STAINLESS CLAD STEELS

- an Evaluation -

by

A. Daglish

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SUMMARY

This work examines and evaluates stainless clad sheet steel.

The history of clad materials is examined to put a following section on marketing in perspective. A section on marketing sees clad steels in competition with conventional stainless steel and coated mild steels. Following this a specification for clad steel is evolved.

Present technology of clad materials is examined and the various ways of making stainless clad steels are discussed. From these a favourable route is selected and evaluated from a technical and economic point of view. The inadequacies of the route are set out to account for the lack of such materials on the market. Following this a specification for a clad steel production route is derived.

Using the specification a new route is devised and a description of a laboratory pilot plant given. Results obtained from the pilot plant are given together with a description of the economics of production, these being compared with the conventional route. Back up work on bonding and compaction is also described.

The route being established as viable, production is anticipated with its attendant problems. Properties are evaluated in advance of production using conventionally produced materials. Both manufacturing and user properties are studied.

Based on an examination of the properties and the economics the future prospects for stainless clad steel sheet materials are discussed and some indication of the 'politics' involved is given.

Extensive appendices describe the procedures used for material evaluation, the economic model used for costing, a theoretical derivation of the 'R' value and the experimental materials used together with analyses of all materials.

Linda Daglish Ian Dil
lamore Don Green Ron
Dewsnap Pete Mella M
argaret Akers BSC-CDL

Thank you

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PREAMBLE

"Mild steel sheet, clad on one side with austenitic corrosion resisting steel is already being deep drawn into cooking utensils and it is likely that many other, and not necessarily domestic applications will be found in which the use of clad sheet will reduce the cost of a deep drawn or pressed article............"

This was written in 1941 by Jevons(1). In 1973 the usage of clad steel in sheet form was about 150 tonnes per year of which nearly all, as far as can be ascertained, is used in the manufacture of domestic holloware(2). The corresponding sales of stainless steel sheet and strip in the UK for the same period was about 70 000* tonnes of which some 28 000 tonnes was produced by the BSC and 15 000 tonnes imported. Mild steel usage runs at about 70 M tonnes per year.

The difference in mild steel and stainless steel usage is very easily accounted for, stainless steel costs between 5x and 10x more than mild steel. It is readily accepted that stainless steels are a highly superior product but with the present cost differentials it is just not economic to use it in place of conventional mild steels. The worlds steelmakers are aware of this and are devoting a lot of effort to developing cheap acceptable substitutes in the form of low nickel ferritic steels and surface coated steels. Powder routes to stainless steel are being developed and these are claimed to have probable economies in the direct production of strip.

The possibilities of using clad materials have been put forward many times in various guises but for one reason or another the use of these materials, especially in the steel using industries, does not seem to be widespread. Clad plates are used to the extent of 1000 tonnes per year but the amount of clad sheet produced is very small.

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* All figures quoted are derived from BSC statistics.

There would seem to be no technical objection to the production of stainless clad sheet steels either single or double clad, and there are in existence several methods of successfully manufacturing this type of product. Most of the methods have been used over the years for the manufacture of clad plates or special coated products. Considerable expertise has been built up in this field.

The reasons why stainless clad sheet is not produced in anything except negligible quantities must be concerned with the more commercial aspects, economics or marketing, of clad steel production. This is assuming that the possibility of bulk clad steel sheet production has been seriously considered.

An obvious objection is that, given that it is technically feasible to produce clad sheet, it may not be possible to produce it at an economic cost level. Factors such as production rate, missmatch between production capability and market and level of investment enter into this. For instance the production rate of a process may be too low to satisfy the potential market unless a large investment in plant is made, which would increase the unit cost hence slowing the rate of market increase. In fact the cost of clad plates below a thickness of about 6mm total is more than equal to the cost of stainless steel. This is probably due to the fact that there is a limited market for this product size which is over fulfilled by a single batch of roll bonded material.

There are other possible reasons for the lack of production of clad steels. There may not be a good market for the product due to lack of development or there may be consumer resistance to a substitute stainless steel. This resistance could be due to the laminate having certain features which make it unacceptable to the consumer at the price at which it is offered, examples could be the existence of corrodible mild steel at the sheet edges or at cut holes, or, in certain applications, the possibility of penetration of the cladding. If the product was introduced at a price approaching that at which it would be competitive with conventionally coated mild steels then the material would be competing with well established products. The marketing of such clad products, given a suitable price level, must attack the high quality end of the coated steel market by emphasising the very real advantages of a stainless steel surface.

Another possible reason for non availability of clad steels in quantities of interest to the manufacturing industries could be the large existing investment in conventional stainless steels. The market for stainless steels is growing steadily and any of the existing stainless steel manufacturers, who are also the most likely manufacturers of clad steels, would probably be reluctant to introduce a new product in direct competition with existing product lines. The possible inducement to do so is the liklihood of taking a substantial share of the coated steel market thus increasing the overall production of stainless steel without too much encroachment on the highly profitable existing solid stainless steel market. In this case considerable thought would have to be given to the product mix that a particular producer would carry.

Potentially the properties of stainless clad steels make them highly marketable, especially in the light of the possibility of attaining a wide lattitude in specification by altering the make-up of the laminate. The surface corrosion resistance is essentially the same as solid stainless steel of equivalent grade except at edges. Certain physical properties (i.e. thermal conductivity) give the material some positive advantages over solid stainless steels. It is probable that a demand for a material of this type could be stimulated by the production of more information relevant to the potential users of such materials rather than generalisations derived from work on plate materials.

It is apparent that a proposed investment in a process for making stainless clad steel sheet would need a close appraisal of the relevant technical and commercial aspects of that process. Without detailed information on these topics it is not possible to put forward a case for the increased production of clad steels.

It is the purpose of this thesis to present and analyse this information and on the basis of this indicate a strategy for the increased production and wider introduction of stainless clad steels into the sheet steel market.

HISTORY

The earliest known uses of cladding metals with metals seem all to have been associated with some form of fraud. There are several ancient Egyptian relics which have been found to have a thin layer of gold clad onto a silver base or in some isolated cases a copper base. Further examples of the use of metal cladding exist in the form of counterfeit coins spanning the whole of Roman history, these were mainly gold or silver clad onto copper and probably made by hammer welding. This tradition has been followed in modern times by the USA who have introduced a range of clad coinage into regular circulation.

The Egyptian cladding habit was re-introduced in last century by Bolsover with his invention of a method for the production of silver clad onto copper. This is the well known Sheffield plate, good examples of which are more highly valued than similar solid silver articles.

Clad steels have been in use since the middle ages when German armourers were producing body plate with superior dent resistance by welding a layer of steel onto a backing of soft wrought iron. Similarly Damascene knives and the famed Samuri swords show a good appreciation of the advantages to be gained from laminate materials. Recent Viking finds in N. Ireland have yielded several iron clad steel axes, a technique still used today for blade steels.

Laminating techniques were used to advantage in the production of armour plate by roll bonding many layers of steel together at the Sheffield Works of John Brown in the 1860's.

The invention of stainless steel was closely followed by the patenting of several methods of putting this, even then high priced material, onto a cheap carbon steel backing material as a material economy. These early methods were mainly casting based with roll bonding methods gaining favour as casting was shown to have difficulty in producing a satisfactory product.

Full production of clad steels using mainly stainless steel was started in the USA in 1938, using roll bonding to produce mainly single clad plates for the chemical industry. The bulk of production was centered on a composite of 20% 18-8 stainless steel clad onto a boiler quality carbon steel backing. Production on a similar basis was undertaken in the UK by Guest, Keen and Baldwins in about 1946, followed in 1947 by Colvilles (now BSC-GSD) who are now the sole UK manufacturer of stainless clad plates, marketed under the name of COLCLAD. This material is produced mainly as boiler quality plate clad on one side and sometimes two with a variety of heat and corrosion resisting materials.

There are about seven companies in the world producing clad plates. Only one company seems to be producing clad steel in sheet form* (Allegheny Longdohs, a Belgian company associated with Allegheny Ludlum). This company seems to be wanting to discontinue this line as they are known to be asking a price approaching that of solid stainless steel, with the prospect of price equality in the future. This, combined with a lack of agressive selling must combine to remove the material from the UK market.

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* It has recently been announced that Ductile Metals of Birmingham are producing stainless steel clad sheet up to 300mm wide clad on one side only.

THE MARKETING OF CLAD STEELS

Over the years austenitic 18-8 stainless steel has acquired a certain prestige value, so much so that the metal is known in GB and the USA as simply 'stainless' and in France it is abbreviated even further to 'inox'. This means that it is difficult to estimate the impact that introduction of a cheap clad steel would have on the current sheet and strip market. There are two levels at which the market could be penetrated, depending on the price at which the product could be marketed. These options are as a corrosion protected mild steel, in competition with existing methods of providing corrosion protection, or, at a higher price level, as a substitute for solid stainless steels.

The possibility of clad steel filling a middle region between the two exists but it is not considered here due to the difficulties of determining exactly where the material could be slotted in.

At this stage no assumptions are made about the cost of the material but marketing strategies will be examined on the basis of either a price bracket near to that of coated mild steels or one nearer to that of conventional stainless steel.

i) Clad Steel in the Mild Steel Market

It is generally accepted that corrosion costs money. It is equally true that corrosion protection also costs money, so any form of protection from the environment must be subjected to some form of critical assessment to decide if it is worthwhile applying it.

The two main forms of coating currently applied to mild steels are based either on organic or inorganic substances. Paints and plastics being examples of the former, tinning and galvanising are traditional examples of the latter. The current usage of coated steels in the UK is about 1.8 M tonnes per year divided as follows:

Galvanised	582 000 tonnes
Tinned	1 100 000 tonnes
Aluminised	1 070 tonnes
Organic	67 900 tonnes
TFS (Cr_2O_3)	13 100 tonnes

It can be assumed that stainless clad steels would not enter into the market for tinned steels because as the position becomes even more drastic than at present it is expected that chromium oxide coatings will steadily replace this type of coating in the canning industry.

It is also a reasonable assumption that the organic coatings (mainly based on PVC) would hold their present share of the market due to their inherent decorative effect, and while it is difficult to compile statistics on the uses of plastic coated materials it is generally felt that this is their major advantage. While coloured stainless steel surfaces are available(3) together with a range of surface textures, these would not be able to directly substitute in the majority of applications for plastic textured and coloured sheet.

This then leaves the galvanised and aluminised coatings, chromised steels are available but their usage in the UK is still very small indeed so can be ignored as a competitor. Chromised steels in the USA are increasing rapidly in tonnage but there is some evidence that the material has inferior surface finish and so would not be competitive for general use. Galvanising adds between £8 and £40 to the cost of mild steel sheet, depending on the thickness and method of application. Given that stainless steel has better corrosion resistance than galvanised sheet, it would still

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* All figures are for 1972 usage.

have to have a selling price of around £150 per tonne to compete in the existing market for such zinc coated steels. This cost is a difficult one to meet for conventional cladding routes. This means that a stainless clad material would have to demonstrate a superior corrosion resistance in places where galvanising is just adequate while retaining adequate formability. It is interesting to note the slowly growing usage of galvanised materials in the motor industry. It is probable that manufacturers of high prestige cars such as VOLVO, who already use a lot of zinc coated materials, could be persuaded to incorporate clad steels instead, especially in high stress, high risk areas of car bodies. This would not increase the cost appreciably but add considerably to the safety of road vehicles. This, of course, could be precipitated by legislation in this field. Car silencers are another field that could be opened up to clad steels by anti-pollution legislation (1976 in Japan).

ii) The Stainless Steel Market

In principle stainless clad steels could be substituted into most applications of stainless steel sheet, especially where there is a large surface area to edge ratio. Where there is a large amount of exposed edge it would probably be more economic to use solid stainless rather than trying to protect the edges. There are many applications however where this problem would be of only minor importance. The problem of exposed edges is discussed later.

There are many individual products that could be cited as examples of the advantageous substitution of clad steels but only the high volume production examples will be discussed here. Perhaps the most obvious and best example of a beneficial substitution is in the manufacture of sink units. These alone accounted for about 9.6% of the total UK market for sheet and strip form stainless steels*. It is probable that there would be cost savings over solid stainless even if the clad were more costly as the superior

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* Figures quoted are for a 1970 UK usage of 70 500 tonnes. Source BSC statistics.

drawability of the mild steel core might be utilised to enable the bowl to be drawn in one operation rather than the present practice of welding on the bowl at a late stage.

The catering industry is another relatively high volume market for stainless steel sheet materials, absorbing about 7.5% of the total usage. Most applications in this industry would benefit from the higher thermal conductivity of mild steel-stainless steel combinations. In, for instance, the manufacture of domestic saucepans, the improved conductivity of the mild steel core is used as a selling point ('RADIANT CORE').

Probably the biggest growth area would be in the field of trans-ocean containers. These accounted for only about 1.4% of the market in 1970 and this figure includes the usage in bulk liquid road tankers. The advantages of stainless steels are generally recognised for these applications but their use is, as always, restricted by the high cost. The need for large areas of stainless steel in containers would make the problem of protecting the edges of clad sheets a minor one compared with the potential cost savings involved. Similar applications would be found in cladding for road vehicles(4). Stainless steel street furniture is being used more and more(5), and even at the higher price competes very well with the traditional painted mild steel. This is mainly on the grounds of low maintenance costs. It is fairly certain that the introduction of a reasonably priced clad steel would enable a heavy impact to be made on the mild steel sales in this growth region.

The building industry is not traditionally a user of stainless steels (2.3%) but this usage is increasing especially in the use as cladding panels and architectural furniture (covings, rails etc.). Most of the potential applications for clad steels in this field involve large surface to edge ratios and hence the problem of corrosion at these edges is minimised. These decorative applications are ideal outlets for clad steels as the requirements are mainly for maintenance-free 'surfacing' only.

Potentially the largest market would be the motor industry. It is un-realistic to hope for the introduction of stainless steel motor bodies for the domestic vehicle at any level of cost reduction. There is, however, a substantial outlet for clad steels in this industry in the form of silencer components. The oxidation resistance of the stainless steel surface coupled with the superior thermal conductivity of mild steel cored clad steels would make them desirable even at a cost approaching that of solid stainless. There are more and more stainless steel silencers sold each year and it is highly likely that even more will be sold when, as is probable, car silencers will have to be run hotter to protect the environment. The Japanese stainless steel manufacturers are increasing output capability now in anticipation of the legislation which will lead to higher exhaust temperatures in silencer components. With new car sales running at about 1 M per year this alone would provide a substantial outlet for clad steels.

The one factor about clad steels which raises recurring doubts in potential consumers about the direct substitution of clad for solid is the problem of cut edges. These edges would be raw mild steel and would thus corrode when exposed to the atmosphere. For many applications there are relatively simple methods of dealing with this problem and some of these will be discussed later when the subject is looked at in more detail.

iii) Some Applications

A list of some applications where clad steel could be advantageously substituted for solid material is given below.

Architectural cladding
Washing machine bowls
Sink Units
Domestic holloware
Refrigerator interiors
Office equipment
Car silencers
High risk car body components
Car trim
Door furniture
Street appliances
Cookers
Domestic radiators
Trans-ocean containers
Canteen fittings
Decorative tiles
Domestic boilers
Furniture

iv) The Future Market

The growth rate for stainless steel usage is expected to be about 16% per annum(6). From the foregoing arguments it can be assumed that the introduction of a lower priced substitute would alter this on a gradually increasing scale as the material gained acceptance. The overall effect on the sales of solid stainless steel sheet should be to lower the growth rate progressively as the sales of clad material increase. As however, clad materials should make inroads on the sales of coated and surface treated mild steels it is highly probable that the amount of stainless steel used would increase even though clad materials would contain only about 20% stainless steel.

A lot of the arguments presented on the marketing of clad steels assume that the price of stainless steel will continue to rise at its present rate. This, of course, is not necessarily a valid assumption as there is vigourous development work going on on the development of powder routes to stainless steel sheet(7) which are expected to bring the cost of production down considerably. This does not invalidate the interest in clad materials as, in a later section, it will be argued that this can in fact lead to a reduction in the production costs for clad steels.

Much development work is in progress in ferritic stainless steels for general use but to date these still have poor formability. If the formability problems are overcome then it will still be possible to make a ferritic clad steel which would have a decidedly advantageous cost benefit. Until, however, the production problems (roping) can be overcome this material is not able to compete with stainless steel for 'user appeal' and can, in most contexts discussed here, be ignored.

SPECIFICATION OF THE PRODUCT

It is reasonable at this stage to specify the product. It must primarily perform at least as well as solid stainless steel in the situations in which it is commonly used. As this work is devoted mainly to sheet products, the properties of a clad product that must be similar are the forming, welding and corrosion resistance. These and other aspects are covered more fully in the section devoted to customer aspects of clad steels.

The internal specification of a clad steel must centre on the usual quality control criteria of stainless steel sheets. The surface finish must be at least as good as that of solid materials, the cladding method must have no effect on this. There must be a good bond between the base and cladding materials, this bond being continuous and at least as strong as the weakest material in the combination. The material must have similar handling characteristics to the solid material and no special precautions should be needed in heat treatment or storage. The further requirement of similar properties from different product size ranges means that the material should have no dependence on fabrication size for its specific properties. The material should be available in a wide range of widths and gauges.

Summarising:

Good continuous bond
High quality surface
Good mechanical properties
Good formability
Easy handling
Wide size range

In all respects the customer should accept the material as being a straight substitute for solid stainless steel except in special high duty applications where erosive or exceptionally corrosive conditions occur or where there are extensive exposed edges which need to be corrosion resistant.

PRESENT TECHNOLOGY

ROUTES TO CLAD STEEL

Many methods have been proposed for the manufacture of clad materials, most of these being variants on a few basic methods. Some of the most viable of these basic methods will be examined below.

For convenience, clad materials will be defined as those which have a substantial thickness of a second material permanently bonded to a substrate. Only cladding techniques which are capable of adding a minimum of about 5% of the thickness to a substrate will be considered. This eliminates processes such as galvanising and electro-plating. For convenience again materials protected by such thin coating processes will be referred to as coated materials.

Casting

There are obvious economic attractions in producing a clad ingot where both the cladding and backing materials are in their cheapest form i.e. in the ladle or just after. Casting processes are used fairly widely in the USSR and other East European countries but not apparently elsewhere. There are difficulties in getting a reliable bond that will withstand subsequent mechanical processing that have led to the conclusion that, for the USA at least, it is not economic to produce clad materials by this route(8). It is claimed that apart from the cost disadvantage the poorer product quality legislates against such methods.

The most successful method in use today is illustrated in fig. 1 where it can be seen that the relatively poor bond quality is overcome by casting so as to totally enclose the inserted stainless steel slab. This is to enable a progressively better bond to be made during the hot rolling process. Enclosing the slab excludes air which would otherwise prevent the roll bonding of areas not bonded on casting. After the hot rolling operation the surplus enclosing mild steel is removed prior to further processing to size.

A fairly recent innovation is cladding by electro slag melting. Here stainless steel is melted through a slag layer and held in contact with the base steel. This is a variant of electroslag welding and differs only in scale from the general principles of weld cladding.

Roll Bonding

This process seems to be the most widely used for the production of clad plates. It is fairly versatile due to the fact that by observing necessary precautions most materials can be roll bonded to plain carbon steels. The most common product is 18-8 stainless steel bonded to boiler quality plate. The surface preparation necessary to achieve a satisfactory bond is a large part of the expense of roll bonding. The prepared surfaces must be protected from the atmosphere when bonding is being carried out. The surface preparation usually takes the form of weld facing or electroplating. This is to replace the tenacious chromium oxide film on the stainless steel with a more friable one. A recent innovation is to explosively bond a layer of plain carbon steel to a stainless steel slab, the bonding of plain carbon steel to plain carbon steel presenting very little difficulty. The majority of material produced by roll bonding is clad on one side only and single clad plates need to be further bonded back to back to get double clad materials. The method of roll bonding is illustrated in fig. 2. There seems to be no production route which produces double clad plates directly, probably due to the convenient geometry of the two single clad plates when welded into a pack.

The bonded plates can be given any degree of reduction but the economics of the process seem to dictate a lower limit of about 6mm at which thickness the composite becomes as dear as solid stainless steel(9).

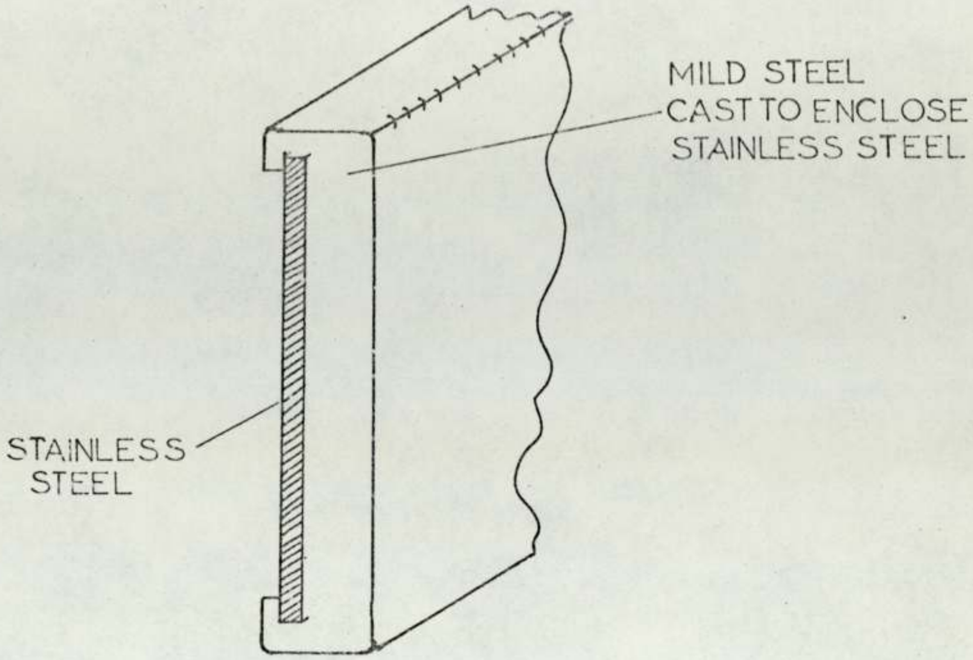


FIG.1 CAST CLADDING

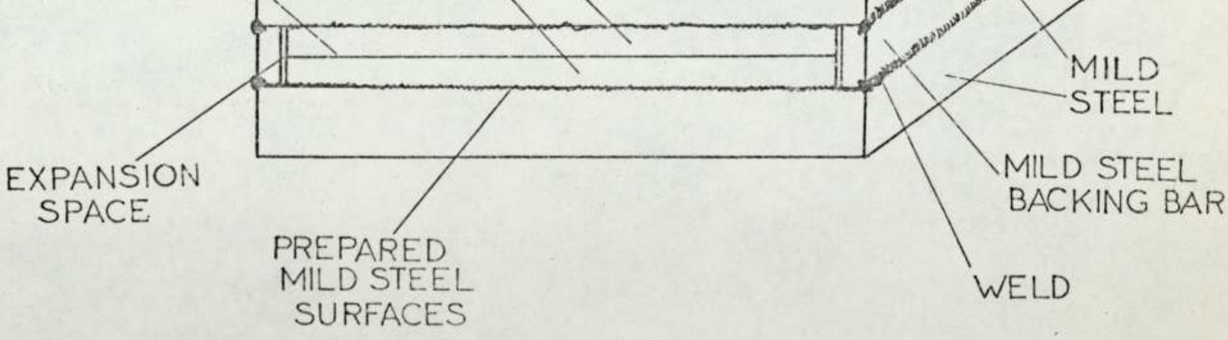


FIG.2 ROLL BONDING

Spray Cladding

Metal spraying techniques are well established in industry for providing local coatings of various materials. Thicknesses usually applied are in the .05 mm range and to get thicker coatings a lot of special precautions have to be taken. This is especially true with readily oxidisable materials such as stainless steel. It would seem that there is not much hope of putting a thick layer onto a billet and certainly nothing even approaching the 20% considered desirable for sheet applications. This is accepted and some work has been done on the direct spraying of sheet(10). At present this is still in the experimental stage but it would appear that the process is technically feasible but at a potentially low production rate of about .25 - .5 m/sec. Cladding is an accidental by-product of research into the production of strip by spraying, too much grit blasting "causing such a strong mechanical bond to form between the substrate and the deposit that separation by peeling is impossible", and though the above rates might be slow for bulk production they might be more economic for the production of a special clad steel.

Figure 3 shows the experimental plant used for this work.

Adhesive Bonding

Adhesive bonding is well developed for certain applications, mainly on finished shapes(11). In recent years adhesives have been developed that will tolerate some forming after bonding. The adhesives used are based mainly on polyurethane and laminates of steels using these can be embossed and even shallow drawn without bond failure(12). Fairly good drawing properties have been reported for iron-copper laminates bonded using synthetic resin adhesives(13).

The technique has the advantage that many combinations of materials can be joined with equal ease. Also the properties of the base materials are not altered by the joining operation. Disadvantages of the system are the temperature limitations of the adhesives currently available and the relatively long process times that are associated with these materials. Another disadvantage is the necessity to start with materials that are already to gauge with a high unit cost. So far no successful attempts have been made on rolling adhesively clad materials.

Also in this category of cladding operation could be included soldering and brazing. No work of consequence seems to have been done on these systems but it can be surmised that even if rolling of materials thus joined was possible then the difficulties of preparing billets to get reliable joining would legislate against the technique. The other alternative of joining sheet gauge materials would probably be too slow for production purposes.

Explosive Cladding

The technique of explosive cladding is in widespread use throughout the world. The cladding layer is simply placed at some small distance from the backing layer and propelled towards it at high speed by means of an explosive charge laid on the cladding layer. Nearly any combination of metals can be joined with very few exceptions, these being very brittle materials. Bonding is extremely good, the bond being frequently as strong as either of the parent metals(17). It is a batch process and there are definite limits to the size of material that can be processed, this usually depending on the site.

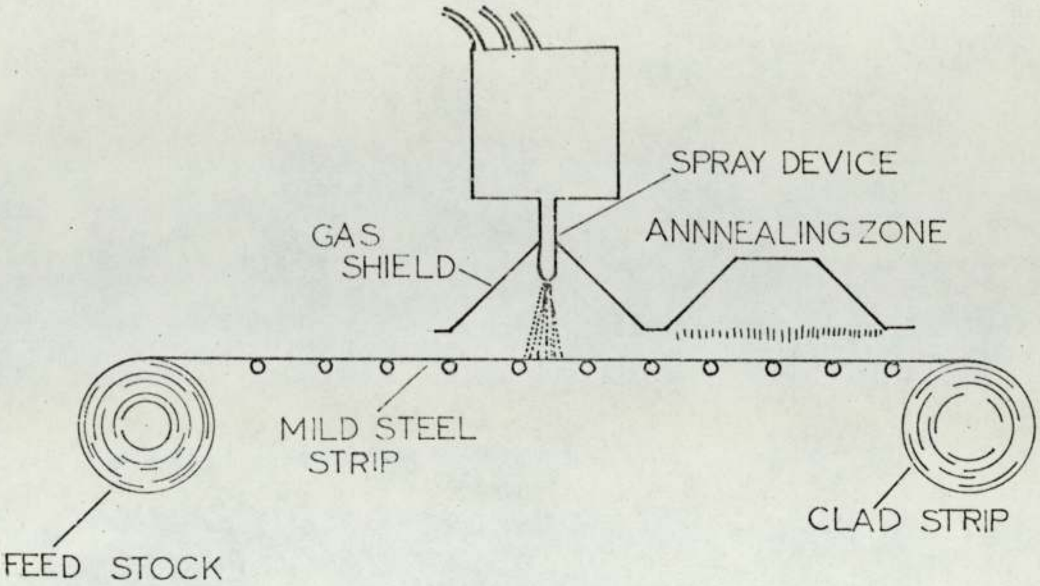


FIG. 3 HYPOTHETICAL SPRAY CLADDING - UNIT

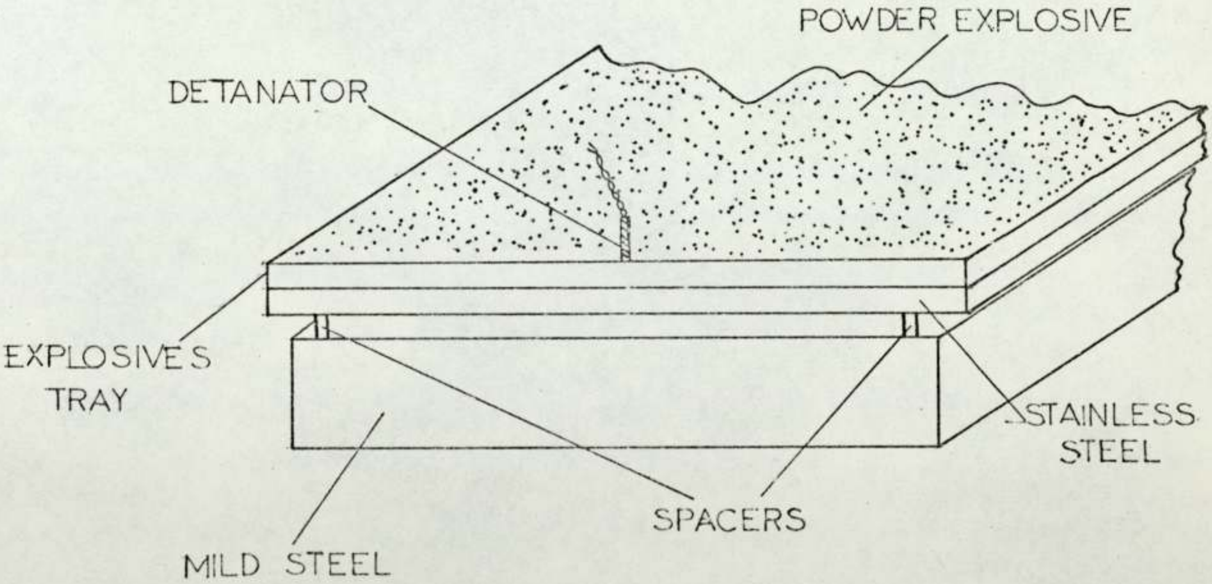


FIG.4 EXPLOSIVE CLADDING

There have been several attempts to perform explosive cladding on enclosed or protected sites (in pressure vessels in the USSR and in tunnels in the USA) but in general it is usual to carry out operations on a remote site. This must add to the cost of the operation. Explosively clad stainless/mild steel combinations can be successfully rolled down to sheet without bond failure. It may be noted that this process is now used in surface preparation for the COLCLAD route in preference to weld facing (see fig. 2). The process is illustrated in figure 4.

Weld Facing

This process is well established in industry, being in general use since about 1965 as a means of cladding. It has a major advantage that it can be applied almost anywhere, i.e. on site, and that it can be applied to irregular surfaces. The welding operation is usally carried out on finished size plates (or structures) and a wide variety of base materials. As with most welded structures, rolling is not usually applied to reduce the thickness as this would appear to lead to unsatisfactory surfaces. The electro-slag deposition process is better from this aspect and also appears to be a favoured method of producing clad plates in the Eastern European countries. There seems to be no sharp division between the electro-slag casting and weld deposition processes so most remarks made about the casting processes using this technique apply here.

Powder Cladding

The interest in powder rolling has led naturally to an interest in cladding by similar techniques. There are several methods which have been suggested but they all require the simple laying down of a layer of stainless steel powder onto a moving plain carbon steel band. This would seem to be a very desirable method of getting a directly produced clad sheet. The major obstacle is getting a thin layer of powder deposited onto the substrate in a form which will permit bonding during the sintering operation. There are Japanese and American patents which overcome this problem but as yet there is no production of clad materials by this method though some chromising routes are based on this method.

SELECTION OF A ROUTE

In principle most of the routes discussed could be used for the production of sheet gauge materials. Some, such as spray cladding and adhesive bonding are especially suited for this class of material. Others such as weld cladding are more suited to the manufacture of larger scale products such as plate. In selecting a route from those available it is necessary to consider both the technical feasibility and the economics of the processes.

From the technical point of view the technique of spray cladding is attractive in that it is a processing operation that can be carried out on a sheet gauge material on a continuous basis. This is obviously advantageous where a large amount of material is to be produced with similar specification. The same arguments apply to the possibility of powder cladding processes. The latter having potentially superior control over powder flow thus giving material economy. At the present state of the art however, both these methods have low production rates and while this might give a reasonable production volume before the material has gained full acceptance it would probably be inadequate if there is a rising demand. This would mean that the production rate could only be increased at the expense of installing more plant. This coupled with the present high price of powder makes both of these processes unattractive at the present state of technology.

Processes which utilise sheet gauge materials tend to have a cost disadvantage in that this is the most expensive state of a material. This doubly rules out adhesive bonding as a production method, even if high production rates could be achieved. Sheet gauge materials, especially the drawing quality mild steels, are usually processed to give certain optimum properties. Any process which modifies these would be disadvantageous. This means that the heat treatment that is usually necessary to obtain optimum bonding and consolidation of the added layer would, in all probability, reduce the quality of the sheet. This effect is noted in analogous processes such as chromising.

Based on the foregoing arguments it can be reasoned that none of the processes so far mentioned would provide a satisfactory bulk production process.

The alternatives to continuous sheet gauge cladding are bulk production processes based on some form of clad billet production. These alternatives are roll bonding casting or explosive cladding. Weld cladding can be excluded due to the difficulty of rolling weld clad materials. Explosive cladding used exclusively as a cladding technique suffers from the fault of being a batch process that can only be applied to relatively small billets, and the nature of the process is such that these must be transported from a remote site to the mechanical working location for further processing. This puts up the overheads to a high level and thus cost can be seen to be a large obstacle to the adoption of this process as a sole means of bonding.

Production of a clad billet at the earliest stage implies that one of the components at least is cast. It has been noted that cast clad ingots give an inferior product to that produced by roll bonding and the scrap rate is high(8), certainly on a large scale. On a smaller scale the process is more reliable but is probably not economic. It is usual in most of the casting on processes and certainly in the successful ones, to cast mild steel onto a stainless steel slab which is of course the most expensive component and thus radical cost advantages are not to be gained from the casting routes.

Roll bonding has the potential for making large economic clad billets but the traditional methods of surface preparation for the stainless steel are very expensive. This has been overcome by the introduction of an explosive bonding step which has reduced the cost and considerably improved the reliability. The method has the advantage of being in daily use and a large body of experience has been built up.

From the arguments presented it can be seen that the route that appears to have the most favourable economic properties as well as a highly developed technology is the roll bonding route. This route is, at the present technological stage, the first choice for the production of clad steel sheet. In view of this the roll bonding route will be further examined as a potential process for the production of stainless clad steel sheet, both from the technical and economic viewpoint. Different production strategies will be examined to determine the most favourable means of integrating the process with the existing structure of the steel industry.

THE ROLL BONDING ROUTE TO CLAD SHEET

There is no unique route, technically or economically to clad sheet via the roll bonding technique. What will be described is a hypothetical route that closely follows industrial practice in the roll bonding field and the sheet rolling field. The route will be appraised in the light of two different strategies:

a) integrated production in a large complex;
b) small plant independent production.

For simplicity it will be assumed that the product will be able to sell itself equally with either type of production strategy. It is assumed also that the end product will be the same in either case.

The steps involved in getting a clad product by a roll bonding route are the same in both cases, the only differences being in the matter of scale.

Roll Bonding Technique

The surfaces of all the materials are prepared for the bonding operation by some form of abrasive finishing. This can be done manually with a hand grinder or if the scale of operations justifies it an automatic abrading machine could be devised. The input materials consist of two slabs of stainless steel of the required thickness and two mild steel slabs of half the required proportions. In addition, two plates of mild steel are required which are to be explosively bonded to the stainless steel. These can be of any convenient thickness providing allowance is made for this in calculating the thickness of the mild steel (or other core steel) slabs. (See fig. 19) The reasons for using this intermediate layer of core steel are as follows: the oxide layer between stainless steel and mild steel make it difficult to get a bond while roll bonding between two pieces of mild steel is relatively easy. If, however, the mild steel core has to be transported to the explosive cladding site, the handling and transportation costs will be increased enormously. Thus it is easier to transport the stainless steel slab and this smaller plate to the cladding site. Thus for a given load more batches can be handled. This intermediate slab provides the possibility of having a barrier layer between a high carbon content core and the stainless steel. If the intermediate layer is a very low carbon steel then it will act as a sink for carbon thus preventing the trouble that carbon is likely to give when it appears in the stainless steel layer as carbides.

After transportation from the explosive cladding site the materials are welded into a pack as in figure 2. An alternative pack is shown in figure 5. These produce single clad and double clad material respectively. The material in pack form is then bonded into a composite billet by hot rolling at 1100°C. Further hot reduction is then given to the composite billet. This can be processed in the normal way to sheet products. The weld beads can be trimmed off at a late stage.

Not all these processes can be carried out in the same plant (certainly not explosive cladding) and so some operations will need transport between plants.

Stainless steel is normally degreased after processing and stored in this state. Where the cut edges are exposed these are liable to corrosion if not protected in some way. This will not be detrimental to the properties but will give a poor image for the material.. The simplest solution would be to coat the edges prior to storage with a non-sulphur bearing grease or other anti-corrosion compound.

The Costs of Roll Bonding

It is not possible to estimate accurately the cost build up involved in the hypothetical roll bonding process. It is possible however to show how these costs are built up and where the major operating expenses are likely to arise. The figures quoted all represent an amalgamation of processing costs gathered from various BSC sources. They do not therefore relate to the practice at any one source plant but could be called 'typical' practice.

The two configurations that will be examined represent the most widely separated strategies. There are, of course, a large number of ways that a steel company could get involved in this field, i.e. by selling off the clad product at various stages, but these will be neglected as the purpose of this section is to show the general trends of cost build up.

A. Large Plant Production

The operating costs of a large steel complex are verry difficult to assess accurately when alterations to the standard line operations are made. Because of this, wherever possible, standard operating costs have been used for each operation which include allowances for depreciation and overheads over the whole plant and are not necessarily restricted to the cladding operation charges.

The cost of transportation to the cladding site has been assessed from the BSC price list. These are quoted prices and provide a reasonable indication of cost.

i) Plant

It is probable that most of the equipment necessary to the cladding operation is already available in an integrated works. This means that there would be no necessity to invest any capital in the process. Depreciation charges are allowed for in individual process costs.

ii) Materials

The starting materials would be available internally and would be charged at cost. These internal prices have been estimated from the basic selling proces of BSC products and deductions have been made from these to allow for the administration and selling costs that would not be necessary in this case.

Stainless steel slab at £350 per tonne bulk rate
Mild Steel slab at £ 50 " " " "
Mild steel plate at £ 68 " " " "

allowing 12% off these prices the charges for material to make the largest pack that can be reasonably handled (4m x 1m x .6m) on a hot slab mill become:

Stainless steel £1168
Core steel £ 696 + £86 = £782

for making a 10% per side stainless steel clad material, making a total material cost of:

£1950

for a 19 tonne billet.

Surface preparation is costed at £2.50 per tonne making a cost of:

£47.5

Explosive cladding costs about £120 per sq,M. This makes the cost of cladding two stainless steel slabs with the intermediate sheet layer:

£960

which together with the cost of transport at about £6 per tonne (Plant about 30 miles from cladding site) makes a total cladding operation cost of:

£1121.5

The explosively clad slabs need welding into a pack necessitating two weld runs at about £6 per meter over a total length of 2 x 10 meters:

£120

Pack heating costs about £1.5 per tonne:

£28.5

The hot bonding operation approximates in cost to a hot rolling process for billets at about £2.5 per tonne:

£47.5

The bonded pack is further hot rolled to hot band at a cost of about £7 per tonne plus reheating:

£133 + £28.5

The cold rolling of this material to sheet gauges is accomplished at a cost of about £16 per tonne:

£304

Finishing costs are an average cost of about £6 per tonne assuming that the material is finished in a manner similar to stainless steel:

£114

To these costs must be added the costs of handling and inspection. The material goes through 5 stages and the cost at each stage is approx. £1.2 per tonne:

£22.5 per stage

£112.5

The material would probably be ordered as fully annealed at a cost of £2 per tonne:

£38

The selling and administration costs for the process are assumed to be fairly standard and set at about 12%.

The total cost of the clad material in sheet form must take some account of the scrap losses during processing. These should be similar to those in stainless steel processing. The bonding operation has a yield of greater than 95% and rolling has a yield (hot and cold) of about 70%. From these losses an allowance must be made for the value of the scrap. Overall a yield of 75% seems reasonable. This means that the original 19 tonnes becomes 14.25 tonnes to share the cost among.

Summarising:

Materials	£1950
Bonding	£1317.5
Hot Rolling	£ 161.5
Cold Rolling	£ 579.5
Handling etc.	£ 150.5
	£4159

These costs must be increased by the administration charge, making a total of:

£4658

This represents the approximate cost of a net yield of 14.25 tonnes so the cost per tonne becomes:

<u>£327</u>

Other allowances must be made, i.e. Corporation Tax (at 40%) so an extra to account for profit must be added, if this is set arbitrarily at about 15% the price becomes about £377 per tonne. This is to be compared with the selling price of sheet stainless steel, for comparable material about:

£500 - £700 per tonne

B. Small Plant Operation

Because this plant is not assumed to be integrated into a larger unit it can be more easily and accurately analysed from the economic point of view. The plant is assumed to operate in a similar manner except in the question of scale. This does mean, however, that the explosive step could probably be disposed of as there is evidence that the simple hot roll bonding technique is more reliable on a small scale than on a large scale. This is confirmed by the decision of a company to set up, quite recently, a small facility for producing single clad material by this method(15). The costs will be analysed on the basis of setting up a plant to produce double clad material in wide strip form. Special features of the route will be brought out as the cost build up proceeds.

A computer programme has been written to model the the process from a cost point of view. This model is fully described in an appendix and only the data used will be presented and justified here together with the results and conclusions.

The assumption is made that the capital needed to set up the plant is removed from surplus and returned after a given length of time, it is therefore equivalent to a loss of income from the surplus. The plant is allowed to depreciate over a standardised time and has no value after this time. Fixed and variable overheads are determined and where applicable these have been inflated at a given annual rate of inflation. Material costs are determined from the selling price quoted by BSC. A sales curve has been assumed which gives a roughly parabolic rise in sales upto a given maximum plant capacity. The scrap rate has been built into the model as has the value of the scrap. The resultant annual cash flows have been discounted at the inflation rate. The discounted cash flows (DCF) have been cumulated over a period of five years. Tax is charged on profit annually at 40%.

Capital

The process is based on a planetary mill which together with its ancilliary equipment would cost in the region of £2.5M. This would be served by a reheating furnace costing about £50 000. The output from the primary bonding planetary mill is fed to a cold mill costing about £250 000. This is served by an annealing furnace at about £50 000.

This equipment, together with such other sundry facilities that are necessary (approx. £100 000) are housed in a suitable building. This building is costed as being on an industrial estate and sold at the current rate of £ 58 per sq. m, with services. It is estimated that all the necessary equipment would be satisfactorily housed in a building approx. 1900 sq.m floor area. This includes an allowance for office space etc.

This makes the capital outlay in the region of:

£4M

This is internally financed and 'loses' 10% compound interest over a period of 15 years. Both these figures representing reasonable examples of current financial practice.

Materials

These are bought in at list selling prices. That is

Mild steel	£ 60 per tonne (DDQ mild steel)
Stainless steel	£450 per tonne (Type 304 plate)

These are used to make a 10% per side double clad material.

Fixed Overheads

There are many ways of assessing the fixed overheads but in this case it is assumed for simplicity that they can be set at a fixed proportion of the capital investment level. This has been assessed from the fixed costs incurred at a BSC plant and is set at 14%. These are inflated at the estimated rate of inflation of 10% per annum.

Variable Overheads

These are difficult to fix and are unfortunately the key to profitability. The charge per tonne of rolling operations is about £14 per tonne. If the preparation costs are limited to a surface preparation operation and a welding operation then these can be set at about the same level as for rolling operations, i.e. at £14 per tonne. These costs include labour charges.

Scrap

No real assessment can be made of the sort of scrap levels that would be found in this cladding process so the scrap level has been arbitrarily set at 20% of the finished product. This is probably exaggerated but will give the outside limits that can be expected. The scrap is assumed to be reused internally as low alloy scrap and has arbitrarily been assigned a value of £10 per tonne. This again is a low figure but takes some account of the difficulties associated in handling low tonnages of scrap.

Administration Costs

The administration charges include selling and promotional costs and are set at 12% of the turnover. This figure was derived from the overall costs incurred by BSC in 1972 and is assumed to be a typical figure.

Depreciation

This is charged in accordance with current BSC practice of depreciating on a straight line basis over 15 years i.e. 6.7% per year.

Inflation

The current estimated rate of inflation is used to discount the annual cash flows and also is used to increase the fixed overhead annually. For the purposes of this exercise this was set at 10%.

The programme is designed to calculate the return over a period of five years and a selling price is calculated such that the cumulative cash flow after this time is positive.

The major uncertainty in these calculations is the sales volume that could be expected if a clad material was introduced into the market. As this would to a large extent depend on the price of the product this will remain indeterminate until a fixed price can be set. The price unfortunately depends on the type of plant configuration set up to make the material and the argument becomes cyclic when the type of plant set up depends on the amount of material that has to be made. Because of this various maximum and initial sales figures were estimated on the basis of different degrees of acceptance of the clad material. These ranged from minimal amounts such as 5000 tonnes per annum maximum sales to the situation where practically all the predicted sales of stainless steels were in fact represented by clad materials. In all cases the plant was assumed capable of supplying the complete market for stainless steels.

Results

The results show that within the bounds of the model set up the return was dependent to a large extent on the maximum sales figure that was estimated. The minimum sales figures had little or no effect on the dependent variable which was in this case the selling price. This was in fact the only sensitivity test performed on the model as it was thought that the accuracy of the model did not warrant exhaustive analysis.

Results are presented in table 1 for some representative situations.

DISCUSSION

By the time that clad materials are put on the market it seems that the cost of a clad stainless will not be significantly lower than the conventional solid stainless steel materials and probably would be about the same as powder route stainless steel. This is unless the sales of these materials could be at such a level that the cost margins would be brought even lower than predicted by the model. This, given a predicted increase in utilisation of stainless steel of about 15% per annum, is not realistic. The costs could also be brought down on a small plant scale by a suitable product mix, utilising the expensive plant investment to produce other materials such as conventional stainless steel and, as the plant will be set up to do batch work for cladding, it would be able to produce other forms of clad material not necessarily of the stainless steel-mild steel combinations. This would add to the profitability if the plant was under-producing to satisfy the market.

On a larger scale plant the relatively low tonnages themselves would ensure that a considerably higher proportion of the production time would be given over to the production of non-clad materials. This would mean that a disproportionate amount of organisation would have to go into the production of clad materials. Although the operations on a large plant would seem from a preliminary costing to be more favourable there would probably be considerable resistance on the part of steelworks management to the introduction of a cladding operation into the scheduling.

The batch nature of the conventional cladding route makes it very labour intensive and to add to this some of the labour involvement would have to be of a highly skilled nature (i.e. welding). This coupled with the high degree of capital investment that would be involved in the setting up of a small plant operation would seem to override the small economic advantages that these processes give when producing a competitor to stainless steel. Batch processes tend also to be more wasteful and are likely to produce a lower amount of clad material per tonne of ingot produced due to trimming and preparation.

These objections coupled with the unsubstantiated cost savings on this material tend to explain the general lack of such roll bonded material on the market.

SPECIFICATION OF A CLADDING ROUTE

It has been shown that there are a number of objections to the introduction of a clad sheet product via the roll bonding route. These reasons are probably sufficient to account for the non-availability of stainless clad sheet in the UK market in anything other than very small quantities. If the assumption is made, reasonably so if the notes on marketing are a valid comment, that there is a potentially large market for clad steels if they could be made nore readily available, then it is worthwhile to set out a specification for a route that will enable the material to be made on a competitive basis.

The prime requirement of a process is that it can be made to operate economically. It is essential for the process to produce material at a price that will enable it to be competitive in the market. Because of the uncertainty of the potential market a further requirement is that the economics of the process must not be markedly affected by the production rate over a wide range of sales volume. This latter requirement can be fulfilled by using a favourable technological process or by a commercial technique such as incorporating the production capacity in a larger plant that can absorb an unfavourable economic situation without dramatic effects on profitability.

On the more technical level, assuming certain predictions can be made about the size of the potential markets, the plant involved in a new process should be such as to be able to produce the predicted maximum and minimum demands with the same efficiency. This involves the design of plant that has a minimum demand on preparation prior to start up and a high degree of flexibility to cope with either intermittent or continuous running. Because of the relatively small potential output (in steel industry terms) the plant should place minimum demand on labour and ideally the same labour force should be able to cope with fluctuating demand on the product.

Process operation should preferably be on a continuous or semi-continuous basis as a large efficiently produced ingot would produce all the expected demand for a considerable period of time. This means that the large scale facilities needed to handle and primary process this ingot would be under utilised unless they could be on a shared basis with other product manufacturing processes. On a large ingot basis all specialised equipment would operate on a stop-go basis and thus need special design and planning to ensure that this would work efficiently. This leads to a specification that calls for a type of plant that can produce clad material on a continuous basis but at a variable rate depending on demand. This eliminates batch errors due to differential processing conditions obtaining between one set up and another.

The basic material inputs should be such that these are produced in their cheapest possible form. This may lead to some in-plant processing prior to use and careful attention has to be paid to this aspect. The materials should be readily available in quantities greater than that required for the product. It is preferable to use the input materials in a form that is produced for wider consumption than the particular process under consideration. This prevents supply from becoming a'special product' problem and offers the possibility of more than one source of supply (though not in the context of BSC). The basic materials should also be in a form that does not require expensive expert or careful handling.

A further specification of the process if this is to show a high profitability, is that the process should form the finished laminate with the minimum of work. This requires that the materials are bought in the condition nearest to the laminate form compatible with material economy.

The finished product should have considerable lattitude in specification as the probable uses of clad sheet are such that relatively small quantities will be used in each of the many applications, each having its own special requirements.

The process should be able to produce wide strip as this is the currently high demand product.

Summarising:

Continuous processing
Cheap input materials
Low technology production plant
Wide material size range
High degree of specification lattitude
Material produced with minimum processing
Highly reliable

DESIGN OF A PROCESS

From a consideration of the specification laid out in the previous section it is possible to design a route which fulfills most of the requirements. It is worthwhile to examine the reasoning that led up to the selection of the particular method of making clad materials that has been devised.

From the point of view of economy and flexibility the process must be continuous and from that of relaibility and well developed technology must utilise some form of roll bonding. It is difficult to manipulate thick sheet materials in any form of continuous process so the process must use as a starting material for roll bonding some form of material which is near to sheet gauge.

A continuous roll bonding process is envisaged using two sheets of stainless steel fed to gether with a core of a mild steel into a roll gap. Sufficient deformation is given to ensure roll bonding. This idea is not novel having been previously disclosed in a patent specification (16). The roll bonding of stainless steel to mild steel is a process demanding deformations at the interface of the order of 70% minimum. This sort of deformation needs specialised rolling equipment of the Sendzimir type at a large capital outlay (£2M). The threshold of deformation decreases as the temperature increases and so a better way to get bonding on standard type rolling equipment is to perform the deformation while the materials are hot. Even at high temperatures the amount of deformation needed is high and there is some doubt as to whether these necessary high specific pressures could be achieved at the interface.

A method of inceasing the specific pressures at the interface is to use a particulate material as one of the components. The two possible situations are shown in figure 6. If the stainless steel outer layer was particulate then the specific pressures at the interface would not be increased to any great amount as powder materials do not consolidate well in thick sections and so the threshold deformation would not be reached. In the case of stainless steel it is necessary to penetrate the oxide film to get bonding. The use of a particulate matter on the inner surfaces of the stainless steel would lead to high local pressures and a consequent penetration of the oxide layer. The general lack of flow in particulate materials would not be of great importance in this case as the surface is the active region.

Feeding consolidation and bonding of a particulate matter compressed between two bands would be preferably carried out at high temperature to allow some diffusion of the component materials. This does mean that the 'active' area would need some protection from the atmosphere. This could be easily achieved by flooding the roll nip and stainless steel feedstock zone with an inert gas. Some further advantage might be gained by preheating the stainless steel feed but the practical difficulties involved in the exclusion of oxygen during this process would be high. It is better then to feed in the stainless steel cold with only the natural oxide present and rely on feeding mild steel particulate material into the roll gap at high temperature. Experience has shown that it is necessary to de-oxidise mild steel powders in a reducing atmosphere during the heating cycle for these materials before they can be successfully rolled into a consolidated strip(17). Following this practice would lead to a clean mild steel powder being forced into contact with the stainless steel surface covered with only a thin natural oxide. These conditions, within the limitations of the specification laid down,

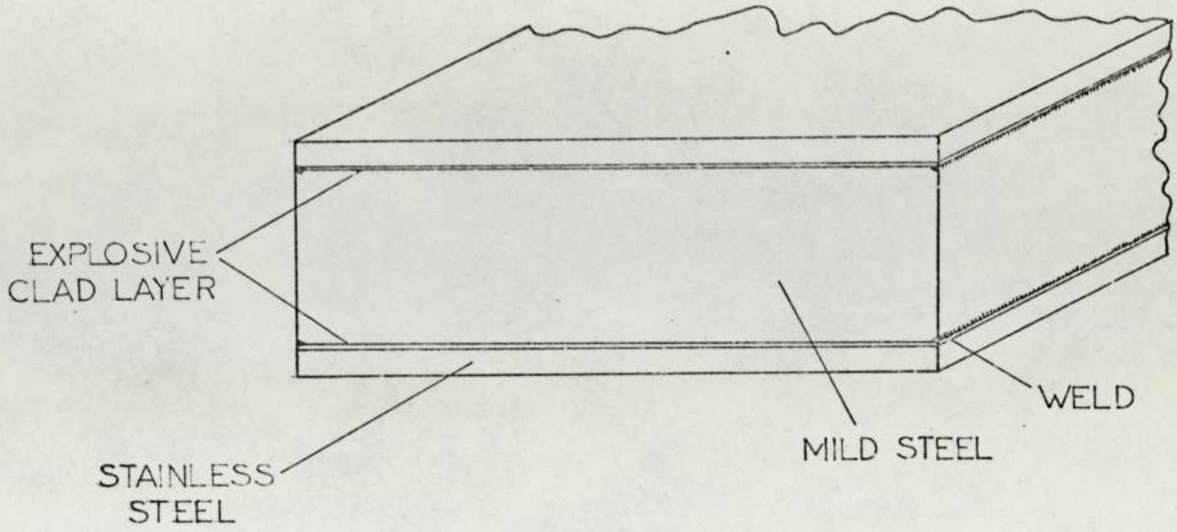


FIG.5 PACK FOR DOUBLE CLADDING

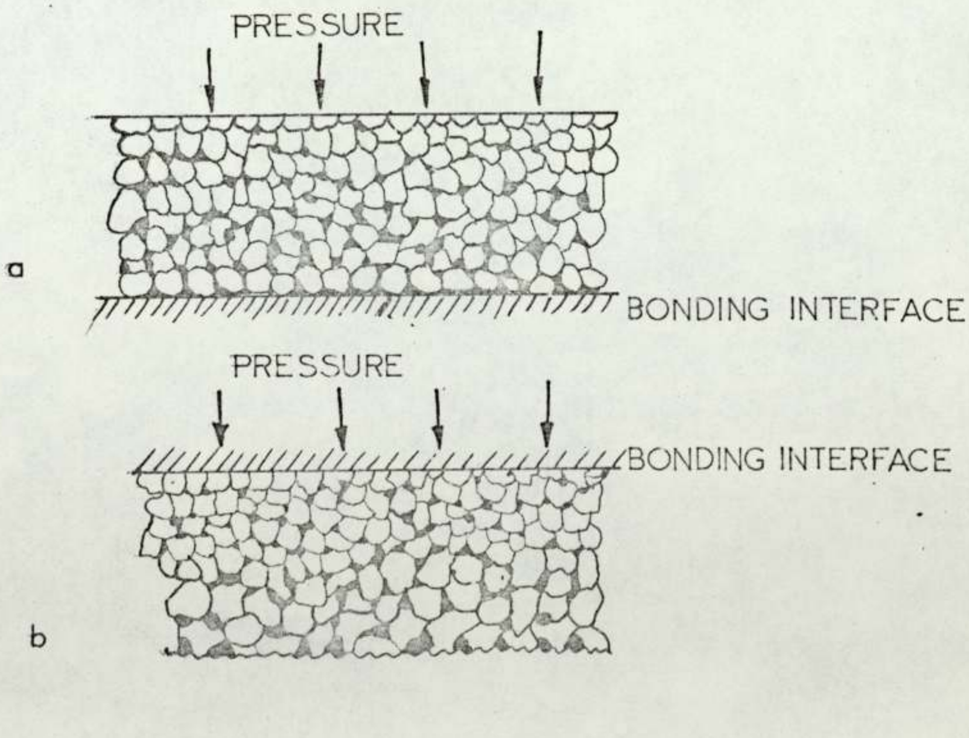


FIG 6. POWDER COMPRESSION

offer a feasible method of continuously producing a stainless steel laminate. All the steps outlined above lie within the bounds of present technology and a rig to produce material by this route is shown in fig. 7.

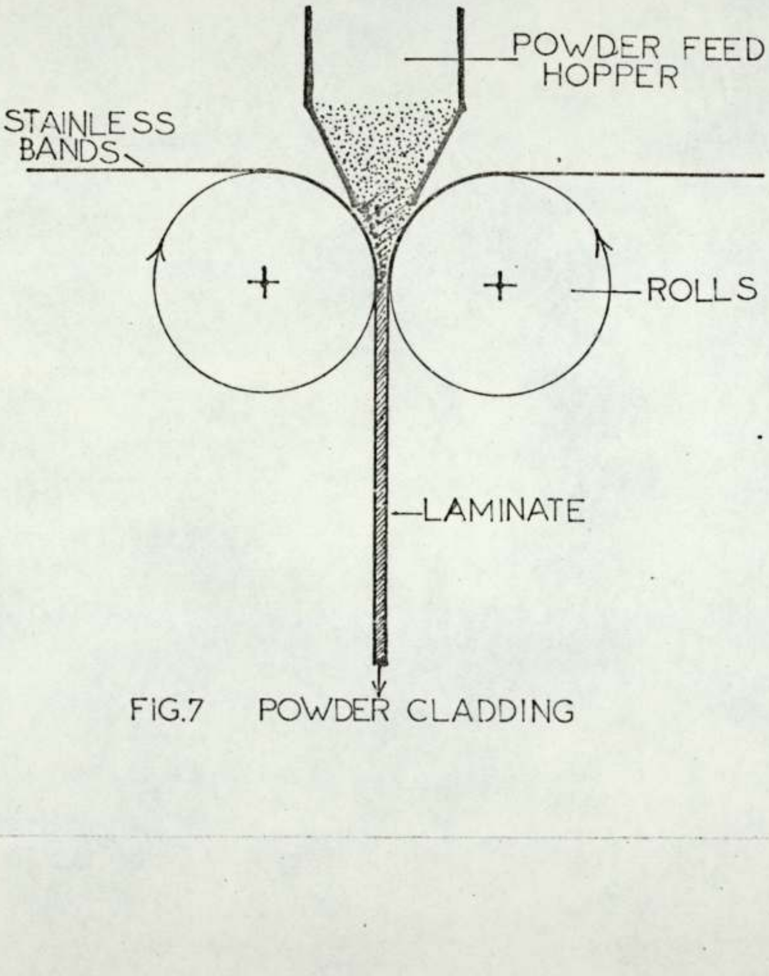


FIG.7 POWDER CLADDING

A NEW ROUTE

On the basis of the foregoing arguments an experimental route was devised and studies were made of the technical and economic prospects for this particular method of making clad sheet. As with the roll bonding route, various production strategies were examined and evaluated.

The Process

An outline scheme of the process is shown in fig. 7. As can be seen stainless steel strip feedstock is fed into the roll gap into which hot powder is delivered. The roll nip is flooded with an inert gas to prevent oxidation of the powder. The powder is compacted between the moving stainless bands and bonding occurs in this zone. The feedstock bands can be varied in thickness upto the maximum that can be conveniently handled. The ratio of cladding to core thickness can be varied with no plant changes. The plant as designed can run continuously or semi-continuously at will and the quality of stainless steel feed can be altered during a run with no difficulty. In principle, there is no reason why the core quality should not be varied at any time simply by fedding from another hopper, which is fed from a separate furnace. The continuous powder feed means that the start up time for the plant is reduced and so is suited to intermittent running i.e. 1, 2 or 3-shift working and the plant is such that the production rate can be varied from very low upto the maximum capability without modification.

This process has a lot of the attributes of the ideal process described in a previous section. Because of this experimental work was carried out on a small scale rig, simulating, where possible, industrial practice as it was likely to be applied.

Experimental Work

Experimental work was conducted both on the pilot plant and to provide back-up information, in the laboratory. The pilot plant work was not under the control of the author except in an advisory capacity. Experimental work in the laboratory was concerned with the physical metallurgy aspects of the process. Studies were made on the compaction and bonding of particulate materials in restricted flow conditions using canning as a simulation of the projected process. Studies were also conducted on the diffusion situation in the composite and the general metallurgy of the system.

The Compaction and Bonding of Powders

i) Compaction

It has been amply demonstrated that metal powders can be successfully processed to thin sheet products. One widely used method is to 'can' powders in typically stainless steel containers and subsequently to roll, extrude or forge the filled container to consolidate the contents. This technique finds its widest use in rare earth metals and materials which are difficult or dangerous to work by conventional processing. The canning technique was felt to be a reasonable simulation of the projected new process in that granular materials are compacted and bonded to solid stainless steel. Experiments on compaction and bonding were carried out using this method.

The aim of the experimental work was to determine how well mild steel powders would compact when worked under restrained conditions and to determine the conditions that are necessary for bonding of the compacted core (or indeed the individual particles) to the canning or restraining material. In all cases the canning material was 18-8 type stainless steel within the specification BS1430 type 304. Mild steel powders were obtained from various sources and ranged in size from 100# to 16# .

The experimental procedure was to fill a tube of the required length with a powder and manually consolidate it by repeated percussion until the apparent volume reached a minimum. The ends of the tube were then sealed usually by simply crushing the end of the tube and folding it over, in some cases, however, where a gas tight seal was required, the flattened end was welded. The degree of consolidation was estimated after working by optical micorscopy on a section, usually both transverse and parallel to the rolling or working direction.

In general compaction was easily achieved with all the powders used, 50% deformation being sufficient in most cases. The degree of deformation necessary must, of course, depend on the original density of the powder mix but because of the geometrical effects encountered when flattening a tube the compaction was not even over the cross section (the tube actually goes dogbone shape due to the formation of plastic hinges at 90° around the tube). This effect would not be expected to occur in the proposed process so this effect was ignored. It was found that temperature had no observable effect on the compaction and 50% was still found to be the approximate amount of deformation to get a consolidated core, this being assessed optically. Rolling at high temperatures, however, (>850°) produced a product with a more even wall thickness in the stainless steel cladding than did cold deformation. As expected the green strength of the core was much enhanced by high temperature deformation. This was apparent when, due to a poor bond between the core and the cladding, the core could be extracted. Hot deformed cores could be bent over at least a 1T radius whereas the cold compacted material, even after annealing at 850°C in an inert atmosphere developed cracks over a similar radius. It is obvious that high temperature deformation disrupts the grain boundary oxide film which would otherwise hinder sintering.

It is proable that an optimum size mix could be devised so that full densification occurs at minimum deformation but no attempt was made to determine this parameter. The well known threshold deformation effect allows bonding to take place only after a minimum amount of deformation(18). For the mild steel stainless steel combination in question this threshold is thought to be in the region of 60%(19). This means that the compact must have more deformation for bonding than the minimum for consolidation of any powder likely to be used.

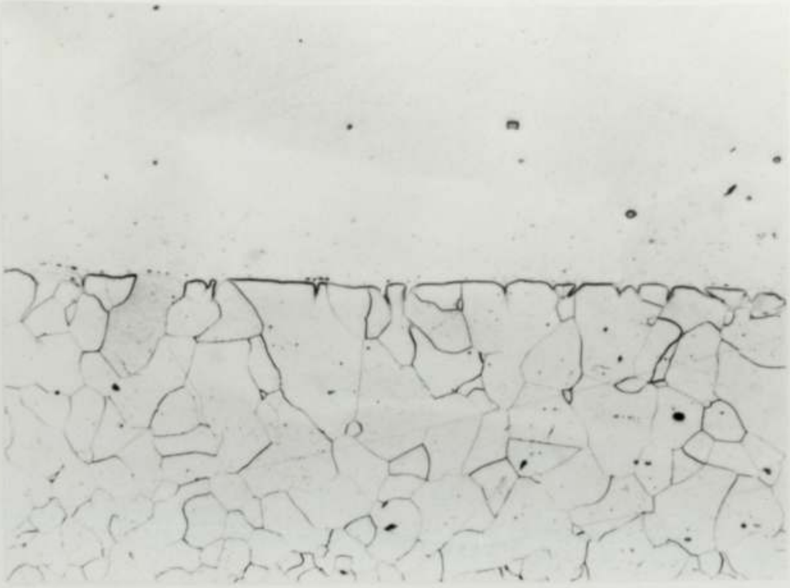
Experimental work on bonding was concerned with defining the minimum conditions that had to be met before bondingof the core to the cladding could be achieved. The minimum conditions are defined here, somewhat arbitrarily, as those which could be met with the least effort in practice. This was felt to be a reasonable definition in the light of the probable need to develop the laboratory procedures devised into industrial scale practice.

ii) Bonding

Initially, good bonds were obtained between the core and the cladding by passing a reducing gas (H_2) through the tube while it was being heated prior to deformation at 1000°C. This probably reduced the chromium oxides present on the tube wall, certainly preventing thickening, and permitted easy bonding. This was especially true where the tube was held in contact with the compacted core for a definite period, i.e. on a press forge. When rolling a similar configuration, only partial bonding occurred. This was due to springback of the thin wall tubes in use. With thick wall tubes the springback problem was eliminated. An alternative approach tried was to replace the hard, tenacious chromium oxide with one that would not form a good diffusion barrier. This was done by electroplating the bore of a tube with soft nickel. On deforming the sealed tube, a good bond was formed as the soft frangible nickel oxide did not form a coherent diffusion barrier but prevented chromium oxides from forming. The bond so formed was as good as the best bond found in the samples bonded using hydrogen and could withstand considerable cold deformation by rolling (>80%). This was found to be a reasonable way of assessing the quality of the bond. The quality of the bond was also found to correlate well with the microstructural appearance. A good bond is shown in fig. 8.

It is obviously preferable from the industrial point of view to be able to dispense with special surface preparations or furnace atmospheres. To this end further experiments were conducted on untreated tubes. These experiments showed that it was very difficult to get a bond on hot rolling that would withstand even 10% cold rolling, using the best rolling conditions (thick wall tubes). The best conditions devised for bonding were a weld sealed tube containing an oxygen getter, in this case, titanium. A satisfactory bond, however, was not always obtained. Altering the grade of powder or its size range did not improve the bonding. It seems that the residual oxygen in the tube is sufficient to form a thick oxide barrier which is not readily penetrated by diffusion during hot rolling. This was confirmed by analyses of the surface of delaminated cores on which no chromium was detected.

The situation was much improved by the introduction of a post hot roll anneal of a few minutes at 1200°C. This permitted diffusion of chromium and nickel through the oxide layer forming a strong deformable bond. This bond could withstand cold rolling reductions of >80%. Typical microstructures of the hot rolled and annealed interfaces are shown in fig. 9. It can be seen from the microstructures that the oxide layer seems to have broken up into discrete particles which are not connected with the grains of the stainless steel. The mechanism of this break-up of the oxide layer is not clear but it is suggested here that some solution of the oxide takes place. Diffusion of Cr and Ni seems to have taken place through the layer rather than at the breaks only. The rate of diffusion is shown in fig. 10 where the extent of the diffusion band is taken from the oxide layer, which is assumed to remain fixed as in the 'Kirkendall and Smiegelskas' experiments, and acts as a marker in a similar way to their tungsten wires. The effective depth of diffusion is taken up to the non-etching layer (assumed 12% Cr min). Experiments on chromium diffusion have shown that the chromium concentration distance curves fall off rapidly below this chromium concentration (20). The simultaneous diffusion of chromium and nickel was confirmed by spot x-ray dispersive analysis on the scanning electron microscope. The length of annealing time, hence the amount of diffusion, appeared to have no effect on the strength of the bond once the initial bond had been formed. This was demonstrated by tear tests which were conducted on the bonded and annealed samples after edge trimming. These consisted of etching



x 175

FIG8 A 'GOOD' BOND

etched NITAL

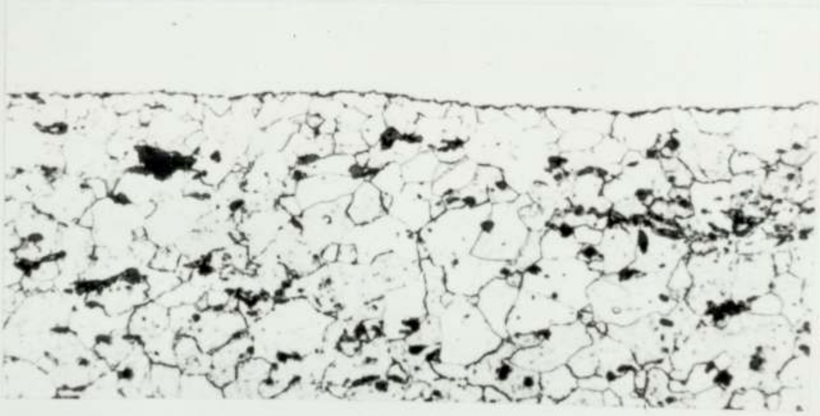


FIG 9a AS HOT ROLLED

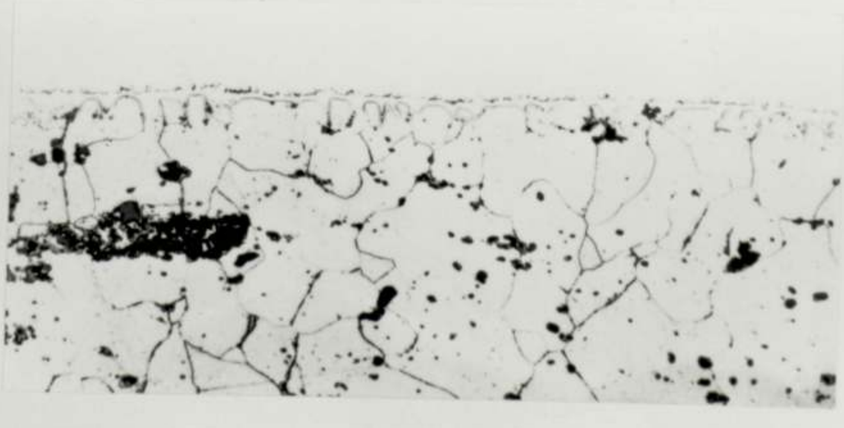


FIG 9b ANNEALED 1100°c

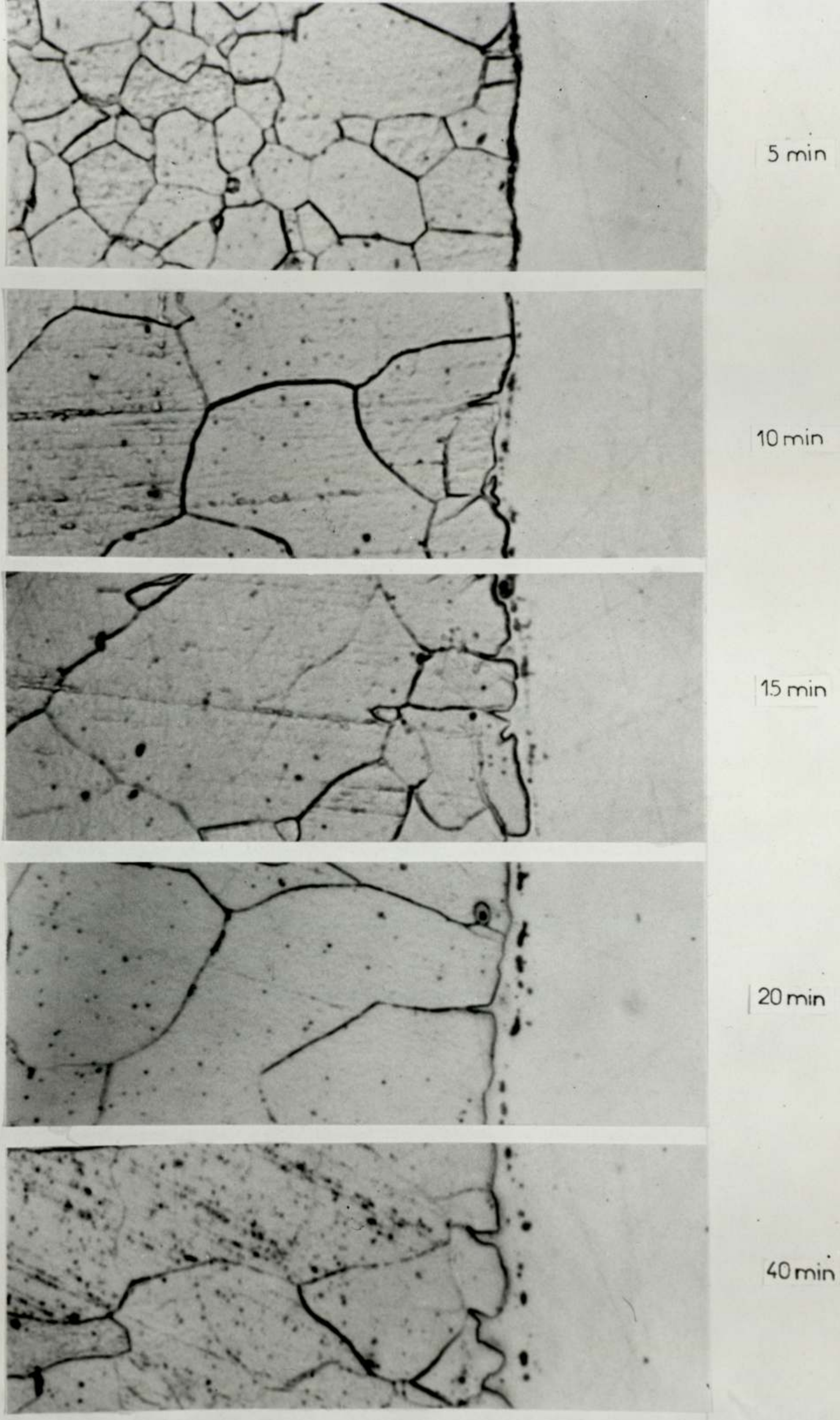


FIG10 DIFFUSION AT 1100°C

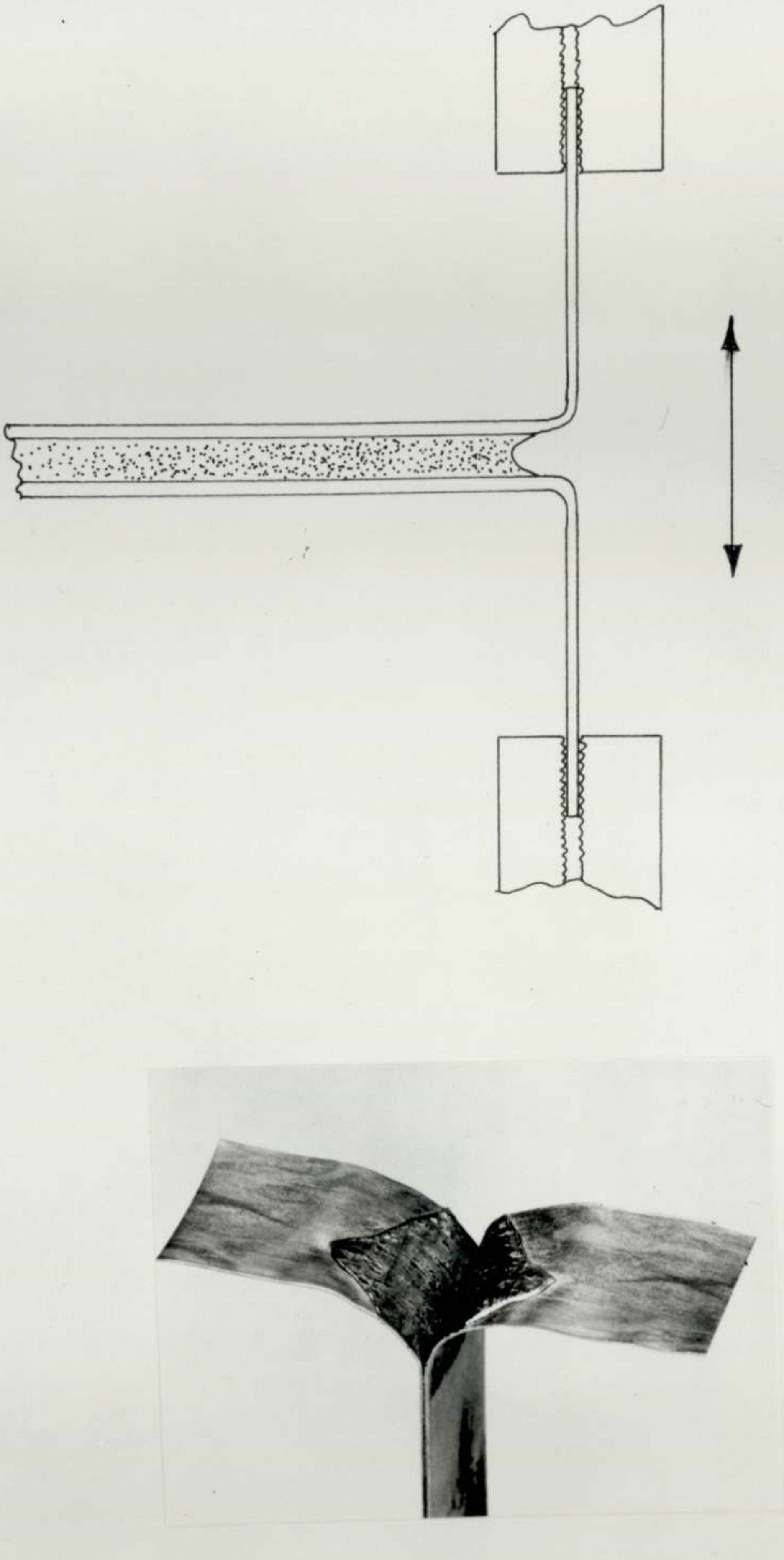


FIG11 TEAR TEST

away a portion of the mild steel core in nitric acid and pulling the remaining leaves of stainless steel apart in a tensile testing machine. By this method the bond was demonstrated to be stronger than either of the parent materials. Failure usually occurred by tearing of the stainless steel or less frequently through the mild steel, this mode of failure being more prevalent in coarse grained powders. An idea of the test can be gained from fig. 11 which shows failure through the mild steel.

iii) Diffusion

Due to the complexity of the system it is not possible to predict the rate of diffusion of the stainless steel into the mild steel from a knowledge of the diffusion coefficients of the diffusing species. It is, however, possible to treat the stainless steel as a single diffusing species and, by using the static oxide layer as a marker, the effective or composite diffusion coefficient can be calculated. Due to the inaccuracies, both experimental and in the theory of multi species diffusion it is better to try to fit the data to a simple case. The simplest solution of Ficks 2nd law that is applicable to the case in question is that for a pair of semi-infinite solids, joined at an interface.

The solution, for the above boundary conditions is,

$$C_{xt} = \frac{C'}{2}\left\{1 + \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right\}$$

where C is concentration
C' is initial C
t is time
D is diffusion coefficient.

By inspection it can be seen that any plane of constant composition moves away from the interface (x = 0) at a rate which is proportional to $\sqrt{Dt}$. By manipulation of this relationship, it is possible to derive D from a plot of bond thickness squared v time. This has been done for data from fig. 10 and as can be seen from fig. 12 it is possible to fit the data to a straight line, indicating that the approximations involved in this particular solution to the second law are reasonable. From this, a composite D has been derived and is calculated as,

$$1 \times 10^{-10} \text{ cm}^2/\text{sec. at } 1100^{\circ}\text{C.}$$

This is in fairly good agreement with the values quoted for chromium and at similar temperatures, nickel diffusing slower(20).

Cr $.82 \times 10^{-10}$
Ni $.19 \times 10^{-10}$

From this it can be seen that the major diffusing species is liable to be chromium. This can lead to unwanted interface effects at critical compositions, i.e. the formation of a ferritic stainless steel at 12% Cr, but it is thought that the range over which this occurs is so small as to be neglectable.

Because of the relative unimportance of the depth of diffusion zone with respect to bond strength no further data was derived in this form so no predictions can be made as to how the behaviour of the composite D changes with temperature but it is reasonable to assume that the composite D will vary in the usual exponential form following the Ahrenius equation down to temperatures where a phase change occurs in the system. It can also be noted that due to the large difference in diffusion coefficients for chromium in α and γ iron that the relationship will only obey the derivation of Ficks law when the concentration of chromium is greater than about 12%. This can be seen from a phase diagram of the Fe-Cr system.

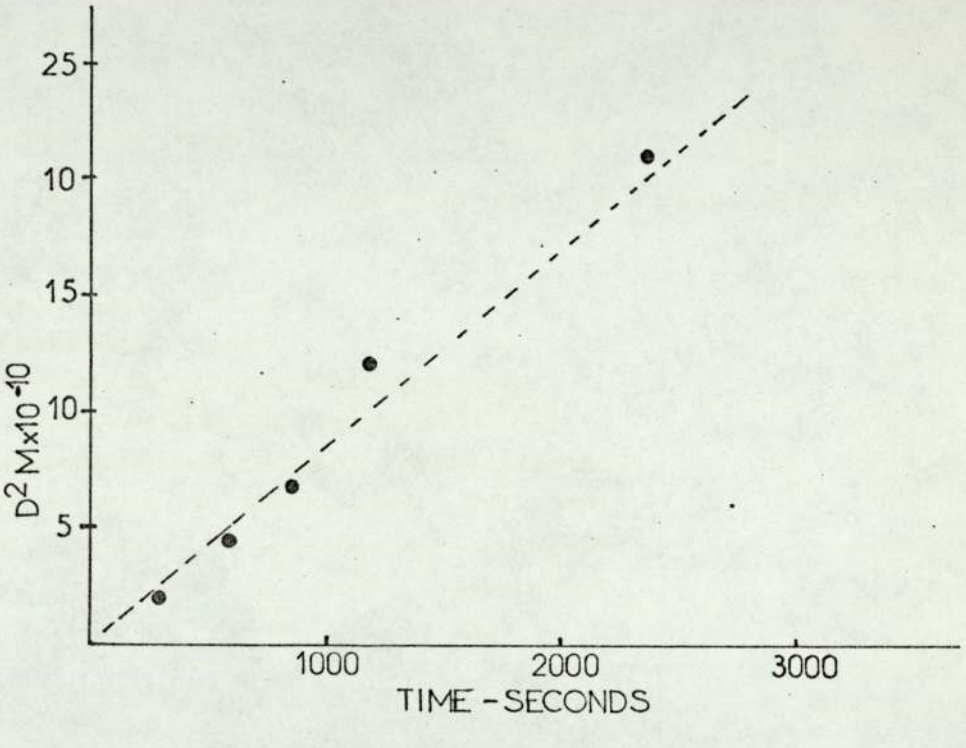


FIG.12 DIFFUSION OF 'STAINLESS STEEL'

Metallurgy of the System

At the early experimental stage of the proposed process it is not possible to specify the exact combination of materials that is likely to be used. With this in mind any work on the metallurgy of the laminate materials made by the tube encapsulation route must be of a purely speculative nature with no guarantee that any findings will be applicable to the new process.

No work was done on the metallurgy of the stainless steel as this subject is adequately covered in the literature.

Microscopic examination of the compacted mild steel cores showed a marked difference between the coarse and the fine powders. In coarser powders (16# to 20#) there were grain boundary films present outlining the presumed original particle boundaries after hot compaction. These 'super grains' were absent in the compacts that had been subjected to a reducing atmosphere. Typical 'super grains' are shown in fig. 13 and as can be seen they are not associated with the material grain boundaries. Confirmation of the original particle hypothesis was given by substituting a stainless steel particle for a mild steel one. Subsequent polishing confirmed that this conformed to the shape of the super grains (fig. 14). The oxide films did not seem to deteriorate with mechanical working until greater than about 80% deformation. Long term annealing of the compact had little observable effect on these oxide films.

The failure behaviour of the laminate in the presence of the super grain oxide boundaries was observed in order to determine whether these represented a plane of weakness or not. Both in tear and tensile testing no evidence of failure along these boundaries was observed for any condition of the material. Microscopic examination showed that failure usually occurred though the stainless steel in

x 100

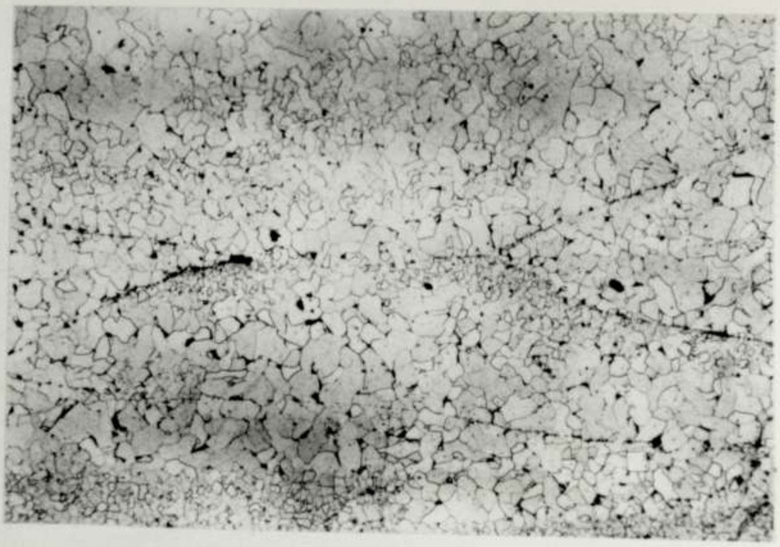


FIG13 'SUPER GRAINS'
(ORIGINAL PARTICLE BOUNDARIES)

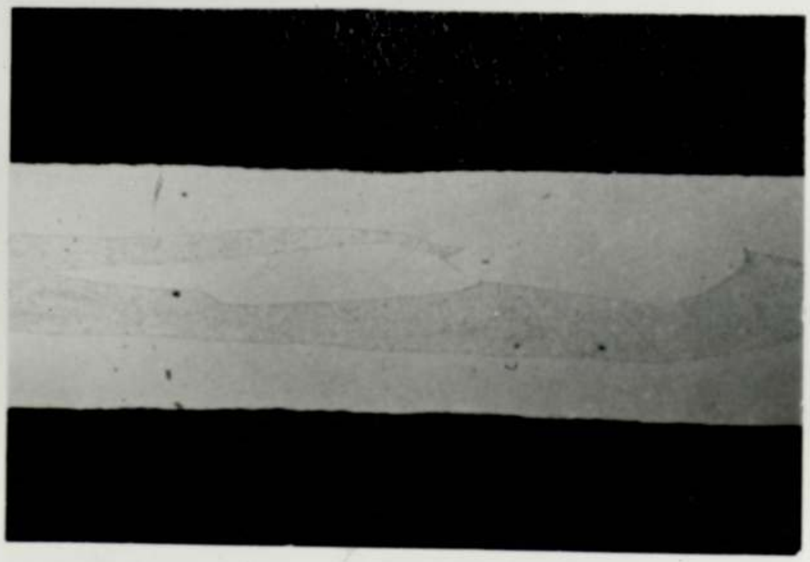


FIG 14 STAINLESS STEEL PARTICLE

x 5

tear testing and with a normal shear type fracture in tensile testing. It is probable that the grain boundary films are not continuous. These are, in any case, disrupted during mechanical working reductions of greater than 80% sufficiently to prevent failure along them.

In fine powders there was no evidence of super grains as is to be expected but it was noted that there were a considerable number of presumable oxide inclusions present.

The oxide layer present on the inside of the tube in materials made by the encapsulation method was also considered to represent a potential failure zone. As was seen in fig. 10 this is a layer that exists, after diffusion as a discontinuous line of oxide inclusions. Examination of the tear and tensile failures showed no evidence of preferential failure along these interfacial oxide lines.

It is highly probable that the high population of oxide inclusions in this type of material would have an effect on formability(22) but, in the projected process, most of these problems could be avoided by a substantial inert or reducing gas coverage in the active regions and during the pre-heating of the mild steel powders.

One of the hopes for a stainless steel clad mild steel was that having a stainless steel outer layer might disguise some of the effects detrimental to surface finish associated with the yield point in mild steels. Defects such as lüders bands visible on the surface of a pressing are among the most common causes for rejection. Elimination of these involves cost increasing techniques such as temper rolling and storage at low temperatures. Stainless steel does not suffer from this particular type of defect. Examination of strained tensile test pieces showed that strain markings were visible on the surface with up to about

20% stainless steel cover, though at this percentage it is much attenuated. The markings were not visible with thicker coverings. An example of these surface defects is shown on a tensile test piece in fig. 15 which has a 10% per side stainless layer. It was also noted qualitatively that the yield point drop became less as the percentage of stainless steel was increased. This is as expected due to the stainless steel not having a well defined yield point.

FIG 15 LÜDER BANDS

EXPERIMENTAL PRODUCTION

The experimental work on the cladding of stainless steel to mild steel powders was carried out on a small modified experimental mill previously used for the hot compaction of powders (23). The mill was readily adapted to encompass the cladding operation. Various combinations of materials were tried and assessment was made of the material produced on the mill.

The results of this investigation were reported and table III summarises these.

It was found that the poor quality powder feedstock then available led to a relatively poor quality product with large areas of non bond, low density areas and edge cracking. Some of these effects can be attributed to the narrow mill that was used. It is considered that the roll width of 80 mm was a major cause of edge cracking. Similarly, the low densification of the strip is attributed to the fact that the mill used in the experimental work had a very low maximum absolute loading capacity. This, coupled with the usual feeding problems with powders, all detract from the possible quality of the product.

In spite of this it was found that it is possible to bond a continuously moving band of stainless steel to a continuously compacted powder core. The quality of the stainless steel feedstock has some effect on the bonding but below a thickness of about .25 mm both conventional and powder rolled stainless steel had similar properties with respect to bonding. At thicknesses up to .5 mm powder rolled stainless steel had better bonding properties. This can probably be ascribed to the poorer thermal conductivity of the powder rolled stainless steel allowing the interface to achieve higher temperatures than the equivalent thickness of conventional stainless steel, which would have a greater thermal equivalent. At the lower thicknesses, lower thermal capacity of the cladding materials would have less of a chill effect on the interface.

The process, accepting the limits placed on the experimental verification of the operation, would seem to be a feasible method of making a stainless steel clad material in a continuous manner.

TABLE I

COSTS OF ROLL BONDING ROUTE

Sales yr. 1	Sales yr. 5	Price per tonne	Cumulative DCF over 5 years
500	5 000	£700	£ -
5000	50 000	255	3 800
1000	20 000	388	7 200
10000	100 000	215	141 000
Large scale price	£377 per tonne		

TABLE II

COSTS OF POWDER ROUTE

Sales yr. 1	Sales yr. 5	Price per tonne	Cumulative DCF over 5 years	
500	5 000	£505	£ 3 600	Solid SS feedstock
5000	50 000	317	42 000	
1000	20 000	351	12 000	
10000	100 000	307	155 000	
500	5 000	415	500	Powder route SS feedstock
5000	50 000	227	10 000	
1000	20 000	262	29 000	
10000	100 000	217	91 000	

TABLE III

Type of Stainless Strip used for Cladding	Rolling Load Tons	Clad Strip Thickness ins.	Degree of Mechanical Bond	Comments
Slurry, 304 0.009", 91% dense	-	0.080	Well bonded	10% H_2 used for furnace atmosphere. Cladding 0.006" after rolling.
Cold rolled, 304 0.010", 100% dense	67	0.095	Partly bonded	Cladding 0.0075" after rolling
Cold rolled, 304 0.010"	60	0.095	Not bonded	No preload on mill
Cold rolled, 304 0.010"	80	0.080	Well bonded	Cladding 0.008" after rolling
Cold rolled, 304 0.010"	73	0.090	Well bonded	Cladding 0.008" after rolling
Powder rolled, 316 0.015", 96.0% dense	67	0.097	Not bonded	Cladding 0.013" after rolling
Cold rolled, 304 0.010"	61	0.082	Partly bonded	Cladding 0.008" after rolling
Cold rolled, 304 0.010"	75.5	0.078	Well bonded	Cladding 0.007" after rolling
Powder rolled, 316 0.015", 96.0% dense	75.5	0.090	Partly bonded	Cladding 0.0125" after rolling
Powder rolled, 304 0.0085", 90.0% dense	-	0.078	Well bonded	Cladding 0.007" after rolling, 2" wide stainless only one side coated

Continued...../2

TABLE III (continued)

Type of Stainless Strip used for Cladding	Rolling Load Tons	Clad Strip Thickness ins.	Degree of Mechanical Bond	Comments
Powder rolled, 316 0.0105", 91.4% dense	61.5	0.085	Well bonded	Cladding 0.007" after rolling, 2" wide stainless only one side coated.
Powder rolled, 304 0.0172", 78.4% dense	40	0.085	Well bonded	Cladding 0.0112" after rolling, 2" wide stainless only one side coated.
Powder rolled, 304 0.0125", 90.77% dense	60	0.088	Well bonded	Cladding 0.008" after rolling, 2" wide stainless
Cold rolled, 304 0.020", 100% dense	57	0.100	Not bonded	Cladding 0.016" after rolling, 2" wide stainless

THE COST OF POWDER CLADDING

The costs involved in the proposed new route can be assessed in a manner similar to that used to outline the costs of the small scale roll bonding plant. It is possible to make allowances in such a fashion as to make it feasible to compare the two similar strategies. A lot of the data gathered and used here is hypothetical in that there is no plant, as yet, set up to produce material by this method. This means that no direct estimation of the various cost increasing processes can be made without reference to plant operations of essentially different natures. As a model, the powder strip rolling plant was used. This process has similar plant requirements and production rates and as such provided a basis for extrapolation and estimation.

Cost Data

i) Capital Investment

The capital investment needed to set up an independent plant is accumulated as follows(23).

Mill	£300 000
Furnace	200 000
Building etc.	100 000
	£1 000 000

This is allowed for at 10% over 15 years.

ii) Materials

There are two possible sources of materials, either using bought in solid stainless steel as the feedstock or, if circumstances allowed, using powder rolled strip from an associated plant. Mass produced water atomised mild steel is specified as the core steel feedstock.

Solid stainless steel strip	£550	tonne
Powder stainless steel strip	£300	tonne
Water atomised mild steel	£ 60	tonne

iii) Fixed Overheads

To make these comparable with the roll bonding route assumptions, these have been set somewhat arbitrarily at 15% of the capital outlay. These are increased at the annual rate of inflation.

iv) Variable Overheads

The overheads in the production of clad strip in this process have been costed at about £14 per tonne. Cold rolling adds about £6 to these making a cost of about £20 per tonne.

v) Scrap

The process being continuous makes a significant contribution to the lowering of the scrap rate. The exact effect cannot be estimated but it has been set at 10% to be lower than the scrap rate estimated in the roll bonding route. The scrap is sold at the same price as the roll bonding scrap, i.e. £10 per tonne.

vi) Administration Charges

These have been set at a standard 12% of the sales volume.

vii) Depreciation

The plant is depreciated at the standard 6.7% per annum.

viii) Inflation

This is estimated at 10% per annum.

Results

The results for five year cumulative periods have been given in table II. These show the effect of sales volume on the cumulative discounted cash flows for various input material costs together with the results for an intermediate cost of stainless steel to account for any fluctuations in the cost of the stainless steel input feedstock.

These costs may be compared with those in table I which gave the results for the roll bonding route.

DISCUSSION

If the estimated selling prices of the three possible routes are examined (tables I & II) it can be seen that the new route has some advantages, especially if the route is able to utilise powder route stainless steel strip at the current estimated cost. It is difficult to judge the significance of the differences due to a lack of information on the criteria for profitability and financial viability that would be used by any industrial concern. For instance, it might be felt that no method of making clad sheet and strip warranted the setting up of a new plant for making it and that the bulk solid route (explosive-roll bonding-rolling) offered the most convenient solution in conditions of uncertain marketability, accepting its price disadvantage. This, of course, would then come into direct competition with powder route stainless steel strip. The new route has its most advantage in the smaller market and it is here also that the technical advantages of flexibility and relatively low capital investment have their impact. Even at the 50000 tonnes level price for price, there is a greater return on capital for the new route.

Given the technical advantages of the new route and indication that there would be some economic advantage it would seem advisable at this stage to examine the various factors involved in the production, processing and properties of stainless clad steels. This is done in the following sections.

PRODUCTION ASPECTS OF CLAD STEEL

THE ROLLING OF CLAD STEEL

THE HEAT TREATMENT OF CLAD STEELS

- bulk heat treatment
- surface heat treatment
- the heat treatment of experimental materials

THE DIFFUSION OF CARBON

THE ROLLING OF CLAD STEELS

The rolling of clad steels has not been studied in any depth from the production point of view. From the literature, no evidence of special problems can be obtained and this would tend to indicate that any difficulty in the rolling of, at least, stainless clad steel is fairly easily overcome. In the rolling of cast clad billets allowances have to be made for the different workability of each component when calculating the final ratios of cladding material to core thickness(24).

Most theories of the rolling of clad materials that have been propounded propose the use of an equivalent yield stress that is derived from the assumption that each component of the composite undergoes equal deformation (the equal strain hypothesis). This yield stress (β) is given by:

$$\beta = \frac{2t_a y_a + t_b y_b}{2t_a + t_b}$$

where t is thickness
y is constrained yield stress
a denotes cladding
b denotes core (ref 23)

This has been shown to fit the observed roll pressures when the above type of yield stress is fitted into existing rolling theory(25) and confirmation of the form of the yield stress equation is given by some early work on stainless clad mild steel(26). These results are presented in fig. 16. All the theories of clad rolling or pack rolling assume that conditions at the interface remain constant. This will only hold in the practical case where a bond is formed between the cladding and the core before working or where no bond is formed at all. In most production processes in use today this condition is not fulfilled as the degree of bonding increases as the deformation process goes on. This is true for cast on

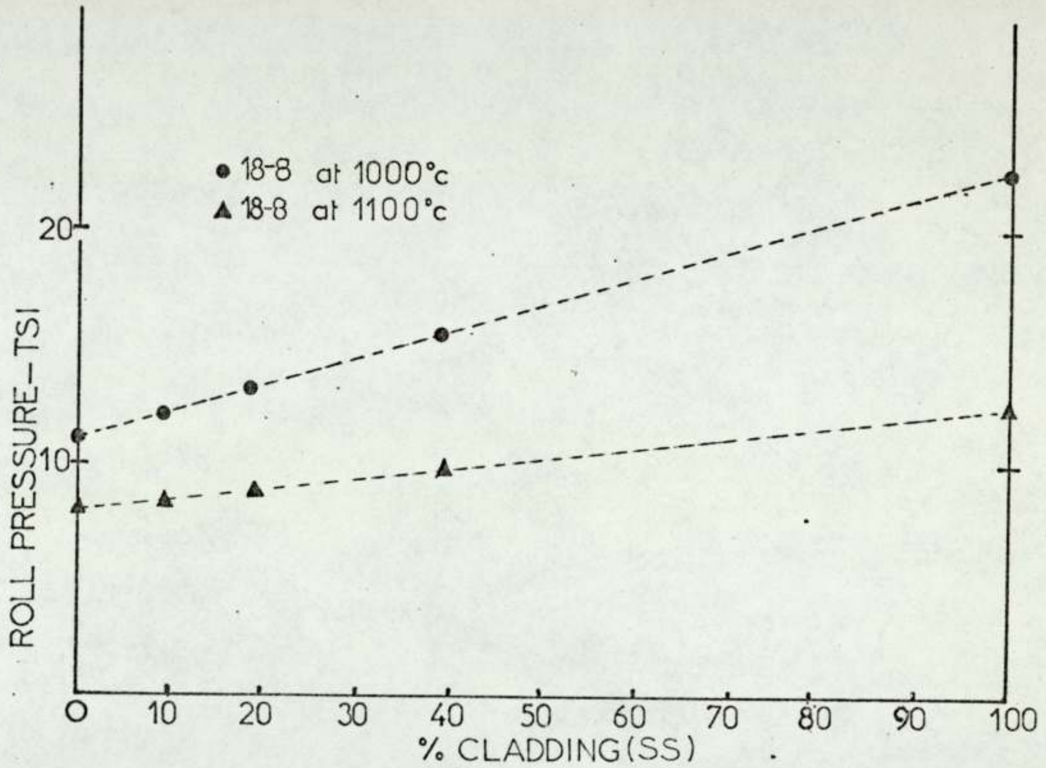


FIG.16 ROLL PRESSURES (from POMP & LEUG)

cladding where the final bond is usually not continuous. The nearest approach to this condition is in explosive cladding where the bond is usually of the order of 98%* In most of the current production processes the geometry is such that the stainless steel is restrained in some way and is not free to deform naturally (see figure 2). This leads to further deviations from the theoretical conditions. Where single clad plates are rolled there is sometimes a problem of curling of the plate, especially in the case of the stainless/mild steel combinations. This is readily adjusted by altering the frictional conditions at the top and bottom of the pack, i.e. by differential lubrication or by using different roll diameters top to bottom. This does not often arise as most clad plates are rolled to size in the bonding configuration and are hence restrained in some way.

There are indications that the restraining rolling of packs leads to special problems$^{(27)}$ and work on the special system of Uranium alloys enclosed in steel cladding packs has shown that two qualitatively assessable parameters 'dog boning' and 'sandwich rolling index' (DBI and SRI) can be used to assess rolling performance.

The two parameters have been found to co-relate with product quality and are defined as:

$$SRI = \frac{L_a/L'_a}{L_b/L'_b}$$

where L' is the length before a given pass

L is the length after a given pass

a and b are the two materials

$$DBI = t_c/t_e$$

t_c is the thickness at the centre

t_b is the thickness at a maximum.

---

* ICI guarantee >95% minimum.

These parameters are illustrated in fig. 17. Other systems have been assessed but not stainless/mild combinations. There is no reason however to assume that this special combination will behave differently in an enclosed rolling situation. Due to the different work hardening rates the SRI should alter with increasing reduction. This has been noted. The order of the pack has also been found to be important. These factors are illustrated in fig. 18.

When rolling materials made by the proposed route 'dog boning' has no real relevance as the edges of the material produced by the new route will not enclose the core material. SRI, however, has some significance in that variations in core and cladding material made during the manufacturing process must be accounted for in the following rolling processes and if SRI can predict to some extent the quality of the product then it is useful to have a measure of it. It is noted that this is a 'practical' index and gives information derived from experiment rather than laminate rolling theory and so might prove a useful guide when, for reasons of efficiency and economy, clad materials have to be rolled on the same mill as other materials. SRI should enable optimum mill settings to be predicted.

Observations on the rolling of clad materials

The theory of rolling applied to laminates has been examined and only general qualitative observations are made here. No attempt was made to verify or otherwise these theories of deformation as these seemed to be reasonably well confirmed, also this work is more concerned with the useability of stainless clad materials.

With all the experimental materials the hot rolling was performed on packs with unrestrained edges. This led to a pronounced barrelling effect. An ad hoc trial with a similarly sized mild steel slab showed that this barrelling effect was more pronounced in clad materials than in solid mild steel under the same conditions. The difference being about 5% greater for the clad material. This is explained by the clad pack being more restrained at the top and bottom by the stiffer stainless steel surfaces. This condition is equivalent to having a high coefficient of friction at the roll material interface. This is well known to increase the barrelling effect. When the material deforms in this manner it effectively alters the ratio of stainless steel to mild steel. The effect can be allowed for in the few cases where the ratio is critical and in any case the relative amount of stainless steel is increased which errs on the good side. There are positive advantages to having a rolled material in which the mild steel has spread to form a continuous edge as it can protect the clad sheet from edge cracking during cold rolling. When sheets were rolled with the edging of mild steel trimmed off it was found that edge cracking due to secondary tensions at the edge occurred at about 50 - 70% cold deformation which is typical of stainless steel. This necessitated an anneal prior to further deformation. Where the edge was left intact it was found that cold deformations in the order of 90% could be given between anneals. The edge protection effect was usually noted only on the wider materials, tube manufactured materials having low width to thickness ratios did not appear to suffer from so much edge cracking. These observations seem to accord with general rolling theory and experience. The extent of the spread in material reduced by 95% total is shown in fig. 19.

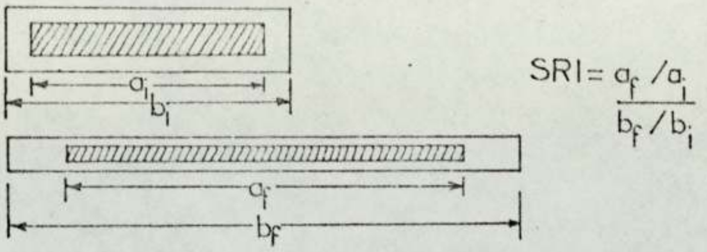


FIG.17 SANDWICH ROLLABILITY INDEX

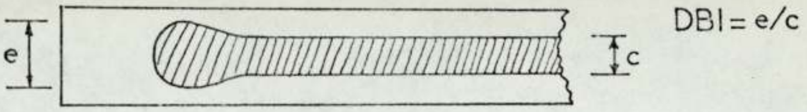


FIG.18 DOG BONING

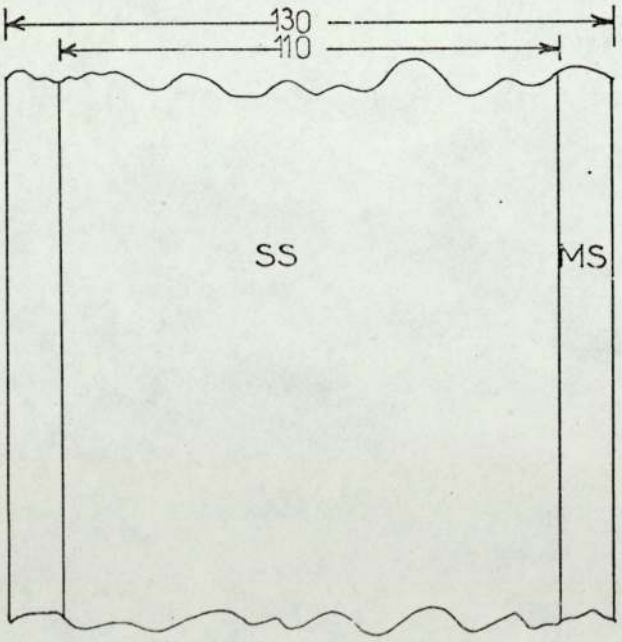


FIG.19 SPREAD IN ROLLING

No special difficulties were experienced when rolling any of the experimental materials hot or cold, except in the cold rolling of the single clad material where, due to the different deformation characteristics of the mild and stainless steels, curling of the material occurred. This was overcome on the laboratory mill by applying lubricant to one surface only. This altered the roll gap conditions in such a way as to overcome the bending moment produced by the varying deformabilities.

Where a successful bond was achieved at the hot rolling stage no deterioration was noted when material was cold rolled. This was shown by numerous tear tests where failure always occurred in the stainless steel rather than along the bond interface.

THE HEAT TREATMENT OF CLAD STEELS

i) Bulk heat treatment

The potential uses of stainless steel are such that it is probable that they will need to be heat treated to get optimum properties such as formability. The heat treatments that are normally given to each of the components of the laminate to develop these desired properties are of a differing nature and would seem to be mutually incompatible. Optimum formability is developed in low carbon steels by a sub-critical anneal at temperatures of 650°C to 700°C usually for long times, in practice a box anneal can have a cycle extending over 24 hours. The heat treatment of stainless steels on the other hand is usually at higher temperatures for shorter times followed by a fast cool. In the case of the mild steel, the heat treatment is to get a reasonably large grain size consistent with an acceptable surface finish on forming. With the stainless steel, the aim is to get everything, especially carbides, into solution and keep them there.

There appears that there is no unique compromise heat treatment though for clad plates a heat treatment of 1070°C to 1175°C for sufficient time to equalise and then air cool(28) is used, this being an annealing treatment for type 321 stainless steel clad onto ASTM A-302 (a .17% carbon plate steel).

ii) Surface heat treatment

An alternative to a compromise heat treatment is a differential heat treatment. This can consist of heating the surface to a high temperature at such a rate that the core does not rise appreciably above its own heat treatment temperature. This would enable the core to be heat treated at its optimum temperature and any carbides precipitated in the stainless steel as a result could be dissolved as a result of the solution treatment temperature achieved at the surface.

There are several methods of surface heat treating steels and these will be briefly considered:

a) <u>Flame heating</u>

This is performed usually by playing a high temperature flame, commonly oxy-acetylene, onto a surface, and traversing the sheet at such a rate that only the surface reaches the desired temperature. Often in sheet materials this is assisted by water cooling the underside of the sheet simultaneously with the heating. This becomes necessary when only a thin surface layer is required to reach the desired temperature. It is claimed that in this manner, surface temperature gradients of 1000°C in .05 mm can be readily achieved (29).

b) <u>Induction heating</u>

The principle involved here is that high frequency eddy currents tend only to flow in the surface layers of materials.

The magnitude of this effect is measured by the penetration depth which is defined as the depth at which the current density is 1/e of the current density at the surface.

$$P = \frac{3560\mu e}{f}$$

where e = resistivity

μ = permeability (30).

f = frequency

This is approximated to:

$$P = \frac{500}{f} \qquad (31)$$

Taking a typical .75mm clad sheet it can be shown that the frequency needed to confine the heating effect to a 0.075 mm layer would be approximately 49 MHz.

There is no apparatus as yet available to heat materials at this frequency. There is available an induction heating set that will heat materials at a frequency of 27 MHz but this apparatus will only heat materials approximately one cm in area. This technique, therefore, at the present state of development, does not represent a practical method of heating the surface layer of a clad material.

c) Electron beam heating

This is a high energy heating method which holds considerable promise for the on line surface heating of clad materials. Surface energies in the giga watts/sq. m range are easily achieved and by rapid traversing of the strip past the source it is possible to confine this heating to the surface layers. The major disadvantages is the need to work in a vacuum and the sealing of a continuous strip annealing system becomes a major obstacle(32).

d) Plasma arc

This method of high energy heating depends on the I^2R heating of a gas as it passes over an arc of high current density. The majority of these devices utilise a circular arc and so are not suitable for strip heating. Wide flame jets are being developed and this method will almost certainly become more important in the future.

None of these systems seems really suitable, at the present stage of development, for incorporation in a conventional strip production line. However, active consideration is being given to the future incorporation of an electron beam heaters into a strip line with a view to surface heating and so there is a distinct possibility that processes of the type outlined above would be available to be added to a new high technology plant such as the cladding line within the expected development span of such a project.

The heat treatment of experimental materials

The major aim of heat treatment was to induce optimum forming properties in the experimental materials. These will be discussed more fully when the formability of clad materials is discussed. Some less specific work was done on heat treating the three materials especially in association with the carbon content problem.

Experimental work was conducted on the resistance of the materials to thermal fatigue. From the literature it was noted that well bonded plates should withstand at least 10 000 cycles without failure(33). These tests were conducted in an integral manner, i.e. the whole interface was heated and cooled cyclicly. It was considered that a more severe test was to subject the laminated sheet to intense local heating and cooling. This creates more severe thermal stresses and is in fact more representative of the sort of abuse that the material would be likely to be subjected to in service. The test was conducted for a short number of cycles by heating a spot approximately 1 cm diameter by means of an oxy-acetylene torch to a temperature greater than 1000°C in approximately .1 seconds. The test piece was immediately quenched in water at room temperature. This was repeated at least 200 times and the interface was subsequently examined optically.

None of the laboratory produced materials showed any signs of bond deterioration after this test. It is

* Evidence for this 'thought'

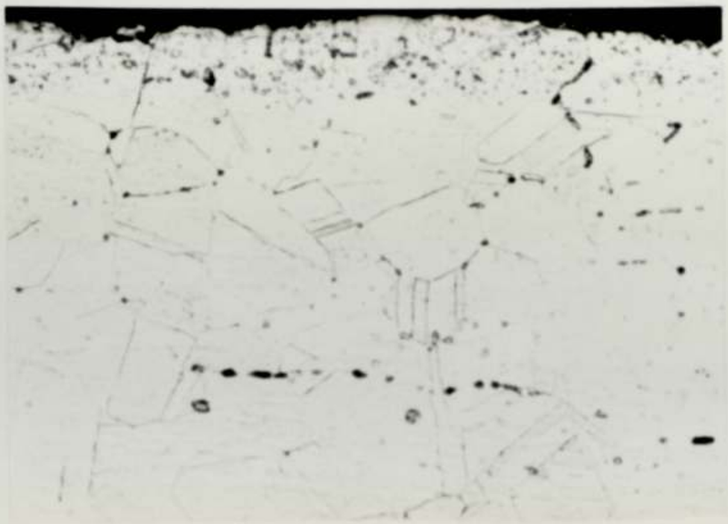
† Inadmissible.

‡ What manner? (See Page 83)

possible however, that a critical temperature could exist where the thermal stresses could be maximised, for instance, at the transformation temperature of α iron. It is thought that these would still be below the tolerance level of the bond. It is also realised that 200 cycles could be insufficient to give conclusive results but, in view of the exceptional severity of the test, it was considered a reasonably efficient quality control test.

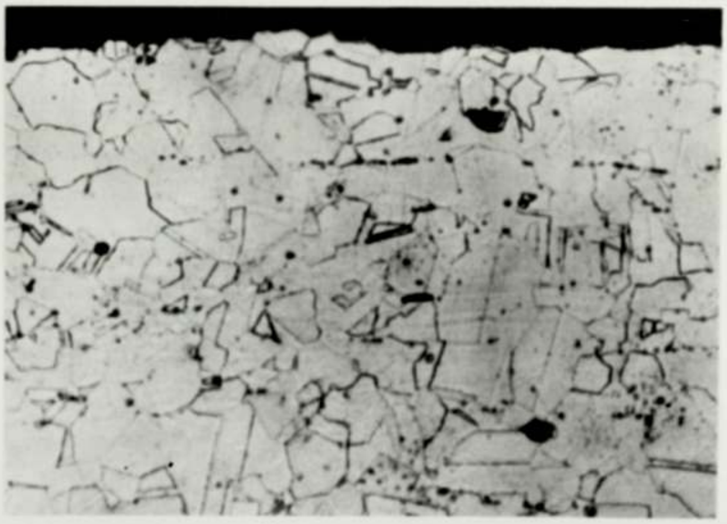
The possibility of giving a differential heat treatment has already been mentioned and some work of an exploratory nature was carried out on various methods of heating the various components of the laminate to their respective optimum heat treatment temperatures. The principle behind this was that the mild steel component could be given a normal optimising heat treatment, this it is known would allow carbides to precipitate in the stainless steel. Then the surface could then be heated in such a manner that the solution temperature of the carbides was reached in the stainless steel layer, while preserving as low a temperature as possible in the mild steel core. This, it would be hoped, should give optimum properties for forming, while removing the carbide precipitation induced corrosion hazard.

Experiments with various surface heating methods (plasma arc, oxy-natural gas flame) showed that this object could be achieved. Control of the laboratory built rigs was not very good and the capacity not sufficient to heat treat material sufficiently large to do any formability testing. Optical examination of the treated materials showed a decrease in the number of carbide present, this is illustrated in fig. 20.



UNTREATED

x 200



TREATED

FIG 20 CARBIDES IN STAINLESS STEEL

With these results and observations in mind, it was concluded that unless heat treatment was found to be technically necessary, a compromise heat treatment would be more economical and technically feasible. This line of attack was therefore abandoned and other methods of heat treating were assessed.

Carbides are taken into solution at high temperatures and precipitated at lower temperatures. Precipitation is not an instantaneous process and there is a time lag between the material achieving a precipitating temperature and precipitation occurring, an incubation time. This has been studied in stainless steels (34) and the time-temperature-effect curve replotted from this data is shown in fig. 21. As can be seen precipitation starts after a very short incubation time at around the optimum heat treatment temperature for low carbon steels. Methods have been developed for heat treating low carbon steels for short times because of the economic benefit to be gained with on line processing. The properties obtained are not exceptionally good (35) but the method offers a potential method of heat treating without carbide precipitation. Using the data reported above, a series of tests were done on the single clad material ONESIDE and softening curves determined for the mild steel and the stainless steel components. The results for this combination are shown in fig. 22. These demonstrate that full softening of the stainless steel layer can be achieved by heating the cold worked material at 850°C for 10 seconds. Referring back to fig. 21 it can be seen that this treatment avoids the precipitation 'nose' at the worst temperature as far as onset of precipitation is concerned. This means that a higher carbon level in the stainless steel can be tolerated, allowing the use of fairly high carbon core materials. It

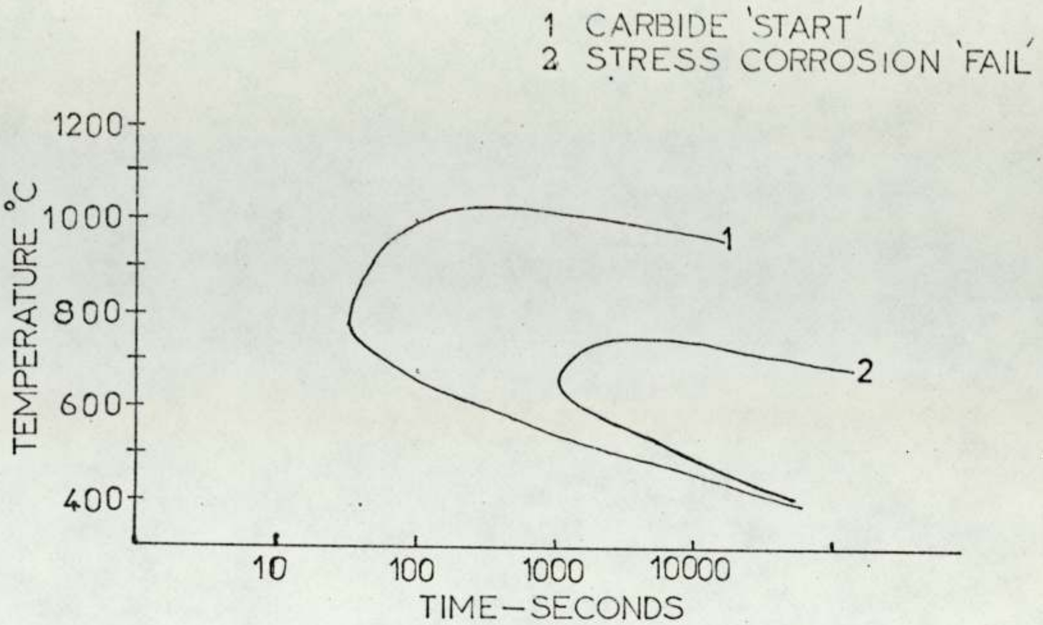


FIG21 CARBIDE PRECIPITATION

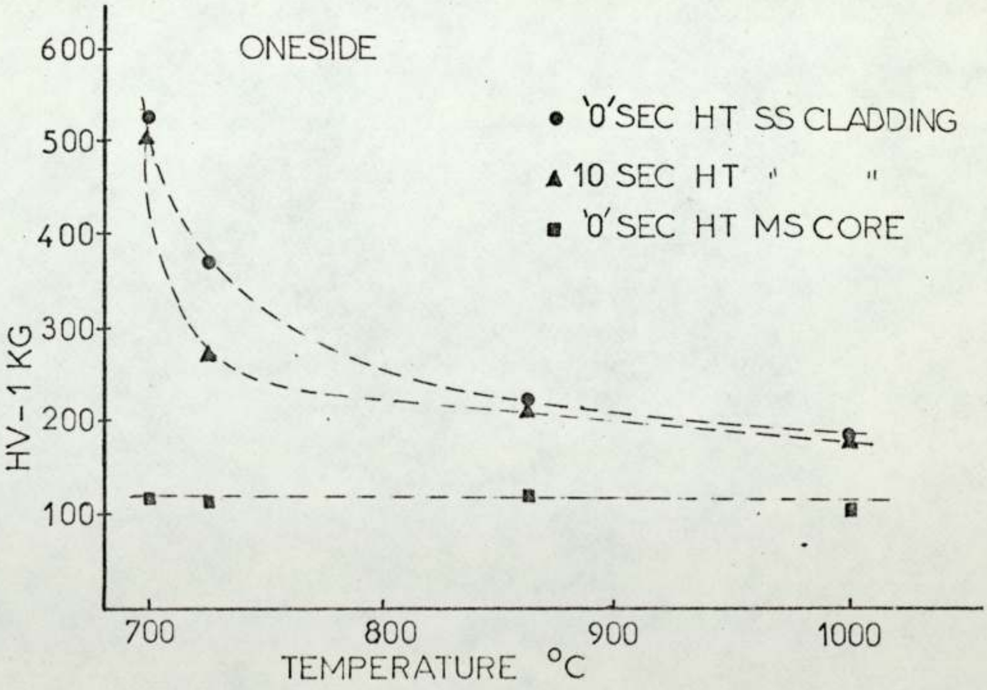


FIG 22 RAPID HEAT TREATMENT

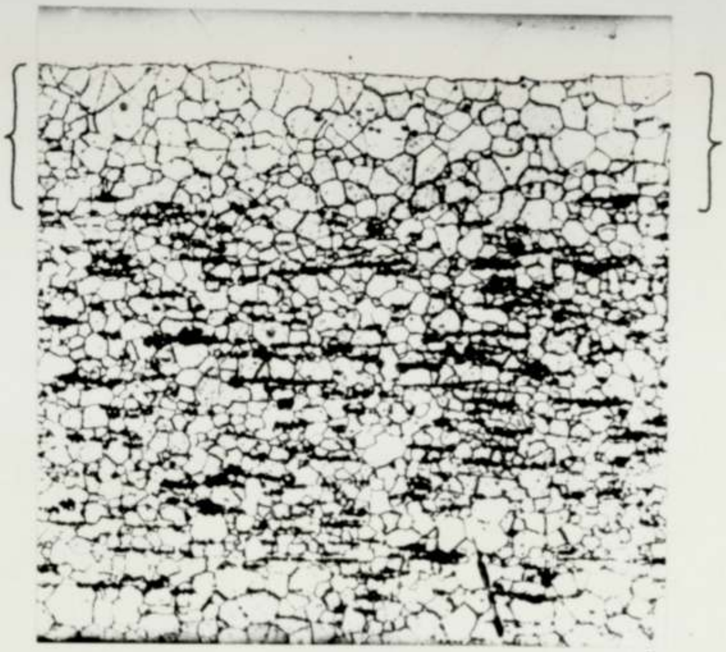
is assumed that the carbon is taken into solution prior to the final cold rolling treatment. It can also be seen from the results that the mild steel component is softened very rapidly at this temperature but this does not necessarily mean that optimum properties would be produced in the core or indeed in the stainless steel. This is, however, a small price for the increased corrosion resistance obtainable using this method of heat treatment.

If a high carbon cored material is treated this way it must not be subjected to high service temperatures and this must be borne in mind when specifying materials for high temperature use.

THE DIFFUSION OF CARBON

One problem that is likely to be present in stainless clad steels is the effect of carbon diffusing from the mild steel into the stainless steel layer. This, if it is excessive, can give rise to the well known weld decay phenomena. Carbide precipitation can also give rise to other corrosion activated phenomena (36), this being amply demonstrated by the pitting experienced in early examples of tube encapsulated materials when these were pickled to remove heat treatment scale. These being made with powders which contained (accidentally) cast iron shot!

Stainless steel technology takes account of the adverse effect of carbon in 18-8 type materials and consequently the maximum carbon content of materials covered by BS 1449 is about .12%. When such materials are combined with, for example, a drawing quality steel, the carbon content can range up to .15% within BS 1449. This gives rise to a thermodynamic inequilibrium and so diffusion occurs down the concentration gradient from the mild steel core into the stainless steel cladding. Chromium has a large affinity for carbon (ΔG Cr_7C_3 is about -40k cals/mole at 1000°C) and so it is likely that a lot of the carbon will be tied up as chromium carbides. In some grades of stainless steel, i.e. type 321 which are to be welded or subjected to high temperatures an addition of titanium or niobium is made to preferentially form carbides. These, of course, prevent the local chromium depletion at grain boundaries caused by the formation of chromium carbide and so remove this case for 'weld decay', Due to the largely one way diffusion of carbon into the stainless steel the mild steel core will be decarburised in the interface region. This effect is seen in fig. 23.



× 150

FIG23 CORE DECABURISATION

Diffusion is negligible at temperatures below about 700°C so the main opportunities for diffusion will be in the manufacturing and processing cycle where hot working takes place at temperatures above 900°C. Further diffusion can take place during annealing and other heat treatment operations.

Most of the work on this problem has been done on the problems arising in clad plate. The problem does not seem to have arisen in the sheet products used for domestic holloware as this material is clad with an unstabilised stainless steel, type 304.

The diffusion coefficients of carbon in the clad plate situation have been measured(37) and these can be used to predict the carbon levels to be expected in sheet materials. After hot rolling, the carbon distribution in the stainless steel can be assumed as in fig. 24(37) and by a simplification of the second law of diffusion solved for the boundary conditions of an initial concentration at the interface with no diffusion across this interface, it is possible to plot the expected concentration distance curves. Due to the initial decarburisation of the mild steel during hot rolling there is in effect a fairly high diffusion potential from the stainless to the mild steel but the thermodynamics of chromium carbide in the system would seem to preclude any reverse diffusion from the stainless steel. This allows the non transport simplification to be reasonably assumed, especially in the light of the complexity of the system and the relatively poor state of the theory. In spite of this there has been found that there is a reasonable agreement between theory and measurement as referred to above.

If the initial distribution of carbon after hot working is similar to that in fig. 24 it is possible to treat the problem by assuming that all the carbon is present in a zone to the left of the Matano interface. The solution to the second law of diffusion for this boundary condition is then (from Crank$^{(38)}$)

$$C = \frac{Co}{2} \left(\frac{h - x}{2\sqrt{Dt}} + \frac{h + x}{2\sqrt{Dt}} \right)$$

The validity of this solution depends on there being no further diffusion of carbon into the interface region from the core or vice versa.

A spectrum of calculated diffusion curves for the initial carbon distribution for a 10% thickness of stainless steel on a .75 mm thick sheet is shown in fig. 25.

These demonstrate that, in theory at least, that the problem will not be serious in terms of excess carbon concentrations at the surface for extended heat treatments at elevated temperatures.

In practice it is possible that an intolerable level of carbon may build up in the stainless steel layer due to to the cumulative effects of cold work enhanced diffusion combined with annealing. An example of this effect is shown in table IV which shows the effect of various final anneals on the total carbon content of the stainless steel cladding layer of ADCLAD. These were measured by a total chemical analysis after dissolution of the core material in nitric acid. It was found impossible to measure the difference in carbon contents of the cladding layers from the interface region to the surface due to their extreme thinness (.075mm≈) but some qualitative idea may be gained by comparing the total carbon contents with the estimated integrals of theoretical diffusion curves. Doing this shows that in the majority of cases it is inadvisable to use a core steel of the carbon content of ADCLAD. If the necessity did arise to use material of this carbon content

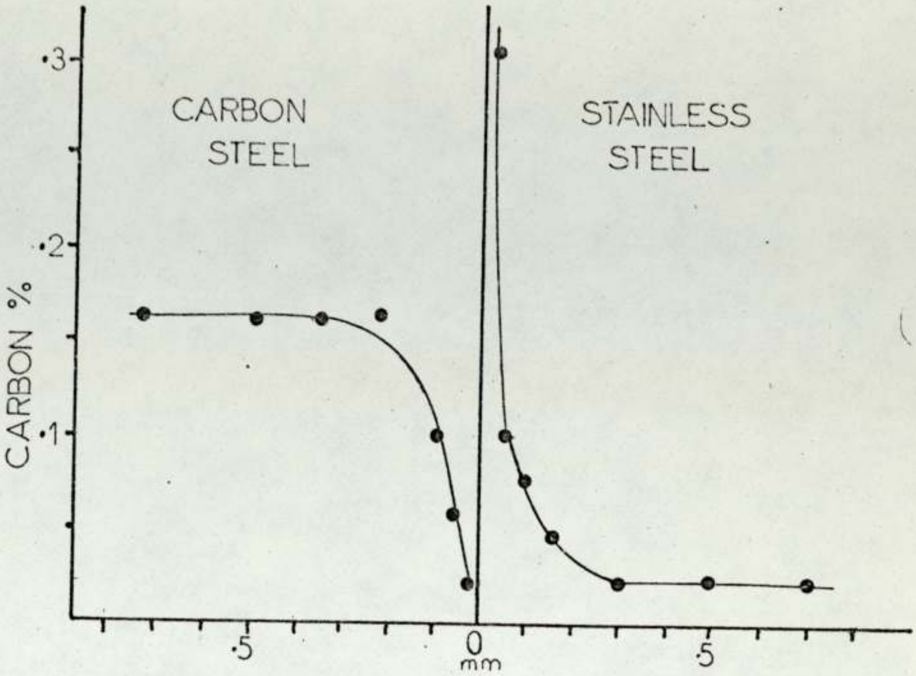


FIG24 PROJECTED CARBON DISTRIBUTION AFTER C.R. (FROM REF 37)

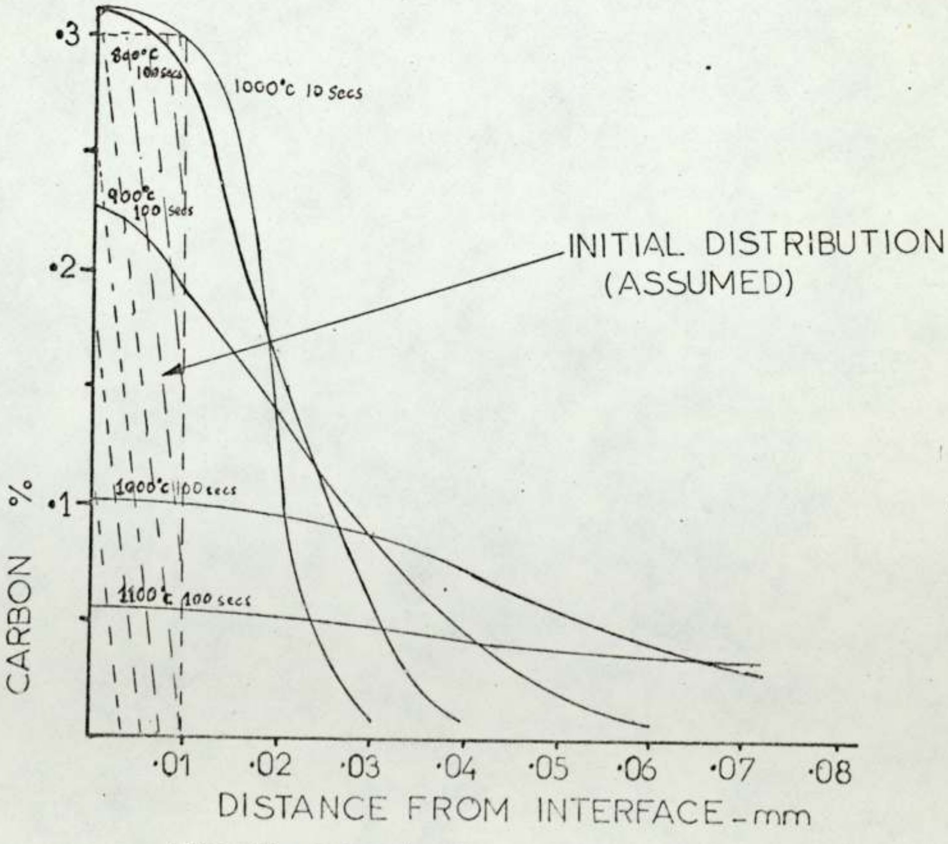


FIG 25 CALCULATED DIFFUSION CURVES

it might be possible to tolerate it if the addition of further carbide forming elements to the stainless steels could be made, i.e. Ti or Nb. As already mentioned titanium is widely used for this purpose though it is not usually added in quantities sufficient to cope with the expected carbon influx from the core, the specified addition for type 312 steels being 5x the carbon content. What effect the large number of titanium carbides would have on the formability and other properties is not known but it would almost certainly be detrimental if these are excessive.

An alternative approach, if the situation demands the use or a relatively high carbon core is to separate the core and cladding by a barrier layer of nickel. This has been shown to considerably reduce the diffusion of carbon across the interface(39).

The improvement to be gained by using lower carbon core materials can be seen from table V, where the three experimental clad steels of varying carbon contents have been analysed for carbon after similar heat treatments.

TABLE IV

EFFECT OF HEAT TREATMENT ON CARBON IN CLADDING LAYER

ADCLAD

HEAT TREATMENT $^{\circ}C$	CLADDING LAYER CARBON %
700 1 hour	.12
800 1 hour	.23
1000 1 hour	.30
700 1 hour + 1000 10 mins.	.26
As hot rolled	.12
As received	.06

TABLE V

EFFECT OF CORE CARBON CONTENT ON CLAD LAYER CARBON CONTENT HT 1000°C 1 hour

MATERIAL	CORE CARBON	CLAD LAYER CARBON
ADCLAD	.11	.30
ONESIDE	.08	.28
EXCLAD	.004	.042
TYPE 321 SS	-	.04

PROPERTIES OF CLAD STEELS

- PHYSICAL PROPERTIES
- MECHANICAL PROPERTIES
  - the tensile properties of experimental materials
- FORMING CLAD STEELS
- THE EXPERIMENTAL FORMING OF CLAD STEELS
  - stretch formability
  - the deep drawability of exclad
  - examination of a commercial clad material
- DISCUSSION

THE RULE OF MIXTURES

A lot of the physical and mechanical properties of clad materials can be derived from the rule of mixtures.

i.e. $\text{Property}_{A + B}$ = Property A x Fraction A +
Property B + Fraction B.......

In fact laminates seem to be the only class of composite materials that obey this rule to a high degree. In most physical properties the order of lamination is not important though, in the thermal properties, it can have an effect (see thermal conductivity). Laminate effects can be important where, in bi-metallic strips, for instance, stresses are set up and bending can occur. With double clad materials, of course, these effects will not occur.

PHYSICAL PROPERTIES

The physical properties of clad steels may be calculated from the law of mixtures. Working equations for most of the more important physical properties have been published (40) and are given below. It may be noted that clad materials have different properties depending on whether the properties are measured in the through thickness direction or parallel to the surface. Only the case of two constituents is considered here.

i) Density

$$\rho_c = \rho_a F_a + \rho_b F_b$$

ρ is density
F is fraction

ii) Thermal Conductivity

a) Parallel to surface -

$$K_c = \frac{K_a t_a + K_b t_b}{t_a + t_b}$$

K is thermal conductivity
t is thickness

This equation predicts a linear variation of conductivity with t. It has been found, however, that under some practical non-equilibrium conditions that the insulating effect of a stainless steel surface causes the lateral conductivity to go through a maximum (41).

b) Normal to surface -

$$\frac{t_a + t_b}{K_c} = \frac{t_a}{K_a} + \frac{t_b}{K_b}$$

It is interesting to note that the thermal conductivity of stainless steels increases with increasing temperature while that of carbon steels decreases with temperature. It is therefore possible to prescribe a laminate that will have almost a zero change in thermal conductivity over a given temperature range. For example, for a 20% stainless laminate (10% per side) the thermal conductivity ranges from 47.6 w/mK at $0^{o}C$ to 31.6 at $1000^{o}C$ whereas the respective figures for stainless and mild steels is 34.8 w/mK to 70.2 w/mK and 52.0 w/mK to 27.5 w/mK. If a 50% stainless steel laminate is used then the variations over the same range is only 5 w/mK.

iii) Thermal Expansion

a) Through thickness

$$\alpha_c = \frac{\alpha_a t_a + \alpha_b t_b}{t_a + t_b}$$ α is thermal expansion coefficient

b) Along length

$$\alpha_c = \frac{\alpha_a + (\alpha_a - \alpha_b)\, t_b E_b}{t_a E_a + t_b E_b}$$

Differential thermal expansion could lead to thermal bending in materials clad on one side only. This effect is not apparent in materials clad on both sides as the bending moments tend to cancel out, this is assuming that the thickness of stainless steel is the same on both sides of the laminate, as would be the case with a practical laminated sheet steel. A possibility is that local thin spots would cause distortion if they occur on one side of the sheet only. It is to be hoped that this problem would be minimised by an averaging out of these local variations over the whole sheet. They could of course be eliminated by careful quality control.

iv) Electrical resistivity

a) Through thickness

$$\gamma_c = \frac{\gamma_a t_a + \gamma_b t_b}{t_a + t_b}$$ γ is resistivity

b) Along length

$$\frac{t_a + t_b}{\gamma_c} = \frac{t_a}{\gamma_a} + \frac{t_b}{\gamma_b}$$

This anisotropy could be important in a spot welding operation.

As stated, all these properties are calculated on the basis of there being only two components present. With the materials in question where diffusion has occurred at the mild steel/stainless steel interface, there will be a gradation in properties over this interface. For accurate calculations of physical properties this diffuse interface will have to be taken into account. In most real situations, however, this effect can be safely neglected.

MECHANICAL PROPERTIES

As with physical properties the mechanical properties of clad materials and composite materials in general may be determined from the law of mixtures. This relationship has been found to hold true over a large range of conditions and materials.

For the case of laminates it is to be expected that the two or more components of the composite deform together under the influence of a stress. This has been confirmed for roll bonded laminates$^{(42)}$. Most of the mechanical properties of clad materials can be calculated from this 'Equal Strain Hypothesis' and methods of doing this will be presented.

i) Stress Strain Curves

Stress strain curves for laminate materials can be calculated, to a first approximation, from;-

$$\sigma_c = \sigma_a \times F_a + \sigma_b \times F_b$$

where σ is stress
F is fraction of component

Numerical values are obtained by substituting suitable expressions for σ (e.g. the Ludwik equation $\sigma = A\varepsilon^n$). The effect that cladding has on the properties of the composite is shown in the theoretically calculated curves of fig. 26.

ii) Elastic Modulus

The elastic modulus of clad materials can be calculated from the law of mixtures and is given by:

$$E_c = \frac{4E_a\left((t_a - C)^3 + C^3 + (E_b/E_a((t_b+t_a)^3) - (t_a-C)^3)\right)}{T/t^3}$$

$$C = \frac{E_a t_a^2 + E_b t_b^2 (2t_a + t_b)}{2E_a t_a + E_b t_b}$$

E = elastic modulus

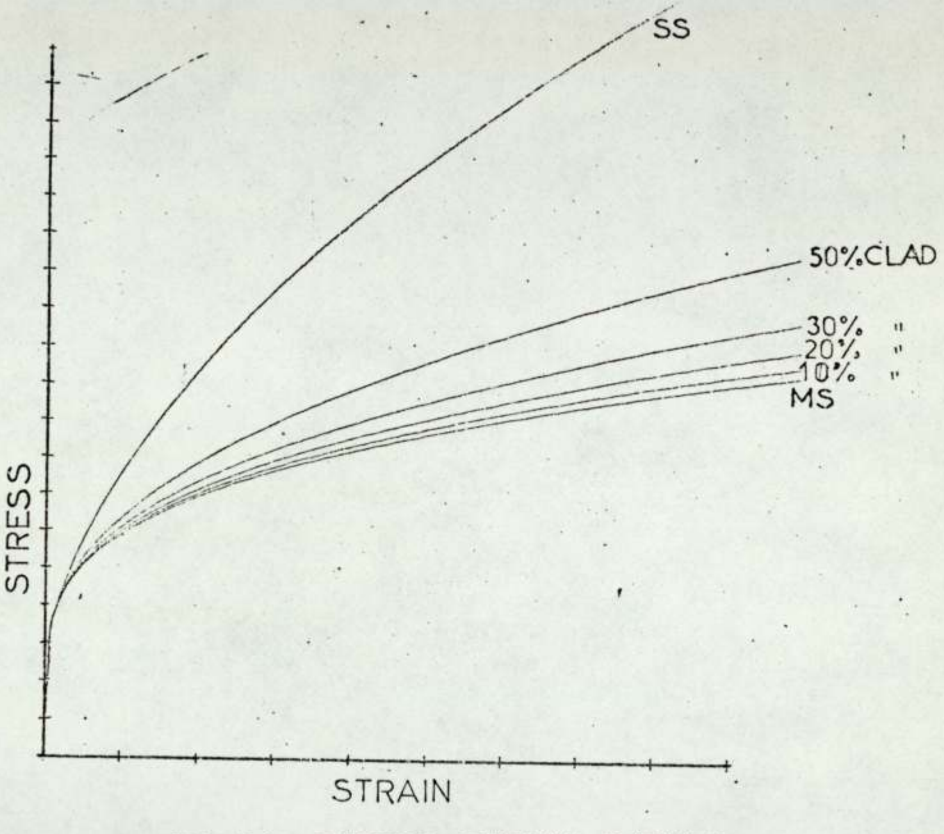


FIG.26 STRESS STRAIN CURVES (COMPUTER GENERATED)

iii) Ductility

The ductility of laminate materials can usually be predicted from the ductility of the least ductile component. There is no direct relationship between the parameters but it can be noted that with the practical case of double clad materials the order of lamination can have an effect on composite ductility. In the case, for instance, of a hard material sandwiched between two more ductile layers the triaxial stress system acting on the more brittle core can, in effect, reduce this brittleness, also the vulnerable surface is somewhat protected thus reducing the liability of premature brittle failure. This effect is well known in the glass filament field. The ductilities of both components of stainless clad mild steel are similar and so most of the arguments presented above do not have much application.

iv) Plastic Anisotropy Factor (R value)

For clad material consisting of only two components the plastic anisotropy can be calculated in the following fashion:

The work done in extending the material is given by

$$dw = \sigma_x * d\varepsilon_x + \sigma_y * d\varepsilon_y$$

where σ = stress
ε = strain
x,y= directions

This can be represented by an equivalent stress in the x direction.

$$dw = \sigma_x' * d\varepsilon_x$$

and $$\sigma_x' = \sigma_x + \sigma_y * \frac{\varepsilon_x}{\varepsilon_y}$$

This can be evaluated from Hill's anisotropy equations(43) and the Levy von Mises equations. This enables σ_x to be plotted as a function of $\Delta(\mathcal{E}_x/\mathcal{E}_y)$. The system will act so as to do the minimum work so the 'R' value will be the minimum of this curve, i.e.

$$\frac{d\sigma_x}{d\Delta} = 0$$

The calculation is applied to each phase in turn and the composite 'R' value is found from the minimum of the summed weighted curved.

$$\sigma_{xc}'' = \sigma_{x\alpha} * F_\alpha + \sigma_{x\gamma} * F_\gamma$$

The value of $\varepsilon_x/\varepsilon_y$ at the minimum is equated with R/1+R to get a composite R value.

The derivation of the functions described is given more fully in an appendix together with some calculated curves that show the effect of differing properties in the core and cladding material.

v) Work Hardening Coefficient

The 'n' value is the exponent in the Ludwik $(\sigma = A\varepsilon^n)$ equation and is known to have a bearing on the stretch formability of materials. It can be calculated from the 'n' values of the constituent parts of a clad material in a manner similar to that used to predict stress/strain behaviour.

$$\sigma_c = \sigma_a \times F_a + \sigma_b \times F_b$$

and from the Ludwik equation,

$$A_c\varepsilon^n = A_a\varepsilon^n \times F_a + A_b\varepsilon^n \times F_b$$

A can be calculated by substituting in a strain of 1,

$$A_c = A_a \times F_a + A_b \times F_b$$

and hence after algebraic manipulation it can be shown that

$$n_c = \frac{\log(A_a\varepsilon^{na}F_a + A_b\varepsilon^{nb}\ 1 - F_a) - \log A_c}{\log C}$$

The Tensile Properties of Experimental Materials

The tensile properties of the clad materials were studied only where they had relevance to the more useful properties of sheet steels, i.e. the formability. A lot of the properties derived from the tensile test were a by-product of the evaluation of R.

No attempt was made to verify the equal strain or mixture laws as it was considered that these had sufficient experimental backing from many other sources.

Typical properties are presented for the three experimental materials in various conditions in table VI,

Examination of these shows no unexpected features except possibly the high yield to ultimate ratio of the Exclad material. In general the tensile strength compares favourably with conventional stainless steel, as does the ductility.

TABLE VI

TENSILE PROPERTIES

Material	Heat Treatment	TS MN/m^2	L of P MN/m^2	Elong. %
ADCLAD	Annealed 1000°C 10 mins	523	324	32
ONESIDE	R.H.T. 725°C	432-477	-	-
	" 850°C	432-462	-	-
	" 1000°C	462	-	-
EXCLAD	Annealed 1 hr. 700°C	462	-	30
	890°C	408	-	36
	1000°C	354	-	50
	R.H.T. 800°C	370	-	-
	" 1000°C	370	-	-
	Annealed 10 min. 850°C	387	180	37.5
	890°C	376	154	44.5
L	1000°C	383	171	40
T		342	152	44.6
45		321	143	46.5
L	Annealed 1 hr. 850°C	335	139	54
T		356	159	44
45		339	142	42
L	1000°C	340	145	56
T		325	149	38
45		316	145	49

FORMING CLAD MATERIALS

Very little work has been done on the forming of clad sheet and except for some work on coated steels, i.e. tin(44) and zinc(45) where the coating has lubricating properties. The only work of relevance to clad sheets has been done on copper clad mild steel(14). It was shown that the maximum draw stress for a composite sheet can be calculated from the draw stress of a simple material by applying the equal strain hypothesis.

There seems to be no published data on the practical performance of clad steels except for some vague indications in manufacturers literature about the performance of clad plates. The claims are that clad plates deform in a manner similar to solid stainless but quantitative information is lacking. There are indications that type 304 stainless steel clad onto a low carbon deep drawing grade steel performs marginally better than solid stainless steel in the manufacture of domestic holloware(2).

Where crystallographic textures of two components are different there is the possibility of a reduction in the caring thus giving material savings.

THE EXPERIMENTAL FORMING OF CLAD MATERIALS

i) Materials

Three materials were used in the investigation of formability in stainless clad steels. These were chosen as being representative of the types of core material that would possibly be produced by the powder route already described. In all cases a stabilised type of 18-8 stainless steel was used as the cladding material.

The materials were:

a) A roll bonded double clad commercial cold forming grade steel of about .11% carbon. The material was code named ADCLAD.

b) A roll bonded single clad deep drawing quality mild steel of about .02% carbon. The material was code named ONESIDE.

c) An explosively double clad interstitial free steel containing about .004% carbon. This material was code named EXCLAD.

Details of the manufacture and working of these materials are given in appendix 2, together with the analyses of the constituent materials.

Due to the size range of the materials that could be produced in the laboratory it was not possible to make a full formability assessment on the roll bonded materials. This was another argument for using explosive cladding for the IF steel cored material. The larger size that this material was produced in enabled a fuller assessment of the formability to be made.

As formability testing formed a large part of the experimental work the apparatus that was used for this and the methods of testing are described in appendix 1 rather than in the text. There were no standard procedures in the author's laboratories for formability testing and so these had to be developed with the equipment available. The reasons for adopting the tests used are discussed in the relevant appendix.

Stretch Formability

Stainless steels usually have superior stretch formability to mild steels. It is possible that the Erichsen cup height, for example, would be favourably affected by having a stainless steel layer on the surface of mild steels. This effect was investigated by performing Erichsen tests on the single clad material ONESIDE.

It is recognised that the failure cup height decreases with decreasing gauge so in order to show up any effects the material was tested at a series of thicknesses. These were produced with similar reductions by cold rolling (80%) and annealing. Material was also produced with various proportions of stainless steel cladding by grinding away the backing material after hot rolling. The range of materials produced was:

Thickness	.25 to 2.3mm
Percent cladding	8% to 30% (also 0% and 100%)

The stainless clad samples were heat treated at 1000°C for 15 mins. Some non-clad samples of the backing steel were heat treated to give optimum properties by giving a slow cool after 15 mins at 700°C. These were compared with the clad and unclad samples treated at 1100°C. Samples of stainless steel were produced by etching away the mild steel after cold rolling.

The results are shown graphically in fig. 27. These indicate that the stretch formability of the stainless steel does not have a beneficial effect on the laminate. In all cases, allowing for the spread of experimental results, the mild steel up configuration gives better

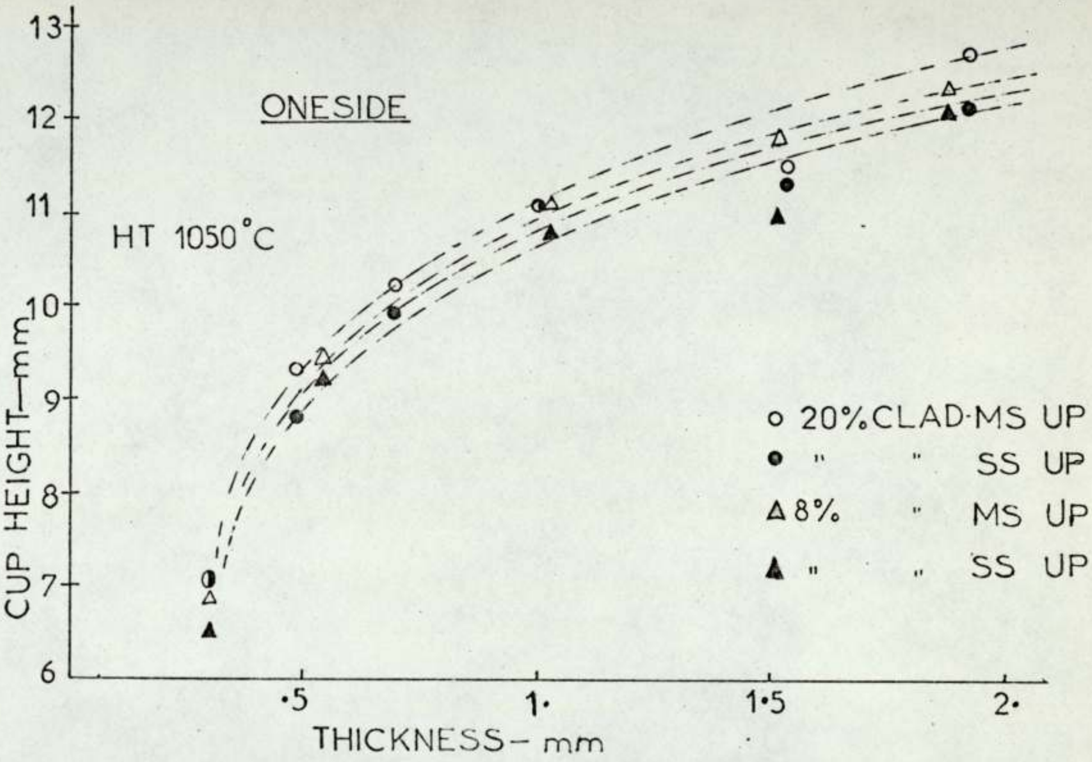


FIG 27 CUP HEIGHT V THICKNESS

drawability than in the reverse configuration. The difference, though fairly small at thicker gauges and non-existent at lower thicknesses, is real. The convergence at thin gauges is no doubt due to the insensibility of the Erichsen test at these thicknesses. The non beneficial effect of lamination is more marked when the curves for the laminated materials are compared with that for the unclad mild steel after similar heat treatment. Un-laminated stainless steel is only represented by a few points but these indicate that the poor performance of the laminate in this stretching test is not due to any inferiority of the stainless steel. Friction was eliminated as a possible cause by increasing the number of layers of polythene lubricant and adding oil between the polythene layers. This modification to the lubrication system had no effect on the cup heights measured on both solid stainless steel and mild steel available generally in the laboratory, when compared with a single polythene layer.

Due to the geometry of the Erichsen test the failure point of the material under test will depend to some extent on the ductility of the outer material and for the systems steel-copper copper-aluminium and stainless steel-aluminium. This effect has been confirmed. This does not however offer an explanation of the 'over riding' of the expected superior stretch formability of the stainless-steel as the ductilities are similar. A possible explanation is the presence of a diffusion zone between the stainless layer and the mild steel, There will be, at a small distance into the diffusion zone, a region containing amounts of chromium and nickel that form what amounts to a ferritic stainless steel. This type of material does not have good stretch formability. The presence of this, near to the surface when the stainless steel is uppermost could account for the poorer observed properties. This layer would of course be further away from the surface when the mild steel is uppermost and consequently it would have a considerably lesser effect.

The double sided material ADCLAD was used mainly for heat treatment experiments described elsewhere, however some Erichsen cups were drawn during these experiments which have relevance here. Cup heights were measured for the material in different conditions.

The grain size of the core material was varied by giving the material a heat treatment of two minutes at various temperatures between 800°C and 1100°C. Erichsen cups were drawn using polythene lubricant and the cup heights measured by a depth micrometer. The grain sizes were determined optically.

The results, given in table VII, show that there is no apparent correlation between the core grain size and the Erichsen cup height. The grain size of the stainless steel layer was found to be constant for all the heat treatments at about 20μ MI. This indicates that the core condition has little discernable effect on the stretch formability of the clad material and that the cladding layer has an over-riding effect. Increasing the time at 1100°C to 10 mins allowed the grain size of the stainless steel layer to increase to a MI of 29μ. The transformation grain size of the core material was not substantially altered from 10.6μ. An Erichsen cup drawn from the material in this condition was measured at 9.5mm. The increase may be attributed solely to the change in condition of the cladding layer, confirming the influence of the outer cladding layer in stretch forming.

Exclad

This material, being produced in a larger size, was subjected to a series of tests to determine as many of the formability parameters as possible, with the equipment available. Assessments were made on the material in a variety of conditions and heat treatment states in order to determine the optimum condition for forming this high quality material.

The core material was selected as a best material both from the carbon problem point of view and the formability point of view. The general properties of interstitial steels have been published(47) and show that there is some advantage in using these materials, though at the present state of the art the material is likely to be very expensive. The analysis of the material is given in appendix 2.

In order to eliminate an unimportant variable all the material was tested at a standard gauge of .75mm.

As a comparision some commercially available material was obtained and the properties of this material determined. This material is used in the manufacture of domestic hollowware and according to the user performs in a highly satisfactory manner and if anything presses in a manner slightly superior to conventional stainless steel. Properties of a conventional stainless steel were also evaluated.

The Effect of Cold Reduction

The Erichsen test was used to determine the effect of varying cold reduction on the material. The test is sensitive to surface condition and, as there is liable to be a considerable variation in strain gradient through the material due to the cladding configuration, it was thought that this would show up any effects due to cold reduction.

The material was initially heat treated for short times at temperatures between 700°C and 1100°C and tested. The results of this are shown graphically in fig. 28. These show that there is no significant difference in the behaviour of the material after different reductions when subjected to this heat treatment. In order to determine whether the core or the cladding was most active in masking the effect of cold reduction some tensile specimens were used to obtain R values after a simulated box anneal (programmed heat to 700°C followed by a soak for one hour and a slow programmed cool). This should put the core material in a highly favourable condition and the effect in the R value should be marked. why? The results are shown in table VIII. These would appear to demonstrate from the $\bar{R}$ values obtained that the amount of reduction has little effect on the plastic anisotropy. This treatment should have given R values in the region of 2 for core material$^{(46)}$ which should be sensitive to the amount of cold work. The failure to do so must mean that the stainless steel is masking the effects of cold reduction. It can be noted here that the amount of variation in $\bar{R}$ value is within the experimental variation using the single strain technique discussed in appendix 1. The stainless steel cladding materials is seen to be relatively insensitive to the amount of reduction. As a further check the transverse R values were measured for the clad material in two conditions of cold reduction. The material was heat treated for 1 hour at a series of temperatures in order to show up any cross over effects (the properties of stainless steel increasing as the properties of mild steel decrease). The results of this are shown in table IX. These are interesting in that they show a similar trend to the Erichsen values with a peak around 850°C to 900°C. Increasing the time of heat treatment did nothing to differentiate between different reductions as can be seen from the results shown in table X, which are

TABLE VII

ADCLAD

Core Grain Size (μMI)	Erichsen
8.4	8.7
9.2	7.9
9.4	8.3
10.4	8.1

TABLE VIII

R AFTER BOX ANNEAL

Reduction	R (mean of 4)		$\bar{R}$
60%	L	1.27	1.19
	T	1.24	
	45	1.12	
70%	L	1.10	1.26
	T	1.48	
	45	1.23	
75%	L	1.08	1.21
	T	1.39	
	45	1.19	
80%	L	1.07	1.26
	T	1.21	
	45	1.38	

TABLE IX

EXCLAD

Reduction	Heat Treatment (1 hr at temp AC)	R_T (mean of 4)
70%	720	1.7
	800	1.8
	900	1.8
	1000	1.1
80%	720	1.6
	800	1.6
	900	1.7
	1000	1.1

TABLE X

EXCLAD

Reduction	Time at 850°C (min)	R_L (mean of 4)
65%	10	.98
	30	1.33
	60	1.07
75%	10	1.14
	30	1.26
	60	1.22

the R values of the material heat treated at 850°C. There are no significant differences between the R values of the two reductions.

The Stretch Formability of EXCLAD

As no apparent differences between the stretch formability of different reductions was found, all other formability assessment was conducted on material which had a standardised reduction after inter-stage annealing of 75% to reach .75mm.

The majority of results for the stretch formability as reflected in the Erichsen test have already been presented in fig. 28. These show that there is a peak value for cup height between 850-900°C. A possible explanation for this behaviour is to be found in the low carbon level of the core steel. At a carbon level of .004% the material should be in the α phase field up to about 900°C. This is mirrored by the continuous increase in core grain size as the heat treatment temperature is raised for a given time. This is illustrated in fig. 29. The grain size suddenly falls after the material is heated treated in the γ phase field. The grain size becomes the transformation grain size. The grain size of the stainless steel on the other hand increases continuously above the recrystallisation temperature of about 700°C, with no fall off, as of course it is in one phase field all the way up. The material properties are thus seen to be additive. This infers that the relative effect of the core on the stretching properties is greater than was admitted in the previous discussion of the stretching behaviour of ONESIDE and ADCLAD. If this is so it would be expected that a change in the condition of the stainless steel above the α - γ transformation temperature of the core would affect the properties of the laminate by altering only the properties of the

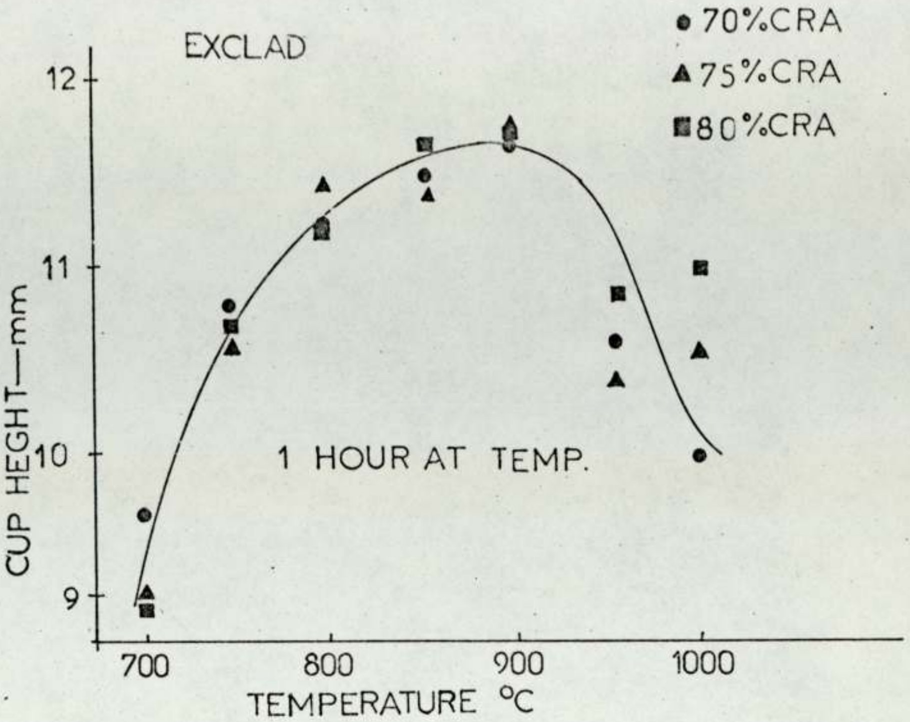


FIG28 ERICHSEN CUP HEIGHT v HEAT TREATMENT

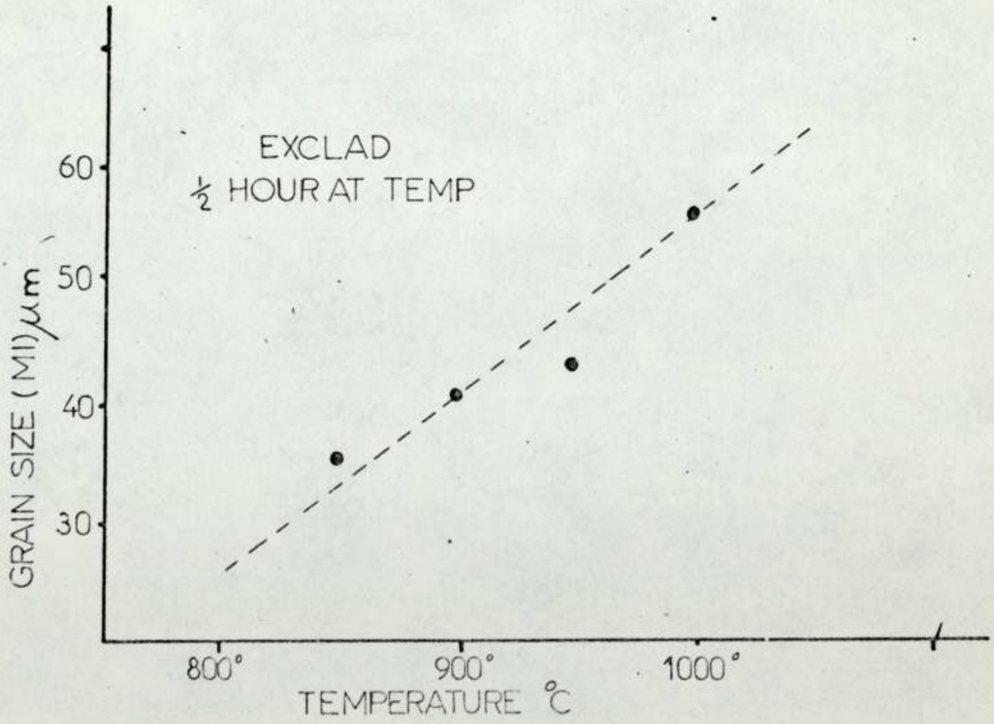


FIG29 GRAIN SIZE – TEMPERATURE

cladding. For instance if the heat treatment time is decreased then it would be expected that the properties would also decrease. If, however, the time is chosen such that the core properties remain fairly constant, the effect of the stainless steel properties on the cup heights can be seen.

It was found by experiment that if the heat treatment time is limited to 10 mins the core transformation grain size did not change appreciably. The results on laminate samples heat treated for 10 mins at various temperatures are shown in fig. 30. It can be seen that the peak is falling at a slightly higher temperature due to the less annealing that takes place in the stainless steel in the shorter time. This demonstrates that stainless steel has a more marked effect than the core steel in determining the stretch formability. This has already been deduced from experimental work on the other materials.

Other stretch forming simulative tests were conducted on the material. Mainly with the object of determining a suitable heat treatment for the combination.

The stretching behaviour of the material when tested with a round nosed Swift punch, showed a similar trend to the smaller Erichsen test. The cup heights were seen to increase up to a maximum at around 900°C and thereafter decrease. This is illustrated in fig. 31. This behaviour was also generally followed for 100 mm dia. circular hydraulic bulges. The falling off at over the optimum temperature is not so marked in this test and the results are presented in fig. 32. It can be seen from the results of the three different tests that the smaller the scale of the test the less sensitive it seems to become to material condition. This, it is argued, could be due to the greater sensitivity of the smaller scale tests to surface condition.

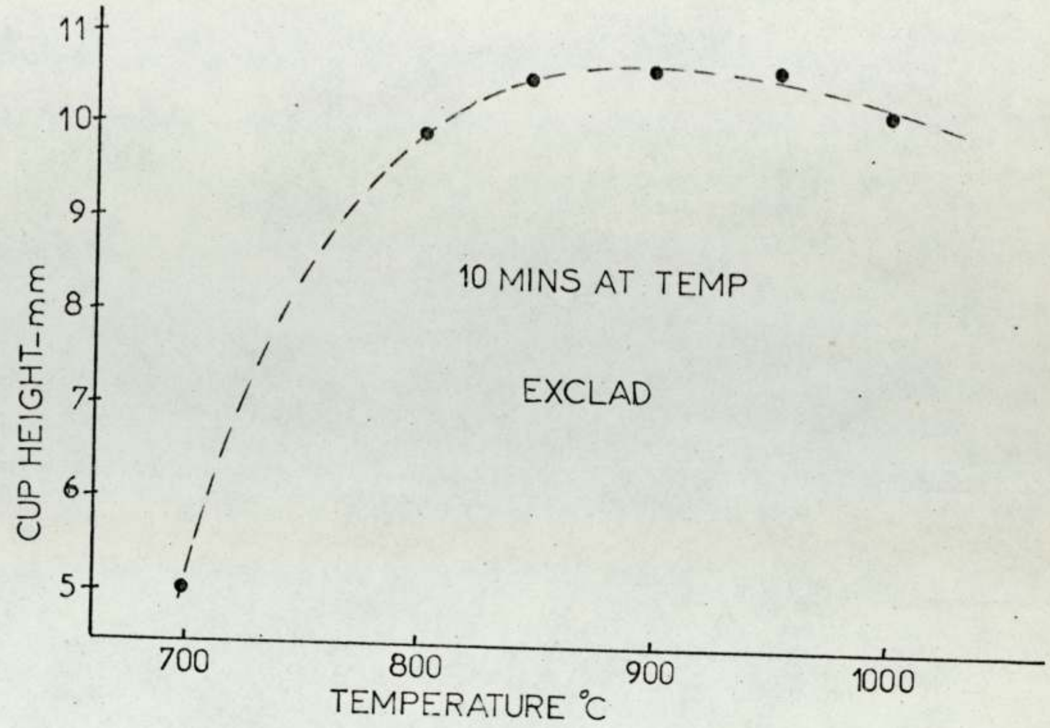


FIG 30 ERICHSEN CUP HEIGHT v HEAT TREATMENT

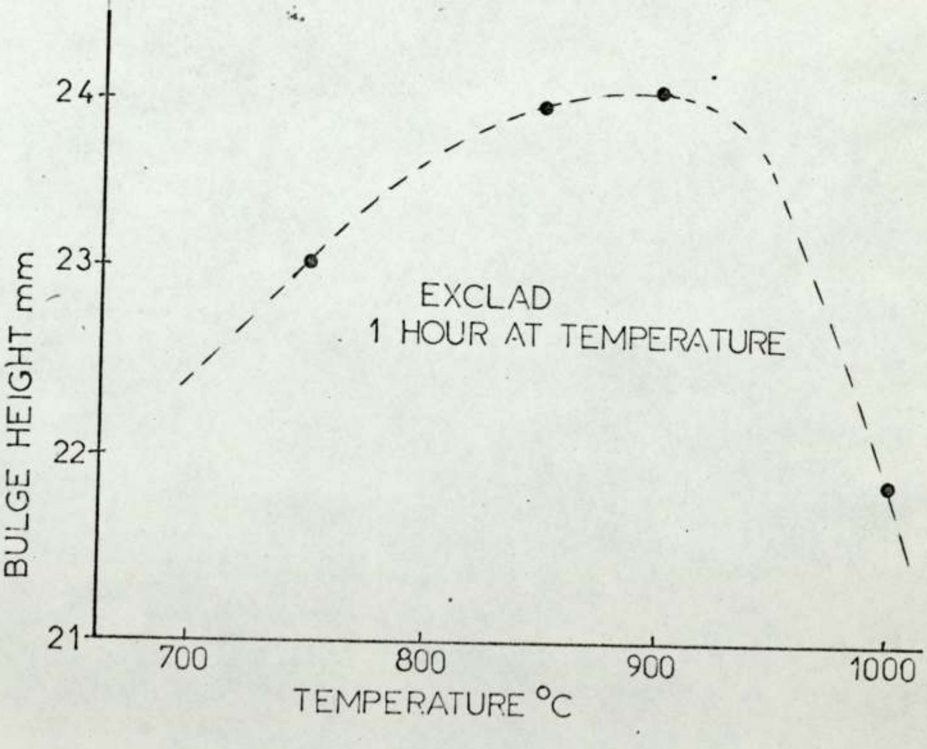


FIG 31 50mm BULGES

The results of stretch formability testing will be discussed later when the formability of the material as a whole is considered.

It may be noted here that the work hardening coefficients ('n') were measured for the material in the three major directions and in the varied heat treatment states. There was no apparent difference between the 'n' values for the various conditions. The results could have comefrom the same population. The results of this are shown in table XI.

Thus there would seem, contrary to the experience on other materials, that there is no correlation between n value and the stretch formability of clad materials.

Forming Limits

In real sheet forming situations there is always a spectrum of strain conditions such that a material is subjected to various combinations of lateral and longitudinal strain. The failure strain under various biaxial strain states can be represented on a single diagram known as a forming limit diagram. The principles behind this representation of failure conditions are more fully developed in appendix 1.

A forming limit diagram was produced for EXCLAD by the method described in appendix 1. The optimum heat treatment time and temperature was derived from the other formability tests and material used in the test was heat treated all together. The resultant diagram is shown in fig. 33. This compares quite favourably with the FLD for a commercial stainless steel in its optimum condition.

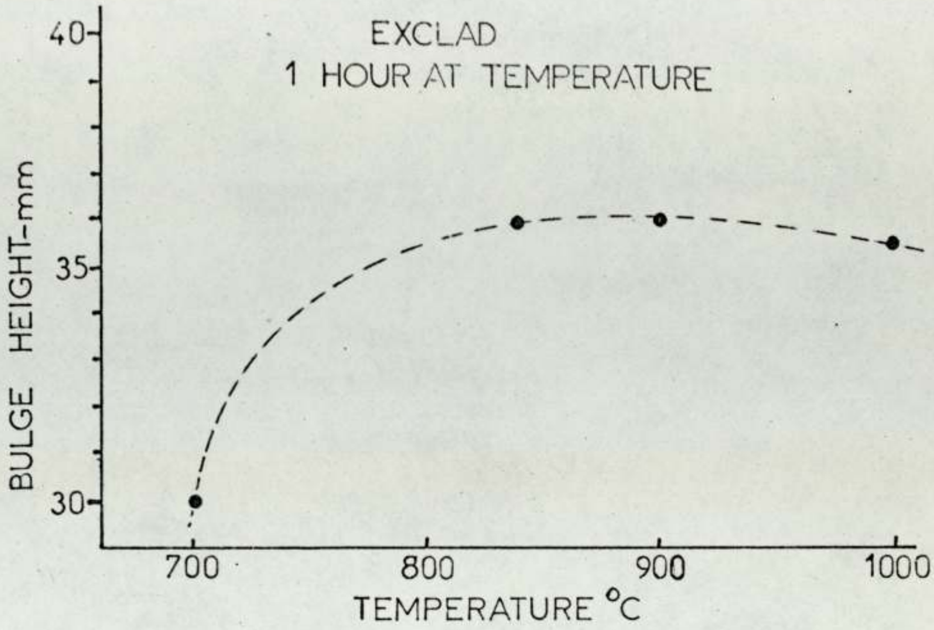


FIG 32 100mm HYDRAULIC BULGES

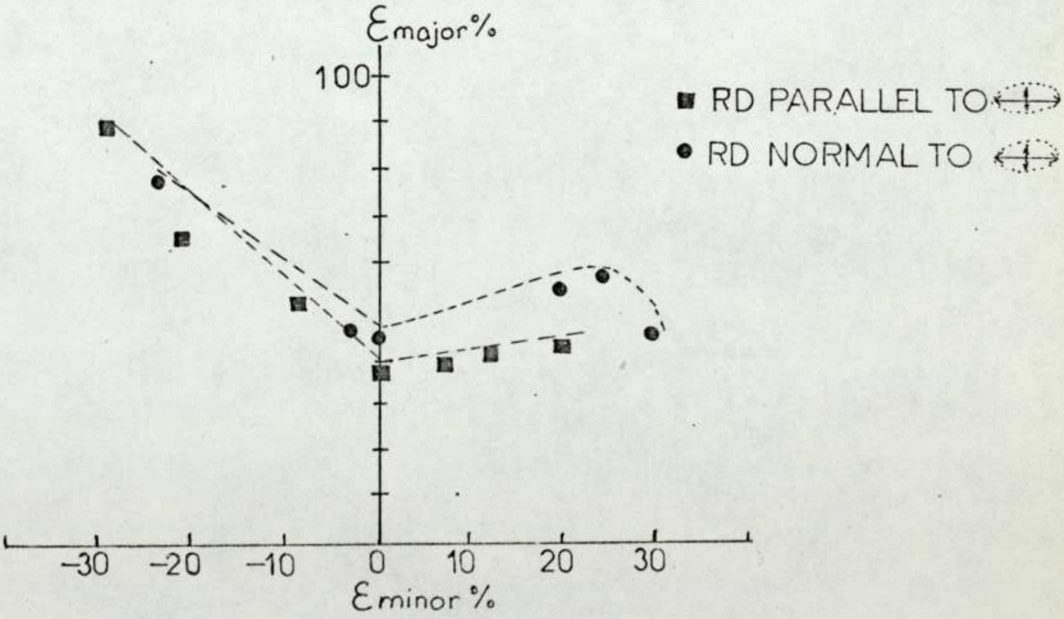


FIG 33 FLD FOR EXCLAD

TABLE XI

EXCLAD n VALUES

HEAT TREATMENT	DIR^{N}	n
850° 10 mins	L	.331
	T	.246
	45	.246
900° "	L	.331
	T	.342
	45	.305
950° "	L	.314
	T	.298
	45	.304
1000° "	L	.325
	T	.306
	45	.306
850° 1 hour	L	.281
	T	.298
	45	.305
900°C "	L	.310
	T	.300
	45	.300
950° "	L	.341
	T	.294
	45	.370
1000° "	L	.310
	T	.310
	45	.30

The Deep Drawability of Exclad

There is considerable advantage in developing good drawability in a clad material as this is a property not normally associated with stainless steels. It is to be hoped that the inclusion of a high quality deep drawing steel in the composite material will improve the drawing properties of this class of materials over that of solid stainless steels.

The relationship between R, the normal plastic anisotropy, and deep drawing performance is well accepted, at least for conventional materials. This measure of plastic deformation was used to assess the response to heat treatment of the material with respect to drawability. The method of measurement together with a discussion of the applicability of the test to laminate materials is given in the relevant appendix.

The material, cold rolled 75%, was heat treated at a series of temperatures to determine the region of optimum response. The results of R determination for the material, heat treated for a short (10 mins) and a long (1 hour) time, are shown in fig. 34. The behaviour shown here is similar to that exhibited during stretch forming tests in that there is a peak in the response at about 900°C, falling off above this temperature. The values for the one hour heat treatment are seen to be lower at the optimum heat treatment but considering the limitations of the test, not significantly so.

The drawability was assessed more formally using a simulative test to determine the limiting blank diameter and hence the limiting draw ratio (LDR). The test and its implications is discussed in an appendix.

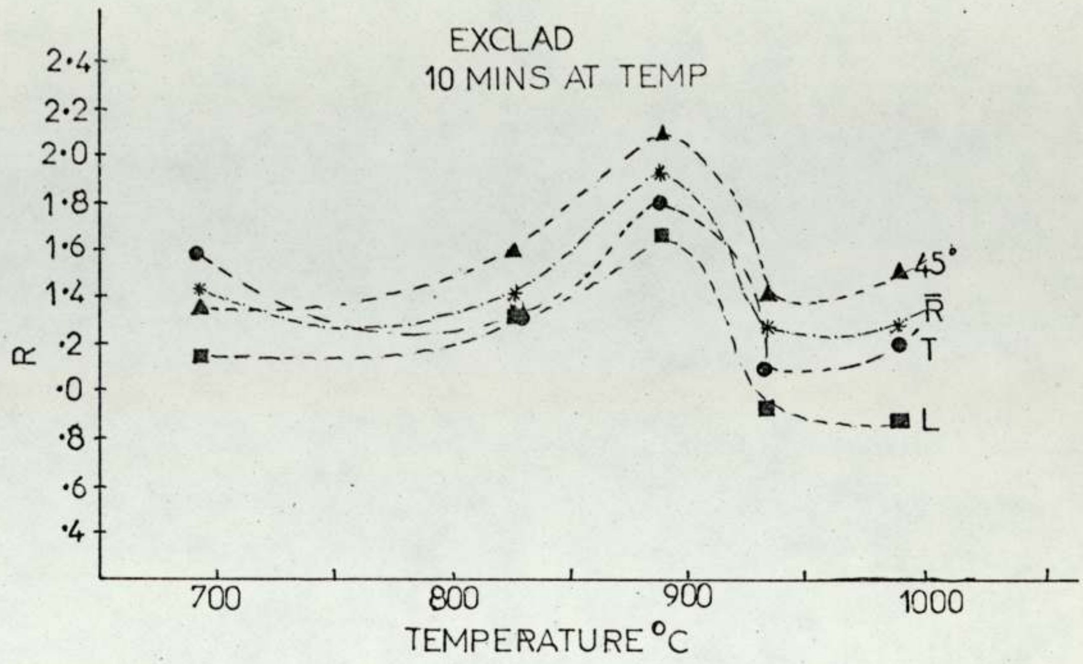


FIG 34a R VALUES

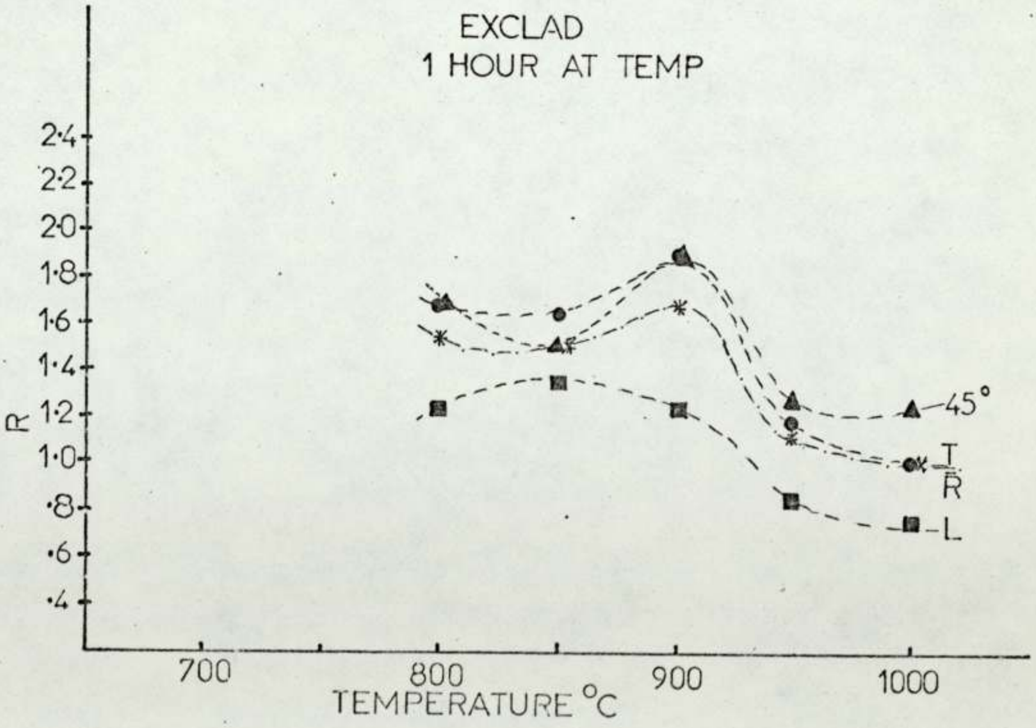


FIG 34 b R VALUES

The material was heat treated similarly to the R specimens giving 1 hour at temperature. The discs for the test were punched prior to annealing with no post anneal work performed on the edges.

The results, shown graphically in fig. 35 show a different pattern to that predicted by the R values in that the LDR increases continually with rising heat treatment temperature, over the range of temperature used. Confidence in the validity of these results was increased by using two discs at each size level making four points for each determination. These results indicate that there is no apparent correlation between R and LDR for these materials. A possible explanation for this behaviour could be found in the mechanism of failure in drawn cups. Cups tend to fail over the nose of the punch at a site of local thinning. The extent of this thinning is governed in conventional materials by the R value. In laminate materials it is possible that thinning occurs more by a shear mechanism between the stiffer stainless steel materials. This will tend to spread the necking behaviour over a larger region thus diminishing the stress concentration and permitting larger strains over the punch. If this is true then the core can be seen as a connector between two relatively rigid plates. The core then has reduced significance and could possibly be likened to the connecting web in a beam, which serves merely to join the two active members. No experimental work was carried out to support this proposition due to lack of time but some evidence is available in that comparing a clad material with a solid stainless steel, shows that in those tests where a punch is used for stretching, the properties are similar but where no punch is used as in the hydraulic bulges then the stainless steel is markedly superior. This could be an effect of the small frictional restraint imposed by the punch allowing the shear mechanism to operate.

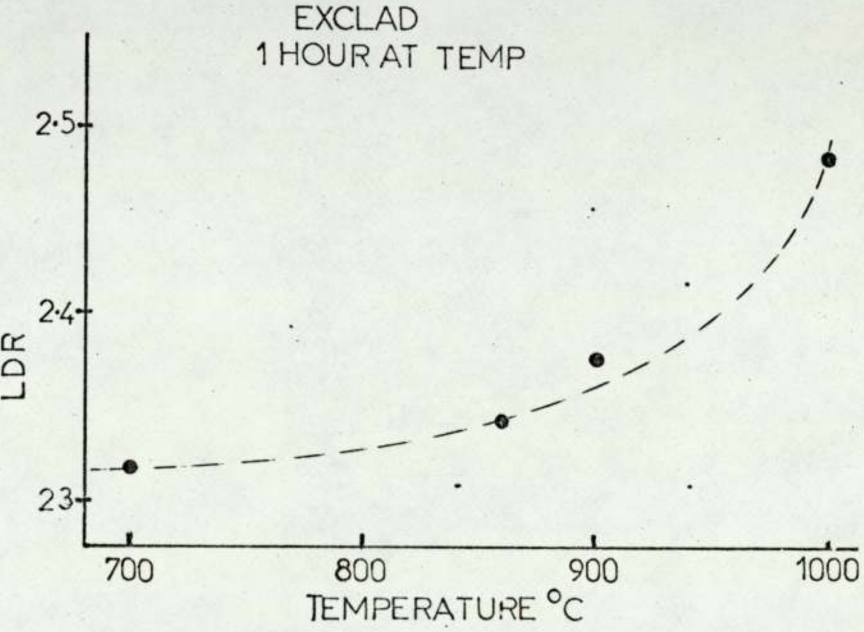


FIG. 35 LDR v HEAT TREATMENT

Examination of a Commercial Clad Material

During the course of this work a sample of a commercially clad material was obtained. This material was said to perform in a slightly superior manner to solid stainless steels by the major user of this material. The material was examined to provide a reference on which to base a specification for the proposed clad materials with regard to formability.

The formability and tensile properties of the material were measured. These parameters were measured using the methods described in the appendices.

The results are presented in table XII . These show that the material compares very favourably with the properties obtained from a sample of commercial stainless steel. Also, for reference the properties of Exclad in its optimum condition are presented.

DISCUSSION

If the forming properties of Exclad are compared with those of a commercial clad steel and a sample of conventional stainless steel(table XII) it can be seen that the drawabilities are similar. This would imply that in cupping tests at least, the core material has little effect on the properties. If the shearing mechanism postulated is acceptable then this may be understood. This places more emphasis on the properties of the stainless steel cladding layer than would have been expected from the results of the drawing tests on single clad materials. It is not possible, from the evidence available,to resolve the problem and shortage of experimental material precludes further experimentation. An explanation of the differences may well lie in the different deformation mechanisms of stretching and drawing and it also may well be that the single sided material does not reproduce the surface and subsurface conditions existing in double clad material.

In general it would seem that it is possible to make a clad steel that has forming properties essentially similar to solid stainless steel and that there is considerable lattitude in specifying the core material.

TABLE XII

PROPERTIES OF CLAD STEELS

A. TENSILE PROPERTIES

		Commercial Clad	EXCLAD (900°)	Conventional SS
L of P	L	302	100	277
MN/M^2	45	280	110	277
	T	292	131	277
TS	L	508	315	667
MN/M^2	45	473	327	622
	T	483	328	651
EL	L	55	55	60
%	45	54	46	59
	T	51	46	59
R	L	.98	1.21	.81
	45	1.02	1.89	1.08
	T	1.04	1.89	1.0
$\bar{R}$		1.015	1.72	.99
ΔR		.001	-.68	-.35

B. FORMING PROPERTIES

LBD	118.5	119	118
LDR	2.37	2.38	2.34
ERICHSEN CUP HEIGHT	11.9	11.7	12.6
50mm CUP HEIGHT	23.6	24.7	23.0
100mm HYDRAULIC BULGE	35.3	36	43.3

TEXTURE STUDIES

Texture formation in both stainless steels and mild steels has been extensively studied. The interest in this work was mainly in the effect of the interface between the stainless steel and the core. It was postulated that the non-coherent interface would exert some influence on the transformation of γiron to αiron during heat treatment and possibly on texture development.

Textures were determined on a Siemens-Schultz texture goniometer using a reflection technique. In general Mo kα radiation was used, detected by a scintillation counter. Quantitative intensity data was obtained in punch tape form and processed in the computer to give a single digit relative intensity plot via a plotter output device. These plots were further manually processed to give a contoured intensity map. Random levels were obtained from a genuine random specimen in the case of mild steels and from a compacted powder specimen in the case of stainless steel.

Specimens from heat treated ADCLAD were prepared in such a way as to expose the interface. In the case of the stainless steel layer the mild steel was simply dissolved away in dilute nitric acid, which, of course, did not attack the stainless steel layer significantly. Separating the stainless steel layer was effected by spark machining away the cladding. The exposure of the core interface was detected by application of copper sulphate solution which was subsequently treated to remove the copper deposit on the non-stainless steel. The spark machining was performed on the lowest range and the surface so produced was compared with a lightly mechanically polished surface to check the effect of this processing on the textural reults. No perceptible differences were found in texture plots made from either surface so spark machined surfaces were examined.

The laminate was examined in various conditions, textures being determined for the interfaces and core after heat treatment in the laminated and separated form. There was no observable difference in textures for any condition and so it was concluded that the mild steel interface had no effect on texture development. Various comparisons are shown in fig. 36.

Textures were also determined routinely for EXCLAD as part of the study of formability.

Examination of the textures of the core steel of EXCLAD taken from the mid section show a gradual development of texture as the heat treatment temperature is raised. The {200} and {211} components of the recrystallisation texture produced by 1 hour at 700°C have faded by the time 840°C is reached and the {111} type components of the annealing texture are present. This type of texture persists upto a temperature of 900°C after which the material transforms from α to γ and a surprisingly strong {200} component appears. There is no apparent reason why the texture should not be considerably weakened by the double transformation except that the material, being low in interstitials, will have a large grain size at 900°C which could transform almost directly to γ without spending long in the $\alpha + \gamma$ region, which is small at the carbon content of EXCLAD anyway. This could lead to a more ordered transformation α to γ, and the subsequent retention of some of the α annealing texture components. The lack of nucleation sites in this material at the elevated temperature could lead in fact to an almost military transformation which could proceed in A-B-A manner or in a A-B-C manner, explaining the appearance of the {200} type component. This new component could in fact be related to the γ texture and by a transformation from it.

+ Badly presented.

D

much better → D

D

D

The textures of the stainless steel cladding layer, taken at mid thickness, show that at 700°C the material has not recrystallised in one hour, still exhibiting the rolling type of texture consiting mainly of a fairly strong $\{110\}$ texture with a small amount of $\{111\}$. Raising the heat treatment temperature brings in the annealing texture consisting mainly of $\{210\}$ and $\{111\}$ components.

Composite pole figures for the two laminate materials are shown in fig. 37.

Much work has been done in trying to correlate texture with formability (see appendix ref. 1) but in general quantitative relationships are lacking. Because of this, no great emphasis has been placed on the development of textures in the particular materials under study. It can be noted, however, that the development of texture in the stainless steel cladding layer confirms the findings on annealing temperatures found in the work on rapid annealing of ONESIDE.

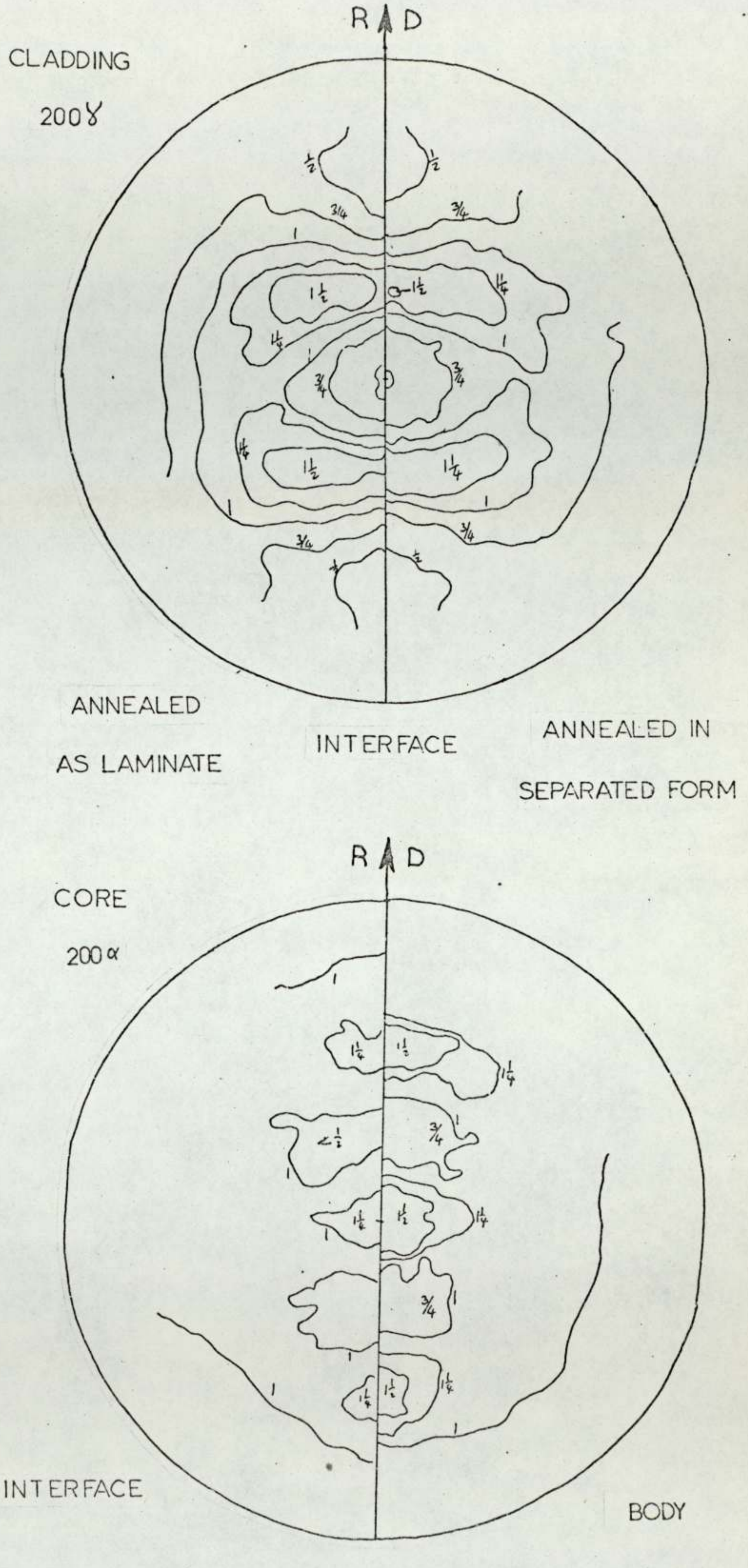
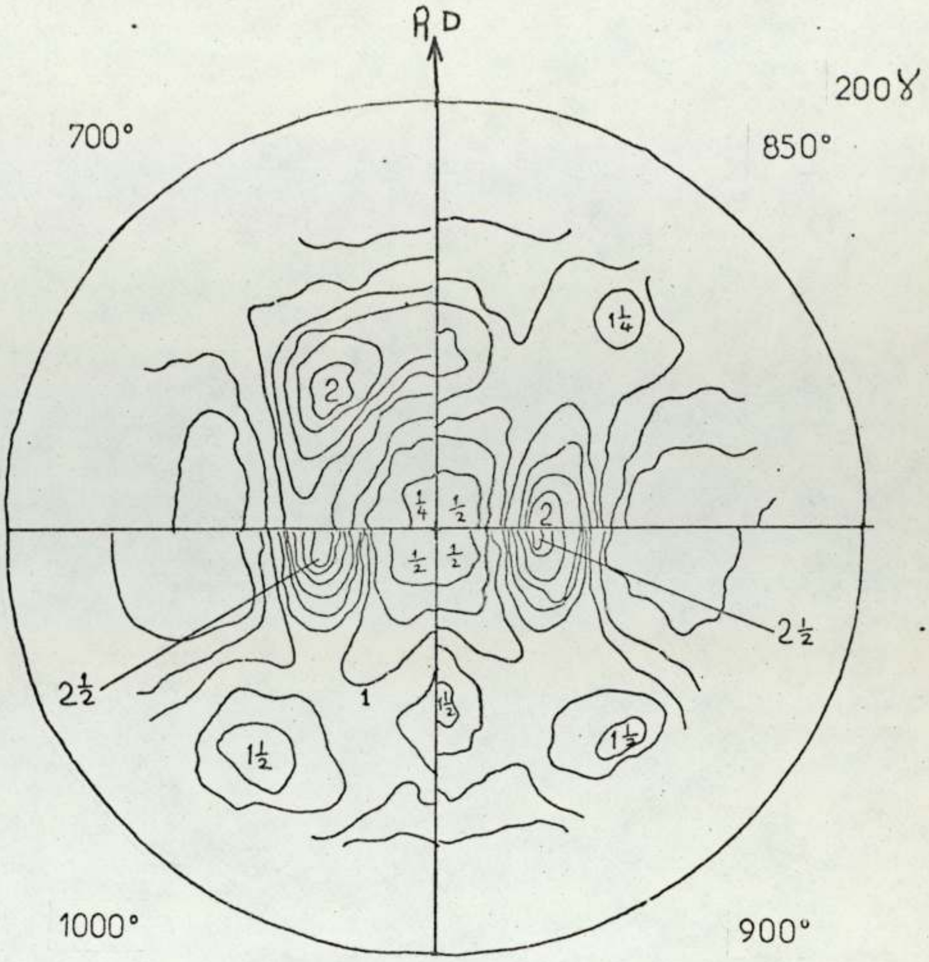
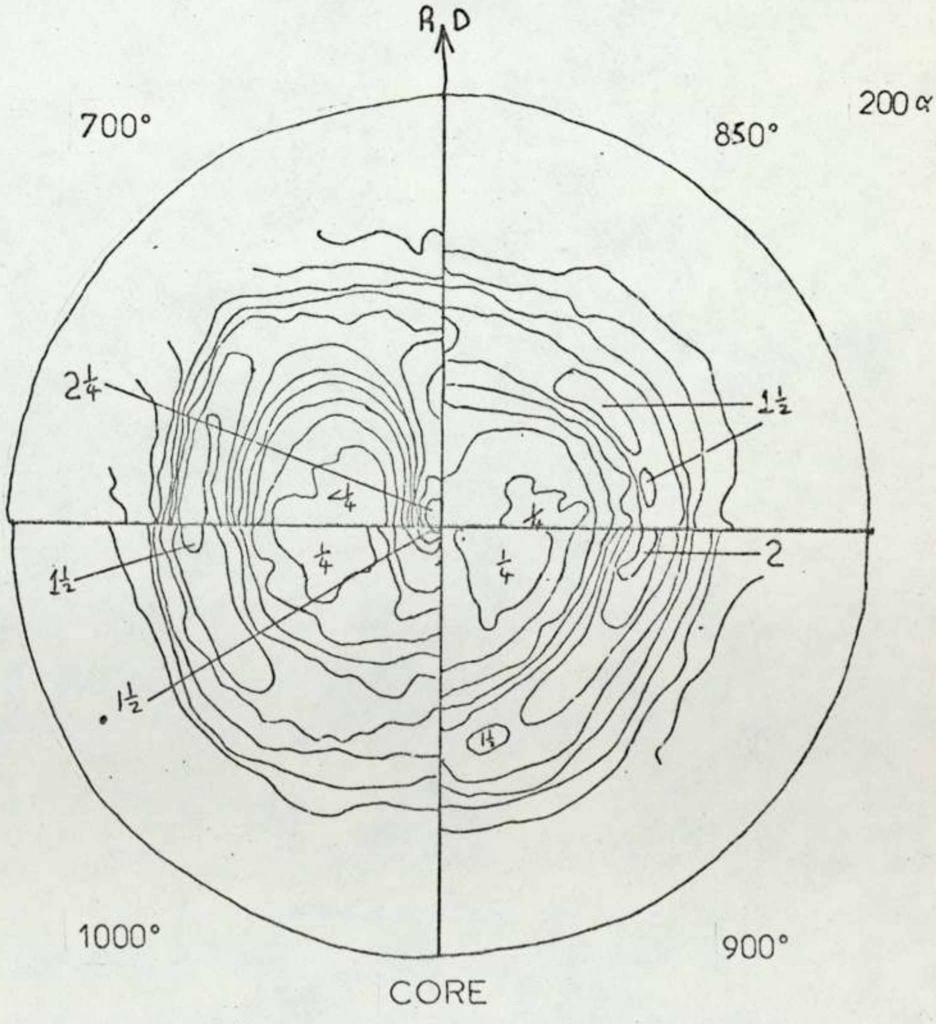


FIG 36 TEXTURES ACROSS THE INTERFACE



CLADDING



CORE

FIG 37 ANNEALING TEXTURES
EXCLAD

USING CLAD STEELS

CUT EDGES

FABRICATION OF CLAD STEELS

CUT EDGES

Discussions about the use of clad steels always raise the problem of the corrodibility of cut edges. In most sheet applications the sheet edge is exposed to the corrosive atmosphere and is expected to show the same corrosion resistance as the plane surfaces. With a clad sheet made by almost any process there would be an exposed non stainless steel core. The problem then is to prevent corrosion at these edges. There are a variety of solutions to this problem and some typical examples of engineering solutions are shown below.

Lock Forming

Where sheet edges have to be joined as in cladding panels, the simplest method of preventing corrosion at a cut edge is to form a joint as in fig. 38. This type of joint is effective in joining the sheets and also folds back the exposed edges out of sight. Where there is occasion to have the joint exposed corrosion in the joint can be easily prevented by application of a sealing compound on assembly. If the use of a sealant is impossible on the grounds of, for instance, high temperatures or contact with a solvent, the joint can be further protected by making a double formed joint.

Rolling Over

This type of edge protection, illustrated in fig. 39, is widely used as a means of protecting the edges of formed parts from mechanical damage. With clad materials the exposed core material can be protected from corrosion by incorporating a sealer compound into the joint. In one brand of domestic holloware this is effected by using an epoxy resin incorporated in such a way as to have a decorative function as well as the practical

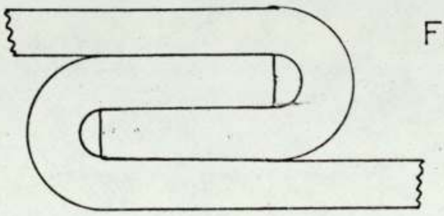
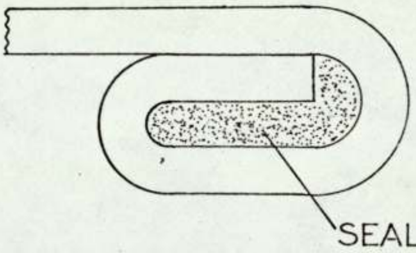


FIG 38   LOCK FORMED EDGES

FIG 39 ROLLED EDGE



function of preventing corrosion staining. It is interesting to note that before the advent of modern detergents this protection was not found necessary as the older type domestic cleansing materials in fact left a thin film of grease over the exposed mild steel which gave adequate protection.

Chemical Protection

Where any form of mechanical protection is not possible due to design considerations, it is possible to modify the chemical properties of the exposed edge. This can be done by the application of a resin or varnish or in more extreme conditions some form of local plating would be needed. This can usually be applied locally on site with various proprietary devices on the market.

It has been noted by the author that a sheared edge has considerable resistance to corrosion in a fairly corrosive atmosphere (highly humid salty atmosphere), this being attributed to a smearing of the stainless steel across the non stainless core during shearing. A similar section of the sheet material used had the edges filed along the edge, removing any smearing. This exposed edge corroded rapidly in the same corrosive atmosphere, This tends to indicate that in a number of domestic and decorative applications no edge protection will be needed.

FABRICATION OF CLAD STEELS

Most of the work on the fabrication of articles from clad steels has been done on plate materials. There are special procedures for welding stainless clad plates which have the approval of most of the relevant certificating authorities. With clad sheet gauge materials the techniques to be used are simpler due to the nature of the welds that are required for sheet materials generally. Some coatings on sheet materials interfere with spot welding which is used a lot in sheet metal fabrication. This does not occur with stainless clad steels and good spot welds are readily made.

IN CONCLUSION

THE FUTURE OF CLAD MATERIALS

CONCLUSIONS

THE FUTURE OF CLAD MATERIALS

Most of the factors involved in the manufacture marketing and properties of stainless clad steels have been discussed in the previous sections. On the face of it there is a good case for the greater involvement of the steel industry in the promotion of these materials. There are, however, counter arguments to the case which must be examined before the material gains acceptance from the manufacturing point of view.

In the section on marketing it was implied, with a high degree of plausibility, that stainless clad steels could be substituted for many of the current applications of conventional stainless steel. This must mean that the sales of these materials would suffer at the hands of clad materials and even though the laminate materials would contain up to 20% stainless steel there would be a substantial drop in revenue. This would, of course, be lessened by the revenue from clad steels but the drop, assuming that the sales of clad sheet were on a straight substitution basis, would be substantial. If a stainless steel manufacturer was considering an investment in a cladding plant this lost revenue aspect must be charged to the clad material thus raising the material price. There is some latitude here for this increase but as there needs to be a substantial increase in material output to make up for the lost revenue, it would seen necessary to keep the price of the clad material as low as possible. A balance is therefore necessary between price level and increased turnover. Much would also depend on the predicted growth rates for both types of materials. Only if the price could be kept low could there be a potential increase in output by attacking the coated steel market.

Because of the relative uncertainty of the market and the current high demand for solid stainless steels it would seem that the arguments previously given would on balance offer little incentive for a manufacturer of conventional stainless steels to change over to a clad product line or even add clad steels to his existing product line. In fact, because of the potential competition from an uncommitted manufacturer, it would seem that the established stainless steel manufacturers would have to take a suppressive attitude towards such clad products, if they were seen to be able to come onto the market in substantial quantities.

If, then, there is to be a future for clad steels there must be answers to the restrictive argument presented above. One powerful counter argument is based on the fairly serious situation with regard to the falling level of ore resources. While at present the nickel supply seems adequate there is no guarantee that this situation will maintain, especially if the demand for stainless steels rises at its present rate. A fall in the availability of nickel with its attendant rise in price could have a serious effect on the stainless steel supply. This could only be countered by the provision of non nickel bearing substitute alloys of the manganese-nitrogen type or by the provision of a clad steel containing overall a small amount of nickel (only 1.6% for a 10% per side clad steel). This means in effect that clad steels will be forced onto the manufacturer by a nickel supply and demand situation.

Stainless clad steels, and indeed all composite materials, have a more positive advantage which could legislate for their introduction. With clad and composite materials there exists the freedom to design an alloy with specific properties which are not available in the conventional materials. Instance of this is the ability to get relatively high thermal conductivity in a stainless steel (composite) by suitable cladding techniques. This in principle gives the engineering designer a new freedom to design a component and have a material designed to do that particular job rather as is the traditional way of designing the component within the limitations of existing materials. It is expected that as conventional materials reach towards their limits in terms of properties then the demand for composite materials will increase. This demand will precipitate movement, towards the production of clad materials and will, it is to be hoped, help to underline the conservationist arguments already presented.

It seems then that there is a positive future for the product described and evaluated in this work. At the present time there seems to be insufficient incentive for the manufacturing industries to contemplate full scale production of this material by any route but the situation is changing such that the appearance of this and similar materials on the market in production quantities is inevitable.

CONCLUSIONS

Much effort in the past has been devoted to the production of a cheap, acceptable substitute for solid stainless steels in the form of a clad material. The most highly developed technique, roll bonding, does not seem to offer an economically attractive route for the production of stainless clad steel sheet materials in large quantities. It is unlikely that this particular route can be developed much further. This means that if the use of stainless clad steels is to reach its full potential a new route for making the product must be employed.

A new route, based heavily on existing technology, has been devised. This route is seen to be technically and economically attractive and is theoretically capable of producing a good quality stainless clad steel. The end product of the proposed route is predictably versatile and above all can be marketed at a price where it becomes attractive to use it in areas where stainless steels are at present excluded by their high cost.

Stainless clad steels have been shown to have properties which enable them to be substituted on a one for one basis in most applications of solid stainless steel sheet materials. This claim is well supported in applications where stainless steels are now used for their surface properties alone. Applications where clad sheets cannot be substituted for solid stainless steels seem to be the exception. Stainless clad steels have some properties, notably thermal conductivity, which not only make them acceptable substitutes, but offer considerable advantages over conventional materials.

The special problems of stainless clad steels, consumer resistance and cut edges mainly, are such that there is no technical reason why this class of steels should not be marketed in the not distant future.

The commercial consideration viz a viz the material seems to indicate that although the product is a highly desirable engineering material the situation is not yet right for the full scale introduction of the material on the market.

"Mild steel sheet clad on one side with austenitic corrosion resisting steel is already being deep drawn into cooking utensils and it is likely that many other, not necessarily domestic applications will be found in which the use of clad sheet will reduce the cost of a deep drawn or pressed article............"

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APPENDICES

1. SHEET METAL TESTING
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    - Formability testing equipment
    - Testing methods
2. EXPERIMENTAL MATERIALS
    - Description
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APPENDIX I

1. SHEET METAL TESTING

When applied to sheet metals formability is taken as the ability of a material to be formed, usually by some form of press forming, into a shape. Press forming is probably the most severe forming operation that is carried out on sheet materials and so it is the behaviour of the material in this situation that is usually taken as an index of quality. Traditionally press formability has been assessed by the simple and direct method of a trial on the component in question. This method, while being the ultimate test, is a very cumbersome method of quality control and, of course, is not much use to the material supplier. In view of this deficiency, tests have been devised which bear a known relation to press performance.

It is not proposed to review the large number of tests in use today, these may be referred to in the literature(1). Only those tests which were used in the experimental program will be discussed.

The testing methods for sheet metals can conveniently be divided into two major categories as far as their relevance to formability is concerned. The categories are -

a) Simulative

b) Indirect

Indirect

Tests in this category usually derive from the tensile test. Their popularity is due to having no need of specialised equipment and the relative familiarity of the tensile test.

Derived properties in common use are the plastic anisotropy factor and the work hardening coefficient. These are known as 'R' and 'n' respectively. The method used in the present work for obtaining these parameters is described later.

It has been shown that R correlates with general drawability(2) and n is known to relate to stretch formability(3). Other tensile derived properties are used to assess press forming performance, a typical function being -

$$\frac{TS.R.n}{.2F} \qquad \text{where } F = \text{flow stress} \qquad (4)$$

These functions tend to be only used internally and mostly in one situation.

R Value

The plastic anisotropy factor R is given by:

$$R = \frac{\epsilon_w}{\epsilon_t}$$

ϵ_w and ϵ_t are derived from length and width measurements

$$R = \frac{\ln(W_o/W)}{\ln(t/t_o)}$$

Thickness measurements are rather innaccurate on sheet materials so the thickness strain is usually calculated from the length strains, R is given by:

$$R = \frac{\ln(W_o/W)}{\ln(L.W/L_oW_o)} \qquad \text{as } \epsilon_w + \epsilon_l + \epsilon_t = 0$$

The R value cannot be used as a direct means of assessing general formability but the relationship between R and the limiting draw ratio (a simulative parameter discussed later) is reasonably well established over a wide range of materials as shown in fig. 1 and on a smaller scale there has been found a reasonable correlation for mild steels, as shown in fig. 2. The R parameter can be generalised for anisotropic materials by averaging over 0°, 45° & 90° to the rolling direction, thus the mean R is usually defined as:

$$\bar{R} = R_o + 2R_{45} + R_{90}$$

In the drawing situation in sheet metals the ability of the material to resist thinning in the cup wall, where there is almost pure tension, is mirrored by the ability to give a high R value and this is what gives the parameter its good performance as a test of drawability.

n value

True stress and true strain are related for most materials by a simple exponential law -

$\sigma = A\epsilon^n$ where A is a constant

σ is true stress

ϵ is true strain

n is a constant.

This is not an exact representation of the behaviour of material, for instance, it is easily recognised that, if the equation was true, the material would become infinitely strong at high strain levels, but for the strain levels encountered in tensile testing (natural strains between .02 - .3) it is sufficiently accurate. An example of the reasonable correlation is shown in fig. 3.

To state that n has a direct relationship with the stretching performance in sheet metal forming is only justified as a qualitative comparison but it can be reasonably expected that

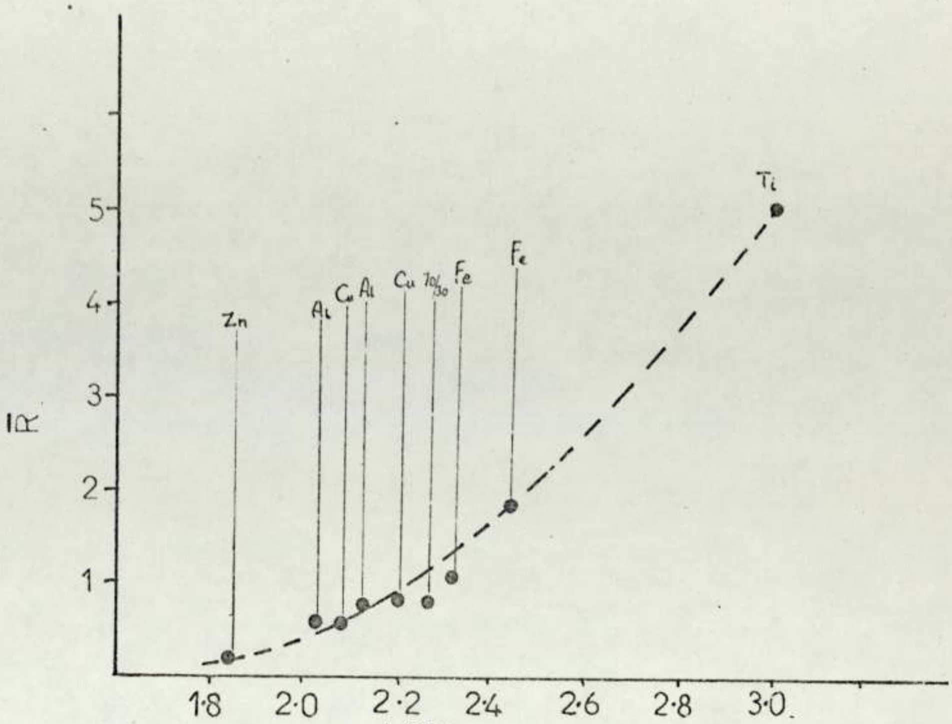


FIG1 $\bar{R}$ – LDR RELATIONSHIP

(FROM REF 2)

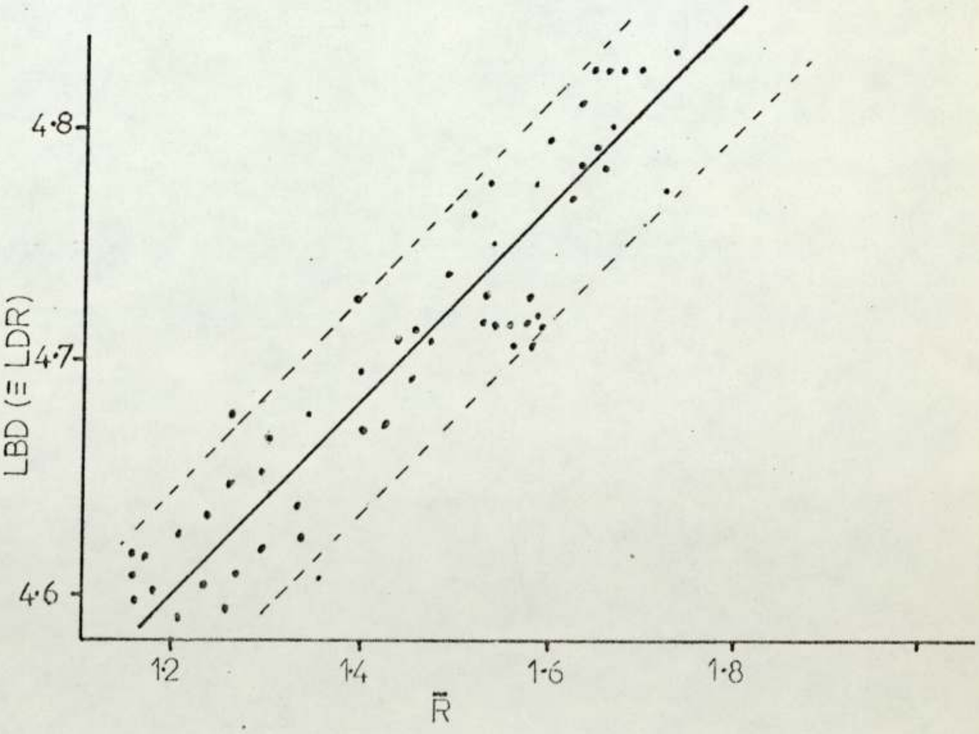


FIG2 $\bar{R}$–LDR' FOR MILD STEELS

(FROM REF 3)

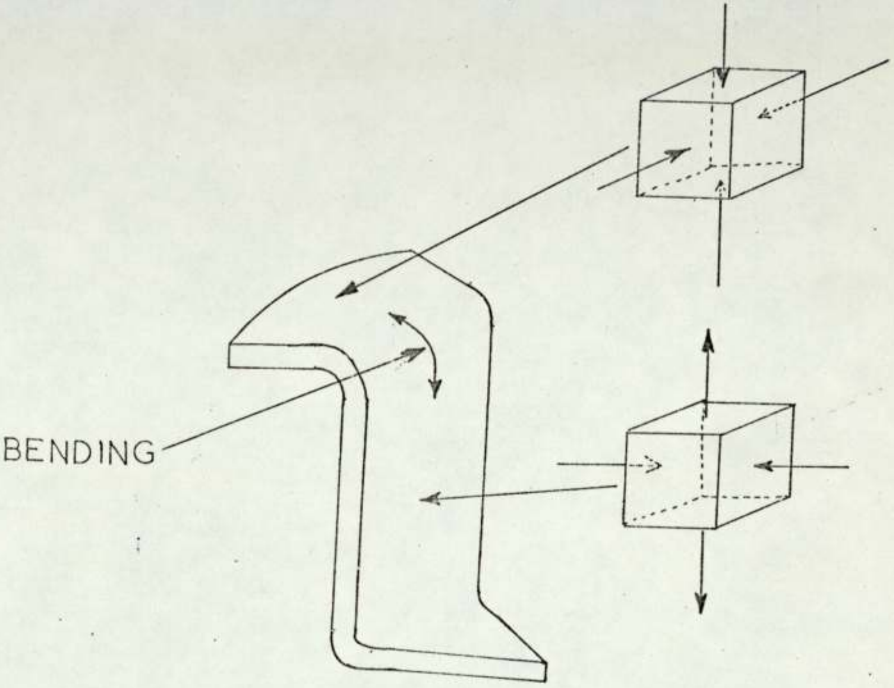


FIG 3 STRESSES ON AN ELEMENT IN CUP DRAWING

a high rate of work hardening, especially if it is maintained to high strain levels must be beneficial to stretch forming operations. The effect of a high work hardening rate is to distribute the strain in a more uniform manner. High n values can be related to high uniform elongations, and a high uniform elongation implies that the onset of plastic instability, which always precedes failure, directly, is delayed.

Other indirect tests are of relative unimportance except where they are used as internal quality control.

Simulative Tests

Press forming operations on most components involve a combination of stretching and drawing, this is illustrated in fig. 3. It is highly impracticable to try and simulate any one combination of stretch and draw in a test and hope that this will provide information on the behaviour of a material under a different combination. Because of this a large number of tests have been devised which simulate one condition or another. Traditionally, the Erichsen test has been used to simulate stretch forming and the Swift flat bottom cup test has been used for assessing deep drawability. These tests were used in the present work to assess the general formability of stainless clad steels in the different heat treatment conditions.

The Erichsen Test

This is sometimes referred to as punch stretching especially where non-standard tooling is used. The test as interpreted in the laboratory is described later.

The geometry of the test enables some information to be gained as to how the strain is distributed over the deforming area and how much strain the material can withstand in this essentially bi-axial deformation mode.

The Erichsen test as such suffers from being a small scale test, this can artifically increase the importance of surface defects and make friction conditions more liable to variation from test to test. It is, however, a very simple and relatively easy test to perform and finds wide application as a quality test, though considerable caution must be exercised when comparing results obtained in other laboratories.

50mm Punch Test

This test is conducted on a larger scale than the Erichsen test and so removes some of the objections. In the laboratory tests were conducted with standardised tooling in a manner very similar to the Erichsen test. The tooling is illustrated in fig.10

Hydraulic Bulging

Frictional variations are known to have large effects on the behaviour of materials in punch stretching, this being a major obstacle to acceptance of standards derived from these tests. The use of a hydraulic bulge to assess stretch formability, by having no problems with friction and readily reproduced standard conditions, provides a higher degree of confidence in the results obtained by this method. It is possible to perform tests over a wide range of sizes, and this is an important consideration in the simulation of industrial practice. It has been noted that smaller bulges tend to give higher bulge heights than larger bulges(5) and it was also noted that the failure direction tends to conform to the rolling direction in larger bulges whereas in smaller bulges the failure direction seems to vary at random with the rolling direction.

A major use of hydraulic bulging is in the production of forming limit diagrams. These provide information on the stretching behaviour of materials over a range of bi-axial strains. The methods of producing these is outlined later. The method of representing the data is somewhat arbitrary in that there is no clear definition of end point for a particular test. In the hydraulic bulge the most convenient end point is failure, where, in fact, the bulge is unable to have its height increased due to the inability to support any more pressure. This criterion, though well defined and convenient, does not really measure the ability of a material to do a job because the useful amount of deformation is reached some time before failure. This failing is compounded by the usual case of not having a measurement station (usually a circle taken from a scribed grid) exactly representing the strains in the region of failure. To overcome this it has been proposed that the development of a large strain gradient constitutes the end of useful strain and this should be taken as the end point(6). Perhaps a better, if difficult to measure, criterion would be the one used in a large number of press shops, especially in the car industry, and that is one based on surface finish. The suggestion is made here that this could be assessed by a variant of quantitative television microscopy. To do this, however, is perhaps reading too much into the technique which after all only is of any use in assessing part of the usefulness of a material in a press shop. In view of this latter argument the simple method of measuring the nearest strained circle to the failure site was adopted.

Limiting Draw Ratio

A parameters which shows perhaps the closest relationship to general drawability is the size of the largest blank that can be drawn into a flat bottomed cup. This blank diameter, known as the limiting blank diameter (LBD) is usually divided by the punch diameter to get the limiting draw ratio (LDR). LBD is defined as the size of blank that is likely to have a 50% failure rate in deep drawing under specified conditions. The method that was adopted for measuring this is described later.

The relationship that exists between LDR and R value has already been discussed, both giving an indication of the deep drawability of materials.

No one of the testing methods or parameters discussed above gives a full indication of the formability but taken as a group they are capable of at least ranking materials for their pressing performance. Most pressings are made by a combination of stretching and drawing that varies considerably and it is this which makes it difficult to predict actual performance from laboratory tests unless, as is the case in a considerable number of situations, the results of these tests are correlated empirically with the known performance of established materials for making a certain part. For example, it may be noticed that there is an empirical relationship between the scrap rate of a sump pressing and the lower yield stress and consequently the LYS could be used as a quality control check, similarly with any other forming test.

It is possible to postulate a test procedure where there is a combination of stretching and drawing to simulate a given pressing. It would be necessary to vary the amounts of these to derive different simulations. The suggestion made here is that a spectrum of stretch/draw ratios could be used for testing. The large number of tests necessary to give meaningful results could be cut down by applying the principles of factorial design.

Forming Equipment

i) The Bulge Tester

The bulge tester used in this work was manufactured in the BSC Corporate Laboratories. It is a hydraulic machine designed for a theoretical capacity of 6000 psi. This is theoretically sufficient to make a bulge of 200 mm dia. in 4.5 mm thick steel with yield strengths up to 450 N/mm^2.

A series of dies are available to make both circular and eliptical bulges based on diameters of 200 mm, 150 mm and 100 mm. The ratios of the eliptical dies were chosen to give equal spacing on a forming limit curve presented by Haberfield(7) for mild steel. Clamping was effected hydraulically over a circular die ring. Sufficient clamping pressure was applied to prevent drawing in of the sheet being tested, this being determined by trial and error.

The machine has not been fully instrumented for automatic recording of bulge height and pressure but some indication of bulge pressure can be obtained from the master pressure gauges fitted in the main pressure line.

The pressure is applied by means of compressed air ratio pumps with a variable pumping rate. The dies are secured by a breech block arrangement which facilitates rapid specimen change and die change. A photograph of the machine is shown in fig. 4.

ii) The Cupping Press

The cupping press used was a 30 ton maximum load machine manufactured by HILLE Engineering. A full range of tooling is available i.e. flat and round nose 50mm punches, 35mm flat and round nose punches, 20 mm flat and round nose punches and a standard Erichsen test punch and die. A comprehensive set of complementary dies is also available including a knurled bottom die for producing high friction conditions.

The press was fully instrumented in the laboratories with facilities to measure both press load and depth of draw, using a strain gauged ram and a precision linear potentiometer. The circuitry and other details of the electronics is given in a BSC/CDL internal report(8).

Ram speed was controllable from 0 mm.sec^{-1} to 20 mm.sec^{-1} and clamping force could be varied between 0 kN and 70 kN. The unit is shown in fig. 5.

iii) Grid Marking

Grid marking was effected by means of an electro-chemical method, using both stencils and electrolyte available commercially from Electromark. AC was used, applied by means of a roller fed from a variac. The most commonly used stencil was a pattern consisting of close packed circles about 2mm diameter.

iv) Tensile Testing

This was carried out on a standard 50 kN Avery tensile testing machine.

Testing Methods

i) R value

Originally the R value was measured by a set of measurements at a fixed strain increment. Length and width measurements being made before and after straining, each measurement being accurate to about 50 μ''. It was found that even using two sets of length measurements and compounding these with two sets of width measurements (calculating a total of four R values for each specimen) that there was a large scatter in results. With a limited supply of material

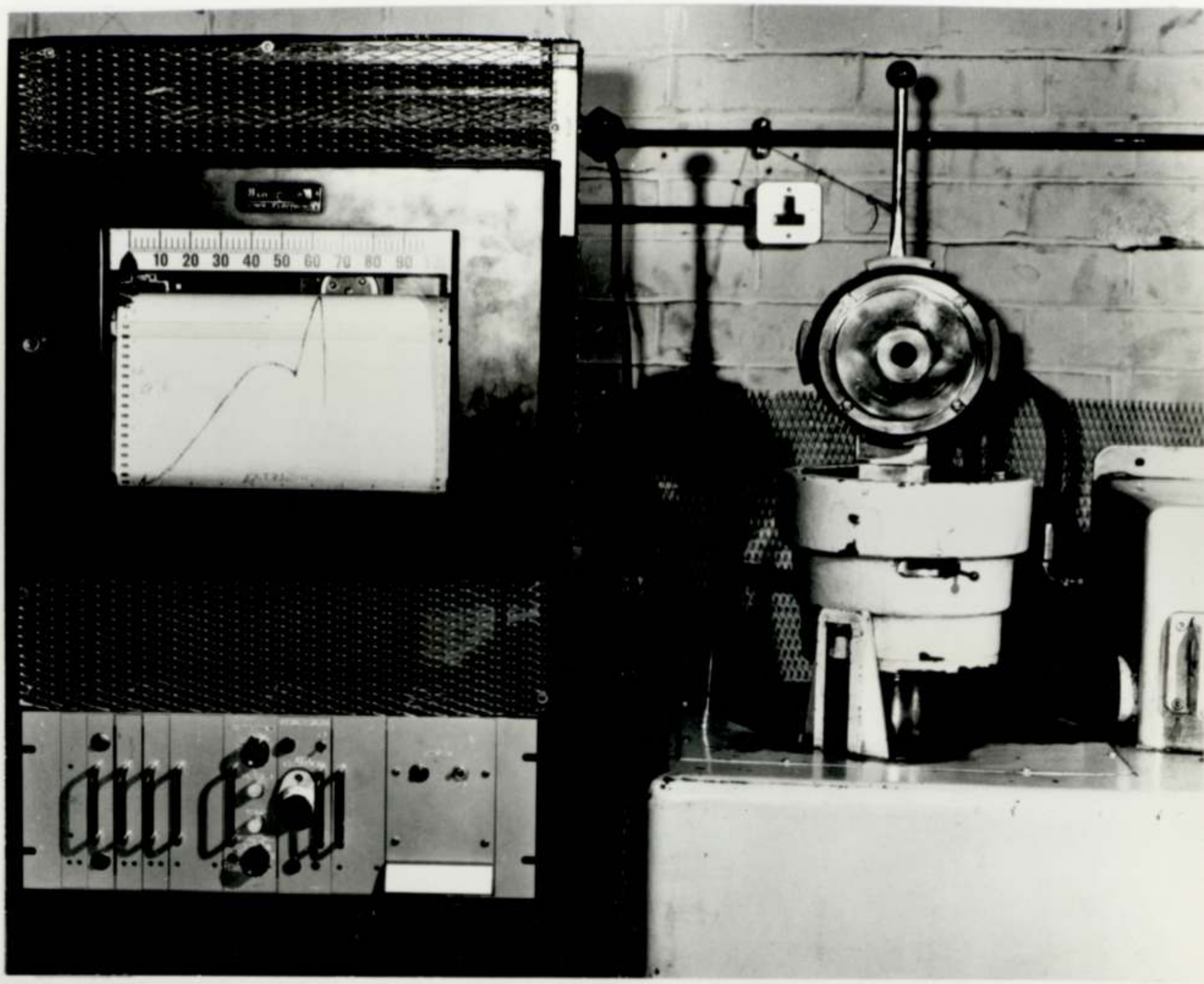


FIG 5 CUPPING PRESS AND RECORDING GEAR

FIG 4 BULGE TESTER

it was considered impractical to perform any form of multiple specimen testing so an incremental method was used for all subsequent determinations. This method is not novel but it has been refined and simplified at the laboratories to enable fairly rapid determinations on a single specimen, these giving a high degree of confidence by the very nature of deriving results. The method will be described together with the method for simultaneously obtaining n values.

Any sheet type specimen can be used. The one adopted was chosen to have a parallel length greater than 50mm and specified such that the gauge length was parallel to better than .01mm total deviation within 20mm from the centre line. The recommended R gauge length is 40mm but this can be varied slightly providing the actual length is known accurately. The specimen is marked out by putting a pop mark at about 20mm from the centre line and using this as a datum an arc is scribed on the specimen at about 40mm radius.

A small tensioning load is applied ($\sim$ 1% of max. load) and width and thickness measurements are taken as for a normal tensile test. These, due to the averaging method used, can be made with a standard micrometer.

The specimen is strained to a fixed small increment which is fixed using the arc and pop marks as datum points. This is measured to .01mm using a micro divider setting device. When the strain increment is reached measurements are made of width at three places along the R gauge length. The results are averaged unless the total deviation is greater than .1mm when they are discarded. This can easily occur during the initial increments due to interference of Luder band phenomena. Similarly towards the end of the test necking will cause significant deviations. At the same time the load at which straining is stopped is recorded for each strain increment.

The values of w_o/w and l/l_o are calculated and hence values of $\log\epsilon_w$ and $\log\epsilon_l$ are obtained. These may be plotted against each other to obtain the gradient of what should be a straight line. R is calculated from the gradient as:

$$R = g/1-g \qquad g = y/x$$

As an aid to calculations some special 1/4 cycle log-log paper has been drawn on the computer which enables ϵ_w to be plotted directly against ϵ_l to obtain the gradient.

The accuracy of the method depends on getting sufficient readings to enable a high confidence straight line to be drawn and while no statistical tests of significant deviation were conducted the degree of accuracy can be readily assessed from the typical graph reproduced in fig. 6. Thus is can be seen that the method does not demand a high degree of accurate measurement as the errors involved tend to be cancelled out.

Using the method outlined above it was found possible to measure three R values in an hour with a further 1/2 hour of calculation. This, it is claimed, is considerably faster than the single fixed increment method that is in general use.

ii) n Value

The work hardening coefficient n is simply calculated from the data gathered during the R value test. The recorded loads are reduced to true stresses by calculating in the following fashion:

$\sigma = P/A \times L/L_o$

p = load

A = area, original

L = length

L_o = original length

This is plotted against L/L_o and the gradient of the resulting straight line gives n. This is facilitated by some special log-log paper again drawn on the computer. A in the Ludwik equation is found by substitution in the formula and not by extrapolation. A typical plot is illustrated in fig. 7.

iii) Forming Limit Diagrams

There are, as yet, no standards laid down for obtaining forming limit diagrams and so results obtained in different laboratories can show large differences due to the use of different failure criteria and the usual problem of different lubricant conditions apart from any differences in the mechanics of testing. Perhaps the nearest to an intercomparable technique is the hydraulic bulge type of test. Lubrication, of course, is no problem and most of the other parameters such as stress ratios and hold down pressures are readily reproduced. This was the method that was adopted after failure to get satisfactory results from a strip drawing technique. This technique, although abandoned will be briefly described for completeness.

The basis of the strip technique for getting differing stain ratios is the allowing of semi or unrestrained drawing in of a sheet in a punch test(2). In standard punch testing the material under test is not allowed to draw in and special precautions, such as knurled bottom dies are used. If, however, the sheet under test has one dimension less than the critical dimension that can be successfully restrained it will draw in, thus deviating from bi-axial tension conditions which are present in the normal punch test. Further ranges of strain ratios at failure can be obtained by altering the friction over the punch. This method has the advantage that both the ++ and the +- quadrants can be determined with the same test. Failure strains are determined by a grid technique.

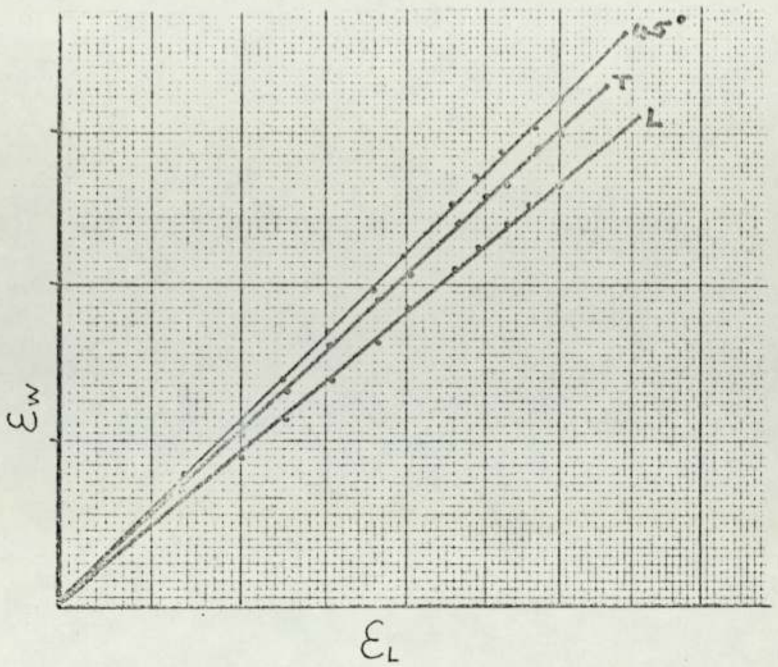


FIG 6 R VALUE DETERMINATION

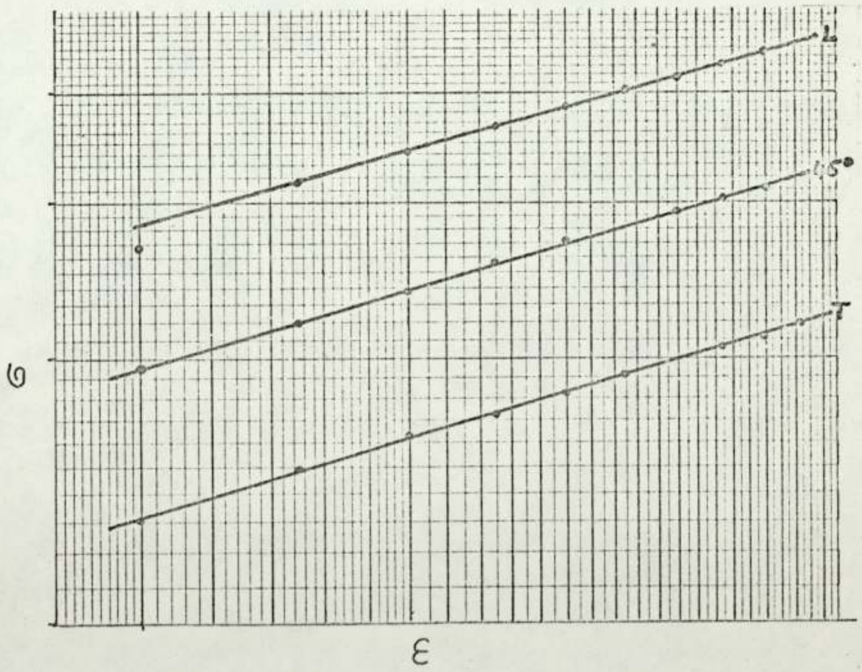


FIG 7 n VALUE DETERMINATION

The hydraulic bulge technique for FLD determination was adopted for its reliability and simplicity.

Dies of eliptical shape are used in this technique to give differing strain ratios and these combined with a circular die to give bi-axial tension cover the region from balanced bi-axial tension to nearly plane strain. It is, of course, only possible using hydraulic bulging to get ++ strains, for plane strain and +- strains it is necessary to use modified tensile test pieces. A series of these were devised to give +- strain ratios varying between plane strain and uniaxial tension. These were arrived at by trial and error and give strain ratios approximating to 1:1, .7:1 and .4:1. They are illustrated in fig. 8. A complete FLD is illustrated in fig. 9.

Failure strains were measured using an electromarked grid. Failure in the hydraulically bulged specimens is immediately obvious from the pressure drop off while some selective criterion must be applied in the case of the tensile specimens. The criterion applied was the initiation of a crack at either side of the necked portion.

Various extrapolative techniques are in use to determine the magnitude of the major and minor strains at the failure site and it is possible, by using multi inspection replication, to predict from a gridded specimen the onset of runaway plastic flow which has been adopted as a reasonable failure strain criterion(6). This technique, though highly accurate, is very time consuming and it is doubtful as to whether the increased accuracy has any significance when applied to real material testing. In view of this, strains were measured by taking the dimensions of the largest grid circle that was found in the vicinity of the failure. The circle was chosen so that the region of non-uniform deformation was avoided i e. the chosen circle was of a regular shape.

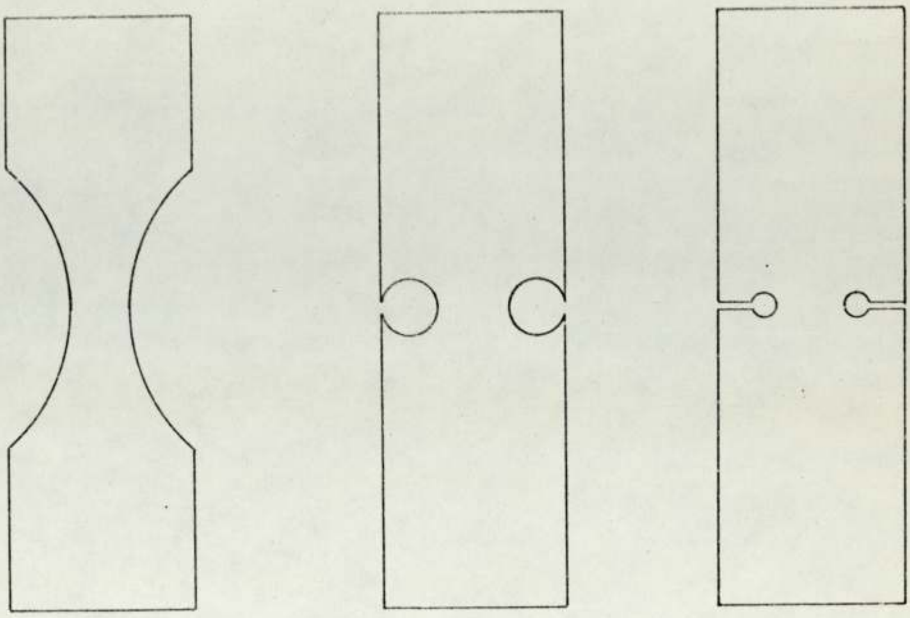


FIG 8 TENSILE TEST PIECES FOR FLD DETERMINATION

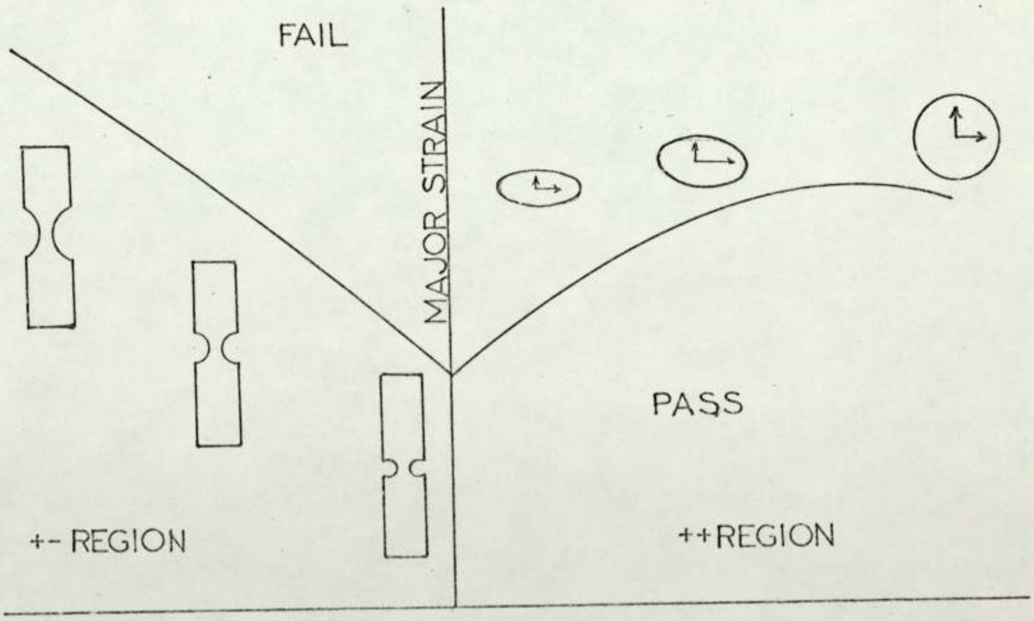


FIG 9 MAKE UP OF A FORMING LIMIT DIAGRAM

Measurements were made using ratio dividers on grid circles observed under a low power microscope. No corrections were made for the fact that the circle was on the surface of a sphere. Using 15:1 ratio dividers it was found possible to resolve about 3% engineering strain when using a micro divider setter to measure lengths.

The use of an extrapolation method, plotting the strains in a series of circles over an arc of the bulge, did not seem to offer any significant increase in accuracy, and so the strains in 4 or 5 of the most highly strained circles, selected as above, were plotted for each bulge.

iv) Erichsen Tests

Tooling and other conditions are laid down in BS 3855. These were followed where possible and tests were conducted using the following conditions:

Tooling	BS 3855
Lubricant	Polythene + oil
Hold down force	70 kN
Ram speed	.3 mm $\sec^{-1}$

The end point of the test was taken as the point at which the load/extension graph showed a sudden drop. Calibration of failed specimens, measured with a depth micrometer, against this criterion on the electronically derived graphical record showed that the load drop was an accurate measure of Erichsen failure. The ram speed was selected arbitrarily, in the absence of a standard. The starting point of the test was given by the first increase in load, measured on the most sensitive load scale.

v) 50mm Punch Test

This was conducted in a similar manner to the Erichsen test and the tooling is shown in fig. 10.

vi) Limiting Draw Ratio - Limiting Blank Diameter

LBD and hence LDR is most easily determined by the single blank draw test. The theory behind this test is that the maximum draw load increases linearly, or at least regularly, with increasing blank diameter. It reaches a maximum at the limiting blank diameter and this maximum coincides with the failure load.

The procedure for carrying out the test involves drawing a cup with just sufficient hold down pressure to prevent wrinkling and measuring the maximum load obtained. The blank, of course, must be of a smaller diameter than the critical. After maximum load is reached the test is stopped and the hold down pressure increased until further drawing in of the blank becomes impossible. This is assisted by changing the bottom die for a high friction plate i.e. knurled. The test then becomes a stretching test which is continued to failure of the cup. The load at which this occurs is taken as the maximum drawing load of an infinitely sized blank. The progress of the test is shown in fig. 11. The loads are plotted against blank diameter taking the die throat diameter as zero load and the maximum drawing load is extrapolated from the zero load through the blank diameter until it reaches a straight line at the level of the failure load. This is illustrated in fig. 12.

Increased confidence in the results obtained is given by performing the test on two blanks of different diameters. Extrapolation of the two points usually gives a good straight line passing through the die throat diameter when the loads are plotted against a linear function of diameter(9) but it is claimed that a logarithmic

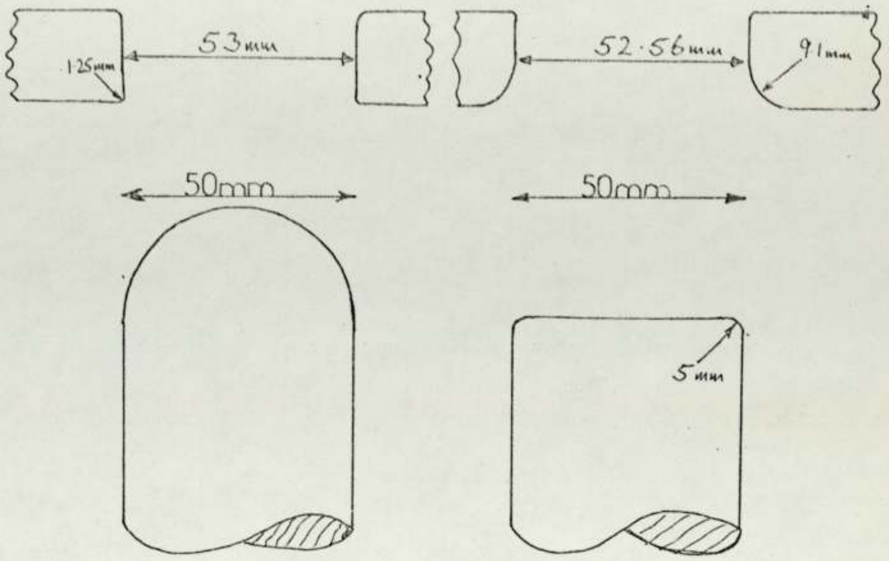


FIG 10 50mm TOOLING

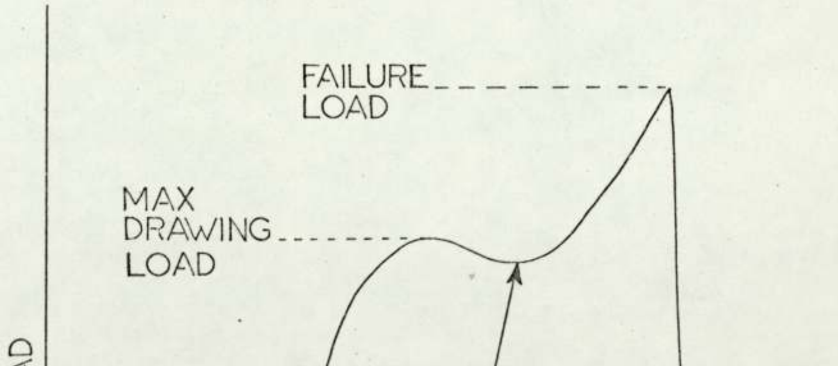


FIG 11 LOAD-EXTENSION CURVE FOR LDR DETERMINATION

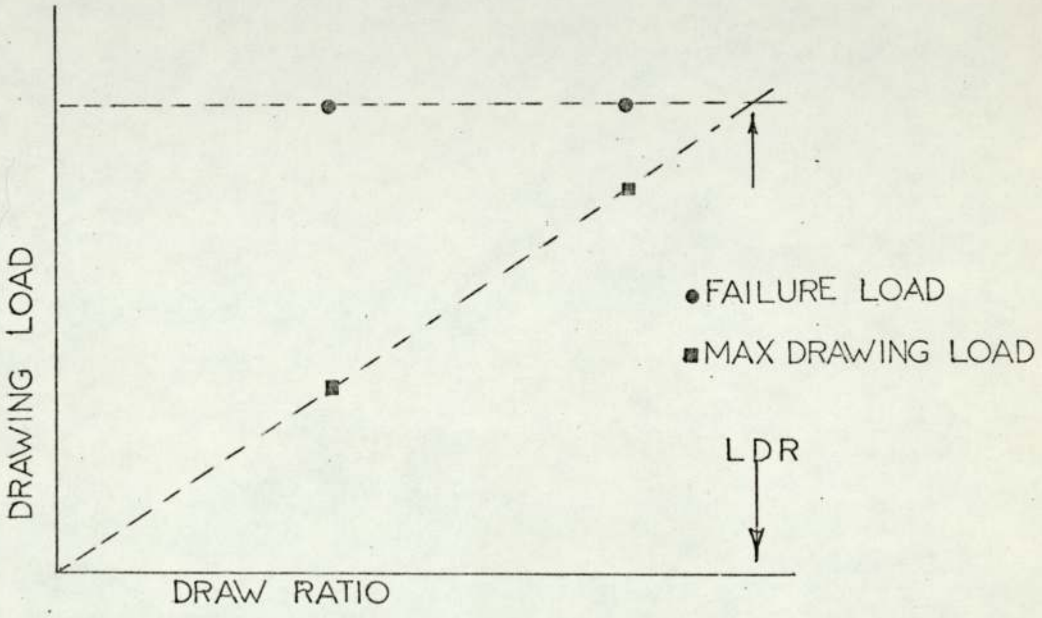


FIG 12 CALCULATION OF LDR

function should be used. Results were plotted both ways but over the small range of blank diameters available for the test it was found that there was no significant difference between the results obtained by either method. In the light of this a linear plot was used.

The conditions used in the test were:

Tooling	see fig. 10
Lubrication	polythene
Ram speed	.3 mm sec^{-1}
Hold down (drawing)	8.3 kN
Hold down (stretching)	70 kN

APPENDIX 2

EXPERIMENTAL MATERIALS

i) ADCLAD

ADCLAD was a double clad material consisting of two pieces of type 321 stainless steel roll bonded onto a slab of BS 970 En2a using the set up as shown in fig T5. The analyses of the materials used are given later.

The pack was hot bonded at 1100°C and reduced, with two reheats to 12mm, giving a total reduction of 80%. Ultrasonic inspection of the reduced pack showed that there was greater than 95% of the area bonded. The areas of non bond were confined to the edges where it is likely that the weld had interfered with the bonding. The pack was annealed at 1100°C for one hour after hot rolling to consolidate the diffusion bond. Microscopic examination of the bond showed that there was a minimum of oxide present which was in any case widely dispersed. The final proportion of stainless steel was 9% per side.

ii) ONESIDE

This material consisted of a slab of deep drawing grade low carbon mild steel clad on one side only with type 321 stainless steel. The laminate was manufactured by roll bonding using a pack set up similar to that used for ADCLAD. The analysis of the components is given in the table following.

After bonding the pack was reduced to 12 mm by hot rolling with two intermediate heats. On inspection there was found to be greater than 90% bond inside the area of the weld. The hot rolled laminate was annealed at 1100°C for one hour prior to cold rolling to a stock size of 5mm.

The final proportions in the cold rolled stock of the stainless steel and mild steel was 13% stainless steel. This was varied by surface grinding the two materials.

iii) EXCLAD

To ensure reliable bonding and maximum yield a slab of a very low interstitial content steel was explosively clad with two pieces of type 321 stainless steel. Explosive cladding was used in preferrence to roll bonding due to the 50% failure rate that was experienced with roll bonding.

The cladding operation was carried out by the Nobel Division of ICI at their Dunside site. Ultrasonic inspection of the double bonded slab showed that there was a very small area of non bond on one side but that greater than their guaranteed % bond of 98 had been achieved.

The bonded billet was cut in half and each half was hot forged at 1000°C to spread the billet to mm which was the maximum size that could be hot rolled in the laboratory. The material was then hot rolled from 1100°C down to a series of sizes calculated such that by giving various cold reductions the material would end up at a finished size of .75mm. Inspection after hot rolling showed that the small area of non bond had healed up. All material was given the customary post hot roll anneal of one hour at 1100°C.

The analyses of the component materials are given below.

iv) Analyses

	C	Si	Mn	Cr	Ni	S	P	Ti	Al	N
Type 321 Stainless steel	.06	.45	1.44	17.9	9.5	.24	.28	.50		
Core ADCLAD	.08	.02	.39	-	-	.053	.23	-		
ONESIDE	.11	.33	.28	-	-	.010	-	-		
EXCLAD	.004	-	.31	-	-	-	-	.08	.009	.005

APPENDIX 3

COST ESTIMATION

Cost estimation was carried out using the principle of discounted cash flow applied to the artificial model of a new plant being set up on a 'greenfield' site. The input and output of the plant is assumed to be unintegrated with any larger complex and no sharing of facilities is allowed.

The philosophy of the model is the simplest that can be justified as being reasonably in line with modern accounting and venture analysis techniques. The various parameters in the model and their derivation and manipulation are described below.

Capital Outlay

It is assumed that money is drawn from the reserve and is repaid into the reserve over a period of years depending on the estimated rate of return. Some account of lost revenue must be made because if the money was left in the bank it would be attracting interest at compound interest. To account for this the original outlay is increased by the compound interest formula and the accumulated total divided by the term in years.

$$\text{Yearly outlay} = \frac{P(1 + i)^n}{n}$$

P = capital outlay
i = interest rate
n = term of years

This method is probably biased towards high cost but does not require complex financial decisions to be made at long range which would be the case if money had to be borrowed or there was assumed a steady replacement of capital in the reserve.

Inputs for this section of the computation are:

a) capital outlay

b) repayment term

c) interest rate

It is assumed that the money is all spent in the same year and the plant comes on stream in that year.

Depreciation

The plant is depreciated on a straight line basis over 15 years, the value at this time being nil. This is equivalent to an annual depreciation of 6.7%. This is standard BSC policy. This method is again probably biased towards the debit side for small plant which is fairly easy to replace.

Material Costs

These are estimated on the basis of bought in materials at price list cost. The amount of material bought is increased by the estimated amount to be scrapped during processing. The material costs are not inflated as might be expected, because these are liable to fluctuations outside the general inflation depending on such factors as supply and technical progress. It will also be noted that in projecting the accounts the estimated price is not inflated for the same reasons.

Overheads

Fixed overheads are estimated as being a fraction of the initial capital outlay. This method is not generally regarded as being accurate enough for accounting purposes but considering the range at which the cost must be estimated the approximation will generally hold true if the fraction is estimated from the known costs of a similar type of plant.

Variable overheads are approximated by summation of the operation costs for the component parts of the process and are considered as a tonnage charge. This again depends for its acceptance on the fact that this is a long range estimate.

The overheads are summed and together they are increased annually at the estimated current rate of industrial inflation.

The inputs for this section of the computation are:

a) fixed overhead % of capital outlay

b) variable overhead cost per tonne

c) inflation rate.

Sales

These are estimated from an algorithm which gives a roughly parabolic increase in sales starting with a given first year sales and a maximum possible demand. The algorithm is:

$$\text{Sales}_i = \text{Sales}_{i-1} + \frac{(\text{Max Sales} - \text{Sales}_{i-1})}{2}$$

This, of course, is purely arbitrary and if anything is optimistic.

The input values are:

a) maximum possible sales, plant at full production

b) minimum sales in year 1.

Scrap

Some processing scrap is estimated for and this is not re-used internally but sold off and the revenue added to the cash flow.

Tax and Administration

Outgoing cash flow is increased to account for the administration and selling charges levied on the process. It is assumed that these are not accounted for in the fixed overhead allowance. Where the incoming cash flow from sales is greater than the outgoing cash flow then the surplus is reduced by a percentage to account for taxation.

Discounting

After reductions the surplus cash flow income over expenditure is discounted at the inflation rate to give the discounted cash flow for that year. This discounted cash is added to a cumulated fund.

Selling Price

The selling price of the processed material is calculated so that there will be a net positive cumulative cash flow over a specified accounting period. This profit represents the return over this period.

Computer Programme

A computer programme is written to perform the arithmetic of the accounts. The actual fortran programme is written for the special situation of clad material production but is readily modified for other situations. Data is read from card and the hypothetical accounts for a five year period are outputted on the line printer.

The input data is:

a) capital outlay

b) repayment term

c) compound interest rate

d) the estimated rate of inflation over the costing term

e) the percentage of the capital outlay that is taken as being the fixed overhead

f) the amount per tonne of sales that is added as the variable overhead

g) the scrap rate and scrap value

h) the cost of mild steel and stainless steel

i) the estimated maximum and minimum sales

The programme proceeds as follows:

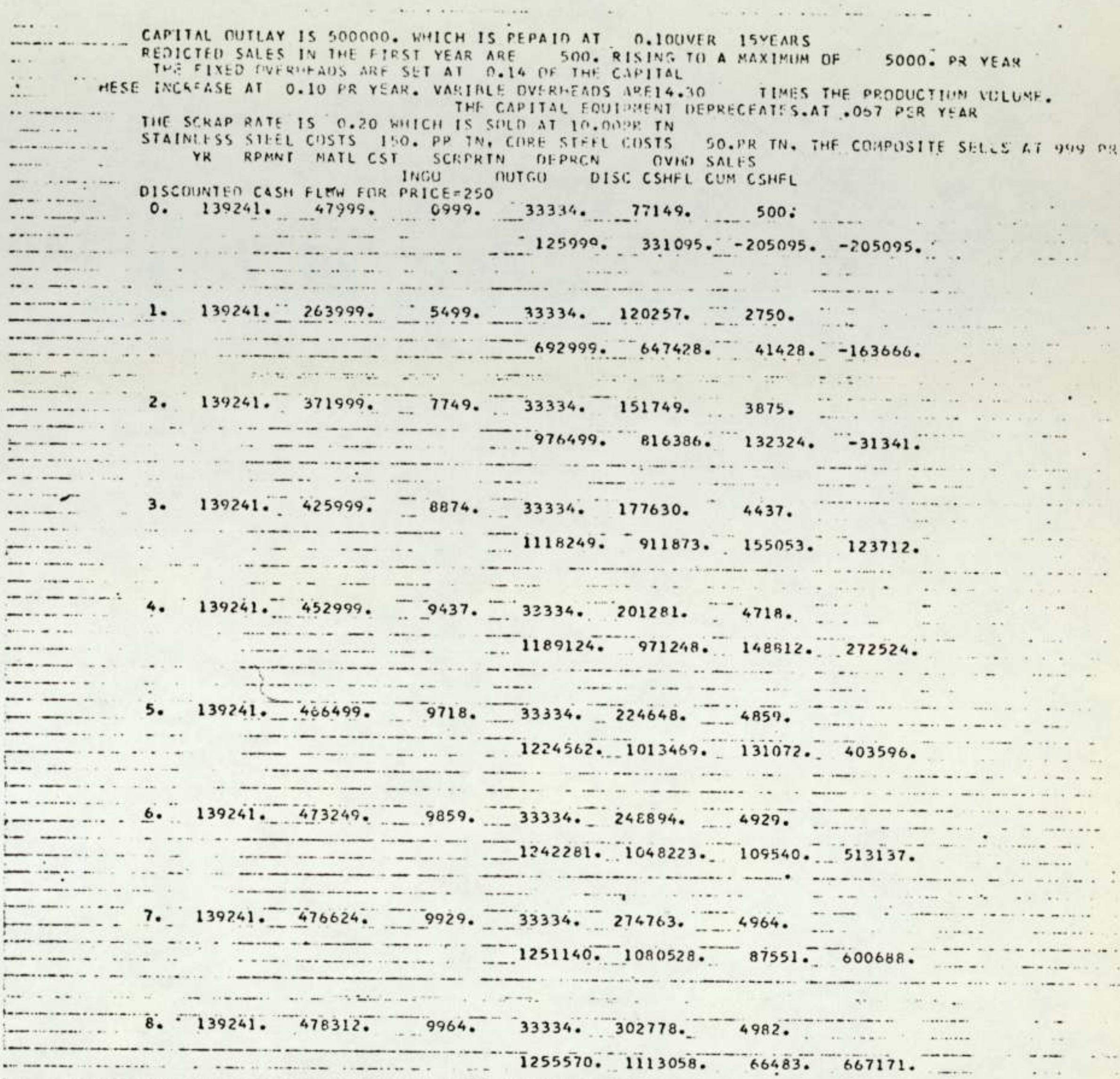
1. The rate of repayment per annum is calculated from the capital sum, the interest rate and the repayment term.
2. The depreciation charge is calculated from the capital investment over the standard term.
3. The material cost is calculated on the basis of a 10% per side laminate from the stainless steel costs and the mild steel costs.
4. The annual sales are calculated from the minimum and maximum estimated sales by the use of the arbitrarily derived law.
5. The scrap return value is calculated from the annual sales and the scrap value.
6. The fixed and variable overheads are calculated and inflated at the current inflation rate in a compounding manner such as used for compound interest calculations.
7. The ingoing cash flow is calculated from the sum of the sales in that year and the return on scrap. The sale price of the material is incremented from a low value during the run of the programme until a satisfactory surplus of income over expenditure is achieved.
8. The outgoing cash flow is calculated from the sum of the overheads, the loan repayment, the depreciation and the= material costs.
9. The outgoing cash flow is increased by the allowance for administration and selling charges of 12%.
10. The net cash flow is calculated from the outgoings and the ingoings and if this is a net positive flow this is reduced by 40% to allow for corporation tax at its current rate.

11. The taxed net cash flow (or untaxed if negative) is discounted at the inflation rate.
12. The net cash flows are cumulated over a period of 5 years and the price of the laminate is adjusted incrementally until there is a positive cumulated cash flow over this period.

A list out of the programme, a typical output and a flow diagram are given in figs. 13 and 14.

```
// JOB    X     X     X   01 JAN 70 00.101 HRS
// FOR AD    01 JAN 70 00.101 HRS
*LIST SOURCE PROGRAM
*IOCS(CARD,1443PRINTER)
      REAL INGO,MATL,MIN, MAX,MSC
      INTEGER PRICE,PRD
       DIMENSION CSHFL(50)
   10 FORMAT(F7.0,I3)
   11 FORMAT(F5.2,F5.2)
   12 FORMAT(F6.0,F6.0)
   20 FORMAT(2X,'   DISCOUNTED CASH FLOW FOR PRICE='I3)
   30 FORMAT(1H1'CAPITAL OUTLAY IS 'F8.0' REPAID AT 'F6.2' OVER'I2'YRS')
   40 FORMAT(5X'REDICTED SALES IN THE FIRST YEAR ARE 'F7.0' RISING TO A
     1MAXIMUM OF   'F7.0' PR YEAR')
   50 FORMAT(5X' THE FIXED OVERHEADS ARE SET AT 'F5.2' OF THE CAPITAL'/'
     1 THESE INCREASE AT 'F5.2' PR YEAR. VARIBLE OVERHEADS ARE'F5.2 '
     2 TIMES THE PRODUCTION VOLUME.'/'
     3 THE CAPITAL EQUIPMENT DEPRECEATES.AT .067 PER YEAR'    )
   60 FORMAT(5X'THE SCRAP RATE IS 'F5.2' WHICH IS SOLD AT 'F5.2'PR TN')
   70 FORMAT(5X'STAINLESS STEEL COSTS'F6.0' PR TN, CORE STEEL COSTS'F6.0
     1'PR TN. THE COMPOSITE SELLS AT 'I3' PR TN')
   90 FORMAT(5X,F3.0,6F10.0,/)
   91 FORMAT(40X,4F10.0,///)
   99 FORMAT(10X'YR   RPMNT  MATL CST   SCPPRTN   DEPRCN     OVHD SALES'
     1  /,30X ,'INGO      OUTGO     DISC CSHFL CUM CSHFL')
C  CORPORATION TAX IS CHARGED AT 40 PERCENT
C  ADMINISTRATION AND SELLING CHARGES AT  12 PERCENT
 1000 READ(2,10)CAP,NYR
      IF(CAP)800,800,1100
 1100 CONTINUE
      READ(2,11)VOVHD,OPCT
      READ(2,11)AINT,AINF
      READ(2,11)SCRAP,SCRP
      READ(2,12)SSC,MSC
      READ(2,12)MIN,MAX
      PRD=10.
      PRICE=999
      WRITE(3,30)CAP,AINT,NYR
      WRITE(3,40)MIN,MAX
      WRITE(3,50)OPCT,AINF,VOVHD
      WRITE(3,60)SCRAP,SCRP
      WRITE(3,70)SSC,MSC,PRICE
      RPMT=CAP*((1.+AINT)**NYR)/NYR
      DO 700 PRICE=1.700
      JJ=1
      KK=1
      DEPC=CAP*.06667
      CUMFL=0
      GOTO 100
  101 WRITE(3,20) PRICE
      WRITE(3,99)
      CUMFL=0
  100 DO 600 I=1,5
      IF(I-1)200,200,300
  200 SLES=MIN
      GOTO 400
  300 SLES=((MAX-SLES)/2)+SLES
  400 CONTINUE
      YR=I-1
      II=I-1
      MATL=(((.3*SSC)+(.7*MSC))*(1.+SCRAP))*SLES
      SCRPR=SLES*SCRAP*SCRP
      VOH=SLES*VOVHD
      FOH=(CAP*OPCT)
      OVHD=(VOH+FOH )*((1.+AINF)**II)
      INGO=(SLES*PRICE)+SCRPR
      OUTGO=OVHD+MATL+RPMT+DEPC
      OUTGO=OUTGO*1.086
      CSHFL(I)=(INGO-OUTGO)
      IF(CSHFL(I))120,120,130
  130 CSHFL(I)=CSHFL(I)*0.6
  120 CONTINUE
      CSHFL(I)=(CSHFL(I)  )/((1.+AINF)**II)
      CUMFL=CUMFL+CSHFL(I)
      GOTO(600,110),JJ
  110 CONTINUE
      WRITE(3,90)YR ,RPMT,MATL,SCRPR,DEPC,OVHD,SLES
      WRITE(3,91)INGO,OUTGO,CSHFL(I),CUMFL
      KK=2
  600 CONTINUE
      IF(CUMFL)700,700,750
  700 CONTINUE
  750 JJ=2
      GOTO(101,1000),KK
  800 CONTINUE
      CALL EXIT
      END
```

FIG 13a COMPUTER COST PROGRAMME



```
  CAPITAL OUTLAY IS 500000. WHICH IS PEPAID AT   0.10OVER  15YEARS
  REDICTED SALES IN THE FIRST YEAR ARE     500. RISING TO A MAXIMUM OF     5000. PR YEAR
   THE FIXED OVERHEADS ARE SET AT  0.14 OF THE CAPITAL
HESE INCREASE AT  0.10 PR YEAR. VARIBLE OVERHEADS ARE14.30      TIMES THE PRODUCTION VOLUME.
                                   THE CAPITAL EQUIPMENT DEPRECEATES.AT .067 PER YEAR
  THE SCRAP RATE IS  0.20 WHICH IS SOLD AT 10.00PR TN
  STAINLESS STEEL COSTS  150. PR TN, CORE STEEL COSTS   50.PR TN. THE COMPOSITE SELLS AT 999 PR
       YR   RPMNT  MATL CST    SCRPRTN   DEPRCN      OVHD SALES
                             INGO      OUTGO    DISC CSHFL CUM CSHFL
  DISCOUNTED CASH FLOW FOR PRICE=250
   0.   139241.    47999.      0999.    33334.    77149.      500.
                                       125999.   331095.  -205095.  -205095.

   1.   139241.   263999.      5499.    33334.   120257.     2750.
                                       692999.   647428.    41428.  -163666.

   2.   139241.   371999.      7749.    33334.   151749.     3875.
                                       976499.   816386.   132324.   -31341.

   3.   139241.   425999.      8874.    33334.   177630.     4437.
                                      1118249.   911873.   155053.   123712.

   4.   139241.   452999.      9437.    33334.   201281.     4718.
                                      1189124.   971248.   148812.   272524.

   5.   139241.   466499.      9718.    33334.   224648.     4859.
                                      1224562.  1013469.   131072.   403596.

   6.   139241.   473249.      9859.    33334.   248894.     4929.
                                      1242281.  1048223.   109540.   513137.

   7.   139241.   476624.      9929.    33334.   274763.     4964.
                                      1251140.  1080528.    87551.   600688.

   8.   139241.   478312.      9964.    33334.   302778.     4982.
                                      1255570.  1113058.    66483.   667171.

   9.   139241.   479156.      9982.    33334.   333352.     4991.
                                      1257785.  1147314.    46850.   714021.
```

FIG 13b COMPUTER COST PROGRAMME

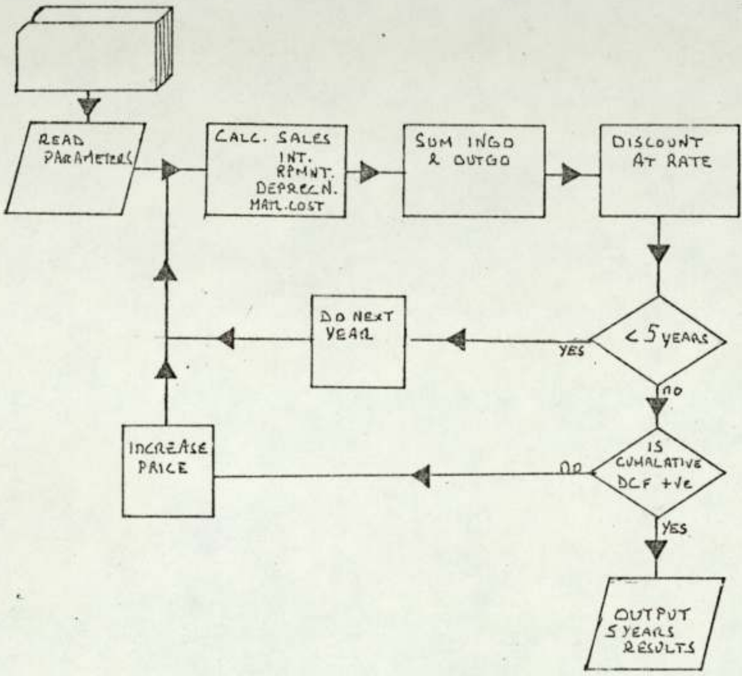


FIG 14 COMPUTER COST PROGRAMME

APPENDIX 4

THE PLASTIC ANISOTROPY COEFFICIENT OF LAMINATE MATERIALS FROM HILLS THEORY OF ANISOTROPY(10).

$$(H+G)\sigma_x^2 - 2H\sigma_y\sigma_x + (F+H)\sigma_y^2 = 2\sigma_u^2 \qquad (1)$$

where H, F, G are constants

σ_x is stress in x dir^n

σ_y is stress in y dir^n

σ_u is uniaxial stress $\bar{z}$

Applying this to the Levy - Von Mises criterion

$$d\varepsilon_x = \frac{d\bar{\varepsilon}}{\bar{\sigma}}\left[2(H+G)\sigma_x - 2H\sigma_y\right]$$

and

$$d\varepsilon_y = \frac{d\bar{\varepsilon}}{\bar{\sigma}}\left[2(H+F)\sigma_y - 2H\sigma_x\right]$$

when

$$\sigma_y = 0 \qquad R_x = \frac{2H\sigma_x}{2G\sigma_x}$$

$$= \frac{H}{G}$$

Similarly putting $\sigma_x = 0$

$$R_y = \frac{H}{F}$$

If H is arbitrarily assigned a value of 1 (a reasonable estimate in view of the uncertainty involved in F, G and H)

$$F = \frac{1}{R_y} \qquad G = \frac{1}{R_x}$$

Substituting into equation (1)

$$\left(1+\frac{1}{R_x}\right)\sigma_x + 2\sigma_x\sigma_y + \left(1+R_y\right)\sigma_y^2 = 2\sigma_u^2$$

to simplify this the equation can be multiplied by $\frac{R_x}{1+R_x}$

$$\sigma_x^2 - 2\left(\frac{R_x}{1+R_x}\right)\sigma_x\sigma_y + \left(\frac{1+R_y}{1+R_x}\cdot\frac{R_x}{R_y}\right)\sigma_y^2 = 2\sigma_u^2\frac{R_x}{1+R_x} \quad (4)$$

after combining equations 2 and 3 and substituting for H and G

$$\frac{d\varepsilon_x}{d\varepsilon_y} = \frac{\sigma_x - A\sigma_y}{B\sigma_y - A\sigma_x}$$

$$A = \frac{R_x}{1+R_x}$$

$$B = \frac{1+R_y}{1+R_x}\cdot\frac{R_x}{R_y}$$

if this equation is made a reciprocated constant C_{xy}

$$C_{xy} = \frac{B\sigma_y - A\sigma_x}{\sigma_x - A\sigma_y}$$

so $$C_{xy}\left(\sigma_x - A\sigma_y\right) = B\sigma_y - A\sigma_x$$

rearranging to get σ_y

$$\sigma_y = \sigma_x\left(\frac{C+A}{B+CA}\right)$$

the constants can be accumulated

$$D = \frac{C+A}{B+CA}$$

and σ_y is simply

$$\sigma_y = D\sigma_x$$

This can be substituted into equation (1)

$$2\sigma_u^2 A = \sigma_x^2 - 2AD\sigma_x^2 + Bc^2\sigma_x^2$$

which can be rearranged to get an expression for σ_x.

$$\sigma_x = \sqrt{\frac{2\sigma_u^2 A}{1 - 2AD + BD^2}}$$

It is again convenient to accumulate the constant side of the expression so

$$\sigma_x = Z$$

The work done in extending the laminate is given by

$$dW = \sigma_x \, d\varepsilon_x + \sigma_y \, d\varepsilon_y$$

This can be made up by an equivalent stress in the x direction.

$$dW = \sigma'_x \, d\varepsilon_x$$

so $\sigma'_x = \sigma_x + \sigma_y \frac{\varepsilon_y}{\varepsilon_x}$ which is the effective working stress.

Substituting in derived constants

$$\sigma'_x = Z + ZDC$$

from this equation σ_x' can be plotted as a function of $D\frac{\varepsilon_y}{\varepsilon_x}$ and as the system will attempt to do the minimum amount of work the value of the plastic anisotropy coefficient will be when the work curve plotted as above is at a minimum, i.e. when

$$\frac{d\,\sigma_x}{d\,D\frac{\varepsilon_y}{\varepsilon_x}} = 0$$

Where a laminate is involved under equal strain conditions each phase of the laminate can be plotted separately and a composite curve derived by adding the two curves weighted by the rule of mixtures.

$$\sigma'_{xc} = \sigma'_{x\alpha} * F_\alpha + \sigma'_{x\gamma} * (1 + F_\alpha)$$

c denotes composite

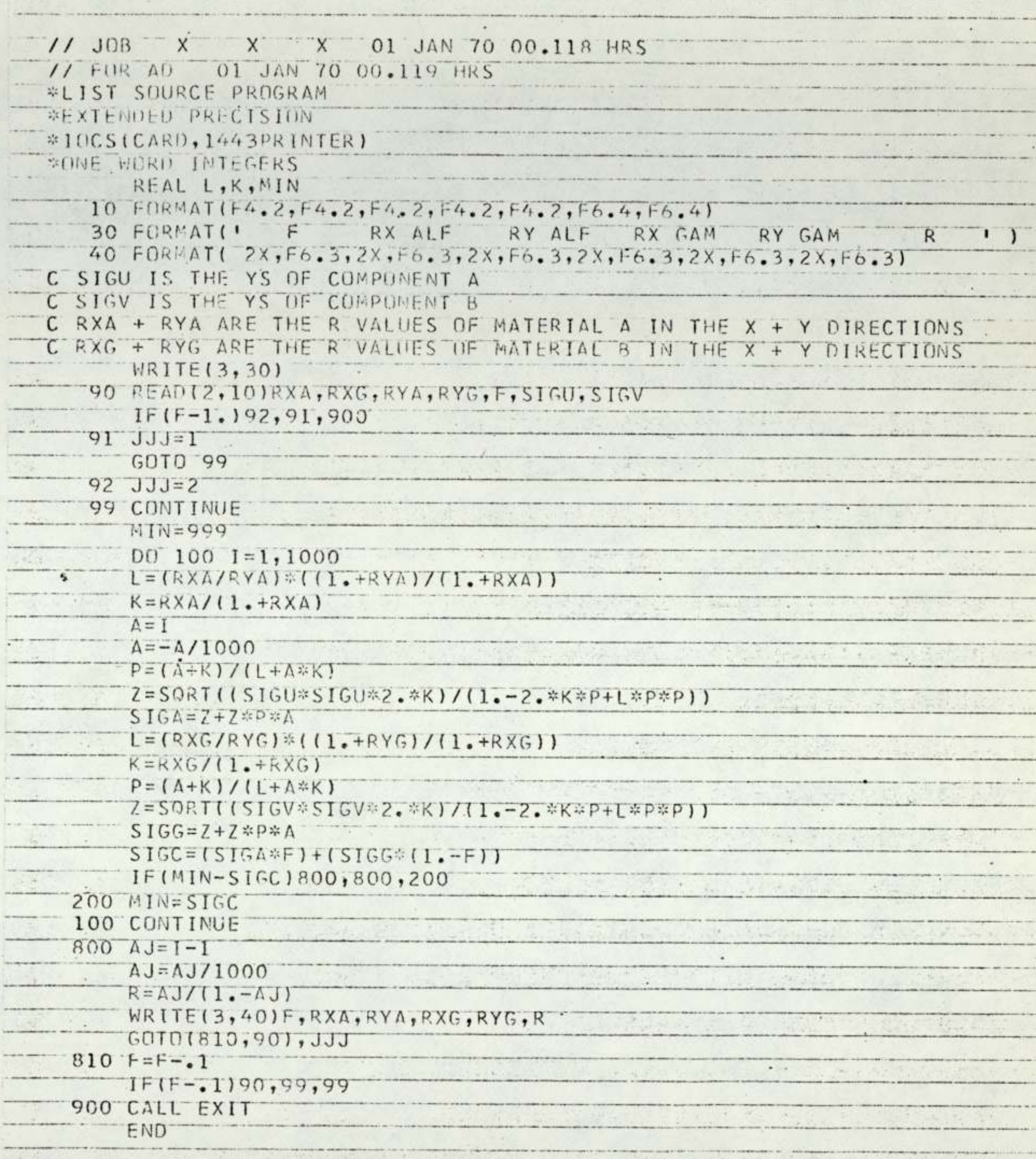
α, γ different materials

F fraction

The calculation is performed by a computer programme written in Fortran and is listed in fig. 15.

Some theoretical effects of cladding thickness on R value are shown in fig. 16.

The difficulty of obtaining values for the constants in the anisotropy equation must reduce this to being of academic interest only.



```
// JOB    X     X     X   01 JAN 70 00.118 HRS
// FOR AD    01 JAN 70 00.119 HRS
*LIST SOURCE PROGRAM
*EXTENDED PRECISION
*IOCS(CARD,1443PRINTER)
*ONE WORD INTEGERS
      REAL L,K,MIN
   10 FORMAT(F4.2,F4.2,F4.2,F4.2,F4.2,F6.4,F6.4)
   30 FORMAT('   F        RX ALF     RY ALF    RX GAM    RY GAM          R     ')
   40 FORMAT( 2X,F6.3,2X,F6.3,2X,F6.3,2X,F6.3,2X,F6.3,2X,F6.3)
C SIGU IS THE YS OF COMPONENT A
C SIGV IS THE YS OF COMPONENT B
C RXA + RYA ARE THE R VALUES OF MATERIAL A IN THE X + Y DIRECTIONS
C RXG + RYG ARE THE R VALUES OF MATERIAL B IN THE X + Y DIRECTIONS
      WRITE(3,30)
   90 READ(2,10)RXA,RXG,RYA,RYG,F,SIGU,SIGV
      IF(F-1.)92,91,900
   91 JJJ=1
      GOTO 99
   92 JJJ=2
   99 CONTINUE
      MIN=999
      DO 100 I=1,1000
      L=(RXA/RYA)*((1.+RYA)/(1.+RXA))
      K=RXA/(1.+RXA)
      A=I
      A=-A/1000
      P=(A+K)/(L+A*K)
      Z=SQRT((SIGU*SIGU*2.*K)/(1.-2.*K*P+L*P*P))
      SIGA=Z+Z*P*A
      L=(RXG/RYG)*((1.+RYG)/(1.+RXG))
      K=RXG/(1.+RXG)
      P=(A+K)/(L+A*K)
      Z=SQRT((SIGV*SIGV*2.*K)/(1.-2.*K*P+L*P*P))
      SIGG=Z+Z*P*A
      SIGC=(SIGA*F)+(SIGG*(1.-F))
      IF(MIN-SIGC)800,800,200
  200 MIN=SIGC
  100 CONTINUE
  800 AJ=I-1
      AJ=AJ/1000
      R=AJ/(1.-AJ)
      WRITE(3,40)F,RXA,RYA,RXG,RYG,R
      GOTO(810,90),JJJ
  810 F=F-.1
      IF(F-.1)90,99,99
  900 CALL EXIT
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS
 EXTENDED PRECISION
 IOCS

CORE REQUIREMENTS FOR AD
 COMMON         0  INSKEL COMMON        0
  VARIABLES       68   PROGRAM     414
```

FIG 15 'R' VALUE PROGRAMME

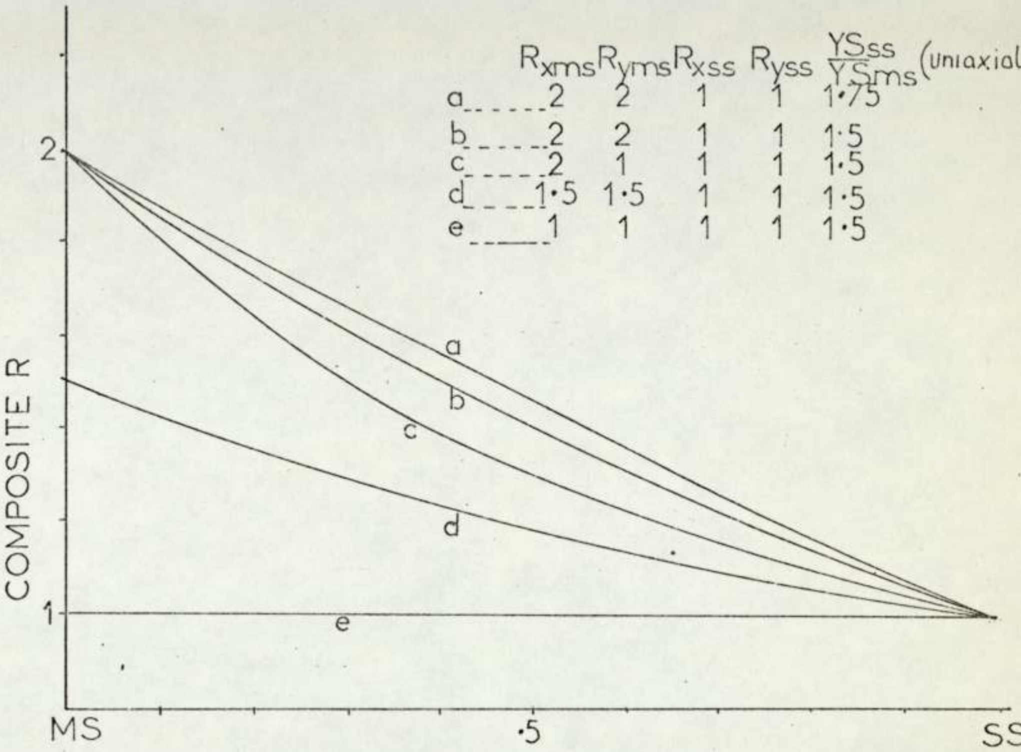


FIG16 CALCULATED R VALUES

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