of low temperature case hardening treatments, e. g. Tufftriding of direct hardening steels could largely eliminate distortion on quenching. Nowhere was this found to be practised on gears; Company H have adopted this idea for distortion-free shaft forgings. However, marquench oils are claimed to have made possible the production of distortion-free gears for automatic transmissions, when incomplete trial results were successfully adopted to batch sealed-quench production usage. Marquench oils are known to be under test by several companies in the automotive industry.

It should be mentioned here that none of the industrial oil suppliers consulted carried out experimental work on production-scale equipment, but relied on the good offices of interested customers - backed by quality control guarantees - to conduct realistic trials in their clients' plant. Also, there is no early co-operation between furnace manufacturers and quenchant producers, at the design stage of new quench plant (36). Optimum characteristics of a quenchant in a given tank are therefore governed by the flexibility of operation of the tank i.e. circulation or agitation rate, temperature control of the quenchant, filtration etc. As has already been mentioned, no active interest was forthcoming on quantifying production quench rates to provide guidance to heat-treatment response likely in a given steel, from a knowledge of its hardenability data.

(c) Induction Heating Treatments.

A chief process engineer predicted that within ten years, induction treatments used in conjunction with direct hardening, medium carbon steels will take over a major part of production at present covered by chemical surface hardening treatments on low-alloy steels. Induction heating treatments are ideal for application to flow-line production, but the adoption of in-line hardening schemes will be dependent on advances in inductor design and technology, and indirectly dependent on improvements in production time cycles on automatic transfer machines. While the theory and practice of inductor design has kept pace with increasing usage, ancillary handling gear was found to have remained crude and insensitive, and production engineering problems are primarily associated with the latter.

Induction hardening treatments are rarely introduced as direct replacements for other established surface treatments. Shaft-like components lend themselves ideally to induction treatment usually by travelling inductor and can employ cartridge loading to charge components to the machine. Elsewhere, the process is employed where other techniques are costly or difficult to apply (e.g. selective area hardening when gaseous carburising necessitates copper-plating shielding). However, the selective nature of induction treatments can promote inflexibility of operation, as each application requires, ideally, its own specific inductor design.

1.3-9 Data Collection.

The purpose of field studies was to establish the present pattern of steel utilisation in the motor industry, against the background of processing and heat-treatment methods employed to produce components to required property and performance levels. Quantitative details of steel usage in both tonnages and section size were requested, related where possible to relevant ruling section size and finished components, but such information was rarely and never comprehensively forthcoming. Where quantitative information was given (see Table 10) it was because it was closely tabulated as a matter of course and so readily to hand or because exercises similar in nature had been conducted within the firm for self-information, or for the guidance of a steel supplier. Generalised information on material selection was given on all visits, without quantitative detail; the large number of drawings in current usage in a given firm allowed only a few examples to be studied in detail.

GRADE	BAR FORM	BS 970 UTS.	SIZE (DIA. OR W.A.F.)	WT. USED (TONS)	
En 1A	Bright	32 tsi	17/32"(7)	4.3 tons	General free-machining purposes. e.g. retainer bar $\frac{3}{4}$" x $\frac{1}{8}$", flat bright.
	Bright	28 tsi	17/32"-$1\frac{1}{2}$"(17)	37.0	
Free-cutting (.2/.3 S)	Bright	25 tsi	$1\frac{1}{2}$"-$2\frac{1}{2}$"(7)	11.4	
	Bright	23 tsi	$2\frac{1}{2}$"-3"(5)	4.6	
	Hex.bright	32 tsi	.520/.525	(1) 0.8	
	Hex.bright	28 tsi	.520/525-1.488/1.500	(13)28.5	
	Hex.bright	25 tsi	1.665/1.670	(1) 0.3	
	Square bright		$\frac{3}{4}$" x $\frac{3}{4}$"	(38 lbs)	
	Flat bright		$\frac{3}{4}$" x $\frac{1}{8}$"	3.0	
				90.9 tons	Stock in hand 250 tons.
En 2	Flat black		$2\frac{3}{4}$" x 3/16"	2.6 tons	Stampings e.g. levers, brackets. (BS970 ruling section 6 ins.)
Cold forming (.2C, .8 Mn)	Flat black		$4\frac{1}{2}$" x 5/16"	1.6	
				4.2 tons	Stock in hand 3.6 tons.
En 4 (.3C, 1Mn)	Black	28.38 tsi	$3\frac{1}{2}$" dia.	2.2 tons	Stock in hand 16.4 tons.

TABLE 10. Bar steel consumption at Company B. (June/Sept. 1965).
NOTE-Bracketed figures refer to the number of bar sizes grouped in the size intervals given.

GRADE	BAR FORM	BS 970 UTS.	SIZE(DIA.OR W.A.F.)	WT.USED(TONS)	
En 6 (.35C,.5/.9 Mn)	Bright	38 tsi	¾"(2)	0.8 tons	Pins. e.g. planet pins
	Bright	35 tsi	¾"-1¼"(2)	3.5	
				4.3 tons	Stock in hand 11.7 tons.
En 7 Semi free cutting (.1/.18S)	Bright	40 tsi	½"(12)	20.0 tons	Machining stock. e.g. bolts, adapters.
	Bright	35 tsi	½"-¾"(5)	16.2	
	Bright	35 tsi	¾"-1⅛"(6)	5.0	
	Bright	35 tsi	1⅛"-1¾"(8)	36.6	
	Bright	30 tsi	1¾"-2½"(6)	10.0	
	Hex.bright	35 tsi	½"-¾"(5)	8.8	
	Hex.bright	35 tsi	¾"-1⅛"(6)	3.9	
	Hex.bright	35 tsi	1⅛"-1¾"(2)	(255 lbs)	
	Hex.bright	30 tsi	1¾"-2½"(3)	2.1	
	Square bright		½"-1¼"(6)	4.2	
	Flat bright		⅝" x 5/16"- 2¾ x 3/16"(7)	4.5	
				111.3 tons	Stock in hand 370 tons.

TABLE 10. (continued).

GRADE	BAR FORM	BS 970 UTS.	SIZE (DIA.OR W.A.F.)	WT.USED (TONS)	
En 8A (.35/.45C, .6/1.0 Mn)	Bright	(42 tsi)	1¼" (7)	40.0	General induction hardening applications, e.g.shafts pins, 2nd/3rd speed selector shaft, nozzle plugs ball end shackle pins
	Bright	(39 tsi)	1¼"-2½" (6)	9.8	
	Bright	(37 tsi)	2½" (3)	3.8	
	Hex.bright		2¼" (5)	7.5	
	Square bright		¾",1.3/16" (2)	0.7	
	Flat bright		(2)	(211 lbs.)	
				61.8 tons	
En 8B	Hex bright		(2)	-	e.g.Pivot pin. Stock in hand 195 tons.
En 9 (.5/.6C .5/.8 Mn)	Bright	(50/65 tsi)	1" (4)	0.8	e.g. rocker levers (induction hardened)
	Flat bright		1¼"x 3/16"	(50 lbs.)	
				0.8 tons	Stock in hand 3 tons.
En 14A (.15/.25C, 1.3/1.7 Mn)	Bright		1¼"	3.0 tons	Stock in hand 4.5 tons.

TABLE 10. (continued).

GRADE	BAR FORM	BS 970 UTS.	SIZE(DIA.OR W.A.F.)	WT.USED(TONS)	
En 15 AM Semi-free cutting (.3/.4C, 1.3/1.7 Mn, .12/.20 S)	Bright	45 tsi	½" (12)	39.01	Higher strength considerations than En1A. General machining stock. e.g. pedal shaft wheel studs washers, brake rods unions
	Bright		½" 1" (8)	19.6	
	Bright		1" 2"(11)	118.0	
	Bright		2" 3" (6)	12.6	
	Black		3" 3¾" (3)	4.7	
	Hex.bright		½" (2)	1.4	
			½" 1" (7)	31.0	
			1" 2" (9)	38.8	
				265.1 tons	Stock in hand 393 tons.
En 16 Direct hardening (.3/.4C, 1.3/1.8 Mn .2/.35 Mo)	Bright		½" (6)	0.9	1⅛" 2½"/55 tons) ⅞" 1⅛"/60 tons } H & ⅞"/ 65 tons) t e.g. shafting eye bolts planet pins collars axle shafts (16 D)
	Bright		½" 1" (10)	18.6	
	Bright		1" 2" (12)	27.5	
	Hex.bright		1" (9)	13.5	
	Hex. bright		1" 2½" (3)	3.0	
	Square bright		1" (2)	1.6	
	Square black		2¾" (1)	1.3	
	Flat bright		1" x ½" (1)	0.5	
				66.9 tons	Stock in hand 190 tons.

TABLE 10. (continued).

GRADE.	BAR FORM.	BS 970 UTS	SIZE (DIA. W.A.F. etc.)	WT.USED (TONS	
En 17 (As En 16 but .35/ .55 Mn)	Bright' Hex.bright		1" 2⅜" (4) (1)	3.1 - 3.1 tons	1⅛" 2½"/60 tons) H 1⅛"/65 ") &) t e.g.adjuster nut. Stock in hand 8.3 tons.
En 19 (.35/.45C .5/.8 Mn .9/1.5 Cr .2/.4 Mo)	Bright Bright Black		1" (6) 3¾" (1) 2¼" (1)	17.3 1.1 0.9 19.3 tons	2½"-4"/50 tons) H & t 1"/80 tons) e.g. Washer Bogie shafts King pins (ind.hard) Stock in hand 9.6 tons
En 24T. (.35/.45C .45/.7 Mn 1.3/1.8 Ni 9/1.4 Cr .2/.35 Mo)	Black Hex.bright	(55 tsi)	4½"(3) (2)	1.1 - 1.1 tons	4"-6"/55tons. H & t. Stock in hand 18.5 tons.

TABLE 10. (continued).

GRADE	BAR FORM	BS 970 UTS.	SIZE(DIA.OR W.A.F.)	WT.USED(TONS)	
En 25	Bright		1" (5)	45.0	2½"/75-100 tons) H
(C.27/.35 .5/.7 Mn 2.3/2.8 Ni .5/.8 Cr .4/.7 Mo)	Bright		1" 2½"(2)	2.4	2½"-4"/65-70 tons} & t
	Hex.bright		1.115/1.125- 1.845/1.860(2)	3.5	e.g. connecting rod bolt.
	Black		2⅝",3" (2)	1.0	U-bolt
				51.9 tons	Stock in hand 260 tons.
En 31 (.9/1.2 C .3/.75 Mn 1.0/1.6 Cr)	Bright		1⅜"(6)	4.8	e.g. valve caps
	Black		1⅛"(1)	(202 lbs.)	thrust washers
				4.8 tons	Stock in hand 8.6 tons.
EN 32A Case hardening (.15C .4/.7 Mn)	Bright	(32 tsi)	½" (6)	1.4	
	Bright		½" - 1"(14)	15.8	
	Bright		1" -2" (12)	26.7	
	Bright		2" - 3" (6)	11.2	En 32A: up to ½" section bar
	Bright		3" (2)	4.2	En 32B: > ½" section bar
	Black		1¼" - 2⅞" (5)	3.6	
	Hex.bright		1.86" (7)	0.6	
	Square bright		1½" (8)	3.3	
	Flat bright		3½"x ¼"(14)	4.7	
				71.5 tons	
En 32B	Bright		1.5/16" (1)	(117 lbs.)	Stock in hand 198 tons.

TABLE 10. (continued).

GRADE &	BAR FORM	BS 970 UTS	SIZE (DIA. A.F. etc.)	WT.USED(TONS)	
En 36B Case hardening (3% Ni, 1% Cr)	Bright	65 tsi	1.315", 1⅝" (2)	1.3 tons	e.g. ball pillar Stock in hand 9.3 ton
En 39 Case hardening (4¼% Ni, 1¼ Cr)	Square bright	85 tsi	¾"	-	Stock in hand 0.4 tons.
En 40 Nitriding steel (.1/.2C .4/.65 Mn .4 Ni 2.9/3.5 Cr .4/.7 Mo)	Bright Black		1.5/16" ⅞", 2⅞"(2)	(644 lbs) 3.4 3.4 tons	6"/45-60 tons H & t e.g. driving shaft Stock in hand 5.2 tons.
En 41 Nitriding steel (1½ Cr, 1Al, 4 Mo)	Flat bright		2½" x (2)	13.0 tons	2½"/55 tons H & t e.g. wearing plates Stock in hand 13.1 tons.
En 57 Martensitic rust resisting. (15/20 Cr, 1/3 Ni)	Bright	(55 tsi)	1¼" (3)	16.7 tons	2½"/55 tons e.g. water pump drive shaft. Stock in hand 19.4 tons.

TABLE 10. (continued).

GRADE	BAR FORM	BS 970 UTS.	SIZE(DIA.OR W.A.F.)	WT.USED(TONS)	
En 58 Austenitic rust resisting (Ni,Cr)	Bright	(35 tsi)	$1\frac{1}{4}$" (1)	6.8 tons	6"/35 tons e.g. water pump drive shaft. Stock in hand 11.1 tons.
En 202 Case hardening Semi free cutting (.18C, 1.2/1.5 Mn, .1/.18S)	Bright	(38 tsi)	1", $1\frac{5}{8}$" (2)	10.1	Misc. machined parts. Carburised/carbo-nitride. e.g. pressure pad.
	Flat		(3)	24.2	
				34.3 tons	Stock in hand 9.4 tons.
En 351 Case hardening (.2C, .6/1.0 Mn, .6/1.0 Ni, .4/.8 Cr)	Bright	(45 tsi)	$\frac{7}{8}$"-$1\frac{7}{8}$" (3)	8.6 tons	e.g. valve caps. Stock in hand (150 lbs.)
En 352 Case hardening (.2C, .5/1.0 Mn .85/1.25 Ni .6/1.0 Cr) Leyland: .18C	Bright	(55 tsi)	$\frac{1}{2}$" 1" (5)	0.4	e.g. small steering ball pillars driving gear pistons
	Bright		1" 2" (4)	14.1	
	Bright		2" - 3" (3)	0.5	
	Black		$3\frac{1}{4}$" (1)	0.5	
				15.5 tons	Stock in hand 32.4 tons.

TABLE 10. (continued).

GRADE	BAR FORM	BS970 UTS.	SIZE(DIA.OR W.A.F.)	WT.USED(TONS)	
En 353 Case hardening (.20C .5/1.0 Mn 1.0/1.5 Ni .75/1.25 Cr .15 Mo)	Bright	(65 tsi)	½" (2)	1.6	e.g. gudgeon pins steering shafts king pins nozzle needles
	Bright		½" - 1" (1)	(500 lbs)	
	Bright		1" - 2" (2)	32.3	
	Black		1" - 2" (3)	21.4	
	Black		2" - 3" (2)	(681 lbs)	
	Square bright		¾" (1)	(630 lbs)	
.18C	Square black		4" (1)	(550 lbs)	
				66.0 tons	Stock in hand 188 tons.

Total bar consumption over 3 month period:

930 tons approx.

TABLE 10. (conclusion and summary).

Total stocks held:

2,230 tons.approx.

Examples of forging manufacture have been given in Table 7, and components representative of general bar-steel manufacture are listed in Table 11. Of small ruling section (3¾" maximum but predominantly less than 2"), it is with such components, auto-lathe machined in large quantities, that considerable material cost savings can be made by sensible application of heat treatment quenching techniques to low-alloy or plain-carbon steels. The use of standard alloy steels is largely "outdated" in this section size range, but "traditionalism" in selection continues to override many obvious costing economies. The inadequate and obsolete guidance in respect of mechanical property development which BS 970 offers is surely a matter for exploration within a given company, with assessment of the potential of heat treatment facilities by steel grade/representative ruling section test samples upon which revision subsequent selection decisions could be made.

The guidance chart to heat-treatable steel selection, as used by Company B, is reproduced (Table 12) and the differences between it and a similar chart drawn up by SMMT are shown. Both selection charts are said to be based on minimum cost materials for consistently reproducable properties in the section sized listed, using ultimate tensile stress as the design criterion. It is presumed that this chart was the basis for steel selection for the bar products described in Table 11.

It is difficult to relate material selection to components which are of standard pattern in vehicles of similar design layout, because of differences in component nomenclature and because of differing power ratings of the sector of the market that each manufacturer tends to serve. Table 13 attempts to do this for four family cars (below 1300 cc. engine rating) all of which are in quantity production, but have differing dates of market release. International comparisons can be made by reference to (37).

GRADE	BAR SECTION.	COMPONENT DESCRIPTION.	HEAT TREATMENT.	PREVIOUS MATERIAL.	RECOMMENDATION.
En 16	$\frac{5}{8}$" dia. bright drawn.	Planet pin and rivet max.o.d. - as drawn.	Bar supplied heat treated U condition. B_H 285-321	Originally En 7 then En 6	
En 16 R.	.75" hex. bright drawn.	Pin (finish - zinc barrel plated). Max.o.d. - as drawn.	Bar supplied heat-treated R condition B_H 212-262		En 15 adequate (En 16 develops R prop.in 6" section)
En 16 T.	1" square bright drawn.	Eye-bolt. max-sq. - as drawn.	Bar supplied heat-treated T condition B_H 255-302		
En 16	1" dia. bright drawn.	Nut for central spray nozzle.	Bar supplied heat-treated S condition <u>or</u>: 820°C/20 min. O.q. Temper 550/ 650°C. A.c. B_H 241-285.		

TABLE 11. Utilisation of heat-treatable bar steels.

GRADE	BAR SECTION	COMPONENT DESCRIPTION	HEAT-TREATMENT	PREVIOUS MATERIAL	RECOMMENDATION
En 16	1⅛" dia. bright drawn.	Steering shaft. Max. o.d. - as drawn.	Hardened and tempered to R. condition. B_H 192-269.		En 15 adequate.
En 16	1¼" dia. bright drawn.	Valve collar (Max.o.d. 1.24")	Hardened and tempered to T condition B_H 241-311		
En 16	1½" dia. bright drawn.	Collar (max.o.d.1.42")	Hardened and tempered to T condition. B_H 241-311.		
En 17	1.5/16" dia. bright drawn.	Nut for automatic adjuster. Max.od. 1.275"	Hardened and tempered to U condition. B_H 285-321.	En 110 U En 7	En 16 (or En 15 with accel. quench?)
En 19	½" dia. bright drawn.	Washer. Max.o.d.15/32"	Hardened and tempered to V condition. B_H 302-341.	En 15.	En 16 En 15 with accel. quench.

TABLE 11. (continued).

GRADE.	BAR SECTION.	COMPONENT DESCRIPTION.	HEAT TREATMENT	PREVIOUS MATERIAL.	RECOMMENDATIONS
En 19S	3¾" dia. bright drawn.	Bogie cross-shaft Max.od - as drawn.	Hardened and tempered to S condition. B_H 241-285. Bearing surfaces hard chromed.		En 16 adequate.
En 25	13/16" dia. bright bar	Connecting rod bolt.	Hardened and tempered to W condition. B_H 321-363.		En 19 En 17
En 25	⅞" dia. bright bar.	U-Bolt.	Hardened and tempered to V condition.		En 16 (En 15)
En 36B.	1⅝" dia. bright bar. (specify basic electric, grain size 5-8).	Ball pillar. Max.od. 1.498"	(Rough machine, Cu plate shank) Carburise ball end 910°C.O.q. Soften 630/650°C-2 hrs. (R_c34). Finish machine. Harden 790/800°C. O.q. Temper 140/150°C - (R_c60).		En 353 (CM80) -preferably convert to induction hardening process En8D.

TABLE 11. (continued).

GRADE	BAR SECTION	COMPONENT DESCRIPTION	HEAT-TREATMENT	PREVIOUS MATERIAL	RECOMMENDATION
En 40A.	$\frac{7}{8}$" dia. black bar, supplied softened.	Pump driving shaft (Max.od 13/16" dia.)	Rough machine, drill thro' length. Harden and temper to condition T (B_H255-302) Finish machine. Salt bath nitride 72 hrs/500°C. Surface grind.	En 32 En 34	
En 202	15/16" x $\frac{3}{4}$" sq. bright bar.	Pressure pad. (Miscellaneous small parts for carburising, carbo-nitrided finish).	Carbo-nitrided in sealed quench furnace to .025" case. Oil quench in Houghtoquench K Temper 140/150°C to give case harden R_c 60-62.		
En 351.	$\frac{5}{8}$" dia. bright bar.	Valve caps. (max.od - as drawn)	Carbo-nitride 850°C for .01"/.015" case. Direct oil quench. Temper 140/150°C.		

TABLE 11. (continued).

GRADE.	BAR SECTION.	COMPONENT DESCRIPTION.	HEAT TREATMENT.	PREVIOUS MATERIAL.	RECOMMEND-ATION.
En 352	$1\frac{7}{8}$" dia. bright bar (specify basic electric, grain size 5-8)	Ball pin. Max. od - 1.2495".	As for pin in En 36B (qv.)	En33	Preferably convert to En 8D variant for induction hardening.
En 352	2" dia. bright bar.	Driving gear and shaft. Max.od - 1.89".	Gas carburise to .025/0.035" case. Harden and temper. Finish grind gear .		
En 352	$\frac{7}{8}$" dia. bright bar.	Piston (Max.od 0.820".)	Carbo-nitride 850°C for .020/.025 case depth.	En33 En34	

TABLE 1[illegible]. (continued).

GRADE	BAR SECTION	COMPONENT DESCRIPTION	HEAT-TREATMENT	PREVIOUS MATERIAL	RECOMMENDATION
En 353	$1\frac{1}{2}$" dia. bright bar. (basic electric S, P ≯ 0.03).	Gudgeon pin (Max.od 1.30025".)	Supplied hardened, tempered to B_H217 (45 tons). Carburised 900/910°C.O.q. Soften 630/650°C, 2 hrs. Finish machine. Harden and temper. Grind and lap.		
En 353	$1\frac{7}{8}$" dia. black bar. (C_{max} 0.18)	Steering shaft. (max.od. 1.813")	Pre-maching: Normalise 850°C and straighten. After machining: Salt-bath carburise worm gear (0.04" case) Reheat carburised end 800°C.O.q. Temper whole shaft (R_c 57)		
En 353	2" dia. black bar.	King pin (max.od 1.873")	Part machined blank carburised 0.03/0.04" case Finish machine. Carburised part-hardened, ground, hard-chromed ground and polished.	En 35	

TABLE 11. (concluded).

		Q	R	S	T	U	V	W
Rounds, Hex.Bar.	Squares Rect.Bar.	40-50	45-55	50-60	55-65	60-70	65-75	70-80
$\frac{7}{8}$"	$\frac{1}{2}$"	(8)						(19)
$\frac{7}{8}$" - $1\frac{1}{8}$"	$\frac{1}{2}$" - $\frac{7}{8}$"		En 15	(18)	En 16		En 17	(19) En24
$1\frac{1}{8}$" - $2\frac{1}{2}$"	$\frac{7}{8}$" - $1\frac{7}{8}$"			(18)	(16) En 17			(25)
$2\frac{1}{2}$" - 4"	$1\frac{7}{8}$" - 3"		(18)			En 24	En 25	
4" - 6"	3" - $4\frac{1}{2}$"			En 17	En 24	En 25	(25) En 26	
Brinell		187-241	212-262	241-285	255-302	285-321	302-341	321-363

Where the above selection chart differs from SMMT Standard 79 oil-hardening and tempering recommendations, the En-steels quoted in the latter are shown (in brackets). The alternative to the SMMT recommendations is more costly in every case.

TABLE 12. Guidance chart to material selection.

Component	Company C		Company D	Company F
Crankshaft	En 16	En 16	En 16	S.G.Iron
Connecting rods	En 16	En 16	En 8R	En 8-type
Connecting rod caps	En 16	En 16	?	?
Gudgeon pins	En 351	En 351	En 351 En 32B	En 32B
Valves: exhaust	214 NS	214 NS	?	En 59
inlet	En 52	En 52	?	En 43c
Push rods			En 8D	En 8
Tappets			?	(Chilled cast iron)
Rocker cross shaft			En32B tube	En 32A tube
Valve springs				
Camshaft				(Chilled cast iron)
Water pump spindle			(GMK2 (En 16T	
Oil pump spindle.	En 31(m/c)	En 31(m/c)	—	En 32 B
Thrust washers		SAE 8615	—	En 32 A
Layshaft	En 12	En 12		

TABLE 13. Steel selection comparisons among 4 'family' cars.(1000-1300c.cs.)

Component	Company C		Company D	Company F
Mainshaft			En 352	
1st Motion shaft	SAE 8615	SAE 8615		
3rd Motion shaft	SAE 8615	SAE 8615		
Laygear	En 352	En 352	SAE 4620	SAE 8617
1st Speed gear	En 352	En 352	SAE 8620	SAE 8615
2nd Speed gear	SAE 8615	SAE 8615	SAE 8620	SAE 8615
3rd Speed gear	SAE 8615	SAE 8615	SAE 8620	SAE 8615
2nd Speed synchro.	SAE 8615	SAE 8615		
Stem wheel				
Reverse idler wheel			SAE4620	
Reverse gear	En 18	EN 352	SAE8620	
Drive gear	SAE8615			
Crankshaft primary gear	SAE8615		En 8	
Synchro hub	SAE8615	SAE8615	En 1A	
Reverse idler wheel shaft			En 352	

TABLE 13. (continued)

Component	Company C		Company D	Company F
Operating sleeve				
Selector fork				En 32A
Sliding couplings	En 18			
Final drive pinion	En 353			SAE 8622
Final drive gear	En 352			
Drive shaft and wheel	En 352 (Pb)			
Differential pinions	En 355 (Pb)	En 355 (Pb)	En 355	SAE 8615
Differential pinion pin	En 352	En 352	En 355	SAE 8620
Differential gears	—	En 353 (Pb)	En 355	SAE 8620
Crown wheel	—	En 35	En 35A	SAE 8617
Bevel pinion	—	En 35	En 35A	SAE 8617
Differential shaft	—	En 16C		SAE 8615
Swivel pin	—	En 12C		SAE 8620
Steering pinion	En 36		En 352	
Steering levers	En 16 C	En 16C		

TABLE 13. (continued)

Component	Company C		Company D	Company F
Stub axles			En 8R	En 8A
Relay arms				En 8
Steering cam		En 351		
Steering peg		En 31		
Fulcrum pin		En 351		
Tie rods	En 16		En 16T	
Upper suspension lever	En 16			
Foot roller joint	En 352			

TABLE 13. (concluded)

1.3-10 Conclusions.

In carrying out a survey of the mass-producing sector of the motor industry - Britain's largest alloy steel user industry - it was felt that the engineering practices observed in the selection and processing of steels would represent optimum conditions for their economic utilisation. The attitude was conditioned by a general consideration of the highly-contested sales market the industry supplies, in which member companies must compete. This is such that mass-production is necessary to meet demand and price considerations and raw material costs may contribute half the cost of manufacture. Thus, it could be argued that the conclusions drawn from the survey would be inapplicable to less closely observed general engineering practices. The development of precision engineering on a mass-production scale has involved the motor industry in heavy capital investment on automatic, continuous processing equipment, justified by output levels not common elsewhere. However, the underlying problems of steel selection in design are essentially the same for all industries, namely the interpretation of specification schedules in the light of real engineering requirements and the adequate attainment of component objectives at minimum overall cost.

It must be assumed that what was observed in the motor industry represented decisions made by each company concerned on what constitutes economy in selection and processing of steels, and that the practices which each follow best satisfy company requirements. Materials specified and used, the form of raw materials brought-in, the subsequent forging, heat-treatment and finishing processes applied are all predicated on component designs, service conditions (i.e. loads carried or transmitted) and the various manufacturing practices available to the individual manufacturer. While such factors alone could explain the differences in material selection for components to meet similar basic requirements of operation mode, durability and strength, it is clearly not a complete explanation. For example, a factor of considerable relevance to this situation is that the sophistication of heat treatment practice has improved in recent years to become a precision operation, which can be relied upon to give high strength properties from relatively cheap low alloy steels. The evidence is that such heat treatment practices have been introduced on a mass production scale by the motor industry, but the efficiency with which they are applied is questionable because the improvement in property development that they make possible has failed to be reflected in national steel specifications, and therefore in many company standards also.

The survey has highlighted the inaptness of steel specifications in providing meaningful guidance to both design and materials staff on material selection and processing route decisions. Mechanical test results as presented by BS 970 for example are rigidly adhered to as design specification data, where this schedule is adopted for company use. The necessity to analyse engineering requirements delineating component function and critical failure modes and the irrelevance of UTS and Izod impact value to in-service performance is frequently stressed (4, 5, 6, 19, 20). For heat-treatable steels, adherence to the latter requires tempering back from the optimum strength condition attainable on quenching, which may well be of greater importance to component life than a high impact value. Thus maintaining this level unnecessarily, implies inefficient material utilisation and therefore an uneconomic "property" on material cost.

Dialogue between designers and materials personnel on steel selection and processing must essentially be in specification terms, but it is observed that the designer - whose the selection decision is - rarely finds it easy to express his ideas in this manner. Both parties are hindered by the limitations that working through irrelevant specifications impose; they are not always aware of this limitation and where it is recognised, there is little done to amend the situation. Company specifications usually echo the BS standards they are intended to replace, with modifications to quality control on purchasing only. As a result, reluctance to question the use of "traditional" steel grades or methods of manufacture on the part of design and materials staff, may rest on assumptions which cannot find technical justification. "Quality", "responsibility towards the customer", are terms still too often confused with material cost, rather than being definitive of practices both efficient in property development and in steel utilisation to meet in-service requirements; over-specification stems from traditionalism and a misplaced sense of values, clearly resulting in uneconomic manufacture.

Thus, current design and steel selection practices depend very little on close definition of component function and loading, primarily because of the complexity of procedures necessary to do this for all but the simplest design form. The same compromise between the ideal and the practical solution was found to be accepted in steel processing, in particular with regard to the development of properties by heat-treatment or mechanical means. Thus, of the basically metallurgical problems requiring considered analysis, the <u>true</u> effects of retained austenite on component performance can only be evaluated by resort to rig-testing or service-testing of variously processed parts (32). Similarly, to conclude that distortion difficulties such as are encountered in conventional carburising treatments could be avoided by the adoption of low-temperature case-hardening treatments e.g. employing medium carbon content, direct hardening steels with a "Tufftriding" process, (35) ignores the fact that carburising is employed successfully in the heat-treatment of components often demanding high dimensional precision. The control of distortion between pre-determined, reproducible limits should be considered more important than its absolute elimination. Problems of retained austenite and distortion are accepted; for the latter, machining operations prior to heat-treatment can allow for subsequent "movement" or volume change while consistency of occurence of either is established by experience in material acceptance checking and by closely reproducible details of heat-treatment practice e. g. load size and the jigging, stacking or packing of components, temperature and time cycles during heat-treatment, details of quenching procedures etc.

Similarly, it is necessary to analyse what seem to be anachronisms in the running and controlling procedures applied to precision heat-treatment plant. The use of outdated methods of carburising atmosphere analysis on the most modern continuous carburising furnace is but one, frequently observed example. However, only by experience in operation can it be determined that the use of infra-red CO-detection devices can measurably improve efficiency of furnace operation and a better product. The replacement of comparatively crude sensors by such apparatus has been found to reveal wildly-fluctuating furnace conditions during continuous processing, never before suspected. Experience - not absolute furnace control - had established "ideal" operating conditions for the production of precision parts, while instrumentation had merely revealed how non-ideal the furnace conditions were, in a theoretical sense at least.

No universally acceptable procedure can be said to exist for the heat-treatment of engineering steels (38), but for their optimum "utilisation" the basic metallurgical concepts of full austenitisation prior to quenching, and a quench to martensite, are generally acknowledged although not always achieved (or even considered desirable!) in practice. Establishing processing routines yielding consistent products largely involves adherence to purely empirical controls because the variables involved are numerous and inter-related. Their influence on processing quality is catered for by codes of practice which experience or, in more progressive firms, exhaustive rig-testing and surveying of processed components have established. Such codes of practice are recognised as being adequate enough to ensure consistency of production of a given component. They are acceptable provided that they ensure minimum overall production costs.

It is clear that metallurgical principles may not be consciously employed in setting up such empirical controls. There is evidence that metallurgists themselves are content to evaluate a process on the results it yields i.e. provide only quality control methods in product worting and testing, - rather than directing the processing itself. The tools available to the metallurgist for doing so are primarily those relating heat-treatment response to steel composition viz. transformation diagrams, end-quench hardenability data and semi-quantitative information derived from steel chemistry. Such tools are based on results of closely-controlled laboratory tests, for the most part conducted on specialised test-specimens. It is conjectured that systematic analysis of component reaction to heat-treatment processing steps would provide information more relevant to establishing process control. For example, cooling rates involved in industrial quenching practice, being sensitive to ruling section, quenchant type, volume, temperature and agitation, job load and distribution et. are virtually unexplored yet a knowledge of the interaction of these variables must underlie realistic attempts at economic utilisation of heat-treatable steels.

Practical understanding of cooling rate has been, and still is, the centre of much metallurgical, physical and mathematical research effort in the United States and in Europe, and several simple methods of quench rate measurement in industrial systems have been proposed (39-41). Contact with British heat-treaters has not found similar interest; the confused selection of quenchant type and method of quenching stems from admission of the complexity of the quenching action itself, while the inaccessibility of sealed-quench systems for instrumentation of tests addes to practical difficulties in studying production conditions. Commercial pressures and widely-differing commercial products available to achieve similar end results i.e. the "ideal" 100% martensite quench, only serve to complicate the situation further. The mutual disinterest of furnace manufacturers and quench-oil makers in <u>production</u> quench research is also unhelpful. It is plain that the hardenability requirements of a heat-treatable steel, for a given application, are reduced as the efficiency of quenching action is enhanced, and this can allow what were once considered "marginally hardenable" steels in a given section size to be adopted, usually at lower raw material cost. This the average practising heat-treater is loathe to do, demanding safe margins of operation in quenching by way of over-specification of steel hardenability. Again, it has been shown that property levels developed by heat-treatment are limited by adherence to BS 970 (29, 38) not only by its reference to absolute practices but also, as is common with the majority of standard and commercial specifications, by failure to detail, quantify, or even to identify qualitatively, the actual hardening process involved in establishing "typical" strength values. The relevance of "limited ruling section" data is lost when quenching conditions are not identifiable and truly reproducible.

Reproducibility and consistency of cooling conditions from batch-to-batch and day-to-day working are equally as important as absolute cooling rate itself. While these factors are not considered as significant as the latter in the operation of modern heat-treatment furnaces, uncertain quench system performance with time also promotes conservative estimation of property potential in steel, "justifying" its under-employment. Similarly, the variation of steel analysis between specification composition limits is beyond the heat-treater's control and he again errs towards a conservative estimate of steel property potential. The simpler the steel composition, the easier it is to set up empirical steel acceptance checks, while a knowledge of quench system performance and control can remove much of the uncertainty over property development stemming from compositional variation.

The influence of buying offices, although un-informed technically in any depth, is often enough to affect the economies of steel utilisation, purely from commercial considerations. This is particularly so where materials personnel fail to provide the technical support and direction the designer needs, through faults in the attitudes of either party. Buying office un-willingness to rationalise sources of supply comes from situations of steel shortage which, although unpredictable, cannot be envisaged again in the next ten years (42). These attitudes do not encourage direct discussion of steel-type requirements between technical staff of both steel user and steel manufacturing sides of industry, which have been shown to lead to developments particularly suited to the user's needs, and directly mindful of raw material costs (5, 7, 23). But the slow generation of interest in non-proprietory steels, although technically and commercially attractive is because of uniqueness of manufacture while they remain outside British Standards. But as between designer and metallurgist, so also in a wider sense, between steel user and steel maker difficulties of communication and expression of needs arise, because thinking tends to be restricted to <u>metallurgical</u> terms rather than being concerned with end-product performance satisfaction.

Where steel grade rationalisation has been attempted, - not so much in the interest of direct raw material economies, but rather in the reduction of over-all processing costs by dropping a multiplicity of processing treatments in favour of high-capacity continuous treatments - this has applied to forgings in particular, while bar steels remain diverse in grade, section size range, condition and source of supply. For most vehicle manufacturers, forgings constitute the greater weight of engineering steel usage, enabling cast ordering and thus facilitating control and identity of material over long production runs. Bar steel consumption, with its diversity of grade and size combinations, rarely merits cast ordering with the expense that stock-holding involves in storage and book-keeping. Difficulties in maintaining effective control on bar stock quality and cast identity are increased where re-rolling and bright drawing intermediaries are involved, unless order sizes merit their co-operation in this. General clauses in BS 970 are such that precise user demands on quality come within unwritten specification intent (26), resulting in one of the larger bar-consuming companies becoming involved in 100% bar inspection. It is debatable whether the 6% rejection rate of raw material that this achieves merits its continued employment; cost implications of tool failures expected from unsorted material should be set against the inspection costs at present incurred, allowing for the rejection of unsatisfactory material which passes through processing at the semi-automatic testing and sorting of critical parts, and already a standard practice. Compare the American attitude: " We build-in quality as we process the raw material, rather than try to inspect quality into it. This is pure, unadulterated economics, and we do it by taking advantage of modern technology" (1).

But to consider material selection in design, it might be said that the most concerted move towards the adoption of lower cost steels, without deterioration in end-product performance, was an enforced one. Strategic material shortages in the early 1950's resulted in the development of the En 350 and En 360 case hardening steels to replace higher alloy grades (43). The repercussions of this are still heard today and from both metallurgical and design personnel alike suspicions were voiced on the continued use of these "economy" grades. Ignoring obvious raw material cost economies which these allowed, reversion to higher alloy content steels has occurred, without any technically coherent reason for doing so. "Unreliability" shortcomings still attributed to them point rather to inefficient heat-treatment, previously masked by high alloy content, than to true steel deficiencies under service conditions.

Similar arguments add to the present discrimination against the controlled-residuals carbon-manganese steels, intended to replace these early economy case hardening grades and limitations on realising their full economic importance may arise from both education and communication deficiencies. It should not be necessary to emphasise that metallurgical advisers to the design staff need to have a precise, technically sound appreciation of engineering aspects of steel properties and their development - adequately backed by purely metallurgical knowledge - which they are able to communicate convincingly to design engineers. They should also be able to draw attention to cost implications of material selection and processing. Thus informed, would they have earned a status within company structure putting them on equal negotiating terms with engineering personnel. The calibre of staff required is high therefore and should as far as possible be separated in its activities from quality control activities of the routine materials acceptance and production line kind. Costing economies and value analysis departments already have such positions in motor manufacturing companies, although their work often aims to improve on earlier selection decisions rather than influencing design conception.

The synopsis has tended to be critical of uneconomic practices likely to be found generally throughout engineering industry. On the other hand, it is beyond the experience of the writer to judge what constitutes consistently good practice. The necessary use of empirical methods in steel selection, processing, testing etc. based on design tradition and manufacturing experience was found everywhere and is unlikely to be wholly supplanted by more sophisticated techniques. That such evolved systems give engineering components which function adequately well in service is clear. But equally so, the minimisation of production costs requires that the solutions be efficient ones. It is held that process optimisation is not possible as it would demand steel consistency beyond that reasonably attainable from existing melting practices, not catered for by the tolerances of compositional specifications. This charge requires critical analysis of course, but on the whole, drastic technological change is <u>not</u> the immediate nor necessary procedure to follow. In the American automotive industry, the revolution in materials and processes application is primarily in the thinking of the participating engineers, designers, metallurgists etc. Change is the rule, rather than the exception, but the changes result from aggressive utilisation of <u>what is available</u> rather than from sensational breakthrough in technology (1).

2. THE SELECTION OF ENGINEERING STEELS IN DESIGN.

2. THE SELECTION OF ENGINEERING STEELS IN DESIGN

Introduction

The manufacture of any engineering product makes the following demands on the basic raw material involved:

(a) That it is capable of achieving property requirements dictated by in-service conditions.

(b) That its formability viz. machinability, forgeability, castability, weldability etc. will ensure optimum production rates from the material-forming plant employed in manufacture.

(c) That established thermal - and mechanical-treatment practices, can be utilised to exploit its material properties to the full.

(d) That it meets conditions of economy and availability.

While such generalisation, common to many sources (21, 30, 44), is sound in its principles, literature is singularly unhelpful in delineating absolute engineering requirements of materials recognizable in terms of behaviour under service conditions. This observation is particularly true of the information presented by material specifications (4-6). Recognition of this fact suggests the technical basis of the present work,-steels, as engineering materials, are specified according to property standards which, although incorporated empirically into design procedures, are admitted to have little relevance to the performance-to-failure of the resulting fabricated components. While there is active metallurgical and engineering criticism of steel specifications in current usage (17, 22, 23, 29, 38) and recasting of BS 970 (13) is in progress, the presentation of data of quantitative significance in design procedure has yet to be realised.

Achbach (19) states that a natural tendency exists for past experiences to influence and even to determine present and future practices. When this was the essence of design philosophy, new engineering products were designed in terms of past experience rather than from a rationalised assessment of the basic in-service requirements of the component. But today, the "evolved techniques" i.e. intuitive shaping of form, quality of finish determined by human interpretation of standards etc. can be supplemented by the accumulated records of laboratory research testing and actual service trials. Even so, the choice of material in design relies to some degree on experience. From the industrial survey conducted as part of this present work, the impression gained was that Achbach's "natural tendency" predominated over the analytical approach to materials selection in design, and the deficiency of specification contributed much towards this.

The following sections consider the specification format commonly used in engineering industry today as a basis for both steel purchasing and steel selection in design. The relevance to these situations of the data which they comprise is discussed, particularly in the fulfilment of the latter role as design specification.

2.1. Engineering steels

BS 970 : 1955 (13) is the current specification schedule covering steels "for automobile and general engineering purposes". It has evolved from a schedule first compiled in 1924 (BS 5005) which specified wrought steels for the motor industry. En-steels which BS 970 specifies, date from 1941, the most recent additions to the schedule being the En 350-and En 360 - series of case-hardening steels, introduced in 1951 as economy grades to be used in place of more highly alloyed steels. The present schedule dates from 1955, but a complete revision is known to be in hand. BS 971 (45) complements BS 970, being "a commentary" on the En-steels, giving further information for guidance in economic selection of steel in design; it dates from 1950.

2.1-1 Steel Specification Format & Function

Engineering steel specifications, typified by BS 970, are commonly based on:

(1) Chemical composition.

(2) Qualitative description of steel condition at the time of delivery to the steel user.

(3) Heat treatment to be applied to material from which test-pieces are machined to determine:

(4) Mechanical properties, specified in terms of parameters derived from laboratory testing e.g. in BS 970, ultimate tensile strength, minimum % elongation and Izod impact value are contractual parts of the specification, derived from "longitudinal" test material. In addition, BS 970 quotes yield stress and Brinell hardness values "for information only" - the yield stress figures are "considered representative for the steels concerned"

while hardness values are calculated from the specified tensile strengths.

A given steel specification is intended to fulfil two primary functions:-

(a) It is a means of communication between supplier and user.

(b) It is a materials data sheet for steel selection in design.

When a specification meets both of these functions realistically, it facilitates the design and production of components which will adequately fulfil service requirements. Gillett (33) defines the best engineering material as that giving the lowest finished-part cost, while meeting the properties required of the part under service loads; raw material cost is of utmost importance and must be regarded as a basic property of any material.

a. Supplier-to-user communication

The specification must be the means by which a customer can define his needs conveniently and unambiguously to the steel supplier, and should therefore be complete in itself for any supplier to work to. However, from the above outline, it is clear that the BS 970-format lacks important detail, - for example, of relevance metallurgically for quality control, the cleanliness of steel would be guaranteed by the unqualified statement that "steel shall be free from piping, harmful degregation and other defects" (13). Also, with familiarisation in the use of a steel a user may progressively increase his demands on it, and his actual needs become implicit to the original specification (26).

Thus, "rigid" control comes to rely increasingly on unwritten intent, and the steelmaker's interpretation of customer requirements.

Unless specifications are phrased in quantitative terms, they are unenforceable (11).

Automobile manufacture for example involves precision engineering components being produced by mass-production techniques. The expansion of the industry to consume 90 to 100,000 tons of steel per month has involved the installation of highly-specialised machining equipment and heat treatment plant. To justify this, close control of fully-automated operations necessitates consistent raw material quality at competitive prices. (22, 23, 44).

b. Selection-in-design data communication

The steel specification should also be the means of conveying data to the designer truly representative of the steel, which is applicable both to engineering design and to product performance. In this respect, BS 970 purports to be more than a material control specification; it is foremost, a design specification in that it advises the designer on steel selection but as such, its adequacy can only be judged by setting it against criteria of design situations. Smith & Scott (6) mention the "artificiality" of design practice which results from such a comparison for most material and product specifications is simply that specific mechanical test requirements will be met by a given chemical composition, melted by a given steel-making process, while the real design basis remains undefined.

Service requirements cannot always be stated in quantitative terms, and design specifications can never give the complete answer to material selection. Similarly, material test data cannot always delineate absolute material performance, even in a standard test piece, as surface treatments, surface finish and environmental conditions can markedly affect test results. The complexity of design engineering is such that <u>direct</u> information is only obtainable by simulated service testing, in which critical component designs, formed and finished under production conditions, are subjected to stresses and environment to be endured in service. These are as much a test of design function as of the material selection, and the optimisation of the design is necessary in order to arrive at the most economical material to be used. Even then, simulated service testing of engineering components require confirmation by field testing before criteria of design, material and processing can be arrived at. These may well be in the form of "conventional" data, but <u>thus established</u> they remain the yardstick by which consistency, quality and reliability of the final product is assured.

In the future, the situation may well be changed as the science of fracture mechanics is extended from its present limited application to simple engineering structures, to complexcomponent shapes subjected to both external loading and internal residual stress systems. Of the change in the engineering concept of ductility in the light of fracture mechanics, Wells (4) states "It is vital that the occurrence of this revolution should be recognized and that such benefits as arise from it should be efficiently assimilated into standards and specifications."

A recent review article (46) has considered the subject of fracture mechanics in simple terms, its theoretical basis, testing techniques and practical importance, and May and Walker (47) have detailed testing methods in the light of particular service requirements. Special application to failure by fatigue and stress-corrosion has also been described (48) while the practical application of the theory and a study of influencing metallurgical factors have been presented by Cottrell and Langstone (49).

The likely range of applicability of the theory is as yet unknown, and only recently has the theory been considered relevant to steels having strength levels less than 80 tons/sq.in (47). It is thus reasoned that its impact on general design engineering thinking is not likely to be effective for many years to come.

2.2. The Analytical Approach to Selection in Design

The effectiveness of the value analysis approach to costing economies and materials utilisation has been noted where employed by component suppliers to the motor industry. The technique is used largely to analyse the functional requirements of existing products and often leads to their re-design to function no less efficiently but with lower overall production costs. Pick (5) has suggested that the same methods of systematic questioning might well be applied to the analysis of materials specifications and the selection of materials in design, scrutinising every specification feature in relation to its relevance and cost. A review is presented here of engineering metallurgical and economic aspects of steel selection and utilisation, based upon the fundamental requirements of the majority of engineering components. It concentrates on the systematic application of well-established ideas only, fundamental to engineering and materials science.

2.3 Engineering Aspects in Steel Selection and Utilisation

The rational approach (53) to the design of a given component involves the determination and equilibration of two factors:

Stress, as imposed by service loading conditions or retained in the component after fabrication or assembly, summarized in terms of "significant stress", and

strength - "significant strength" is that required to sustain significant stress.

The two factors are dependently variable and a knowledge of both is essential to "successful" engineering design. Successful here presumes the optimum utilisation of material and processing plant to produce parts at minimum overall cost, to carry service loads without failure for a given working life. Should this latter condition not be satisfied, i.e. working stresses exceed significant strength, re-evaluation of component requirements can result in:-

(a) Design modification, e.g. attention to design detail on fillets, keyways, surface finish etc. to lower localised stresses.

(b) Processing modification e.g. increasing material strength by way of hardness increase, accomplished by changing heat-treatment or by applying localized hardening treatments.

(c) Material up-grading, e.g. adopting a material of higher heat-treatment response for the same processing route.

(d) Dimensionally up-grading the component.

Of these methods, the first is the direct responsibility of the designer, as is the last which must be regarded as the least desirable method of correction because of costs incurred not only from the extra material involved but primarily from the cumulative effects on the whole design of which the component forms a part.

Again, assuming that plant is available to effect minor processing modifications in order to increase component strength, this is to be preferred to the adoption of another material, possibly more expensive but not necessarily so, than the original choice. Clearly, the most efficient approach is to provide the designer with material property data closely related to processing method in order that significant strength can be defined more accurately at the design conception.

2.3-1 Conditions of loading

Traditional development of design calculations to satisfy general and specific engineering stress/strain systems, stems from principles of applied mechanical theory and the strength of materials. It involves not altogether realistic assumptions from the theory of elasticity (18) requiring both homogeneity and isotropy of material. For non-critical components, detailed stress analyses are rarely employed, design being based on mean stresses likely to be met in service, and often well covered by experience with earlier designs. For critical components, the failure of which disrupts the efficient operation of the whole structure, the designer must provide an adequate solution to the question:

"Under foreseeable conditions of operation, i.e. mode of loading, environment, temperature etc. by what mechanism is the component most likely to fail?"

The failure of any component subjected to load can be defined as "any behaviour of the component rendering it unsuitable for its intended function" (20). The forms that failure can take, from actual fracture to plastic deformation or excessive elastic deflection, under conditions of static or dynamic loading, both with and without the impingement of temperature and chemical effects on "normal" environment conditions, are well covered in the literature (18, 20). This reveals, for example, that conventional dynamic loading design derives from static strength properties of materials, modified by factors of safety to indicate significant strength. Since design practice attempts to eliminate all chance of failure, or accepts only a limited number, significant strength thus derived tends to be a conservative value.

The present treatment can only refer to basic principles of design but it is in the failure to recognize these that misapplication of steels or processing method most frequently occurs. It is thus important to recognise the loading conditions existing in a component (20), for which simplified classifications are:-

Axial loading, in which the significant stress is the normal stress in the component and uniform over the component cross-section.

Bending loads, in which the significant stress is greatest at the free surface of the component, falling to zero on the neutral axis.

Torsional loading, where four significant stresses magnitude equal to the maximum shear stress arise, also at a maximum at the surface of the specimen.

In addition, most engineering components operate under dynamic loading conditions, introducing a "life" factor into performance and the fatigue concept of progressive breakdown with repeated loading or load reversal.

Purely axial load application is rarely found in practice - for which uniform strength over the component cross-section is necessary - any offset in loading resulting in the introduction of bending moments about the neutral axis. Maximum stress is generated at the free surface for either bending or torsion loads, and surface condition has the most important influence on the durability of the component therefore, particularly where fatiguing conditions are promoted by load fluctuation. The metallurgical consequences of the correct engineering application of a given steel are discussed later but it may be seen that, under such circumstances, there is no justification for the use of a fully through-hardened steel, as the strength this attains at the neutral axis from optimum conditions of heat treatment will be redundant to the performance of the component under load (5, 20, 38).

Component performance under load is also influenced by contact conditions existing between it and adjacent parts of the structure as a whole, where loads are transmitted to or from the component. Simple classification of contact conditions include (34):

Static contact, where fretting is the primary failure mode.

Rubbing contact, giving rise to scuffing of the component surface.

Rolling contact, which is responsible for pitting attack.

Whatever the form of wear mechanism relevant to a given load/contact situation, the degree of damage incurred is dependent on environmental conditions also. Decisions on material selection to meet wear conditions alone are in themselves specific to the loading and environmental conditions involved, while the effect upon surface conditions arising with time in service is important from other engineering aspects, notably in fatigue. The specific nature of such problems is illustrated for scuffing wear requirements as follows:-

(a) For maximum scuffing resistance in rubbing contact only, chill cast iron is a common choice e.g. for tappets in an i.c. engine (50).

(b) Where maximum scuffing resistance must be combined with strength under dynamic bending loads e.g. for gears, a carburised steel is a likely choice, perhaps phosphated to enhance wear resistance still further when run in an anti-scuffing oil (50).

(c) Plug dies used in tube-drawing work under compressive loads, in high temperature environments. A chill cast iron die is given a highly polished chromised working surface to meet environmental and scuffing wear conditions.

2.3-2 The special significance of fatigue failure in engineering components.

The failure of a component by fatigue deserves special consideration, if only for the following statement:

> "The Feilden Report on Engineering Design (51) notes that more than three-quarters of service failures referred to the National Engineering Laboratory for analysis, are due to fatigue."

Commenting thus on the Report, Phillips and Frost (52) indicate the complexities of designing against fatigue failure, when it is apparent that fatigue properties of all materials of engineering interest, under all possible combinations of stress systems, surface finish, surface condition, heat treatment, temperature environment and rate of application of stress cycles will never be available. Intrinsic fatigue properties of a given material may enable an efficient design to be produced for a solid component of uniform section to withstand fatigue loading, but even for the simplest shape the design problem is a prodigious one. Few components are of uniform shape, and most contain stress raising discontinuities such as changes of section, grooves, keyways, oil-holes etc. essential to the component's function and as a result, fatigue failure can stem from lack of attention to design detail, or from the unsatisfactory manufacture of an otherwise satisfactory design. Laboratory tests on deliberately notched test pieces are of limited use in assessing the value of local stress intensification in practical circumstances or in providing data on the design performance of un-tested shapes (52).

Under cyclic loading conditions, fatigue cracks will be initiated when local stress amplitude just exceeds the intrinsic fatigue limit of the material. If this is derived from highly polished laboratory test specimens, it is found to be approximately half the inherent tensile strength of the material, although it is well known that the amount gained in fatigue strength by going to a higher tensile strength material can vary from 0 to 100%, (fig. 1) so dependent is this property on surface and environmental conditions (24). But, Frost (54) points out that whether or not a component fails catastrophically may depend less on the value of cyclic stress required to initiate a crack than on that required to cause a crack to grow, the "life" of a given component under cyclic stress being the summation of the number of cycles to initiate a crack and the number required for crack growth to complete fracture. Frost concludes

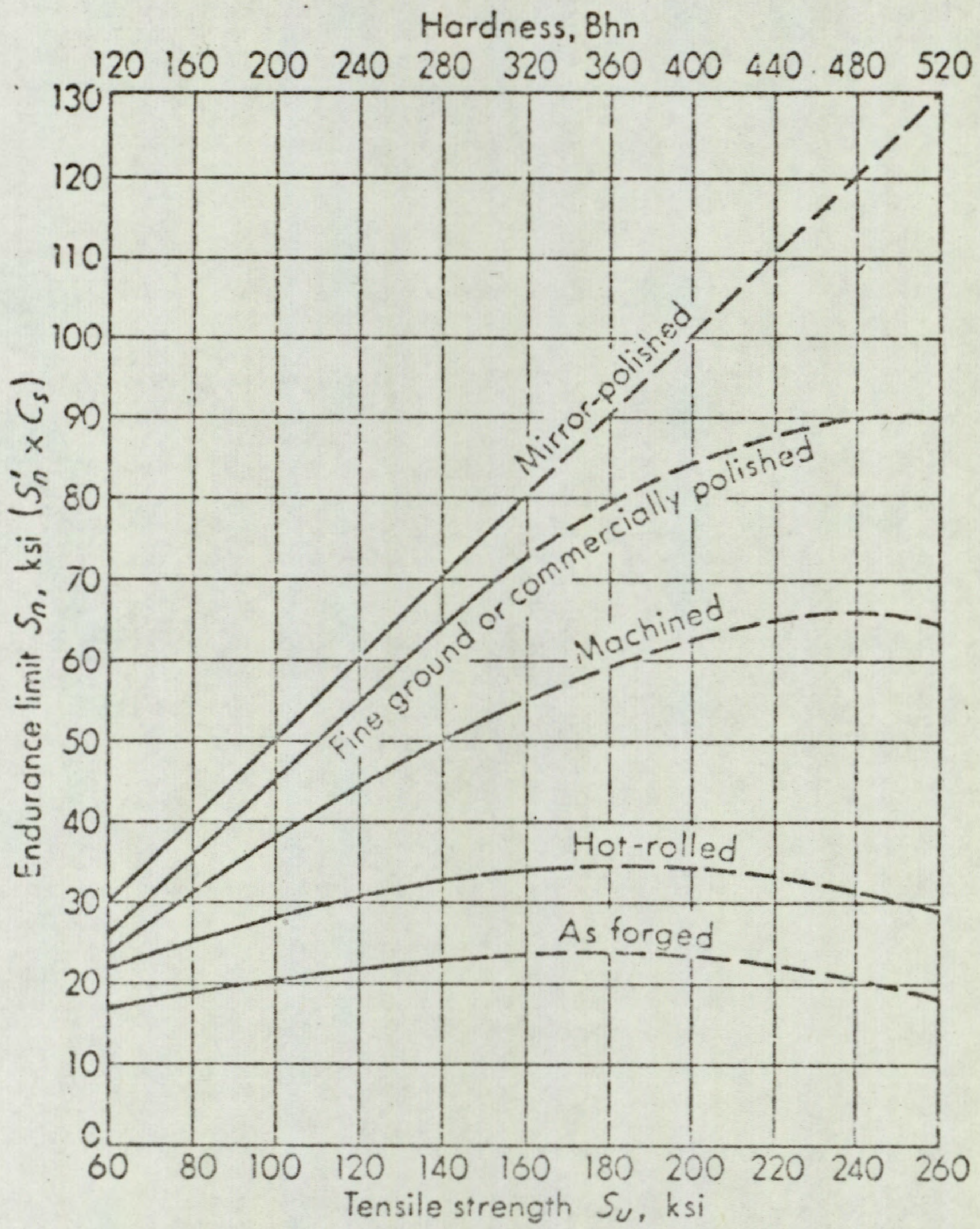


FIGURE 1. Effect of surface finish on the endurance limit of steel. (from Juvinall (20)).

that designers must cater for a low rate of crack propagation and high residual static strength in the presence of a crack, in addition to optimising on design detail, surface finish and material homogeneity within economically sensible limits. Thus, although alloying a steel puts up its plain fatigue limit, the rate of crack propagation remains the same as in a mild steel, and the crack growth before catastrophic failure becomes considerably less! (Table 14). For such reasons, Frost considers the results from notch fatigue testing misleading and best ignored in design (52, 55).

	Plain fatigue limit $(FL)_P$	C	$\frac{C}{((FL)_P)^3}$ ≡ Progress as micro-crack	$k_F = \frac{(FL)_P}{(FL)_N}$
Mild steel	± 13 tons/sq.in.	5.5	0.0025	3.4
Ni Cr steel	± 30 "	5.5	0.00017	8.4
Copper	± 4 "	0.6	0.0094	2.2
Al-4.5 Cu	± 9 "	0.2	0.00024	7.1

TABLE 14.

Comparative plain fatigue performances - (after Frost (55)).

2.4 Metallurgical Aspects in Steel Selection and Utilisation

The following discussion attempts to formulate the basic metallurgical considerations determining the properties of heat treatable steels and outlines the essentials of established practices whereby they can be derived in engineering components using methods and materials which give optimum overall economy in production costs.

2.4-1 Carbon in steel.

Carbon is the most important constituent in any engineering steel and its "manipulation" within steel primarily by means of heat-treatment is the basis of any specific property optimisation, e.g. strength, hardness, machinability, corrosion resistance etc.

The first requirement of an engineering steel is strength, and for a given carbon content all steels when quenched from the fully austenitized condition to a 100% martensite structure exhibit the same optimum tensile properties and hardness (56). The steel cross-section in which a given quench can effect this is determined by the hardenability of the steel. In plain carbon steels, this is small and full hardening is limited to light sections, under average commercial quenching conditions. Alloy additions to the carbon base increase the fully-hardenable cross-section for a given quenching severity, by delaying the decomposition of austenite in preference to its transformation to martensite. While the relative effects of alloying elements and austenitic grain size on the transformation kinetics have been widely studied and are established qualitatively, quantitative means of predicting hardenability response in such terms for a given steel, where successful, have proved to be specific only to narrow compositional ranges covered by the original experimenters (57). Practical expression of hardenability is derived from the jominy end - quench test (58), -

intended originally to be no more than a quality control test, - while comprehensive description of austenite transformation and decomposition during cooling is given by continuous cooling transformation diagrams (59) which delineate optimum quench-rate for the fully martensitic state.

That it is microstructure which determines the properties of a steel was first reported by Janitzky and Baeyertz (60), who noted a marked similarity in the mechanical properties among heat-treated steels, regardless of alloy content. The fact permits prediction of the mechanical properties of tempered martensitic steels from a knowledge of carbon content alone. But in engineering situations employing the heat-treatment of sections greater than say 1" diameter, continuous increase in carbon to achieve higher strengths by through-hardening is restricted to 0.5 to 0.6% carbon maximum, - raising carbon content increases the risk of cracking and distortion in heat treatment (by lowering the Ms temperature (61)), adds to machining and other metal forming difficulties only alleviated by pre-processing heat-treatments to derive the optimum carbide dispersion (27), and increases the chance of brittle failure under static or impact loading situations (62).

By the use of selective hardening treatments, as described elsewhere in this survey, hardness and strength of a component may be increased exactly where design requirements merit this, after major forming processes have been carried out at lower strength levels. Thus with carburising for example, high surface hardness to combat wear is combined with toughness and ductility of a lower-carbon core achieving mutually incompatible service requirements of surface and bulk from the same steel.

The relative effectiveness of alloying elements in promoting depth of hardening is discussed later in this report on a basis of cost return; the cheapest method of increasing hardenability at a given carbon level is to increase the manganese content (63,64). Use of course grained steel, when engineering and processing circumstances permit, is also a cheap approach to increased hardenability in a given composition (65).

Thus, to summarise, to minimise raw material costs a steel of carbon content no higher than is necessary to achieve the desired strength properties should be selected, while the hardenability of the steel should be no more than will adequately attain the required distribution of strength, under given quenching conditions. Such generalisations are basic to the selection of any heat-treatable steel.

2.4-2 <u>Heat treatment method and steel performance</u>

Economic satisfaction of any component design minimises the tendency to failure under working stresses or more positively, achieves life expectancy by combining design expertise with optimum condition of the materials of manufacture. With heat-treatable steels, the following principles are well established:

(a) For optimum resistance to fatigue failure in combination with high notch toughness, <u>through-hardening</u> steels are quenched to a fully martensitic structure. Subsequent stress-relieving or minimum temper treatments should be applied solely to meet true engineering ductility requirements. Any tempering operation implies a decrease in hardness and therefore a final strength below that which the carbon content of the steel is capable of developing, given adequate hardenability and quenching conditions to do so (20).

(b) Similar conclusions are applicable to carburised steels. Love, Allsopp and Weare have presented an analysis of heat-treatment effects on the bending fatigue strength and impact strength of carburised gears (32). They have showed that these are optimised by direct quenching from the austenitising temperature, and left untempered. Increased fatigue resistance accompanied increase in core hardness, while tempering reduced bending fatigue strength of the components under test by some 7 to 23%. Although impact strength was improved by this treatment, this was not a common failure mode for gears; conventional impact tests on notched bars failed to indicate the impact properties of processed components, demonstrating the lack of significance in particular engineering situations of Izod test values assigned to steels by specifications. BS 970 Izod values refer to specialised test specimens representing the core material only. Love et al. showed that even carburised notched bar test pieces gave no indication of gear strength, possibly because of marked discrepancies in notch configuration on test bars and the gear root fillet.

(c) While it is established that optimum hardness results from a 100% martensitic structure, the effects on fatigue strength of small quantities of retained austenite is not altogether clear. Industrial practices involving the mass-production case-hardened automotive gears have been found to give up to 10% retained austenite in the case. Heat treatment schedules quote "base structure - martensite with a moderate amount of retained austenite ....", without further guidance to the "satisfactory" condition, check comparisons being made occasionally against standard micrographs.

Love et al. (32) found that retained austenite was associated with the stronger gears in their test series, some 25% being present in a gear exhibiting a fatigue strength of more than 130,000 lb. per sq. in . The combination of austenite retention with high fatigue strength was common to carburised and high-temperature direct quenched gears. In contrast, Love et al quote the findings of Frankel, Bennett and Pennington (66) who investigated the effects of retained austenite in through-hardening steels. These workers recorded a decrease in fatigue strength with increase in retained austenite. Here, deep freezing to remove the austenite improved fatigue strength, while Love et al. recorded an adverse effect on bending fatigue strength for similar cryo-treatment.

(d) While increasing the intrinsic strength and hardenability, higher carbon and alloying element content in a heat-treatable carbon and alloying element steel result in the depression of the upper temperature of martensite formation Ms; a given percentage increase in carbon content depresses the Ms temperature by a factor ten times that due to a similar increase in any other common alloying element (67), approximately 33 C degrees per 0.1% carbon increase. Formulae have been derived for the calculation of Ms temperature from statistical analyses of compositional data (68, 69). The later the onset of transformation, the greater is the resistance of the steel to the 1½% volume change incurred by the martensitic transformation, and hence the risk of distortion and cracking increases, particularly at abrupt changes in component section. For carbon steels, the "critical" carbon level is about 0.4% (67) but the overall hardenability of the steel (determined by manganese level and residual element content), as well as component size and shape, contribute to criticality.

Murray (35) has recently investigated metallurgical features affecting the amount of distortion that occurs in the treatment of carburising steels. The essentials of his experimental work are largely borne out by industrial experiences and practices conditioned by them:

(1) An inverse linear relationship between distortion and transformation temperature was proved, but in any steel, distortion was minimised by applying direct quenching from the hardening temperature.

(2) Cast-to-cast variation in chemical composition and grain size gave considerable scatter in distortions measured for a given treatment, primarily because of their effect on Ms temperature.

(3) Core depth and case carbon content in particular, asserted major effects on distortion, varying inversely with the strength of the core material, but Murray stressed that in order to understand and therefore to counteract distortion the transformation characteristics of the steel and component part cooling conditions in heat-treatment are considered together.

2.4-3 <u>Effect of surface condition on component performance</u>

While the surface condition arising from method of fabrication and finishing exerts considerable influence on the service performance of a component, Frost's conditions for slow fatigue crack propagation (54) are approached most directly by surface treatments which result in highly localised strengthening of the component at the position of highest dynamic stress level. Depending on the means employed to achieve this, the enhanced strength associated with surface treatments appears to result either from metallurgical structures arising from the treatment or from residual stresses thus generated, or from a combination of the two. (20, 38).

Love (50) quotes the following approximate values of significant strength modification by surface conditions under bending loads:-

Fabrication effects:

Decarburisation - strength reduced by 20 to 80%

As-forged - strength tends to be independent of tensile value.

Turned surfaces v. polished surfaces - turned surface 10% weaker in a 35 ton tensile strength steel, and 20% weaker in a 60 ton steel.

Surface treatments:

Carburising - strength increased by 40 to 120%

Nitriding - strength increased by up to 50%

Carbo-nitriding - strength increased by 20 to 100%

Induction hardening - 60% improvement

Flame hardening - 60% improvement

Cold working operations:

Shot peening on unmachined surfaces - improvement in strength 25 to 75%

Shot peening on polished surfaces. - up to 20% strength increase

Surface pressing - 20 to 30% improvement

Surface rolling - 20 to 100% improvement

Roll-forming of threads and splines - 150% strength increase possible

In contrast, Love quotes cold straightening as reducing the inherent strength of a component by as much as 25%, while the use of plating to counteract corrosive effects may weaken the component by 10 to 40%. (It is emphasised that these figures are factors to be applied to the significant strength of a given component.)

Experience has shown that through-hardening methods are generally restricted to hardnesses up to 54 Rc, several workers reocrding widely varying fatigue strength values above this hardness (70). Surface treatments enable higher case hardnesses than this to be utilised successfully together with associated residual stresses in the promotion of good wear resistance and superior fatigue performance. Carburised and hardened gears have been reported to give from 20 to 90% improvement in fatigue strength over through-hardened steel gears (71); a further comparison showed that for a given pitting wear criterion, case-hardened gears had a load-carrying capacity 70% higher than that for similar through-hardened gears (72).

The combination of heat-treated low alloy or carbon-manganese steel with surface treatments to satisfy dynamic loading conditions has already attained universal adoption, particularly with the use of carburising. However, as figures again due to Love (50) show, the less-frequently applied alternatives can offer even more attractive economies (see Table 15).

It is to be expected that no one surface treatment has universal economic application. Carburising treatments are selected for high contact-load application, where case in depth and high fatigue properties are required. Nitriding can be applied in situations demanding close dimensional control during treatment; the nitrided case itself is little affected by tempering treatments subsequently

Box carburising to 0.040-0.050" case depth	1/3 per lb.
Gas carburising to 0.040-0.050" case depth	1/1 per lb.
Nitriding	average 9d. per lb.
Induction hardening	average 4d. per lb.
Surface rolling	average 4d. per lb.
Salt-bath treatments	$3\frac{1}{2}$d. to 5d. per lb.

TABLE 15 - due to Love (50).

(July 1966 prices).

applied to the component as a whole. A comprehensive review of surface treatments recently published (38) tabulates the engineering properties to be obtained by industrially-applicable surface treatments. However, in the light of processing economics which Love's figures indicate, considered engineering application of induction heating treatments is likely to increase, particularly where mass production on automatic transfer machining plant adopted for new installations can incorporate these at in-line stations. As was recorded on the industrial survey, future thinking is in terms of induction hardened medium-carbon steels to replace many present-day surface treatments on low-carbon steels, but the production engineering problems which this will entail will require informed appraisal and practical solution if large-scale introduction of induction heating methods is to be realised.

2.5 Economic Aspects in Steel Selection and Utilisation

2.5-1. The cost of steels

In accordance with the Iron & Steel Act 1967, the British Steel Corporation publish from time to time Notices of Prices (73) which recommend steel purchase prices within the United Kingdom from the publicly-owned sector of the industry. Extracts from the Notices may form the price lists for a given steel manufacturer. The system has replaced the former Iron & Steel Board price determinations and related schedules (74) although the pricing structure closely follows earlier practices, expressing basis price terms modified by cost extras or allowances.

Basic prices for steels apply to specified conditions of quality, quantity and product form and size, as sketched in Table 6. "Extras" include the following:-

Special work, processing or quality rendered necessary by, and carried out to the technical requirements of the customer's specification, e.g. compositional requirements at variance to basis conditions - viz. free-machining additives, restrictions on sulphur or phosphorus, residual elements etc.

Heat treatments.

Controlled grain size.

Special shapes, statements on length, cross-sectional tolerances, special identification, testing, inspection etc.

Bavister (22) emphasises the necessity of accurate detailing of steel quality features to costs, exampling cost extras arising from time-honoured descriptive terms not easily quantified, - the interpretation of "forging quality" is a prime example. Bulk purchasing, placing orders by cast is a more obvious approach to costing economies; rationalisation of steel grades, section sizes and qualities can, in addition, contribute directly to product manufacturing consistency over long production runs. Whether to purchase heat-treated steel or to heat-treat components after manufacture should be judged against relative costs of the two approaches, although hardened and tempered bar stock may be unsuitable for ease of component manufacture at overall minimum cost. The efficiency and reproducibility of heat-treatment of steel in bulk is often suspect when out of the purchasers' control entirely; it is commonly found that a purchaser will normalise all forging blanks prior to machining to ensure consistency of manufacture thereon, whatever their condition on receipt from the forger.

It was openly admitted in buying offices visited during field studies that cost extras on special customer requirements were negotiable, and rarely paid in full. The following paragraphs consider metallurgical and engineering cost implications not commonly considered capable of reduction because of adherence to traditional attitudes to steel as raw material, and to manufacturing method.

a. Cost and steel composition

Honeycombe (3) has described the development of the present generation of low-alloy engineering steels as a process of "intelligent evolution combined with inspired empiricism", inevitable in the light of the complexity of the metallurgy of steels and the lack of basic understanding of the physical metallurgy involved in their exploitation. Gemmill (2) questions the true meaning of a "steel composition" range, which he sees as having been derived "for reasons of history or steelmaking convenience" with little real understanding of the property consequences. Evidence bearing out the essential truth of these statements is found in BS 970 - for example, a steel user requiring 45 tons/sq. in. tensile strength in a component with a $^{7}/_{8}$"

ruling section can choose from some eleven heat-treatable steel specifications meeting these conditions. Similarly, 20 specifications can be drawn upon to satisfy 55 tons/sq. in. in a 1" diameter section. The Society of Motor Manufacturers and Traders specification SMMT 70 includes a costs-based analysis of BS 970 heat-treatable steels in terms of mechanical property and ruling section, which is frequently adopted as a part of company specifications by SMMT member firms. A cost-based assessment of case-hardening steels has been carried out (75) for a range of bar diameters more in keeping with the needs of industry than the standard $1\frac{1}{8}$" section of BS 970 mechanical property determinations. That such exercises are possible would prompt the economic necessity to consider Honeycombe's suggestion (3) that "80% of the needs of the engineering industry could be met by a very compact group of inter-related steels, manufactured in bulk in a wide variety of sections, with a much closer control than is at the moment considered reasonable."

Thus, to return to Table 6, the development and continued usage of steels of the En 27 type - which BS 970 guarantees will attain 70 tons/sq. in. tensile strength in a 4" section, in the heat-treated condition - epitomises Honeycombe's evolution theory, when the complexities of its composition are considered. The price differences in billet steel in Table 6 arise almost directly from the cost of alloy additions made during steel manufacture; the cost to the steel manufactuer of the more important ferro-alloys are listed in Table 16.

The prime reason for the presence of alloy additions in engineering steels is to promote heat treatment response in section thicknesses

Alloy	Description	Price *)
FeCr	High carbon, 60 Cr	£74-£77 per ton
	Low carbon (0.01%)	2/- per lb.
SiCr	37-39 Cr 40-47 Si	£89-£90 per ton
FeMo	65-70 Mo	18/1 per lb. metal content
	Molybdic oxide brick	16/3 per lb.
	Calcium molybdate	16/8 per lb.
FeMn	78 Mn (U.K.)	£51.5.0. per ton
	" " (imported)	£50.10.0. per ton
	" " (refined, 0.1 C)	£165 per ton
	" " (refined, 2 C)	£100 per ton
	Speigel	£34.5.0. per ton
SiMn	65-75 Mn 20-25 Si	£60 per ton

*) as at 5th November, 1968.

TABLE 16.

where cooling rates cannot be achieved to utilise the inherent strength of a plain-carbon composition, - in sections thicker than $\frac{3}{8}$", carbon steels require the severity of water or brine quenching to develop full hardness (16), when distortion or quench cracking is difficult to avoid or control (76). The well known potency of chromium and molybdenum in promoting hardening in depth is witnessed by their traditional adoption for such purposes, but the proven effectiveness of the cheaper, more abundant manganese (61, 64, 77) in this role has been neglected.

Manganese is used essentially as a deoxidant in steel-making and to prevent red-shortness at hot-working temperatures by "fixing" sulphur, but its cost-effectiveness as an alloy addition in heat-treatable steels has received little practical attention in the past. Although "standard" heat-treated carbon manganese steels are used in quantity in engineering manufacture (e.g. En 15, En 201, En 202) their desirability cost-wise is not matched by their performance, - they are shallow hardening, which limits the section size of components manufactured from them, and they exhibit considerable spread in heat treatment response and therefore in mechanical properties. Residual element content, not always effectively controlled from cast to cast by the relevant compositional specification, strongly influences the response of these steels to heat treatment (7). By exploiting this latter effect, carbon manganese steels have been developed as economic substitutes for traditional low-alloy heat-treatable compositions (5, 7). Residual levels are regulated by selective scrap melting and their hardening potential used but compositionally, these steels remain outside the alloy steel definition (8) and are not therefore subject to alloy cost penalties. With or without boron and grain refining treatments, such steels are attractive commercially, as economic replacements for standard steels. Table 17 lists some of the steels for which carbon-manganese grades, as yet outside British Standard steel schedules, are claimed to be technically equivalent, and shows that their adoption can result in cost savings of up to £50 per ton in the bar section specified.

The use of boron is more expensive than manganese to attain a given hardenability, but cheaper than using chromium for example. Optimum boron content present in solid solution, lies in the range 0.0005 to 0.004%, above which little further return on hardenability is secured. With 0.30 to 0.40% carbon - 0.85 to 1.05% manganese base, Sellars & Cormack (17) found an addition of 0.003% boron to be more effective than an additional 0.5% manganese and, in conventional engineering alloy steel terms, equivalent to En 16 manganese-molybdenum steel costing 12½% more than the boron steel. Commercially available boron-treated carbon manganese steels referred to earlier offer attractive and substantial price reductions over alloy steels (7), of which En 16 is one.

Steel grain size, the control of which carries a cost extra, contributes to heat treatment response; it is claimed (65) that the hardenability of steel of given carbon content may increase as much as 50% with an increase in austenitic grain size from ASTM (6-10) to ASTM (1-4). Where there is remote danger of quench cracking, on uniform sections, it can prove cheaper to use a coarse-grained, carbon or carbon-manganese composition with water or accelerated-oil quench, than to depend entirely on steel composition to give the hardenability required. It is necessary to analyse engineering considerations to determine the advisability of this procedure. Some sacrifice of notch-toughness, and an increased tendency to distortion on heat-treatment is

Alloy steels replaceable by (CMn + controlled residuals) steels.

Cost ratios shown thus: (122).

Based on December 1967 prices (50 ton lots, $1\frac{1}{2}$" round bar).

a. Carburising steels.

<table>
<tr><td>En 351</td><td>(121)</td><td rowspan="12">"70-ton"
(100)</td><td rowspan="15">"80-ton"
(100)</td><td rowspan="18">"90-ton"
(102)</td></tr>
<tr><td>En 361</td><td>(122)</td></tr>
<tr><td>En 362</td><td>(122)</td></tr>
<tr><td>En 363</td><td>(122)</td></tr>
<tr><td>SAE 8617</td><td>(123)</td></tr>
<tr><td>SAE 8620</td><td>(123)</td></tr>
<tr><td>SAE 8622</td><td>(123)</td></tr>
<tr><td>SAE 8627</td><td>(123)</td></tr>
<tr><td>En 352</td><td>(124)</td></tr>
<tr><td>En 353</td><td>(135)</td></tr>
<tr><td>En 34</td><td>(138)</td></tr>
<tr><td>En 33</td><td>(148)</td></tr>
<tr><td>En 36</td><td>(165)</td></tr>
<tr><td>En 354</td><td>(140)</td></tr>
<tr><td>SAE 8630</td><td>(123)</td></tr>
<tr><td>En 355</td><td>(158)</td></tr>
<tr><td>En 39A</td><td>(182)</td></tr>
<tr><td>En 39B</td><td>(188)</td></tr>
</table>

b. Through-hardening steels.

En 16 (121) - CMn equivalent (100).

TABLE 17.

reported for coarse-grained steels (17, 65) but claims that fatigue resistance is enhanced by fine grain size per se (17, 31) require rigorous practical analysis. However, a coarse-grained carbon-manganese steel, Phoenix CM 70, developing 70 tons/sq.in. tensile in ½" section, has been in regular production for more than five years and is used under mass-production conditions as an economy steel replacement for En 354 (7). In the bright-drawn condition, a cost saving of £50 per ton was achieved over the standard steel (5).

b. Cost and steel-making practice

With the exception of higher-alloy grades, steel basis prices refer to basic open-hearth melting practice. Sulphur and phosphorus contents are limited to 0.035 to 0.040% maxima, and cost extras for lower levels reflect the adoption of electric arc, single - or double - slag melting practice to achieve this. Average limitations on sulphur and phosphorus are:-

Basic electric furnace	0.025% max
(double slag 0.01% max)	
Basic open hearth	0.040% max
Acid electric furnace Acid open hearth	0.050% max

(78)

BS 970 specifications set sulphur and phosphorus maxima only in engineering steels, other than free-cutting steels.

Sulphur is retained in steel as manganese sulphide. The effect of MnS inclusions on fatigue life, for example in acid open-hearth melted En 31 bearing steel (79, 80) is not considered deleterious and may even ameliorate the deleterious effects from other inclusions which are brittle at rolling temperatures. Manganese sulphide inclusions promote machinability of engineering steels and machining difficulties are frequently reported (23) when sulphur content falls to 0.015% or less, - for example as a result of double slag practices or the vacuum treatment of the molten steel. As a result, maximum and minimum sulphur values are frequently called for, in company specifications. This is primarily to prevent steelmakers giving very low sulphur levels as a "bonus" or by-product of stringent refining practices. It is thus considered unnecessary to order to sulphur content other than to basis content, provided a minimum sulphur level can be agreed with the supplier.

On the other hand, phosphorus increases the susceptibility of a steel to temper embrittlement, partially or totally controllable by rapid cooling from the tempering temperature. Molybdenum is commonly used to counteract this effect; the cost implications of this can, in some respects, be evaluated by comparing En 15 and En 16 (0.2 - 0.35 Mo) prices, as Pick (81) has recently done, together with a consideration of the economics of ordering to lower phosphorus levels. However, phosphorus makes a contribution to the strength properties of a steel, either by promoting hardenability - it is claimed to be almost as potent as carbon in this respect, and of greater influence than any metallic element (82) - or, in unhardened steels, by ferrite strengthening (78) although in this case, the effect is small in comparison with metallic alloying elements. Thus, a decision on tolerable phosphorus level must rest on an analysis of property requirements to be met by the raw material before departing from the basis price condition.

Steel cleanliness must be similarly considered. It is well established that fatigue properties in high strength steels in particular are enhanced by steel cleanness, although inclusion type and

and distribution is equally as important as inclusion volume (83). In highly fatigue sensitive conditions it may prove that the cost extra of £2 8s. per ton that vacuum degassing incurs is justifiable in guaranteeing clean steel; it is claimed that steels treated in this way can attain the quality of more expensive vacuum melted or vacuum consumable arc melted steels at considerably lower cost (84). Figure 2. shows the improvement in fatigue properties of carbon bearing steels resulting from degassing practices.

Methods of steel cleanliness assessment in general usage are such that there is little merit in purposely ordering to an inclusion count number unless this can be correlated with manufacturing and property requirements of the end product. Inclusion size, type and location - all critical to a given forming operation or stress situation need quantifying before cleanliness standards can be applied. General clauses in BS 970 are so loosely phrased that precise user demands on quality, including cleanness, come within unwritten specification intent, and a total bar reject level of 6% has been recorded as the result of a company substantiating BS 970 ordering by its own acceptance codes. Material deficiencies arising from dirty steel are usually revealed by forming or machining manufacturing processes, and thus rarely reach final component inspection without prior detection, making it necessary to set any steel inspection costs arising either prior to or after receipt against possible costs incurred by loss of production, tool wear etc. that such a 6% rejection would give.

c. Cost and machinability

Although their exact action in promoting machinability is not known, the results of re-sulphurisation or the addition of lead,

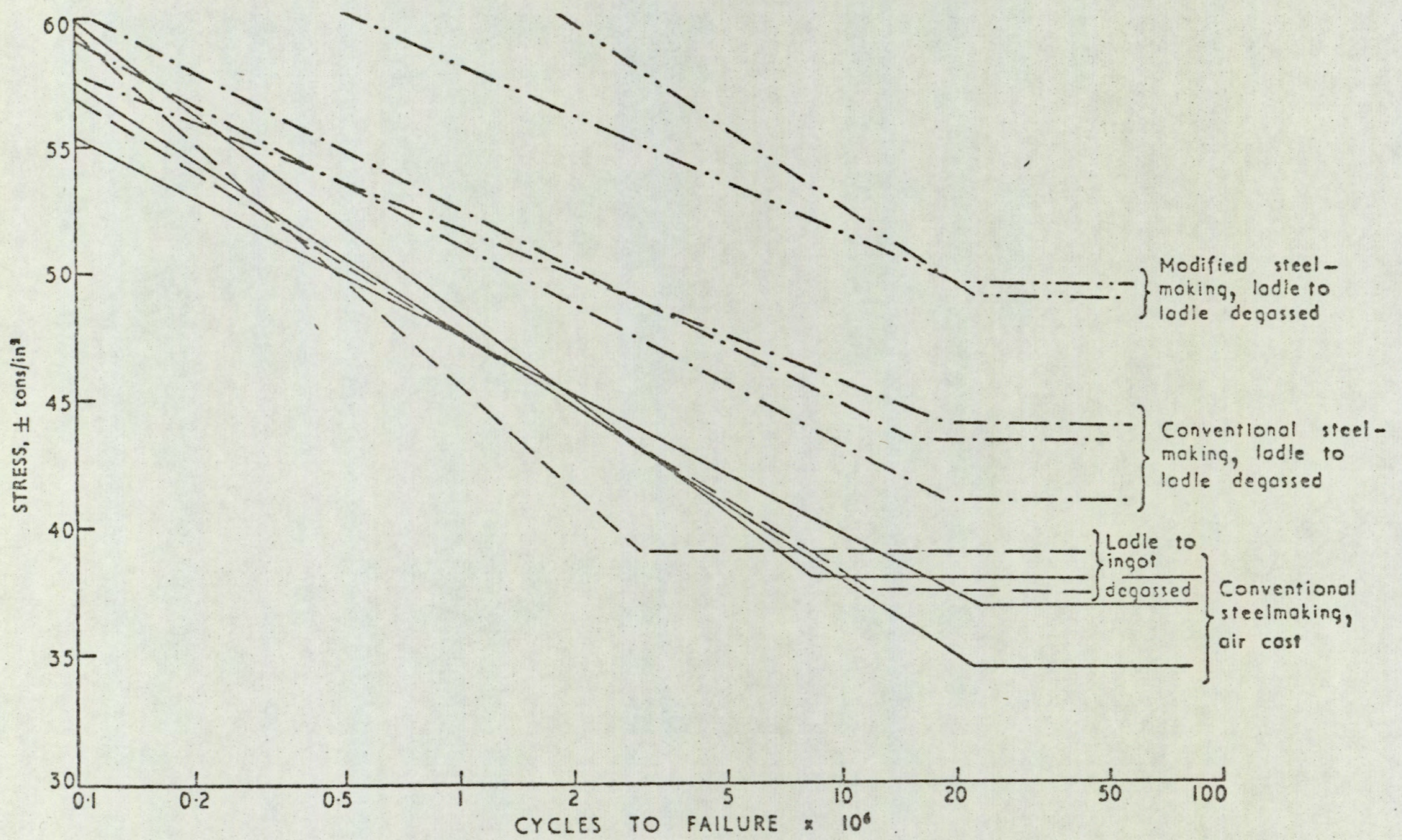


FIGURE 2. Effect of vacuum casting on fatigue properties of carbon bearing-steels.
(from Hewitt (84)).

tellurium or bismuth to steel are well documented in terms of increased production by higher machining rates, improvement of machined surface finish and improved performances of cutting tools (27). Differences in machining performance of steels chemically similar except for sulphur contents of 0.02 and 0.05% have been mentioned earlier; in the extreme, the free-cutting steel En 1B specifies 0.30 to 0.60% sulphur although the maximum sulphur level in alloy steels (non free-cutting) rarely exceeds 0.2%. An analysis of work by Shaw et al (85) shows that while machining performance continues to improve with increasing sulphur content, the cost return in terms of increased rate of metal removal falls off above about 0.3% sulphur. It is also known that the size and distribution of the free-cutting phases are equally as important as the quantity of additive; in resulphurised steels, optimum sulphide distribution and effectiveness is directly dependent on silicon content (absolute minimum level) and oxygen content of the steel and is thus related to the standard of steel-making practice (86, 87).

For <u>any</u> steel, whether free-cutting or not and whatever its microstructure, optimum machining conditions, in terms of cutting speeds, feeds, tool geometry etc. exist. It has been known for the habitual usage of a free-cutting steel to be shown inapt and uneconomic, when a batch of "non-free-cutting" steel has been processed by mistake, without significant change in cutting performance, tool wear or component finish quality. Machining additions should be employed only to enable a given machine to perform consistently at its optimum work rate.

Table 18 (88) lists the "extra machinability" obtainable, and the cost extras involved for commercial variants of En 1A (0.2 - 0.3%S). It is necessary to derive machining costs per ton of steel - from the

Claimed Improvement	Grade	Description	Extra/Ton on basis	Cost/Ton
-	-	5 tons, bright-drawn bar. 1" dia. (Basis condition and price)	-	£62.14.0
-	En 3B	0.25C, 1.0Mn, 0.35Si, 0.06S, P	£2.7.0	£65.1.0
"at least double production rate"	En 1A	0.15C, 1.2Mn, 0.1Si, 0.2/0.3S, 0.07P	£3.7.0	£66.1.0
"25% increase in cutting speed, or 40% increase in feed."	En 1A leaded	As En 1A + 0.2Pb (max.)	£7.14.0	£70.8.0
"40% average improvement in machining production"	En 1A + lead + tellurium	As En 1A + 0.2Pb + 0.03/0.05Te	£23.14.0	£86.8.0

TABLE 18.

derived from (88).

machine hourly rate and the time to process 1 ton of material - before any decision can be made on either the adoption of a free-cutting variant of a given steel or, once taken up, the move to higher additive levels still.

In general, it is found that the adoption of resulphurised free-cutting bar steel is not merited unless the amount of metal machined off during component production approaches 20%, but, should surface finish be a prime criterion of acceptability, free-cutting additives can eliminate the need for fine finish-cuts and the extra labour and machine costs this entails. (89).

d. Cost and steel form

Table 6 incorporates comparisons between the costs of black and bright drawn bar, showing that for a given grade, differences in excess of £30 per ton result from the additional processing.

B.S.C. figures (8) show that 22% of all bar steels sold to user-industries, and 42% of bar purchased for motor vehicle manufacture is in the bright-drawn condition. The higher raw material cost that this incurs is justified by claims that:-

(a) close dimensional tolerances, scale-free surface and straight bar results, and

(b) bright-drawing effects work-hardening in steel, enhancing its machinability and its strength.

The claims of (a) justifiably support the choice of bright-bar for high-volume machining production, although close tolerance black bar is available commercially which can be handled by multi-spindle automatic lathes equipped with variable collets and chucks. Bright bar tolerance of -0.004" on 1" diameter bar (B.S. 970 tolerance) incurs no cost extra on the bright bar price, but it is still unecessarily close and therefore unjustifiable economically for autolathe production. In certain applications, the use of peeled black bar has proved more economical than bright drawn bar, the extra cost of peeling or pickling and machine-straightening of black bar still giving costing advantages (see survey report).

Work-hardening imparted by bright-drawing, makes an insignificant contribution towards improved machinability in most metal-removing operations (27). Also, above 0.25% carbon level, the extra strength that bright-drawing imparts to steel is negligible (90), but cold work at lower carbon levels, and on small cross-sections, can eliminate the need for strengthening by heat treatment. This is economically significant in carbon steels only, because the higher cost of alloy steel is disproportionate to the additional mechanical strength to be obtained from cold drawing, compared with strength gains in carbon steel.

2.5-2 Conclusions

The foregoing analysis of the costing of engineering steels as raw material of manufacture has shown the need for the direct application of established principles of metallurgy and engineering to extend through design selection to major aspects of processing also. Too often is such a critical analysis neglected in favour of traditional attitudes - unnecessary expense in terms of material cost is incurred by processing alloy steels, for example, in equipment capable of the precision necessary to handle leaner alloy or carbon-manganese steels; free-machining steels are used without questioning their optimum performance, and without considering whether the machines on which they are used are capable of the cutting speeds necessary toutilise this; the real need to use heat-treatable grain-refined steels without exception requires an objective assessment of the engineering, metallurgical and processing consequences of applying this cost extra.

It is felt that the development of economy steels with hardenability response based on manganese and controlled residual levels (7) is but a start to the costs conscious rationalisation of steel compositions envisaged by Honeycombe (3).

2.6 Summary

The foregoing discussion of engineering and metallurgical factors most directly influencing the degree of economic effectiveness with which the selection and utilisation of steels is pursued has, in spite of its direct elementary treatment, highlighted many deficiencies in general industrial practices. These persist through the adherence of designers and materials personnel alike to traditional ideas, often with some empirical foundation based on long-term experience and only rarely upon established principles of the metallurgy of steels. The report has stressed the following points to be of highest importance and an analysis of the subject as a whole will show that all other traditionally-held views and practices stem from them:-

1. The lack of realism of steel specifications in defining true engineering requirements, - what is known of the revisions proposed for BS 970 for example, will not improve on it technically as a design specification.
2. Complexity of steel composition, coupled with "traditional" selection of engineering steels to some extent based on confused interpretation of responsibilities towards the produce purchaser, has tended to mask the true function of alloying components within a given steel.
3. The utilisation and manipulation of heat-treatments remains on a "rule of thumb" basis, perhaps understandable in the light of inability to quantify even the simplest quenching operation, - but an experimental assessment of such operations can, it will be demonstrated, enable empirical controls to be established for closer hardenability tolerances to be applied to steel compositions thus processed.

Each of the above factors is considered in turn with reference to established principles or readily available data and thus offered as guidance to more comprehensive work. It is envisaged that this would involve their critical assessment and implementation within an engineering company, who would require the active support of a steel manufacturer at research, development and manufacturing levels. This kind of co-operation is unique, but certainly not unknown (5, 7) and, where already successful, cost economies effected have been the yardstick of that success.

3. THEORETICAL AND PRACTICAL INVESTIGATION INTO SELECTION AND UTILISATION FACTORS.

3. THEORETICAL AND PRACTICAL INVESTIATION INTO SELECTION AND UTILISATION FACTORS.

3.1 Proposals for re-writing engineering steel specifications

Introduction

It has been proposed (5) that the cost effectiveness of material selection procedures in engineering manufacture could be improved by considered, systematic analysis of materials specifications in the light of service requirements of the engineered products. The proposer finds that artificial restriction of material choice is consequent of engineers and metallurgists alike adhering to unrealistic property standards, based on test procedures which are purely quality-controlling in nature. For such reasons, it is concluded that the most cost-effective combination of material and processing method may be denied (5).

Widely prevalent "traditional" practises in engineering industry give clear examples of dependence on materials data which fail to address design requirements realistically. For example, fairly precise definition of steel composition may be demanded of a steel supplier and obtained by the user at a premium, although such detail may be relatively unimportant to product performance (2, 3, 6). The overall problem has been discussed extensively elsewhere in this report, as have some of the more obvious material selection considerations truly important to product function. The object of this present section is to suggest how the "systematic" approach (5) might be applied to engineering steel specifications in particular.

.1-1 What is the function of a specification?

The application of a "specification" to a material, process, or product implies detailed, comprehensive description of the subject in unambiguous terms. It is presumed that the re-enactment of the terms of the specification will ensure perpetuation of the subject thus specified; in the case of an engineered product, service performance is guaranteed by meeting specification at each stage of manufacture.

Thus, in the area of steel usage that this present work has considered, specifications written into company procedures whether "standard" (i.e. B.S, S.A.E, etc.) or user-generated, become codes of practice which guarantee that the steels will allow given levels of product quality and uniformity and product performance to be achieved and maintained. Clearly, the demands made on a product are peculiar to the product itself. How then can the standard steel data format, typified by BS 970, effectively control and be representative of the manufacture and performance of the infinite number of process/design/service loading combinations that industry can assign to one given steel composition ?

The artificiality of this situation has been discussed in section 2 of this thesis; specific examples which contrast <u>true</u> engineering function required of engineered products, with practised selection procedures based upon steel specifications are numerous in the literature (5, 6, 29), and serve to demonstrate this artificiality. Concern at this disparity may seem exaggerated when one considers the continuous advances made in engineering sophistication which may seem to bring the need for its correction into question. Designers interviewed spoke of new design being the blending of 5% new thinking with 95% reliance on well-tried techniques. This philosophy is well provided for by generalised guides to steel selection (1.3-3), masking the shortcomings of steel specifications which are by no means obvious to all designers or materials engineers.

1-2 <u>Engineering design considerations summarised</u>.

The importance to design primarily for dynamic loading in the vast majority of engineering structures has been ably demonstrated (51). Fatigue is the prime failure mechanism to be designed against in dynamic loading conditions, but the problem in creating specifications to cater for steel selection against fatigue is that fatigue life of a material is <u>not</u> a property like a modulus, i.e. it is not a material constant. The fatigue life of a given engineered component is specific to that component, its finish and design, the environment in which it operates, the mode of loading it sustains etc. etc.

However, from "fatigue testing" where highly idealised conditions of test-piece preparation are used, the fatigue endurance limit of a given steel that the test determines approximates to 0.5 UTS of the steel. The apparent relationship under such prescribed conditions has not been explained; fatigue properties are generally anisotropic, while UTS usually derives from testing "longitudinal" specimens and is isotropic. It seems purely fortuitous in the light of Cazaud's (91) summary of seven empirical derivations of fatigue limit from one or more of the standard tensile test quantities, - UTS, yield stress, elongation and reduction of area. However, Juvinall (20) summarises useful guidance to "average" fatigue performance of standard test specimens, and Table 19 shows his factors. In addition, Juvinall (20) presents empirical curves derived from an analysis of work by Peterson, Heywood and others on the effects of notch stress-raisers. Provided the diagrams and factors which such simple analyses yield for a given steel, are regarded purely as representing "ideal" test piece behaviour, there is a case for their inclusion in <u>design</u> specifications, but the specific nature of fatigue performance renders it an impractical feature of steel specifications. As Table 19 indicates, for effective usage of fatigue data for design guidance, - and possibly for steel selection guidance - it is essential that the methods of data derivation approximate to the principle load modes to be supported by the manufactured component under consideration. Quantitative data are, however, no substitute for rig-testing on full-scale components in as-manufactured conditions.

.1-3 <u>Choosing a workable design criterion</u>.

The difficulties of converting a steel specification into a meaningful design document, allowing steel selection to match engi-

Life (in cycles)	Load application	Fatigue strength UTS multiplying factor
10^3	Bending	0.9
	Torsional	0.9
	Axial	0.75
		Fatigue strength Factor on standard bending fatigue
10^6	Bending	1.0 (≈ 0.5 UTS)
	Torsional	0.58
	Axial	0.9

TABLE 19.

after (20).

neering requirements, are seen to be manifold. While specifying a steel via some fatigue endurance criterion may be considered an ideal approach to satisfy dynamic loading consideration, the foregoing discussion shows the impracticality of doing so. One might wonder , were such an approach possible, if designers would be able to use such a criterion effectively, being so accustomed to the UTS criterion and efficient in its use, having learned to live with its shortcomings? UTS remains a *universal* design criterion, virtually. It is concluded that this "indirect" approach to steel selection in design, by way of UTS, must continue, allowing the engineer to use his "traditional" knowledge, and his Goodman diagrams, formulae and ratios to meet all service loading situations. The metallurgist's or material engineer's aim must be to ensure that the criterion chosen is realistic in value, for a given steel i.e. for heat-treatable steels, specification UTS is related to known reproducible heat treatment conditions. Efficient presentation of UTS in this manner would enable a systematic elimination, - or at least a reduction - of the "multiple choice" which BS 970 offers at present (see 2.5-1a), by matching performance against steel costs. Cost effectiveness would thus become a realistic part of the steel selection procedure.

1-4 The strength of engineering steels.

The nature of steel strength has been considered earlier from both engineering and metallurgical viewpoints and it was postulated that *potential* strength of a given steel is a function of its carbon content (see 2.4-1). This potential can be realised to the full if heat-treatment of the steel results in a completely martensitic structure, - which may or may not be desirable when the *overall* property requirements of the end product, such as a manufactured steel component, are considered. Reasons that a user may give for the undesirability of such a state are more frequently heard than those which find it a desirable structure; the severity of quench necessary to achieve the transformation may introduce its own problems of distortion, - of concern to many manufacturers yet found capable of control by others doing very similar work - while the hard, brittle nature of the martensitic component may be considered undesirable for a given component's engineering function in some engineering circles but accepted in others.

The role played by alloying elements in promoting the hardenability of heat-treatable steels has also been discussed (see 3.4-1) and qualitatively at least, the cost- effectiveness in heat-treatment of those elements commonly used in steel-making is well established. Put simply, for a given section size and carbon level, an alloy steel can be fully-hardened with a reduction in quench severity over that required to effect the same hardness in plain carbon steel. Alternatively, for a given quench severity and carbon level, full hardening in thicker section will be possible in the alloy steel (41). In addition, grain size of the steel exerts its own influence on the hardenability of a given composition (17, 3, 65).

In general engineering practice, where heat-treatment installations must be capable of processing a wide range of component shapes and cross-sections, quench severity is fixed, to all intents and purposes (see 3.3) and properties attainable in finished components are directly dependent on the hardenability of the steels involved. Only in specialised quench systems can quench severity be treated as a true variable, discounting the unintentional variations encountered in any system due to quenchant deterioration, quenchant temperature control or circulatory problems.

Engineering considerations alone should determine the basic requirements of a steel, although the type, condition and form of the steel to be used may be dictated essentially by the least costly manufacturing route for a given component shape. However, strength via carbon content is a fundamental premise, but conditions of loading the engineered component will determine the optimum strength distribution required (see 2.3). The desirability of using a case-hardened steel as opposed to a through-hardened steel in certain dynamic loading situations has been cited (see 2.3-1). Likewise such factors as steel cleanliness and steel grain size must be considered (2.5-1). For the latter, toughness considerations at a given strength level may preclude the large grain size favoured for enhancing heat-treatment response at a given alloy content, while the final metallographic structure may not be the "optimised" fully martensitic form. As must always be the case, a balance among conflicting requirements is best resolved by rig-testing fully processed pre-production components. Rig-testing may determine that the optimum metallurgical structure for one component is 100% martensite, for another full-hardening followed by tempering, for a third only partial hardening, and so on, confirming or otherwise the validity of what may well be "traditional requirements" for a specific component.

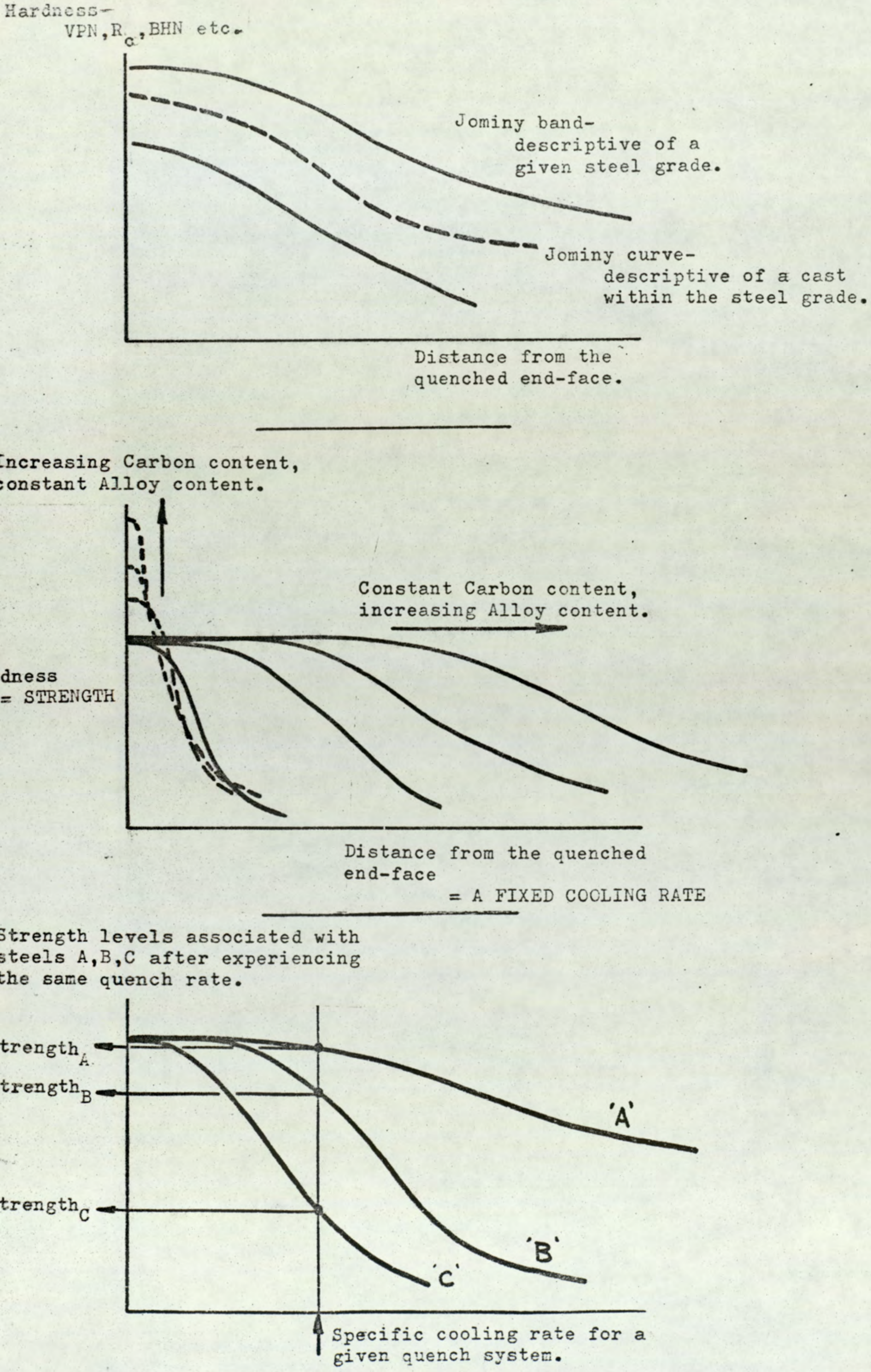
Whatever strength gradient may be generated within an engineered component, whether by quench-hardening, work hardening, surface treatments etc. strength at a point may be established by measuring the hardness at that point. The hardness/strength relationship (60) is widely used in engineering circles often without due consideration of its significance. In this present argument, its importance in establishing workable engineering specifications stems from the fact that the relationship holds whatever the carbon content of the steel, and whatever its metallurgical condition. Hardness measurement can be used to determine the strength at a point within a component, whatever the "ideal" state of the microstructure of the component. This means that the restrictions which a standard test-piece impose on the validity of data it yields are removed. Strength, as UTS, derived from standard specimens heat-treated with a component batch cannot exactly represent the strength of the components themselves, although once the optimum finishing conditions required for the latter are established, such test-pieces may be meaningfully employed as quality control standards (see 2.1-1). Hardness is undoubtedly a metallurgical concept, and such are openly derided by practising engineers (see page 17). However, because the hardness/strength determinations to be proposed would refer to measurements made on engineered components, in situ as it were, it is hoped that certain engineers' (justifiable!) suspicions aroused by BS 970-style test-piece-based metallurgical data , would be removed by this direct approach. The BS 970 heat-treatment requirements for standard test procedures would also be removed; these seldom parallel modern industrial practises and cannot be quantified for accurate reproduction (3.3-3). The heat treatment conditions related to the proposed testing procedure would be those of the production process itself. Quantification of production heat-treatment is discussed in depth elsewhere in this report (see 3.3).

-5 Establishing a data-base.

It becomes necessary to project back to standard data at some stage in establishing *any* workable and dependable "yardstick", - whatever this may determine - and, in the case of the heat-treatable engineering steels, with which the bulk of this present work has been concerned, the (strength/hardness) versus (steel composition/cost) versus (production heat-treatment) three-pronged approach to specifications is unified in the Jominy curve. The Jominy test is used as a measure of hardenability, or heat-treatment performance, for *a given* heat-treatable steel. For a steel grade, a hardenability band is more reasonably descriptive, being drawn up to accommodate not only an acceptable scatter of individual element levels from cast to cast of a given composition, but also to incorporate the effects of grain size variation as well. By and large, users of BS 970 heat-treatable steels depend solely on steel chemistry to ensure hardenability requirements and the same is true for many SAE-steel users also. However, the SAE-H steel series is based on the "band" principle just mentioned. H steel compositions are modified somewhat from the ranges or limits applicable to the same grades when specified by composition alone, permitting adjustments to suit the differing melting practices of steel suppliers. However, the modifications are not great enough to influence the general characteristics of the original SAE composition. No universally accepted set of hardenability bands appears to exist in this country for the BS 970 steels, for which published, consistently-presented Jominy data is scarce in any case.

The accompanying diagrams (Figure 2A) may help to illustrate the "unification" which Jominy hardenability data achieves. It is customary to plot hardness (which, it is proposed, shall be equated to strength) as the dependent variable against distances along the test bar from the quenched end, at which hardness readings are taken. Numerous workers have determined the specific cooling rate which can be associated with a given distance from the quenched end in the standard Jominy test (107, 114, 138), and section 3.2 of the present report deals extensively with a meaningful interpretation of cooling rate as it applies in this instance and in industrial heat-treatment practices. In the Jominy curve (or band), the means exist therefore, to match equivalent strength to equivalent cooling rate for a given steel (or steel grade). The relationship is independent of the absolute microstructural components present at the point of hardness measurement, but for a given carbon value in differing base compositions the maximum hardness possible on the corresponding Jominy curves will be the same, denoting fully martensitic structures. The

FIGURE 2A.


Hardness-
VPN, R$_c$, BHN etc.
Jominy band-
descriptive of a
given steel grade.
Jominy curve-
descriptive of a cast
within the steel grade.
Distance from the
quenched end-face.
ncreasing Carbon content,
onstant Alloy content.
Constant Carbon content,
increasing Alloy content.
dness
= STRENGTH
Distance from the quenched
end-face
= A FIXED COOLING RATE
Strength levels associated with
steels A,B,C after experiencing
the same quench rate.
trength$_A$
trength$_B$
trength$_C$
'A'
'B'
'C'
Specific cooling rate for a
given quench system.

Jominy distances to which a given hardness persists are indicative of relative hardenabilities among steels. Thus, steels of increasing hardenability yet of a given carbon content, will generate a family of J-curves as figure 2A shows; cooling rate available to process steels in a given quench system will be equivalent to a certain Jominy distance and, where the vertical from this point on the distance axis intersects the curves, the expected hardness/strength level to be derived from each steel is given. In steel A of Figure 2A maximum possible hardness will be possible at the cooling rate selected, indicating virtually complete martensite retention. In steels B, C etc., of progressively lower hardenability, lower hardnesses - and therefore strengths - will result, and their metallographic structures will be mixed.

The location within a specimen or component where the cooling rate equivalent to that at a given Jominy position pertains must be determined by separate experiment (see section 3.2) but clearly, that rate existing at a point of critical loading, and therefore of critical strength, is a greatest interest. It is thus difficult to publish comprehensive data of this form, because of the infinite number of requirements for which engineers can call and also because of the individual nature of every user's heat-treat facilities. One can, however, aim to present a standardised set of Jominy <u>bands</u> from which any desired derivations can be made, using regularly monitored quench system cooling rate determinations made over the range of component cross-section sizes heat-treated there. It is suggested that SAE-H steel criteria are followed in establishing Jominy bands for each steel grade, accommodating variations in hardenability due to such factors as steel-making practice and grain-size. As previously mentioned, steel selection may be determined by other engineering requirements, e.g. cleanliness, toughness, but such extra restrictions should allow hardenability of the selected melt to remain within the "standard band". Jominy data presentation for case-hardening steels may require special consideration, but already curves have been plotted and published (136) for carburised steels, including case carbon level variation together with curves for core material hardenability.

Carrying this analysis to its logical conclusion should result in re-writing BS 970, or at least taking a set of imaginary but relevant requirements and manufacturing conditions and making a selection survey of the commonly-used engineering steels. This was attempted in this present study but it was soon evident that such an exercise would form a major study on its own. The following points are clear:

1. Published hardenability information on BS 970 engineering steels is inadequate for establishing Jominy bands of the SAE-H kind. It is known that this information does exist in the hands of some steel users, who already apply their own hardenability criteria to steel selection. This data is often well documented and has consistency of presentation, points well appreciated when one attempts to categorise and correlate most of the published sources of information on British steels. The inconsistencies of presentation referred to primarily concerned every possible combination of Vickers or Rockwell C hardness scales with Jominy distances measured in sixteenths, tenths or eighths of an inch or millimetres. It is no more than a tedious exercise to correct to some standard presentation format, but less easy to group steels into bands representing a given composition when chemical analyses may or may not be quoted, when grain size is rarely quoted and when inconsistencies in test-bar size and pre-test heat treatment exist also.

2. Not enough is known of heat-treating efficiencies in standard production furnaces. A further section of this present work (3.3) discusses the problems encountered in quantifying quench efficiency and a means of investigating industrial systems is demonstrated.

Table 19A suggests that the range of quench severities likely to be encountered is more than adequately covered by the cooling rates applicable to the standard Jominy test-bar especially when it is considered that the majority of engineering ruling sections encountered in design are less than $1\frac{1}{4}$", with few in general engineering exceeding $2\frac{1}{2}$". The data collected into Table 19A come from several sources (65). It offers useful guidance to industrial heat-treatment quantification (75) but, as 3.2 of this present report argues, the lack of specific detail on quenchant composition and circulation prevents unqualified acceptance of the bar diameter-equivalents quoted.

3. Costing information is quickly obsolescent!

-6 Typical data representation.

Figure 12 (section 3.3) gives a specific example of using a Jominy band to determine strength values over a given component section when heat-treated and quenched in a given production system. Figures 2B and 2C summarise data for SAE-H steels (98), quoting both the cooling interval used by Garcon (92), - detailed in 3.2-3 - and the maximum Jominy distance to a given *minimum* UTS value. Where possible, rough equation of the B.S. En steel equivalent to the SAE steel is made, based on composition only rather than inherent performance. The En steel cost ratios (En 8 = 100) were derived from basis prices for machining bar stock, as quoted in SMMT standards (15).

The "equivalent cooling interval" and "expected strength variation" relationship detailed for specific heat-treat conditions in Figure 12 could be summarised for *all* heat-treatable steels in the form of the bar-charts given in figures 2B and 2C. For example, should a minimum strength of 60 tsi be required at a point in a finished component (as quenched), where subsidiary quench tests have shown the 800° to 500°C interval to be 17.5 secs., then steels satisfying this condition most exactly will include En 18 or SAE 4047.

J. dist 1/16 in.	Bar dia. (ins.) for equivalent cooling rate at:					
	¾ radius		½ radius		Centre	
	Oil 200 fpm	Water 200 fpm	Oil 200 fpm	Water 200 fpm	Oil 200 fpm	Water 200 fpm
1	-	0.65	-	0.6	-	0.3
1½	-	0.90	-	0.8	-	0.45
2	-	1.2	-	0.9	-	0.65
2½	0.4	1.5	-	1.1	-	0.8
3	0.6	1.8	-	1.2	0.3	0.95
3½	0.7	2.05	0.5	1.4	0.45	1.1
4	0.9	2.35	0.7	1.5	0.6	1.3
4½	1.05	2.6	0.8	1.6	0.7	1.45
5	1.2	2.9	0.9	1.8	0.85	1.6
5½	1.4	3.2	1.1	1.9	1.0	1.7
6	1.55	3.5	1.2	2.1	1.1	1.85
6½	1.7	3.8	1.4	2.2	1.25	2.0
7	1.85	-	1.5	2.4	1.35	2.1
7½	2.0	-	1.7	2.5	1.5	2.2
8	2.1	-	1.8	2.7	1.6	2.35
9	2.35	-	2.0	3.1	1.8	2.6
10	2.6	-	2.3	3.4	2.0	2.8
11	2.8	-	2.4	3.7	2.15	3.0
12	3.05	-	2.6	3.9	2.3	3.2
13	3.25	-	2.8	-	2.45	3.4
14	3.45	-	2.95	-	2.6	3.55
15	3.65	-	3.1	-	2.7	3.7
16	3.85	-	3.3	-	2.8	3.85
18	-	-	3.45	-	-	-
20	-	-	3.6	-	-	-
22	-	-	3.7	-	-	-
24	-	-	3.85	-	-	-

TABLE 19A.

after (65).

BS(En)	Cost Ratio	SAE-H
207	160	5120
361	178	8617
35	191	4620
8D	100	1042
49A	109	1045
49B	109	1050
		4027
		4812
362	178	8620
		4720
363	178	8622
35	191	4621
		4815
363	178	8625
325		4320
		5046
		4037
		4042
		8627
		1330
		8630
18A	165	5130
18B	165	5132
		4047
15	108	1335
		5315
8D	100	1041
18D	160	5140
		4053
		4640
		8637
		8640
		4135
		4063
19	180	4137

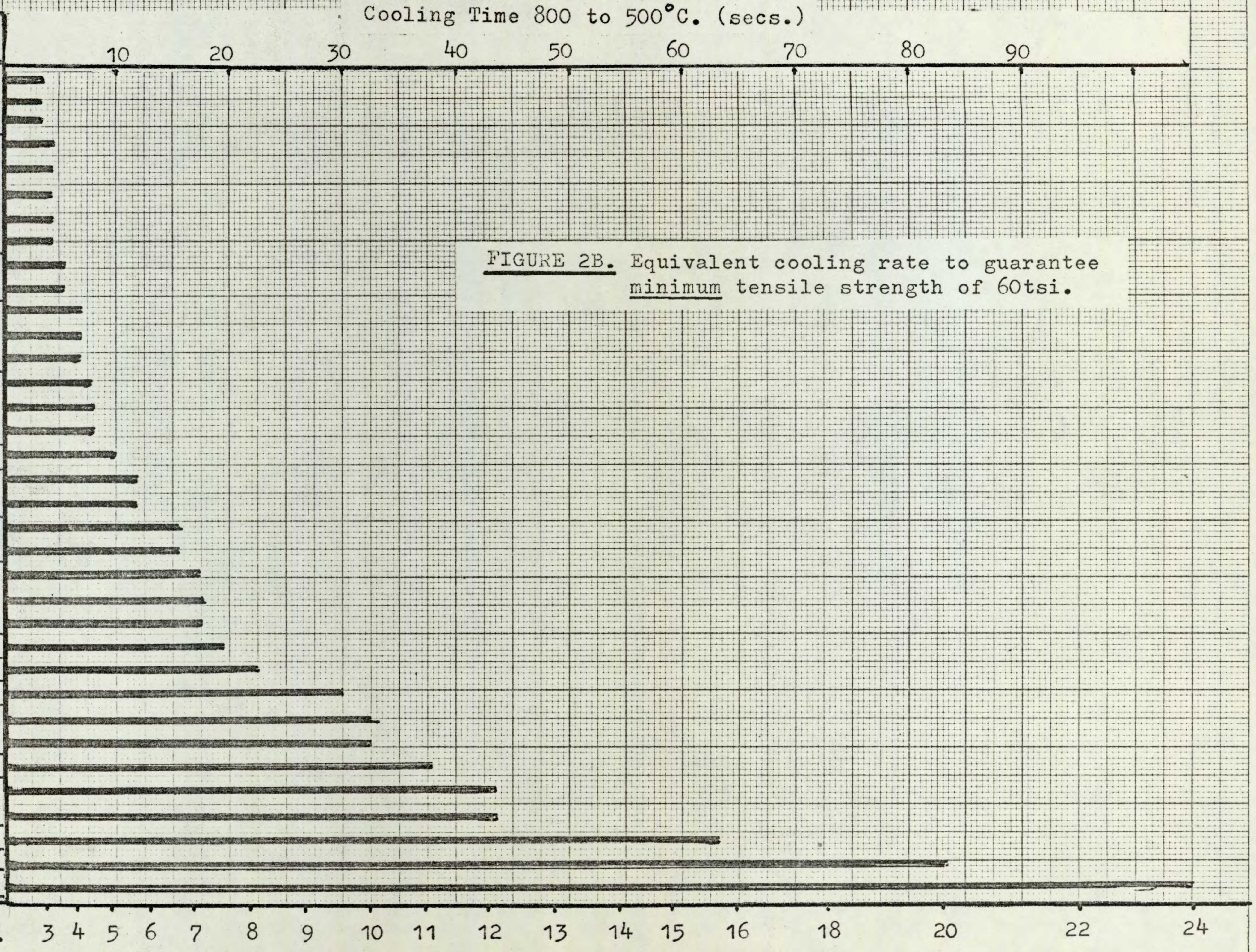


FIGURE 2B. Equivalent cooling rate to guarantee minimum tensile strength of 60tsi.

FIGURE 2C. Equivalent cooling rate to guarantee minimum tensile strength of 80tsi.

BS(En)	Cost Ratio	SAE-H
362	178	8620
35	191	4620
		4720
325		4320
363	178	8622
		4027
8D	100	1042
49A	109	1045
		8627
		4037
15	108	1335
18A	160	5130
		5046
		8630
18B	160	5132
		4042
		4047
		5315
18D	160	5140
		4053
		4063
		8637
		4640
		8640
		4135
45A	130	9261
19	180	4137
48		5147
11	160	5160
50	182	6150
		8650
		8655
19B	178	4145
		4147

However, En 15 is a cheaper steel and will in fact attain the same minimum strength requirement under slightly slower cooling conditions, or in a heavier section. It would therefore prove a more economic choice of steel in this instance, on grounds of hardenability alone. To use either En 15 or En 18 at such a strength level is beyond the scope of the data presented in BS 970, although extrapolation of the figures quoted there would suggest En 18 to be of superior strength.

-7 Conclusions.

The case for revising the format of steel specifications has been made, considering what is really required of a steel as a primary engineering material. Predominance of dynamically-loaded designs would suggest that the specification of fatigue resistance would be of direct value to engineers but it has been shown that it is necessary to continue to use UTS as a basis for engineering steel specification. Tensile strength has been adopted universally as a design criterion and as such, has become a central pillar of engineering philosophy, incorporated into design formulae and algorithms for dynamic as well as static loading conditions. Existing specifications quote UTS values derived from specially prepared specimens, a procedure which is useful for quality control checking by steel supplier or user. The present work has suggested the means whereby the minimum UTS to be realised in a given section can be derived indirectly for a given steel grade, becoming truly relevant to both design and production requirements. The method presents initial difficulties in that it requires the establishment of agreed hardenability bands for all heat-treatable engineering steels; it is suggested that these should be similar to SAE-H steel Jominy data. Accurate application of the method requires the characteristics of the users' furnace quench systems to be determined, a topic considered in depth in section 3.3 of this report. Tentative exploration of the technique would seem to confirm the under-employment of steels which adherence to BS 970 data may foster, which was admitted by most material engineers consulted during the field studies described earlier.

Hardenability and heat-treatment are not the only factors to be considered in the specification of an engineering steel, but the adoption of Jominy-band information as described would infer not only property derivation from steel chemistry but would also incorporate the effects of grain size variation (not considered by BS 970) and steel-making practice, where this has a bearing on steel cleanliness requirements. It is difficult to formulate a ready replacement for the "infamous" General Clauses of BS 970, although their revision and partial deletion would become possible with hardenability-based specifications, in the areas just referred to. Their true worth as quality control procedures would be more readily recognized.

The proposals discussed in this section converge on component testing to confirm suitability and effectiveness of the processing environment, making manufacturing procedures, the establishment of quality criteria, the costs of material and processing integral parts of the material selection method. Experimental and production research into the form of data presentation suggested could well form the topic of a major development project. Historic data on hardenability of BS-steels is known to be held in comprehensively documented form by some enlightened user companies. This present work has relied to a considerable extent on the good offices of steel users, for furnace trials and quench system assessments, and it is anticipated that, using the thoughts and suggestions presented here together with further cooperation from industry, a meaningful techno-economic revision of steel specifications could well be achieved.

3.2 Quenching in industrial heat treatment

Introduction

It is desirable that the guaranteed minimum performance of an engineering component shall be achieved or exceeded at minimum overall production cost. Where an alloy steel is employed as the raw material of manufacture, its heat treatment response is determined by the inherent hardenability of the steel and by the efficiency of quenching, these factors being inversely related. Field studies have indicated that much of the diversity of steels used across industry to satisfy similar mechanical requirements may have arisen from this fact, inadequate understanding of heat treatment plant potential being compensated for by over-specification of materials. The situation is further exaggerated by steel specifications tending to level down on "guaranteed" property levels based on inefficient and obsolete heat-treatment practices. It is contended that the development of simple methods of quench system assessment and operation control would be a useful contribution to the effective utilisation of steels.

3.2-1 Quenchant assessment

Quench-hardening of steel may be qualitatively defined as "the relatively rapid cooling of the steel from a temperature above or within its critical temperature range, by the use of media more drastic in effect than still air". In commercial practice, such media as brines, water, oils and fused salts are in common usage; in certain applications, gaseous quenchants may be employed.

Practical description of quenching action is most frequently presented in the form of cooling curves, derived from thermocouples attached to the body being quenched. Plotting these in terms of rate of change of body temperature with time clearly reveals the various stages in quenching, characteristic of the physical and chemical properties of the quenchant employed (93, 94). Thus a semi-quantitative rating of quenchants can be given by inter-comparison of cooling curves recorded on a standard test specimen, quenched from a given temperature and pressure (94). Alternatively, the time for the test-piece temperature to fall through a given interval may be considered adequate to rate a series of quenchants, eliminating the need for accurate temperature plotting (95). While such experiments give information of use in the development and compositional control of quenchants, they give little guidance to the behaviour of a complete quenching plant where factors other than quenchant composition and properties contribute to quenching efficiency. It is necessary to consider the effect of such variables as:

Quenchant volume and circulation rate.

Quenchant temperature and temperature control during plant operation.

Batch size of components being quenched.

Surface condition of components.

Packing or jigging of components in the load.

The provision of quantitative description of quenching efficiency achieved in mass-production heat-treatment operations is of considerable importance if steels are to be effectively utilised but practical determination in situ presents complex problems of instrumentation and observation of test probes particularly in sealed-quench units. A qualitative description of quenching presents the difficulties encountered if an exact solution is sought, and a review of some 30 years intensive research activity records the limited advances made towards a quantitative understanding.

3.2-2 The quenching operation

Figure 3 presents a qualitative description of the rate of change of temperature in a simple steel shape, initially at uniform temperature Ti throughout, when quenched into a liquid maintained at temperature Tq. The boiling point of the quenchant (Tb) is such that Ti > Tb > Tq. The sketch also indicates changes in the physical nature of the quenchant as heat is removed at the surface of the steel. The heat content of the system is considered constant. Almost instantaneously, the surface temperature of the body falls to Tq, by direct conduction of heat across the solid/liquid interface, termed the "initial thermal contact stage". Under the temperature gradient thus set up, radial heat flow from the centre of the body initially exceeds the rate of heat transfer by conduction across the solid/liquid boundary, and the surface temperature of the body rises to some value Ts (where $T_i > T_s > T_b$). The subsequent "vapour blanket stage" - where heat supply to the quenchant exceeds that needed to create a continuous vapour layer over the body - sets up a convective boundary across which heat transfer from the body is comparatively slow i.e. the surface film resistance is high.

The collapse of the vapour film gives rise to violent boiling action over the whole surface of the body, and heat transfer to the quenchant is greatly increased. The "vapour transport stage" is marked by a steepening

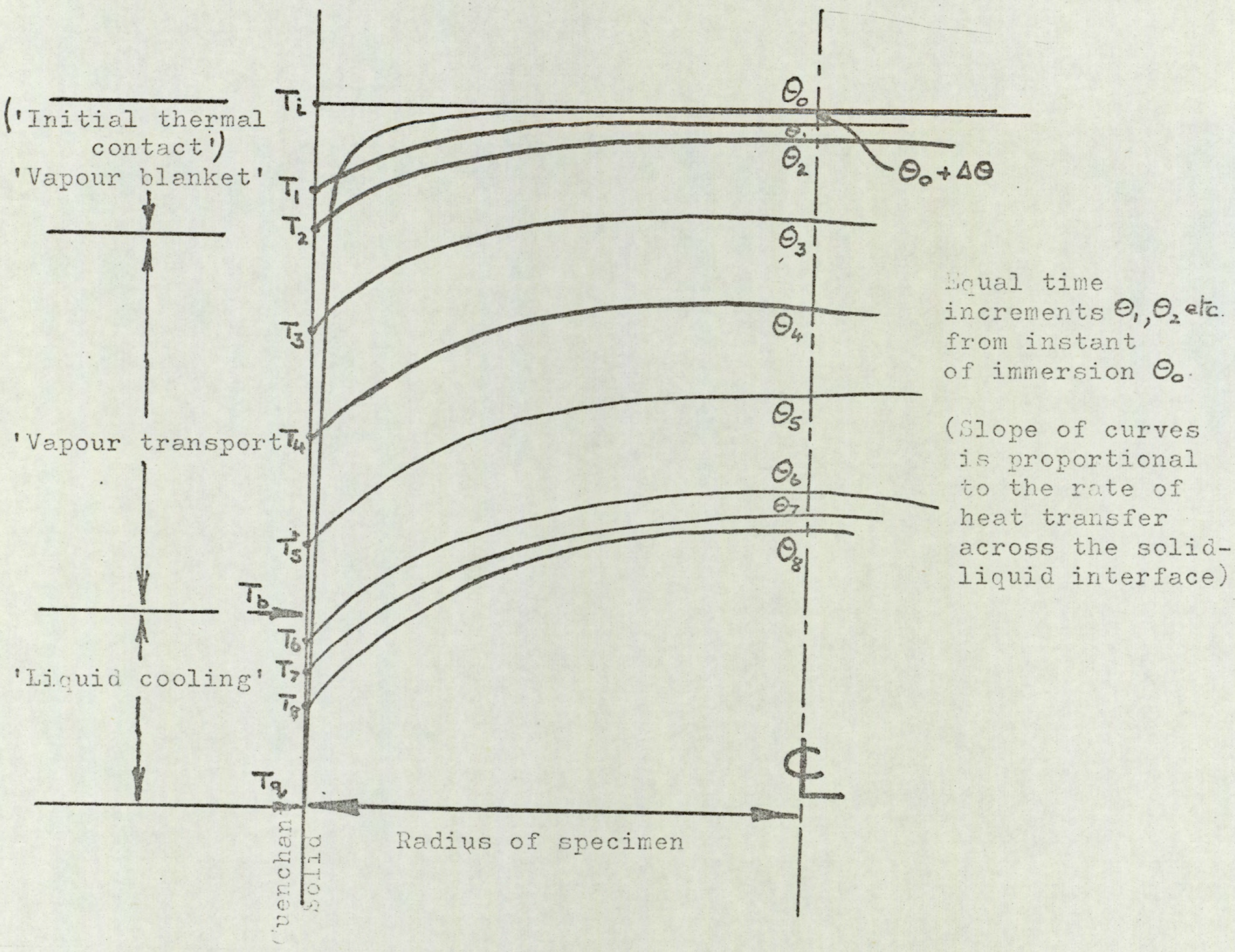


FIGURE 3. Diagramatic representation of temperature variation with time in a cylindrical specimen initially at uniform temperature T_i, quenched into a bath at T_q with boiling point T_b.

of the cooling curves, the slope of which represents qualitatively the heat transfer rate to the quenchant at any point in time (96). This stage in quenching terminates when the surface temperature of the body falls to the boiling range of the quenchant, when the "liquid cooling stage" follows. Slow cooling down to the ambient bath temperature is by conduction and convection.

Experimental evidence supporting the sequence of events represented in Figure 3 is given by Bühler and Schmidt (97), but it should be stressed that this description is only directly applicable to liquid quenchants. The vapour blanket cooling arrest is absent with fused salt quenchants, and its relative importance to the overall quench rate is modified by the use of additives in oil- and water-based quenchants (98) e.g. accelerated quench oils, poly-vinyl water additives, ionic salts in water. In addition, quenchant agitation whether by circulation alone or together with "micro-agitation" conditions (99) strongly modified the cooling detail expressed in Figure 3.

3.2-3 Quantitative research into heat-treatment practice - a review of the literature.

It is clear that conditions existing close to the surface of the body, determine the thermal history of the quenching operation. A state of "transient conduction" exists; the complexity of exact mathematical solution of the heat transfer coefficient at the solid/quenchant interface at any instant in time is acknowledged by Jakob (96) among others, who records several graphical methods of solution for the quenching of simple geometric shapes. Russell (100) however, attempted to apply mathematical theory to establish practical heat treatment on an exact scientific basis. His analyses of heat-flow characteristics in simple shapes, heated or cooled under different boundary conditions drew upon the fundamental equations due to Fourier. Russell's tables and mathematical procedures were applied by Grossmann et al (101) in establishing so-called "H-values",

- ratings of the severity of quench experienced by cylindrical test specimens in various standard quenchants.

The failings of the Russell and Grossmann type of mathematical approach are summarised concisely by Sinnott and Shyne (102), as an introduction to their own experimental data on the quenching characteristics of salt baths. They note that the errors lay not so much in the numerical data employed, but rather in assuming boundary conditions that do not apply consistently throughout practical quenching operations. Russell's assumption that Newtonian conditions of cooling applied to quenching was the greatest source of inaccuracy, while the variability of temperature-sensitive physical "constants" (e.g. specific heat, density, thermal conductivity) was not corrected for.

For Newton's Law to hold, constancy of H-value is implied, i.e. surface heat transfer coefficient is constant throughout the quench. Grossmann's H-values (101) were, at their best, average values for a given set of quenching conditions, but if accepted as such, they remain usefully indicative of comparative quenchant effectiveness.

Continuous development of the analytical technique initiated by Russell's work (100) by precise application of Fourier equations of heat-flow, - of which the Newtonian law is an approximation - has been pursued by electrical analogue studies and subsequently by computer analysis (103, 104).

In recognising the complexity of phenomena occurring at the metal/quenchant interface, Economopoulos (105) notes that a rigorous understanding of them is of no interest as far as the thermal evolution of the body is concerned. Surface temperatures are difficult to determine during the rapid thermal evolution associated with quenching, but by using what he terms the "inverse problem of heat conduction", Economopoulos is able to incorporate temperature-dependent physical property values of the body into his computer model to yield heat transfer solutions which, he claims, cover all aspects of heat treatment of forgings up to 100 cms. diameter. Experimental verification of the method is limited as yet, but Economopoulos envisages the "eventual derivation of abacii which will supply coefficients of heat transfer at the metal/environment interface..."

While the object of the earlier mathematical treatments (100, 101) was the prediction of cooling rates throughout simple shapes quenched at given H-values, the recognition of the standard cooling conditions associated with the Jominy end-quench test (58) gave practical means of relating the properties of an as-quenched test piece to its prior cooling history. Originally, the Jominy test was developed for the routine inspection of bar stock for uniformity of hardenability. Jominy compared rates of cooling at various distances along an end-quenched test piece, from the quenched end, with cooling rates at the centres of variously-sized bar stock subjected to production quench hardening. It was claimed that positions of equal hardness in test-piece and bars of the same composition would have experienced similar rates of cooling. The definition of the term "equivalent cooling rate" was open to question (58, 106) and Russell (107) inter alia showed that the general accuracy of such correlations varied considerably with the cooling rate criterion selected. Adoption of such hardness comparisons to evaluate mean quench severity H-factors was found to be subject to considerable error (108). Carney (109) demonstrated experimentally the true variability of H with temperature, the size of component being quenched and temperature-recording position within the component. But his work showed that equivalent hardness positions on the Jominy test bar and within the component, where martensite contents exceeded 50%, had cooled at approximately the same rate. Considered use of the technique to quantify practical heat treatment was thus justified, any discrepancies being suggested to arise from differing residual strains in end-quench bar and test probe. This echoes Manning's theory (110) which he based on direct experimental comparison of cooling rates. Carney warned, however, that the use of average H-values may predict less depth of hardening than is actually obtained in small section sizes, and greater depth in larger diameters.

Bullens (61) observes that the equation of hardnesses does not necessarily mean similarity of microstructures. "Considerable amounts" of bainite may exist in martensite without markedly altering the hardness below that of pure martensite. However, graphical correlations of equivalent cooling rates in end-quench test bars and in quenched round bars have been published (111, 112) which are said to provide data considered to be adequate guidance to the selection of heat-treatable steels against given engineering requirements (75). The curves shown in Figure 4 summarise both theoretical and experimental results from several sources and cover quench conditions in the range "still oil" to "brine-violent agitation". If required, such descriptive terms can be quantified in terms of an average H-value, by referring the curves to a modified Grossman diagram (fig. 5. after Rushman (40)).

Much German work on heat treatment has been summarised in the Max Planck Institute "Atlas" (113) to provide a comprehensive and authoritative journal on theoretical and practical aspects of the industrial heat-treatment of steels. Recently, Peter and Hassdenteufel (114) have considered the "information value" of Jominy test data and continuous cooling diagrams in predicting as-quenched hardnesses in round bars. While previous workers had attempted to characterise cooling rates in quenching, the exponential form of cooling processes means that any cooling rate description must apply

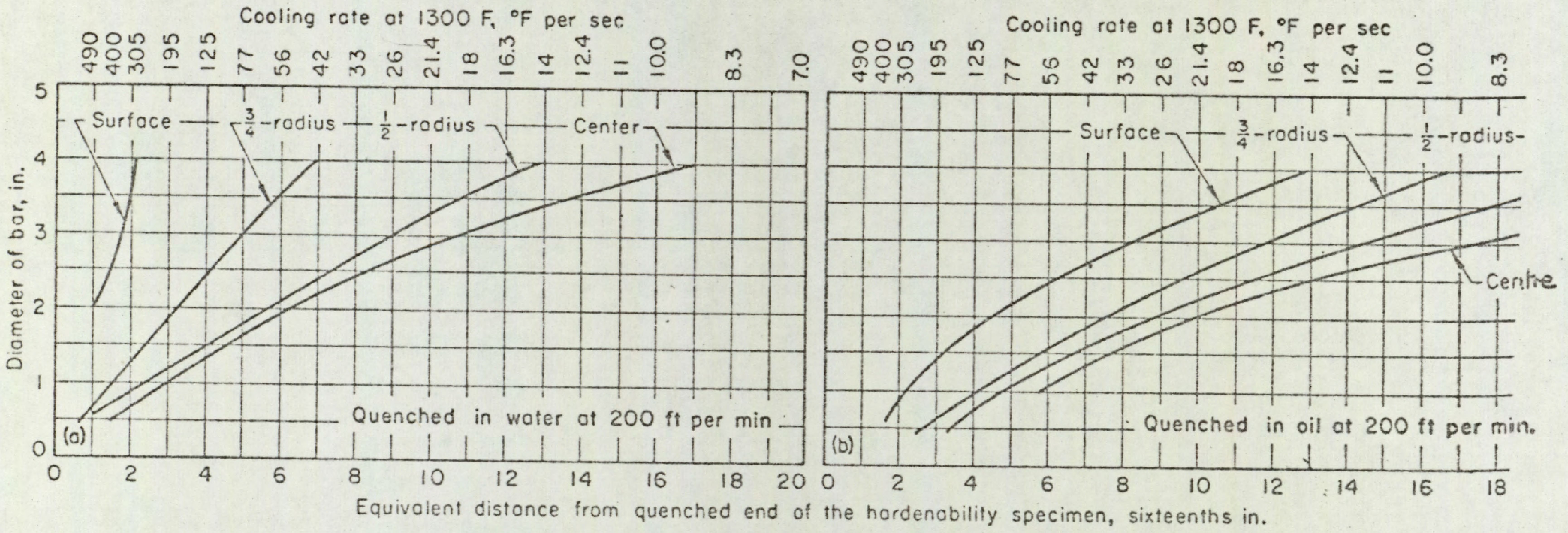
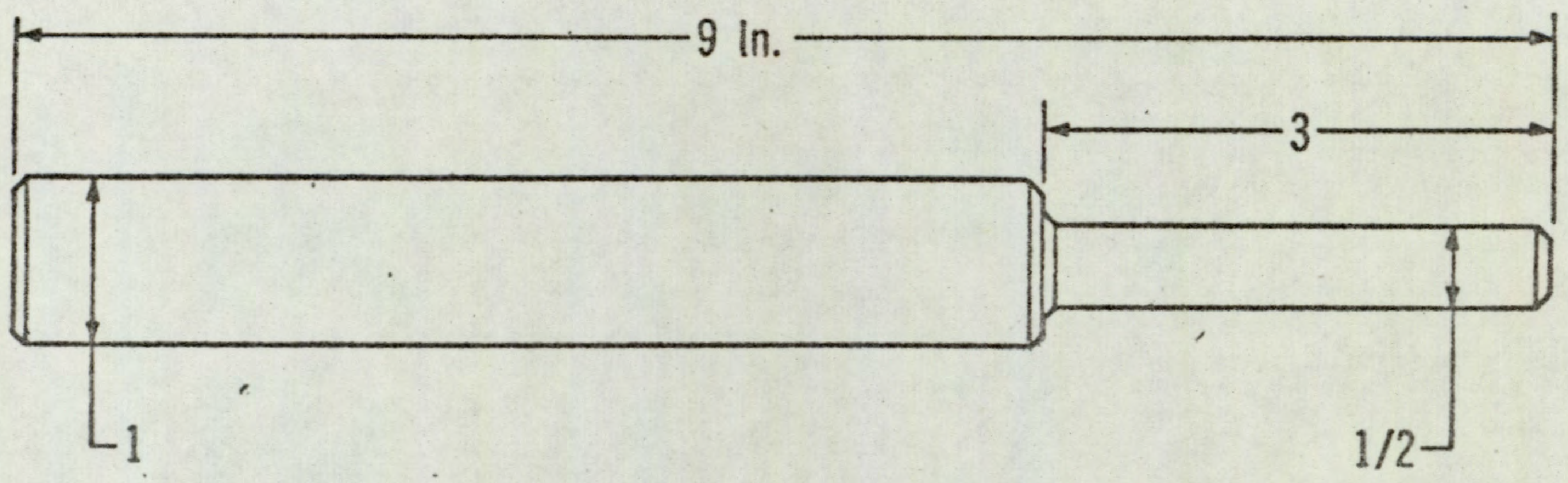


FIGURE 4. Correlation of equivalent cooling rates in the end-quenched hardenability specimen and quenched round bars, free from scale. Data for surface hardness are for 'mild agitation'; other data are for 200ft. per min. quenchant circulation.

(from Metals Handbook (98)).



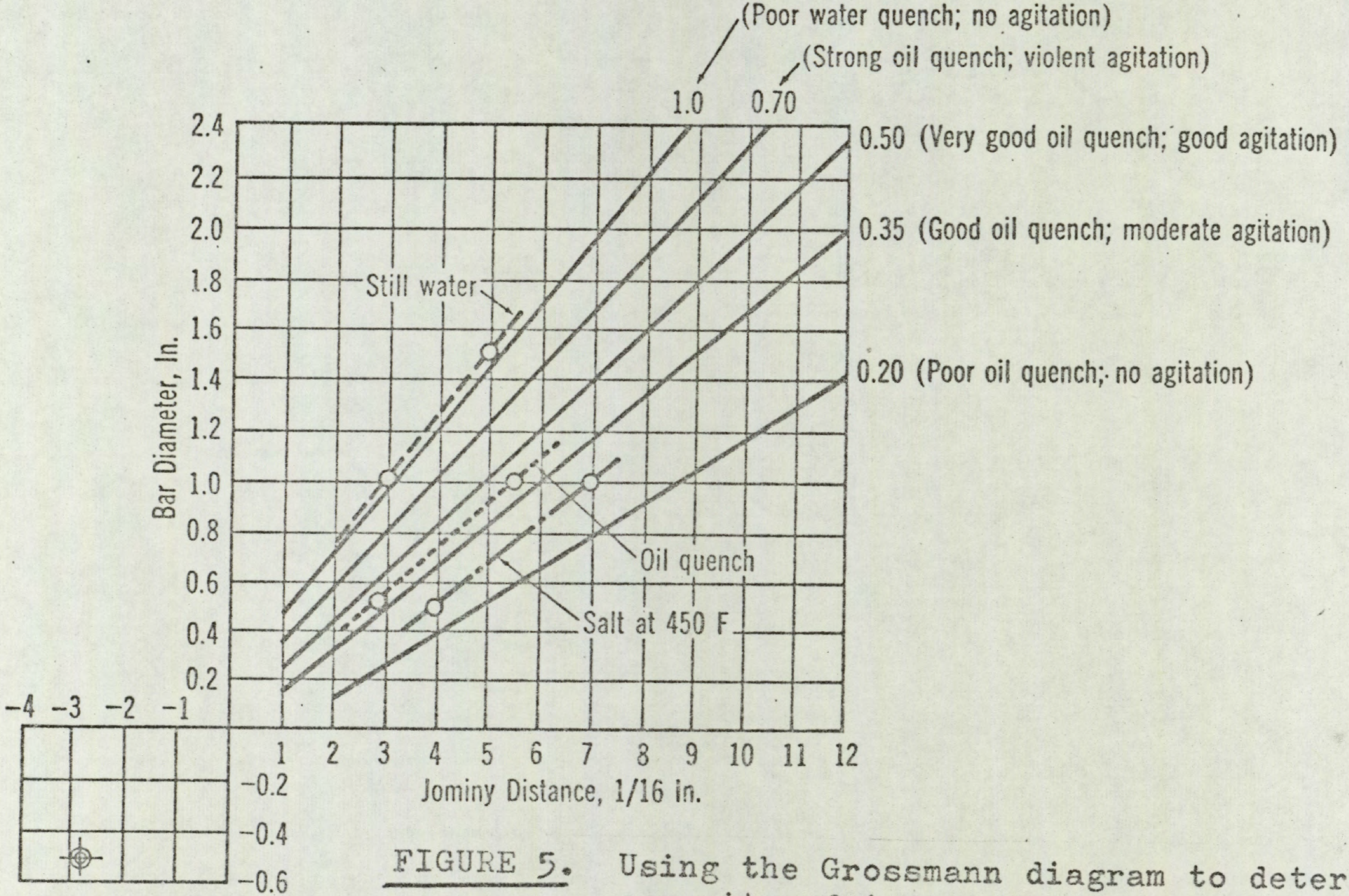


FIGURE 5. Using the Grossmann diagram to determine the quench severity of industrial quench systems. (from Rushman (40)).

to a very narrow temperature range. Peter and Hassdenteufel therefore chose a method of characterisation which is independent of the austenitising temperature, but is connected with a specific temperature range, and adopted Garçon's (92) " λ -criterion", defined as "the number of seconds to cool from 800°C to 500°C (x10^{-2} for convenient expression)". They present experimental evidence to show that predictions on the oil- and water-quenching of bars are verifiable up to 100 mm. dia. and 150 mm. dia. respectively. The limitations of their analysis are:-

a. Continuous cooling diagrams apply to a specific melt, and required modification for chemical composition deviation from this standard.

b. Increasing bar diameter promotes chemical segregation with resulting hardening response variation.

c. λ -values are slightly modified by heat of transformation and thermal conductivity differences between different compositions.

d. What constitutes "oil" or "water" quenching?

The simple diagrams presented are claimed to give practical guidance of sufficient accuracy for the hardening performance of a given steel to be predicted, together with the microstructural products of quenching.

3.2-4 Summary

The foregoing review covers some 30 years of research activity aimed at establishing industrial quenching practice on a scientific footing, providing the means for consistent heat-treatment of steels. The complexity of mechanisms associated with the simplest quenching operation has been outlined qualitatively; the limitations of proposed theoretical analyses of the operation have only served to underline the likely inaccuracies which practical investigations may encounter. Absolute

H-value determination for industrial quenching installations is neither practical nor truly meaningful, the variability of the heat-transfer coefficient with component or test-piece size, shape, surface condition etc. having been frequently demonstrated. However, published graphical and tabular data (112) referring to cooling rate equivalence for quenched round bars and Jominy test bars indicate a means of quantifying and standardising any given quenching operation which may well provide adequate guidance to material selection and quality control on the basis of hardenability of steel, as indicated by Jominy testing.

Technical objections remain to the direct application of any such published data to the industrial situation, with the possible exception of results covering "still water quenching" and some salt-bath treatments, where experiments are usually precisely detailed and laboratory conditions parallel industrial practice (102, 115). Otherwise, published semi-quantitative data is of limited general usage as it suffers mainly from inadequate description of the actual quenching conditions being rated. Such terms as "oil, 50 fpm", "brine, violent agitation" give insufficient indentity to:

a. Quenchant composition, and hence its chemical and physical characteristics, which are applicable to its effectiveness as a quenchant.

b. Quenchant volume and circulation rate.

c. Quenchant temperature and the efficiency of temperature control under given loading conditions.

d. Test-piece characteristics i.e. physical characteristics, surface condition, temperature at the time of quenching etc.

To record quenching conditions by means of instrumented test-pieces would be extremely difficult if normal production conditions were to be maintained (in, say, a sealed-quench furnace). A simple indirect procedure is required whereby norms could be established to ensure consistency of operation or to indicate hardening response in steels when heat treating in a given quench system.

3.3 Practical assessment of industrial heat-treatment practice

Design of heat-treatment plant places considerable importance on:

a. Technological developments in furnace heating methods, and the means of heat transfer to the charge.

b. Sophisticated techniques of furnace atmosphere control (e.g. CO/infra red sensors are gaining widespread application in continuous furnace operation)

c. Quenchant circulation, continuous filtration and temperature control (e.g. for modern quench-plant associated with sealed-quench batch- or continuous furnaces).

However, the furnace manufacturer makes no recommendation on the types of quenchant most suitable for use in his product, and gives no indication of the potential quenching "efficiency" of the system. Conversely, industrial quenchants are promoted by means of laboratory demonstration and bench-test results, the goodwill of customers being relied upon for quenchant assessment under practical heat-treatment conditions. During discussions with both parties, no instances were recorded of any direct co-operation between furnace manufacturers and quenchant suppliers, at the quench system design stage or in the commissioning of new installations. When some 6,000 gallons of oil may be involved in charging a quench system it is in the operator's interest to know the optimum working conditions for consistent development of properties within a given range of steel chemistry, and in keeping with an economic quenchant "life" and "topping-up" or regeneration rate. Exact solutions to these problems are excused by the insistence that plant shall be run with "something in hand", to allow for hardenability variation in the steels being processed. This attitude is at variance with some American practice, where versatility in quenching is one of the requirements of the heat treatment department, especially where several types of steel are processed (41).

3.3-1 Established methods of quench severity measurement

Practical determination of average H-values experienced on quenching out typical production loads has been achieved by the analysis of hardness traverses taken on simple stepped-radii test bars which have formed part of the actual furnace charge.

a. White (39) standardised his test-bar against an instrumented single-diameter test bar, quenched under similar conditions; Rushman (40) more conveniently used hardenability data expressed on a modified Grossmann diagram (figure 5), where changes in quench severity over a period of time, but under standard test conditions, would be shown by a shift on the Jominy distance axis.

b. Analysis of hardness traverses on step-bars by Lamont's method (116) has also been adopted as a standard procedure for determining production quenching rates (average H-value) (41). The method can be used to quantify the range of quench severity potential for a quench system under different operating conditions.

The above methods incorporate the equal cooling rate/equal hardness criterion. Crafts and Lamont (116), warning of the errors inherent in the basic calculations, suggest that their applicability should be qualified in the case of small sections, but otherwise a useful order of accuracy may be achieved.

3.3-2 General quality control methods

While the determination of severity of quench may be of some interest, the maintenance of optimum quenching conditions for processing a given steel is considered to be more important. The simple, practical means of determining quench efficiency referred to above, may be employed as quality control monitors without attempting to quantify heat treatment procedures directly. Quenching step-turned test-bars, or cropped lengths of bright drawn bar of different diameters but the same composition, may facilitate:

Quenchant control checking, when standard material test specimens are used, or:

Assessment of heat-treatment response in different batches of steel, under standard quench conditions. (40)

Actual test detail is dependent on the application, i.e. type of load being quenched, critical ruling section of components, - but the following recommendations can be made:-

(1) The combination of steel chemistry and test-specimen dimensions should be chosen to give measurable hardness variation for small changes in quench efficiency. A "hardness tolerance" at a given diametral position on the testpiece can be defined below which minimum component properties cannot be guaranteed. Thus, the steel should show a distinct hardness transition on its Jominy curve, about which the hardness of the critical region of the test-bar should vary.

(2) Selection of test specimen material and dimensions should recognize the effect of chemical heterogeneity of the steel in giving irregular hardening.

(3) The specimen should not intrude on quenchant circulation through the production batch; recommended length to diameter ratio of not less than 3 to 1 avoids end-effects (41), when taking a test survey at the mid-length of the specimen. Dimensions should be related to the predominating ruling section among the production batches to be worked with.

Guidance to steel selection for test-bars may be drawn from published charts (112), which relate equivalent hardness positions in Jominy testpieces and in quenched bars for various unspecified quenching conditions. Available technical information and practical observation suggests that the range of quench severities likely to be encountered are in the range 0.3 to 1.5 on the Grossmann scale (still water = 1).

/ Note:

The traditional hardness traverse method of assessment, although accurate and reproducible when carefully applied, is somewhat laborious in use and requires skill in section preparation to prevent tempering of the hardened structure (110). It should be possible to derive a non-destructive technique for rapid and reproducible analysis on re-usable standards. For example, eddy-current testing is used for automatic sorting of mass-produced heat-treated components - ball-pins, for example (117) - where core-hardness is correlated to a meter reading or an oscillograph trace. That small differences in residual austenite content in martensitic structures can be detected, although no measurable hardness differences can be found (118), suggests the high sensitivity of the method./

3.3-3 A survey of industrial quenching practice

a. Aim

Continuing the assistance given by industry in the earlier stages of this project, several companies offered cooperation in an exercise which attempted to compare practical quenching rates in various types of industrial plant and quenchant, under normal production heat treatment conditions. The technical basis of the assessment was, in effect, a comparison of Garçon's λ-criterion (92) at radial positions on central transverse sections of simple cylindrical test-bars, of identical composition and pre-test treatment, which were heat-treated in production loads. Where possible, this was carried out with components of similar steel composition and cross-section to the test-pieces in order to investigate realistic time and temperature processing cycles.

b. Procedure

Steel selection for test-pieces being limited to readily-available bar, an assessment of hardenability response in material of about 1" diameter in relation to the anticipated H-range 0.3 to 1.5 resulted in the choice of carbon-manganese steel; 1⅛" diameter bars in the bright-drawn condition and of the following composition, were used in the form of 6" sawn lengths:

C 0.16, Mn 1.23, Si 0.38, S 0.043, P 0.017
Ni 0.12, Cr 0.28, Cu 0.12, Sn 0.033, Mo 0.13.

Test-bars, carefully stamped, were delivered to various plant for processing, care being taken to ensure that they were recovered from the production loads immediately after quenching, and not subjected to stress-relieving or tempering operations.

After retrieval, the bars were sectioned on a slitting wheel and a cross-sectional metallographic surface prepared to correspond roughly with the mid-transverse section. Vickers hardness traverses were made on perpendicular diameters, under a 30 Kg. load, with impressions at $^1/16$" intervals. 4" Jominy bars were machined from the same batch of material and end-quenched from 920°C under standard laboratory conditions. Vickers hardness impressions (30 Kg. load) were taken on 0.050" flats, ground and polished for subsequent microstructural examination, at intervals of $^1/32$" for the first ¼", thereon at $^1/16$" up to 1" from the quenched end and then at ⅛" intervals for the next inch.

c. Results

In order to counteract any possibility of hardness traverse inconsistencies arising from chemical segregation, all impressions were plotted as representing a "mean" traverse, with radial pairs of results being mirror-imaged across the bar centre axis (108) and summarised by a fair curve. Traverses representative of a range of quenching severity conditions are shown in Figure 6, the key to which summarises all operating data from the six furnaces thus compared.

The hardness plot for the Jominy end-quench bar is shown in Figure 7.

d. Analysis of results

The means of comparing quench-severity among the systems surveyed was primarily, the use of the metallurgical "axiom" (41) that:

> "Equal hardnesses in different specimens from the same steel are achieved by similar cooling histories".

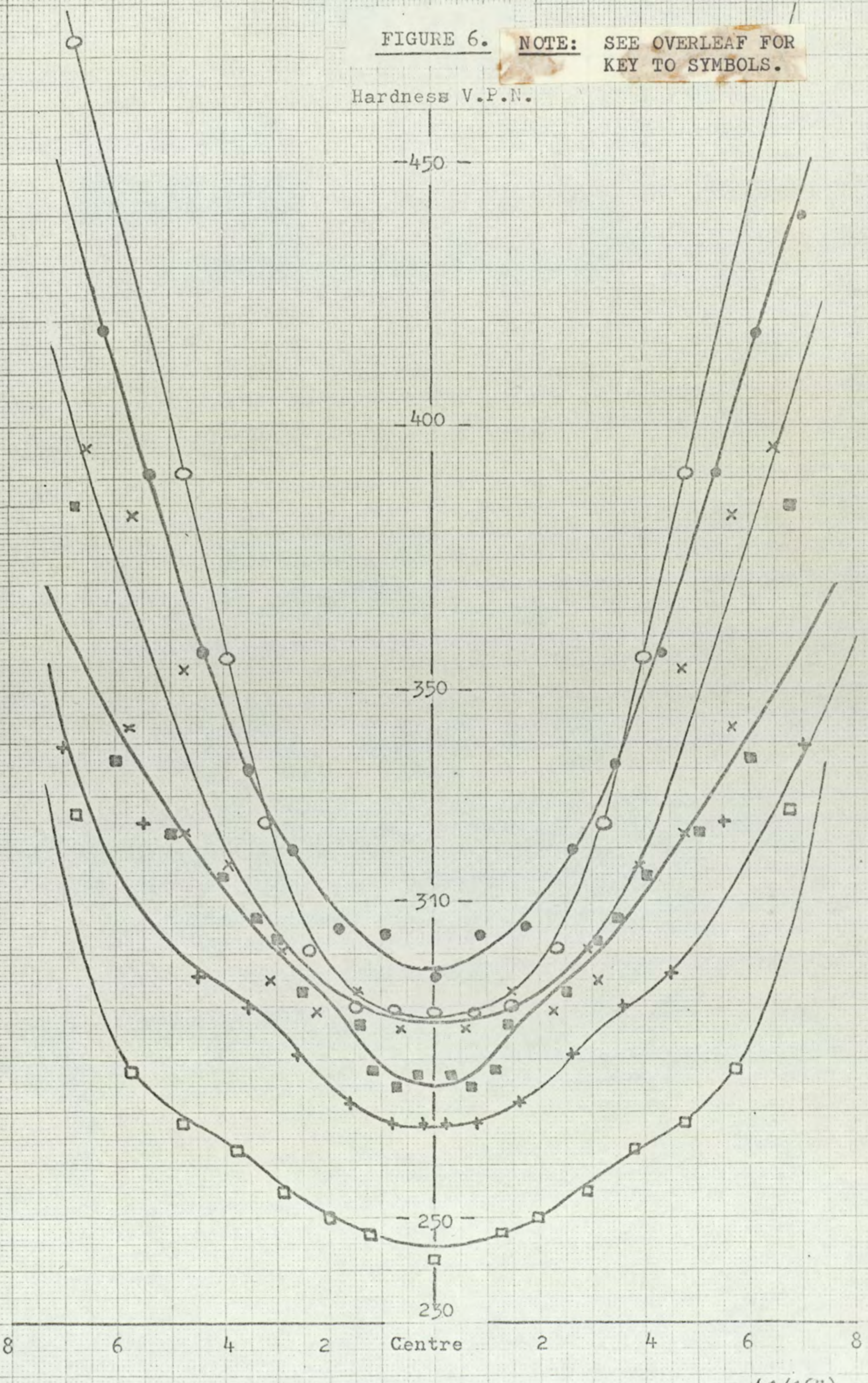
The limitations of this statement are acknowledged (41, 61, 109) and, where possible the correlation between equi-hardness positions on test-bar cross-sections by microstructural comparison, and adjustments made accordingly in the equivalent Jominy distance. Garçon λ -values (92) were derived from Figure 8, which summarises information from several published sources on the cooling times over the temperature interval 800°C, at various positions along the Jominy bar.

Figure 9 shows all λ -values derived in this manner, for centre, half-radius and three-quarter radius positions in the test specimens returned for analysis.

The curves in Figure 9 are not a basis for absolute H-value determination but merely compare and contrast, semi-quantitatively, the quenching capabilities of the systems tested. In this instance, the direct correlation of hardness to Jominy distance would have demonstrated this equally well. The conversion of the latter quantity into a λ -term enables <u>individual</u> curves to be used to predict the quench

FIGURE 6.

NOTE: SEE OVERLEAF FOR KEY TO SYMBOLS.



KEY TO FIGURES 6 and 9.

○	Test 1	Ipsen sealed quench pusher furnace. 120 lbs.wt. gross load, direct quenched from carburising at 925°C into 370 gallons Houghtoquench KE at 55-80°C.
●	Test 2	Efco sealed quench batch furnace. 400 lbs.wt. gross load, direct quenched from carburising at 925°C into 600 gallons Houghtoquench KE at 55°C.
×	Test 3	Birlec sealed quench batch furnace. 250 lbs.wt. gross load, direct quenched from carburising at 925°C into 400 gallons Houghtoquench KE at 55°C.
■	Test 4	----- sealed quench continuous furnace. Load carburised at 925°C, furnace cooled to 840°C and quenched into Castrol Tudor Quench No. 2 at 95°C.
+	Test 5	British Furnaces sealed quench batch furnace. Load carbo-nitrided at 875°C and direct quenched into Castrol Tudor Quench No. 2 at 75°C.
□	Test 6	British Furnaces sealed quench batch furnace. Load carburised at 925°C, furnace cooled to 840°C and quenched into Esso 1812 (Fenso 70) at 180°C.

FIGURE 7. Standard Jominy hardness traverse for the CMn test steel.

FIGURE 8. The derivation of λ-values from a standard Jominy test bar.
(from ● Birtalan et al (138)
▲ Russell (107)
+ Peter and Hassdenteufel (114)
× Max-Planck-Institut (113)).

FIGURE 9. (see FIGURE 6 for key to symbols)

hardening behaviour of any other steel, of similar diameter to the test piece, when quenched in the same quench tank. Such is the basis if work described in section 3.3-4.

In spite of its limited "yield" of specimens upon which sensible assessments could be made - for reasons of excessive oxidation/decarburisation, inadvertently tempering of the quenched test-piece etc. - the survey indicates a considerable spectrum of quench-system performance. This is all the more disturbing when it is realised that, for the most part, the furnaces were within two main categories (sealed-quench batch or sealed-quench continuous), operating under standard production conditions to heat treat components of similar ruling section to optimum property levels. In addition, all systems could be said to use "oil quenching"; the diagram demonstrates the caution necessary in accepting published data thus classified. In Figure 10, the range of λ - values encountered are superimposed on a diagram taken from the Max-Planck "Atlas" (113) falling into the category between water- and oil-cooling as might have been expected.

3.3-4 The correlation of properties attributable to heat-treatable steels with heat-treatment practice.

a. Aim

B.S. 970 mechanical properties data refer to $1\frac{1}{8}$" bar section only, subjected to a double-quench heat treatment. The failure of this process to develop optimum strength properties in the test-piece, and the mis-representation of "true" tensile strength properties in section sizes smaller or greater than $1\frac{1}{8}$" has been discussed elsewhere (29, 38). In addition, inadequate composition description of some En-case hardening steels is rarely recognised as giving rise to further discrepancy between "true" and "apparent" (B.S. 970) strength levels; Figure 11 (38) has been constructed to provide guidance to their selection, to meet minimum core tensile strength requirements on direct quenching from carburising.

FIGURE 10 (adapted from (113)).

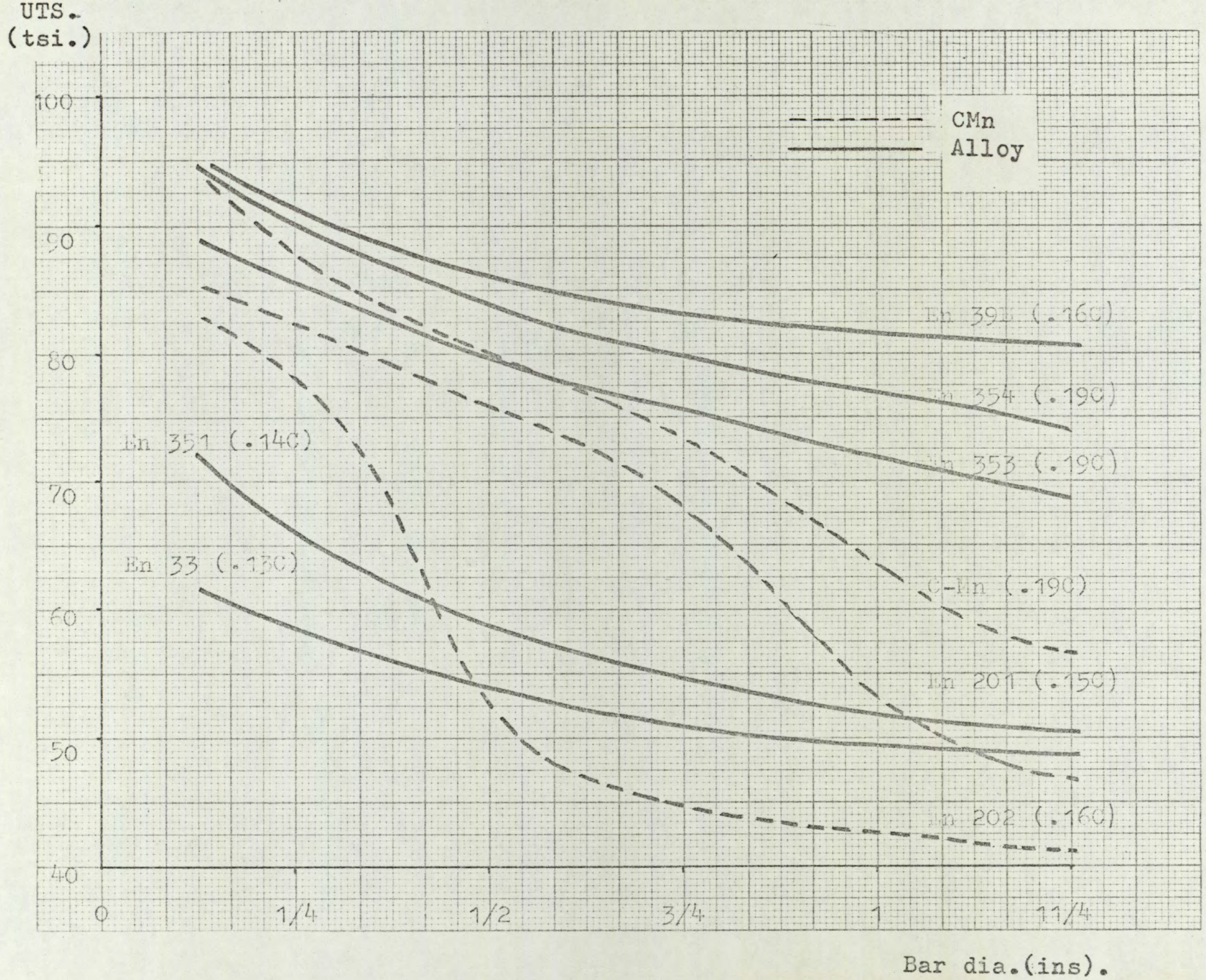


FIGURE 11. Tensile properties after blank carburising at 925°C, direct oil quenching and tempering at 150°C.
(from Dawes and Cooksey (38)).

While the merit of these analyses over B.S. 970-data in facilitating material section decisions cannot be disputed, they suffer essentially from inadequate description of quenching conditions. The test-piece hardness traverses alone of Figure 9 are qualitative evidence of the diversity of quench-severity the term "oil quench" covers. A means of correlating the quench-hardening potential of any quench system, by a series of such experiments with steel composition, is suggested for the prediction of optimum strength properties attainable in a given batch of steel. It is contended that the correlation could form the basis of specifications of direct relevance to material selection in design decisions.

b. Procedure

The technical basis for the correlation proposed rests on the assumptions that:

(1) Cooling rates during quench do not change appreciably from one heat-treatable steel grade to another, for given section size and under reproducible quenching conditions.

(2) Hardness values are directly indicative of tensile strength.

The first of these assumptions infers that the thermal properties of engineering steels are similar for all compositions, and experimental evidence (41) suggests that this is essentially true. It implies that λ -values (92) for the quenching of bars are dependent only on test-bar section and independent of composition (114), thus enabling their general use once determined for a specific composition. Hardness/ tensile strength tabulations are frequently found in the literature (56).

The correlation requires the following data, determined from simple readily-performed experiments or derived from the literature:

(1) For general specification purposes, a range of λ -values representative of cooling conditions at diametral positions on test-bars representative of the "ruling section" size range common to engineering manufacture in general, i.e. from ½" to 6" diameter.

(2) For each steel grade, a representative Jominy hardenability band is required.

Specific application of the method, advanced as material selection guidance, would attempt to describe strength values to be derived from heat-treatment of a given composition in a given quench system. Accurate determination of λ -values to cover the section size range normally processed in the plant, under standard operating conditions, would establish over a period of time λ -value confidence limits. Guaranteed strength levels would be derived from their application to a purchasing quality control Jominy hardenability band.

c. <u>Results</u>

Figure 12 summarises measurements taken on one of the furnace survey bars (test no. 5), for which λ -values at ¾ -, ½ - and centre-radius positions are given. When these are superimposed on a Jominy hardenability band - re-scaled to show strength equivalent of hardness on the abcissa, and λ -cooling time replacing the customary "distance from the quenched end" - it is seen that a 1⅛" section of En 352 could be expected to develop between 53.5 and 79.0 tsi. on its centre axis and 60.0 and 88.0 tsi at the ¾ - radius, if quenched in the test furnace under the standard conditions originally measured. Realistic estimates of strength development in a specific case can be derived from its own Jominy curve.

FIGURE 12. Derivation of strength levels to be expected in $1\frac{1}{8}$in.dia. En352 steel quenched out in the system calibrated by test no.5 (see FIGURES 6 and 9).

NOTE: The curves have been redrawn from the En352 Jominy hardenability band given in reference (133).

d. Analysis of Results

It is unfortunate that comprehensive testing of the suggested procedures, over a period of time, was not possible. The method remains therefore only a basis for further experimentation but it is argued that it incorporates a realistic approach to steel selection, enabling the likely response of a given steel heat-treated in a given plant to be quantified.

3.4 The Estimation of Response to Heat Treatment in Low Alloy Steels by the Analysis of Published Data

Introduction

The previous section has considered the means by which optimum properties may be attained in heat-treatable steels, and a practical method of determining the same for a given steel processed in specific plant has been suggested. In introducing the topic of quenching in industrial heat-treatment, reference was made to the loose inverse relationship that exists between quenching efficiency and the inherent hardenability of a steel in attaining a given strength level. Thus, deficiencies in the former can be made up for by using steels giving depth of hardening under "slow" quench conditions from their alloy content alone. A combination of good heat-treatment practice with minimum-cost steels is desirable for the economic utilisation of materials.

3.4-1 Hardenability of Steels

The term "hardenability" describes that property of a steel which confers hardening in depth below the surface of a steel specimen quenched from the fully austenitic state. While the derivation of isothermal transformation diagrams (119) gave a means for observing qualitatively the effects of alloying elements on the transformation of austenite it was the development of the Jominy end-quench test (58), which provided specific data on austenite decomposition under continuous cooling conditions, more applicable to heat-treatment practice. Subsequently, the influence on hardenability exerted by the common alloying elements in steel was widely investigated.

Grossmann (77) proposed a method of calculating the hardenability of a steel from its chemical composition, deriving a system of factors for each alloying element percentage by which an iron-carbon base composition factor was enhanced. Grossmann's system was based on the assumption that there are no interactions between carbon and the alloying elements, or between the various alloying elements. Subsequent investigators (56, 64, 116, 120-5) repeated or extended Grossmann's work, either supporting his concept, but disagreeing in its detail and the values he had assigned to element factors (120-2), or concluding that interactions between the compositional components of a steel make a general solution impossible (123-5). In particular, Glen (64) showed that the effects of alloy additions do not necessarily follow a linear law and concluded that the effects are not satisfactorily represented by multiplying factors. He found that were the necessary complicating factors introduced, the elegant simplicity of Grossmann's approach was largely lost. The literature on the derivation of hardenability factors is critically reviewed by Bullens (61), who concludes, -

> "The calculation of hardenability has no sound basis and is in a state of chaos. We might better be satisfied with a qualitative understanding, and use that as a basis for experimentation than rely on pseudo-quantitative calculation."

Nevertheless, the experimental derivation of multiplying factors is still pursued (126) and further modification of Grossmann's original concepts are proposed (127); while results may not be applicable to heat-treatable steels in general, adequate evaluation of hardenability can be achieved in narrow compositional ranges covered by original experimentation. Aaronson has recently predicted that "tailor-made" compositions, to meet property requirements at lowest material cost, may be determined "within a generation" (128). His work on the influence of individual alloying elements on the diffusion rate of carbon in otherwise pure iron-carbon base material suggests that the confused picture of which Bullens (61) was most critical, is due to interaction effects and even qualitative assessments of some individual element contributions to hardening response are suspect.

3.4-2 Hardenability Data Summation and Presentation

In proposing a means of estimating the response to heat-treatment of a given steel from a knowledge of its chemical composition and its structure and temperature at the instant of quenching, it is necessary to consider the nature of the experimental data available for analysis.

The parallel between mechanical properties and microstructure of an as-quenched component (60) has already been drawn; knowledge of the carbon content/martensitic hardness relationship is the basis for routine quality control testing whereby hardness measurements are used to indicate the consistency of heat-treatment operations and to give an estimate of mechanical strength. To suppress the formation of austenite transformation products and to give optimum mechanical properties at a point within a steel component by ensuring a fully martensitic structure, some critical cooling rate must be exceeded at the point.

Graphically, the combination of all factors influencing the transformation or decomposition of austenite in heat-treatment is summarised for a given steel by means of a continuous cooling transformation diagram. Semi-quantitative treatment of isothermal cooling diagrams - " just avoiding the nose" - is still widely applied throughout industry by heat-treatment engineers, to describe the critical cooling criterion necessary to prevent the separation of transformation products. This is slow to give way to the more exact approach which continuous cooling diagrams allow because such information is still largely incomplete, for BS 970 (En) steels for example. Attempts to derive continuous cooling data from comprehensive isothermal data (130) have met with poor success, due in part to the deficiency of actual experimental information from both types of cooling experiments performed on the same steels.

Two methods of continuous cooling data presentation are used:

(1) British workers favour data presentation for a given steel in terms of structures and hardness developed at axial, mid-radial and near-surface positions in a range of bar diameters for water and oil quenching and for cooling in still air (59, 131-3).

(2) American and German workers favour data presentation in terms of time and temperature (113, 114, 129). Transformation temperatures are superimposed on a series of cooling curves taken from steel speciments cooled from the austenitic range at standard cooling rates. The loci of such points show the time and temperature conditions which limit the formation of specific micro-structures.

This latter form of diagram shows the range of micro-structure possible in a given steel and the cooling rate required to produce any given micro-structure. Blank (59) recognises that to make any practical use of this type of continuous cooling diagram, it is necessary to know the cooling rate of the stock to be treated. He finds this impractical and proposes instead the expression of cooling rate in terms of "equivalent bar diameter", a form "readily applied to commercial heat treatment practice". The foregoing section to the present work has shown the limitations of any quench assessment based on "oil" or "water" quench conditions, and it is argued that knowledge of stock cooling rate is essential to optimisation of heat-treatment practices. The means of determining this has been suggested by the work of Garçon (92) and Peter and Hassdenteufel (114), and demonstrated on the quench-system surveys already described.

It makes possible the use of the "comprehensive" form of continuous cooling diagram to quantify heat-treatment response in a given steel.

3.4-3 Derivation of Empirical Formulae to Quantify Heat-treatment Response in Low-alloy Steels.

It has been recorded that although steels usually fall within the compositional limits of standard specifications, appreciable variation in properties arise from varying composition-dependent response to heat treatment processes (29). Thus, chemical composition, austenitic grain size and austenitising temperature are known to influence the hardenability of steel; qualitatively at least (61) their effect is understood. For a given steel, they represent a known set of variables which may be amenable to statistical treatment so that given a dependent property for many steels it should be possible to derive a formula representing the general dependence. Thereafter, within similar composition limits, the formula is of value for calculation of the same dependent property in other steels.

The method has been used by several workers, (68, 69) to establish various transformation temperatures, e.g. Ac_1 , Ac_3 and M_s temperatures and it is suggested here as a means of quantifying cooling times over the temperature range 800°C to 500°C for the attainment of specific martensite contents - and indirectly, calcuable strength levels - at points within a quenched steel test-piece or component. Two approaches are described, one by way of data derived from continuous cooling diagrams, drawn exclusively from a German source (113) and the other by way of Jominy end-quench test results from several sources.

It is stressed that any formulae of this nature apply to steels with compositions within the ranges for each of the independent variables covered by the sample from which the formula was derived, and is reliable only to the extent that the sample was representative. Thus, differences between formulae derived by the two methods are determined by the range of the contributing variables used in each case, and the evenness or otherwise of the distribution of variable values within the range (69).

a. Aim

The strength of an as-quenched component can be determined from a knowledge of the martensite content and the carbon content of other steel (56). It was required to derive formulae determining cooling conditions at a point within a component to give a fully-martensitic structure or 95%, 90% and 80% martensite, the means of describing these conditions being dependent on the nature of data presentation in the literature. Micro-structural definition was considered more useful than hardness criteria because of the dependance of the latter on carbon content. The method chosen enables the analysis to unify data for steels of any carbon content; the results can be interpreted into hardness or strength terms as required. The same multiple regression analysis technique was applied in all cases.

b. Procedure

(1) Continuous Cooling Data

The Max-Planck-Institut "Atlas" (113) provided the only consistent information on cooling conditions necessary to achieve 100% martensite (and 50% martensite) on quenching steel from fully homogeneous austenite. Critical cooling time was taken as the time for cooling from Ac_3 to 500°C, and the analysis expressed this in terms of:

Chemical composition (C, Si, Mn, P, S, Cr, Cu, Mo, Ni, V)
Austenitizing temperature (or hardening temperature) γ-temp.
Austenitic grain size G.s.
Ac_3 temperature

35 complete sets of data were collected for analysis.

A summary of the data used and data analyses is presented in Table 20. It is seen that the mean Ac_3 is 810°C, so the critical cooling time should not differ markedly from the Garçon criterion (92), which uses the interval 800°C to 500°C. Data was not available in a form allowing meaningful application of a small correction to the (Ac_3-500) cooling time.

(2) Jominy End-quench Test Data.

Several sources of information yielded consistent sets of data to cover critical cooling condition evolution from Jominy end-quench testing (58). Multiple regression analysis of such information has been explored by other workers, e.g. to establish the "shape" of J-curves (134), to determine the distance from the quenched face at which a given hardness results, in a given steel composition range (135), and it is known to be established as a quality control technique by Volkswagon (37). In the present investigation, it has been used to give information on simple two-and three-component compositions, providing pointers to the "design" of heat-treatable steels. The analysis has been prepared to yield results in the manner now "traditional" to the Jominy test; distances from the quenched face to 95%, 90% or 80% martensite content in the micro-structure are quoted in 1/16th. in. but figure 8 enables these to be translated into λ-time intervals - more consistent with a measure of heat-treatment response under practical conditions.

% martensite J-distances were derived in two ways:

1. By direct reading from curves plotted with martensite content of the micro-structure at a given point as the dependent variable. This information was limited to one source only (136).
2. By interpolation from hardness values, as a conventional Jominy-data presentation, using Hodge & Orehoski's curves (56). In order to check the validity of the method, the data which allowed direct reading was treated in the same manner, and fig. 13 shows actual and calculated martensite contents plotted together. The deviation of

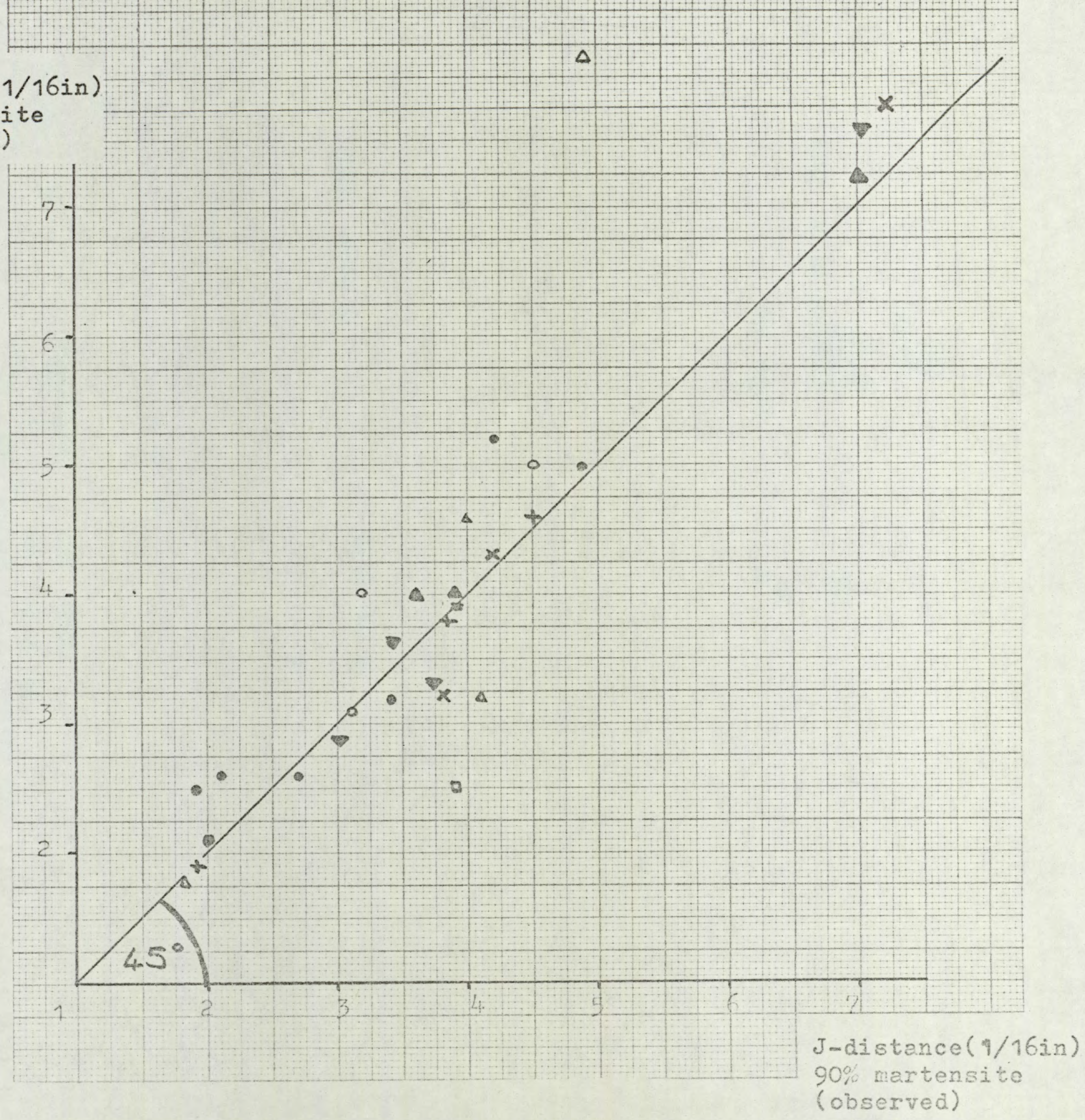


FIGURE 13. Comparison of the calculated J-distance to 90% martensite with that determined by metallographic observation. (from U.S.Steels atlas (136))

△ CMn
× CCr
+ CNi
● CMo
■ CNiCr
○ CNiMo
▲ CCrMo
▼ CNiCrMo
□ CNiCrMoSi

points from absolute correlation is considered to be within the limits of accuracy of the interpolation procedure; other than the effect of carbon, on which the Hodge & Orehoski (56) relationship is based, no influence of compositional variation is apparent.

Alloy combinations studied were:

C Mn steels using methods 1 (17 steels) and method 2 (28 steels)
C Mn Mo steels using method 2 (18 steels)
C Mn Cr steels using method 2 (36 steels)

In each case, the variables subjected to analysis were:

Chemical composition (C, Si, Mn, P, S, Cr, Mo, Ni)
Austenitizing temperature
Austenitic grain size

Variable ranges are included in the results summation Table 21. The first group of carbon-manganese steels was drawn from a single source, and comprised steels of high purity i.e. low in residual element content. The second group was assembled from several data sources and included the first group. Otherwise, it comprised steels of general engineering compositions, with residual element levels which would be expected to exert their own hardenability contribution to heat-treatment response. This latter consideration must necessarily apply to the three-component steels, whose compositions largely represent commercial melting practice.

Some guidance on possible interactions between alloy components is given in Glen's paper (64) which describes work originally intended to test theories advanced by Grossmann (77) and others on the calculation of hardenability from alloy element multiplying factors. It is unfortunate that Glen's published results on high-

Continuous cooling data:
Analysis for (Ac_3 - 500) critical cooling interval for 100% martensite.

a. Simple analysis.

Data range	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V	γ-temp.	G.S.	Ac_3	Const.	S.L.	%V
Min.	0.11	0.21	0.43	.009	.007	.005	.005	.005	.005	.005	840	5.5	710			
Mean	0.31	0.39	0.84	.021	.017	0.77	0.17	0.14	0.49	0.04	881	8.1	810			
Max.	0.73	1.62	1.82	.044	.030	2.29	0.22	1.02	5.00	0.31	980	12.0	890			
σ	0.15	0.31	0.35	.090	.060	0.63	0.08	0.24	1.05	0.07	33.3	1.55	43.1			
Factors	40.2	-	9.5	-	548	12.3	-	-	3.6	-	-	-	-	-33.5	5%	60.8

b. Product term analysis, with (C)(Mn), (C)(Mo), (C)(C), (Cr)(Cr) and variables from (a) <u>except</u> Si, P, S, Cu, V.

	C	Mn	Cr	Mo	Ni	γ-temp	G.S.	Ac_3	CMn	CCr	CMo	C^2	Cr^2	Const.	S.L.	%V
Factors	-	-	21.2	-	2.3	-	-	-	-	60.6	-	-	7.3	1.6	5%	70.2

TABLE 20.

S.L. = Significance level.

%V = Percentage variation explained.

purity two, three and four-component alloy steels are insufficiently detailed to render them suitable for multiple regression treatment. However, his results show that the promotion of hardenability in a given iron-carbon base by alloying additions holds to a straight-line relationship only for the simpler steels, and that the residual levels considered in the commercial compositions analysed are sufficient to produce non-linear equations to represent Jominy distance to a given percentage martensite. Hence, in view of the possible influence of second order terms, analyses were attempted using products of alloy elements and carbon.

c. Results

Tables 21 & 22 summarise the results of regression analyses carried out to establish formulae to describe the critical cooling intervals for given percentages of martensite to result from quenching a steel from the austenitic state. These are:

For 100% martensite :

$$(Ac_3 - 500) = 1.6 + 2.3\,Ni - 21.2\,Cr + 60.6\,(C)\,(Cr) + 7.3\,(Cr^2)$$

This formula explaines 70.2% of composition variation within the compositional limits of the data analysed, at 5% significance level. It is based on data drawn from continuous cooling diagrams (113).

Jominy end-quench data has been used similarly, and formulae describing the equivalent Jominy distance to 95, 90 and 80% martensite are summarised thus:

For carbon-manganese steels:

(a) Very Low Residuals

$$J_{95} = 0.025 + 5.41\,(C)\,(Mn)$$

$$J_{90} = 0.147 + 6.04\,(C)\,(Mn)$$

$$J_{80} = 0.118 + 7.64\,(C)\,(Mn)$$

These formulae describe respectively 93.8, 91.4 and 80.8% variation in composition, at 0.1% significance level.

(b) Commercial Grades

$$J_{95} = 1.33 + 4.37\,(C)\,(Mn) + 0.43\,(C^2) - 8.46\,C + 48.5\,P$$

Summary of Jominy-curve analyses, - J-distance to 95%, 90% and 80% martensite.

1. CMn steels (high purity).

Sample size	Data range	C	Mn	Si	Cr	Mo	Ni	S	P	G.s.	γ-temp.	S.L.%	%V
17	Min.	0.17	0.34	0.07	0.01	0.01	0.01	.015	.010	2.0	815		
	Mean	0.54	1.16	0.25	0.04	0.02	0.06	.025	.019	6.3	882		
	Max.	1.00	1.88	0.42	0.11	0.04	0.31	.044	.032	8.5	930		
	σ	0.23	0.59	0.08	0.02	0.01	0.08	.008	.005	1.5	37.4		
	J_{95}	0.025 + 5.41 (C)(Mn)										10 → 0.1	93.77
	J_{90}	0.147 + 6.04 (C)(Mn)										10 → 0.1	91.36
	J_{80}	0.118 + 7.64 (C)(Mn)										10 → 0.1	80.81

TABLE 21.

2. CMn steels (commercial qualities).

Sample size	Data range	C	Mn	Si	Cr	Mo	Ni	S	P	G.s.	γ-temp.	S.L.%	%V
45	Min.	0.17	0.35	0.07	0.05	0.01	0.05	.014	.010	2.0	815		
	Mean	0.45	0.99	0.26	0.10	0.03	0.16	.027	.022	6.5	886		
	Max.	1.00	1.88	0.42	0.33	0.11	0.61	.044	.047	9.0	1050		
	σ	0.17	0.49	0.07	0.07	0.02	0.12	.009	.008	1.7	64.3		
J_{95}		$1.33 - 8.46C + 48.5P + 4.37(C)(Mn) + 0.43(C)^2$										$\rightarrow 5$	89.8
J_{90}		$-0.25 + 7.47Cr + 4.11(C)(Mn) + 0.83(C)^2$										$10 \rightarrow 0.1$	87.0
J_{80}		$0.51 + 4.7(C)(Mn) + 1.10(C)^2$										$5 \rightarrow 0.1$	81.8

TABLE 21. (continued)

Steel composition ranges covered by multiple regression analysis of Jominy data.

1. CMnMo steels

Sample size	Data range	C	Mn	Si	Cr	Mo	Ni	S	P	G.s.	γ -temp.
18	Min.	0.20	0.17	0.15	0.02	0.02	0.01	.007	.010	3.5	816
	Mean	0.41	0.93	0.24	0.14	0.40	0.11	.024	.020	7.1	876
	Max.	0.97	1.88	0.47	0.54	1.96	0.45	.039	.036	9.5	1040
	σ	0.19	0.47	0.07	0.14	0.43	0.12	.009	.007	1.2	49.0

For regression analysis results, see page 126.

2. CMnCr steels

Sample size	Data range	C	Mn	Si	Cr	Mo	Ni	S	P	G.s.	γ -temp.
36	Min.	0.30	0.40	0.14	0.50	0.01	0.03	.003	.011	2.0	830
	Mean	0.38	0.62	0.25	1.15	0.03	0.17	.018	.021	5.7	933
	Max.	0.60	0.80	0.35	1.55	0.12	0.35	.038	.036	9.0	1050
	σ	0.06	0.12	0.05	0.26	0.03	0.09	.009	.007	2.4	100

For regression analysis results, see page 126.

TABLE 22.

$$^{J}90 = -0.25 + 4.11\,(C)\,(Mn) + 0.83\,(C^2) + 7.47\,Cr$$

$$^{J}80 = 0.51 + 4.7\,(C)\,(Mn) + 1.10\,(C^2)$$

These formulae describe, respectively 89.8% (at 5% significance level), 87.0 and 81.8% (both at 0.1% significance level) of variations in composition.

(c) <u>For carbon-manganese-molybdenum steels:</u>

$$^{J}95 = 10.2 + 41.9C + 15.6\,Mn + 9.9\,Si + 5.3\,Cr - 13.2\,Mo - 47.0\,(C)\,(Mn) + 35.2\,(C)\,(Mo) + 19.0\,(Mn)\,(Mo) - 0.03\,(\gamma\text{- temp.})$$

$$^{J}90 = 38.0 + 38.3C + 24.3\,Si - 32.4\,(C)\,(Mn) + 24.4\,(C)\,(Mo) + 6.0\,(Mn^2) - 0.06\,(\gamma\text{- temp.})$$

$$^{J}80 = -5.0 + 6.2\,C + 382\,P + 8.7\,(Mn)\,(Mo)$$

The molybdenum $^{J}95$ formula describes 98.2% compositional variation at 0.1% significance level. The other formulae describe 89.0% and 80.7% variation respectively at 5% significance level.

(d) <u>For carbon-manganese-chromium steels</u>

The sample of 36 commercial C.Mn.Cr steels did not appear to be as amenable to regression analysis as the former groups tested. J-data analysis yielded:

$$^{J}95 = 117.6 + 209.8C - 362.7\,Mn - 76.7\,Cr - 32.9\,Mo + 15.3\,Ni + 94.3\,S - 160.2\,P - 198.9\,(C)\,(Mn) - 66.3.\,(C)\,(Cr) + 180.8\,(Mn)\,(Cr) + 180.8\,(Mn^2)$$

This formula covered 73.2% compositional variation at the 5% significance level. Correlations for $^{J}90$ and $^{J}80$ were even poorer than this.

<u>Jominy Data Summation</u>

From the groups described in (b) to (d) above, 84 steels were selected for regression analysis of their Jominy data. Again, as in (d), correlations were poor (rarely better than 60% composition variation covered without the formulae degenerating into very complex form). However, the following $^{J}95$ analysis is considered worthy of presentation, representing a general solution covering the compositional range of commonly-used engineering steels

$$J_{95} = -1.3 + 3.67\,Cr + 44.9P + 5.57\,(C)\,(Mn) + 7.63\,(Mn)\,(Mo)$$

This formula (explaining 78.2% variation in the compositions covered, at 1% significance) is based on the simple variables generally used throughout the survey, together with the products C-Mn, C-Cr, C-Mo, Mn-Cr, Mn-Mo, and Cr-Mo

d. Analysis of Results

The analyses presented have been based on the principle that the mechanical properties at any given point in a heat-treated engineering component are dependent on micro-structure (57). Hardness is not a true criterion as it is carbon-dependent, but it can be converted to equivalent structure terms by applying it to Hodge & Orehoski curves (56). It is an observed qualitative fact that the influence of the elemental components of steel on hardenability is cumulative; whether this effect is best described by arithmetic or multiplicative formulae must depend on such qualitative information, although Bullens (61) finds no theoretical justification for the adoption of the multiplicative form. Gittus (137) has analysed formulae to describe the effect of alloy element increments on the "ideal critical diameter" and has concluded that either a multiplicative law, - as determined by Grossmann - or an arithmetic law is valid, according to the definition of ideal diameter used. If alloy element increments are considered in terms of their effect on the <u>prevailing</u> ideal diameter, a multiplicative law offers closest correlation (but errors tend to increase with increasing alloy content). The arithmetic law best covers the effects of alloy additions on the <u>initial</u> ideal diameter.

The use of logarithmic terms in the multiple regression enabled a multiplicative equation of the form

$$J = A\,(E_1)^{x} \cdot (E_2)^{y} \cdot (E_3)^{z} \quad \text{etc......}$$

to be developed (A is a constant, E_1, E_2, E_3 represent alloying elements with x, y, z "hardening factors"). Correlations were generally poorer than for the simpler additive formulae. However, correlation really expresses the degree of "fit" that a chosen set of variables gives and because of alloying element interactions (64) the dependence on established qualitative facts on the hardening influence of individual elements to effect a closer match, is not always of value. For example, in some of the analyses carried out for carbon-manganese-chromium steels, the J-value to given martensite content was found best expressed by factors of the residual nickel and phosphorus contents alone, at the 5% significance level.

General Formula Derived from Continuous Cooling Data.

The attempt to describe the critical cooling interval to yield a fully martensitic structure on quenching gave a relatively poor correlation. The data analysed gave specific cooling interval values for 100% and 50% martensite only; the former is of most practical use, but intermediate values (for say 90% and 80% martensite) would, it is conjectured, prove more amenable to analysis, tests showing some improvement in correlation for the 50% figures over those for 100% martensite. The sample of 35 steels was small for a general analysis of engineering compositions, too small to break down into narrower specification ranges.

The nature of continuous cooling diagram construction makes the cooling intervals derived specific to a small, particular specimen. This may be said to be true of any test condition, hence requiring the analysis of many sets of data to establish the pattern or property variation for a given commercially-used composition. It is unfortunate also that the test itself is tedious and expensive to perform and is never likely to be used as a "standard" quality test; hence the accumulation of data is slow. Although it is considered that the test offers detail in the most direct form which, suitably analysed, can contribute to the understanding and control of industrial heat treatment practices, it must be rejected at the present time in favour of Jominy data analysis, for which information yield is much greater.

Formulae Derived from Jominy and quench data

(a) Carbon-manganese steels.

It is clear that, of all "primary element" combinations considered, only the first group of carbon-manganese steels (U.S. Steel melts. (136)) approach the ideal two-component system. The critical Jominy distance (i.e. cooling "time") at which a given % martenite is developed, common to good engineering practice, is best described by a factor of the carbon and manganese product, neither element being significant on its own at the 5% significance level, in common with grain size and austenitising temperature. This simplicity is lost when "commercial" compositions are subjected to similar analysis; minor differences in residual chromium, molybdenum and nickel levels in particular, exert little direct influence on hardenability at the 5% significance level of regression analysis, but additional factors are necessary to describe conditions with similar accuracy. Thus, chromium residual contributes to the 90% martensite definition at 0.1% significance level but does not appear in the other equations. Phosphorus appears in the 95% martensite equation only; its hardenability potential has been referred to by other workers carrying out similar analyses (82) The apparent adverse effect of carbon in the same equation cannot be explained. Negative factors for carbon appeared in all other analyses on carbon-manganese data for a 95% martensite determination, the result given expressing the closest "fit" to the data analysed (i.e. 89.8% of variation with composition explained at 5% significance level). Otherwise a dependence on the carbon and manganese product, and the square of the carbon content persists in the three equations.

(b) Carbon-manganese-molybdenum steels

Only eighteen commercial compositions were found in the literature having complete sets of data matching Jominy end-quench curves. Molybdenum contents up to 2% were investigated (mean level 0.4%), together with manganese levels in the range 0.17 to 1.9%. Other "alloy" levels were kept within commercial residual levels as far as possible.

The % variation in composition explained by the regression analyses presented in Table 20 is high, but the simplicity of the carbon-manganese equations has been lost. It is difficult to read the significance of any given component from these equations, although the importance of element interactions is again seen; simple linear equations omitting these terms explained only 60% data variation.

(c) Other analyses

Other cooling condition correlations were poor and the tendency was for high correlation to be achieved only at the expense of complex formulae. Elemental interaction introduces considerable "guesswork" into the initial selection of variables for regression analysis; increasing the number of variables reduces the degrees of freedom available, which can severely limit the general applicability of high correlation formulae derived from small data samples. The general formula for the 95% martensite Jominy distance i.e. critical cooling interval λ_{95} is presented as a basis for experimental testing and operational verification. It is felt that its 78.2% correlation may well be capable of improvement by introducing further variables for regression analysis, at the expense of increasing its complexity.

The design of steels

A prime aim of this data analysis has been to establish formulae offering guidance to steel compositions yielding guaranteed properties.

The complex equations which have evolved are not entirely suitable for use in this manner. It is stressed that they can be used only within the compositional boundaries of the steels whose data was analysed and form a possible basis for experimental procedures. For costing economies, hardenability is preferably derived from manganese, which the formulae for carbon-manganese steels can demonstrate. However, without extensive practical verification and further regression analyses of larger data samples, progress in steel composition evolution cannot be envisaged by this method. The recent pronouncements by Aaronson (128) on the design of ideal engineering steel compositions may well explain the disappointing results of this present work.

e. Conclusions

Regression analysis has been applied to: Jominy end-quench data
and: continuous cooling data
taken from comprehensive steel compositional specifications in the literature. Equations have been derived which attempt to quantify the critical cooling interval on quenching from the austenitic state, for attaining a given percentage martensite at a point in a component.

It is stressed that the correlations derived do not necessarily imply that the factors of the equations are correct for alloy combinations other than those analysed. The work carried out is intended merely to indicate how knowledge of the critical cooling rate can be determined and thence used as a quality control device, in conjunction with ancillary studies of quenching as described earlier. It is known that such analyses are already used for quality control in heat-treatment in engineering manufacture (37). They can enable closer matching of hardenability potential of a given steel and hardening potential of a given quench system - and thus promote improved utilisation of both raw materials and plant.

The equations presented indicate that in only the simplest steels, based on carbon and manganese with low, generally non-commercial residual levels, is a simple solution derived. These apart, in all steels primary component interactions and trace elements contribute towards the expression of cooling rate. This makes it difficult for the equations to be used as a basis for the design of commercial quality steels with guaranteed heat-treatment response as was earlier hoped possible; in any case the formulae should be applied only to compositions within the limits of the regression analyses. Extrapolation can thus offer only tentative guidance to the effects of, for example, continuing to increase manganese content above present commercial levels, in order to promote hardening otherwise given by more expensive alloying elements.

The analysis of existing data to establish heat-treatment practice quantitatively and to create test-compositions designed to yield guaranteed properties could well form the basis of a complete programme of research in itself. Planned use of computerised data analysis programmes is considered an essential requisite of any such investigation.

4. CONCLUSIONS.

CONCLUSIONS

1. Field studies conducted in several sectors of engineering industry, where intensive use of mass-production methods is made, have indicated widely differing attitudes towards steel selection in design and processing. Raw material costs comprise between 40 and 70% of total cost in mass-production manufacture but, for the following reasons, this rarely seems to motivate costing economies by way of the engineering steel selection decision:

(a) "Traditionalism", extending through all sections of engineering design and processing, metallurgical services and purchasing and stock-holding departments, whereby safe, well-proven - but often over-specified - materials and methods are perpetuated from one design to another without meaningful assessment of true component requirements and the most economic means of satisfying them.

(b) Difficulty of inter-disciplinary communication, particularly between design engineers and materials staff. Much of this is due to the general low standing of metallurgical departments throughout manufacturing industry where they are primarily regarded as quality control laboratories. Here, the status of the chief metallurgist or materials engineer within the management structure largely determines the effectiveness with which he can influence the designer's selection decision. The calibre of metallurgical staff in general and their limited awareness of true design requirements in particular, can serve only to perpetuate the quality control image.

2. For engineering industry as a whole, no analysis of steel utilisation by grade and section size is undertaken by any authority. Data collection in the widest sense is sparse and fragmentary with the result that quantitative guide-lines to steel utilisation patterns do not exist. This situation, on a national scale, prevails at company level; steel purchase and utilisation records exist, but these are rarely analysed with a view to effecting costing economies whether by grade substitution or other means e.g. order size, tolerance extras, compositional limitations etc.

3. The significance of heat-treatment response in engineering steels, rather than exact compositional requirements, has been recognised by some sectors of the steel industry. As a result, a range of carburising and through-hardening steels has emerged, marketing at prices well below those "standard" steels conventionally, - or traditionally - used in general engineering manufacture. Their slow market growth is a further reflection of the factors discussed in 1. and 2. above, together with the stigma of being proprietary steels, peculiar to single sources of manufacture and, as yet, outside national specification listings.

4. It is suggested that the root cause of both 1(a) and 1(b) above is the continued dependence upon steel standards which fail to reflect the needs of the design engineer, in terms that realistically represent engineering performance. Engineering steel standards are based on quantities which cannot, in themselves, define true engineering behaviour and cannot be related precisely to industrial processing. Thus, a tensile strength criterion is used by the engineer to cover both static and dynamic loading considerations. This quantity (UTS) is calibrated by means of tests which are largely irrelevant to any practical design loading situation. However, the universal incorporation of UTS into empirical design formulae to satisfy all

possible practical loading conditions has precluded the adoption of another more realistic criterion to any extent, - were its complete displacement indeed at all possible. It is suggested therefore, that any steel specification revision must ensure that UTS-values attributable to a given steel reflect the potential of that steel which advances in heat-treatment and manufacturing technology can fully realise. A means has been proposed whereby this may be determined and continuously revised to suit any users' need. The standard cooling conditions associated with the Jominy hardenability bar are employed to monitor both heat-treatment performance of a steel and the quenching characteristics of industrial quench systems. Generalised information relevant to a given grade of steel could be presented on a hardenability band, similar in derivation to SAE-H steel Jominy date representation, but the shortage of consistent published information of value in compiling such bands for En-steels prevents a complete presentation and analysis of the method at this stage. Its successful adoption would necessarily require steelmaker and steel-user agreement on the compilation of hardenability bands, while their meaningful usage in presenting design information, - relevant to a given design team - would require the steel processor to determine the true quench characteristics of his heat-treatment plant and its subsequent monitoring and maintenance, as outlined in 5 below. Examples presented have considered the quenching of direct-hardening steels; the approach to case-hardening steel specifications should follow similar lines, with further refining of the method for tempering treatments, such J-curve "modifications" already occurring in the literature.

Manufacture of precision engineered components under mass-production conditions has enforced the adoption of high volume throughput heat-treatment equipment often fully automated with close instrumented control of furnace atmosphere, temperature gradient, timing schedules etc. Quenching procedures to achieve optimum properties in the heat-treated condition are still largely empirical in formulation and control. The manufacturer is confronted with an array of quenchants of widely differing compositions and physical properties. Technical data significant to quenchant performance under operational conditions is negligible; quenchant manufacturers do not have operational facilities for such testing, while furnace manufacturers do not concern themselves with the specification of quench system characteristics. As a result, the optimising of heat-treatment systems is rarely considered, although simple means of doing this, - or at least of maintaining quenching efficiency at a given level - are available.

The design of steels, with material cost as an important parameter, has attained fruition as in (3) above by the consideration and application of basic principles of ferrous metallurgy. The present work has included an analysis of steel hardenability and continuous cooling data to give guide lines either to heat-treatment response in steels of known composition and physical constants or to the basic chemistry requirements to ensure a given heat-treatment response. The disappointingly inclusive and often complex equations resulting from these analyses cannot be subscribed to the incoherency of the data sets analysed - although this cannot be neglected entirely - but must also be seen due to the alloy element "interactions" recorded by numerous other workers in this field.

7. Economic aspects of this investigation have suffered not only from the general lack of quantitative detail on steel supplies to engineering industry, but predominantly from the denial of access to costing detail of any form. While this is understandable from the user's point of view, in the interests of commercial secrecy, it is to be regretted that such information is not available to a non-aligned observer attempting a critical assessment of importance to engineering industry as a whole. However, it is hoped that the level of cooperation achieved from industry for such a venture as this, in a field as yet unusual to university - based research can be built upon in the future. The present work has only been able to touch upon the subject of techno-economic utilisation of engineering steels, but it has served to show the paucity of quantitative documentation in this field. It is regretted that it was not possible to carry the conclusions reached, however limited and generalised their nature, back into the industrial environment for their implementation and assessment under commercially-viable operating conditions.

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