HOT ROLLING OF IRON POWDER

A thesis submitted in application for the

degree of

Doctor of Philosophy

in

THE UNIVERSITY OF ASTON IN BIRMINGHAM

by

Abbas Torabi, Dipl. Ing.

February 1977

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SUMMARY

Iron powder was compacted at different pressures and heated to different temperatures, for 20 min before hot rolling. Metallographic examination indicated three stages in the deformation process of hot rolling. These were: restacking and rearrangement of particles during entry into the mill, followed by localized deformation and folding-over of the particles, and finally bulk deformation leading to elongation and recrystallization of the grain structure.

Further, a study was undertaken to examine the effect of several variables of the powder rolling process, including compaction, preheating, hot reduction, cold reduction and annealing on the final properties of the finished product.

Six different stages with three commercially available powders, Höganäs ASC 100 and NC 100, and Rospol MP 32, have been investigated. The products formed were examined at the end of each stage of the process. The results show that ultimate tensile strength, elongation and surface finish comparable to those of conventional strip are attainable by adjusting the process route and amount of cold reduction, irrespective of the powder used. Variables which most affect the mechanical properties are sintering and annealing temperature, percentage hot reduction and cold reduction. Hardness is shown to be constant across the strip and a very good surface finish is obtained.

SECTION I.

INTRODUCTION

1.0 ORIGIN

Sauerwald the German scientist first investigated the powder metallurgy of iron in the 1920's. At nearly the same time, a German company (I.G. Farbenindustrie AG) produced iron pentacarbonyl which was used as a motor fuel anti-knock additive. Subsequently, American companies began to produce and use electrolytic powder, at comparable purity and lower cost than the carbonyl powder used by the Germans.

It was not, however, until 1937 when HÖGANÄSof Sweden manufactured from high purity ores sponge iron powder which, although of lower purity, was cheaper than either carbonyl or electrolytic powders and hence became extremely popular for the production of sintered parts.

1.1 THE GROWTH OF POWDER METALLURGY

The technique of powder metallurgy was introduced with Wollaston's method for making ductile platinum disclosed in 1829. The idea of producing strip from metal powder was first embodied in a German patent[1] in 1902.

Over the last three decades there have been several periods of intense interest in new developments within the iron powder industry. The first of these occurred in Germany and was connected with the wartime demand for the replacement of copper, particularly for the driving bands of shells. The second period ended with the construction of a number of iron powder production plants in the U.S.A. around 1953-54. The technology of this second period has been described by Jones.[2]

The third period, which began some ten years ago, when the North American industry (Canada and the U.S.A.) passed through a rapid market expansion and undertook a large development plan to produce additional facilities.

Although the general concept of the continuous production of strip from metal powder originated early in the present century, the subsequent modifications to the basic idea have been both numerous and varied. A brief survey of these has already been made by Franssen.[3] The process which is of considerable interest today, was first described in detail in 1950, by Naeser and Zirm.[4] It is essentially the compacting of powder between a pair of rolls, into the form of a continuous strip followed by sintering and processing the strip by conventional cold rolling and annealing operations.

The study and development of this basic process received considerable attention in the 1950's[5-8] and with the advent in powder form of certain relatively cheap raw materials produced by the hydro-metallurgical, carbonyl, and other methods, the process was able to compete effectively with conventional methods for the production of Ni and Cu strip, in the early 1960's.

With Cu and Ni production, the cost saving may be reckoned in pounds (£) per tonne on an annual output of a few hundred tonnes. Attention is now being focussed on the production of iron strip

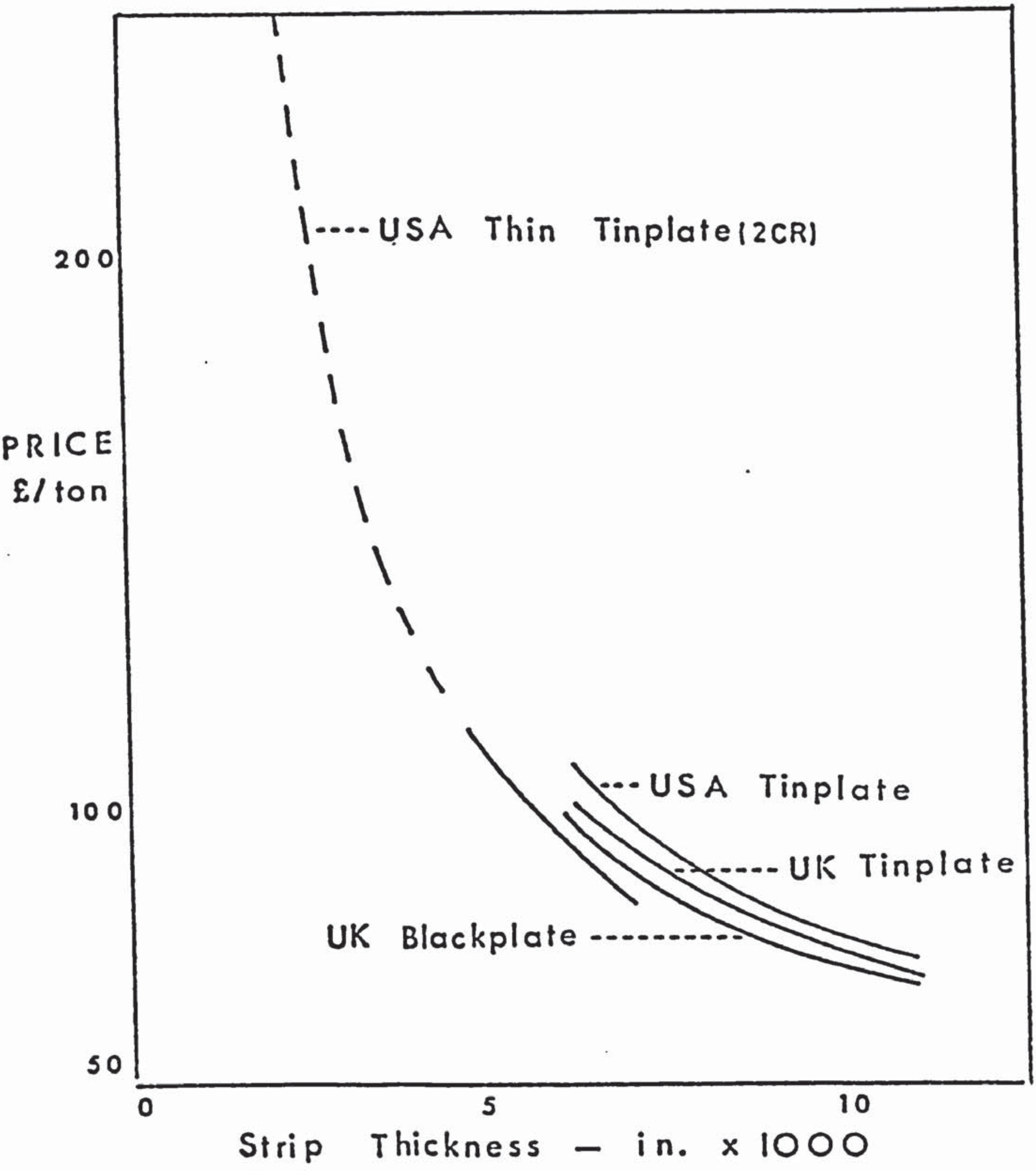


Fig.1. An illustration of rising cost with decreasing strip thickness

where a cost saving reckoned in pence per tonne on an annual output of a few 100,000 tonnes is considered to be just as worthwhile.

1.2 WHY POWDER METALLURGY?

In the face of increasing competition in recent years from such materials as aluminium and plastic, the steel industry has been investigating ways of reducing the cost per unit area of mild steel and other steel strips. This is particularly the case in the packaging field, where savings in materials' costs achieved by the introduction of thinner, stronger grades have enabled tin plate to remain competitive. The costs involved in producing thin steel strip are extremely high, as indicated in Figure 1, and further economies in processing costs are difficult to achieve; therefore the steel industry is investigating other possible production routes. Continuous casting is one such process, but, whilst it can improve the overall yield, the product of the casting machine is only two or three times thinner than the conventionally cast ingot, and still requires considerable working to reduce it down to blackplate or tinplate.

Another process is the direct rolling of iron powder into strip of blackplate or tinplate gauge, i.e. 100 times thinner than the conventional ingot. The direct rolling process is a versatile method of producing strip in a wide variety of materials. It is, for example, possible to produce strip in nickel, copper, iron, steel, brass, etc., in brittle alloys which cannot normally be rolled by conventional methods, for example, "Alnico" magnetic alloys, 50-50 Co-Fe magnetic alloys, very high aluminium heat resisting alloys, and razor blade

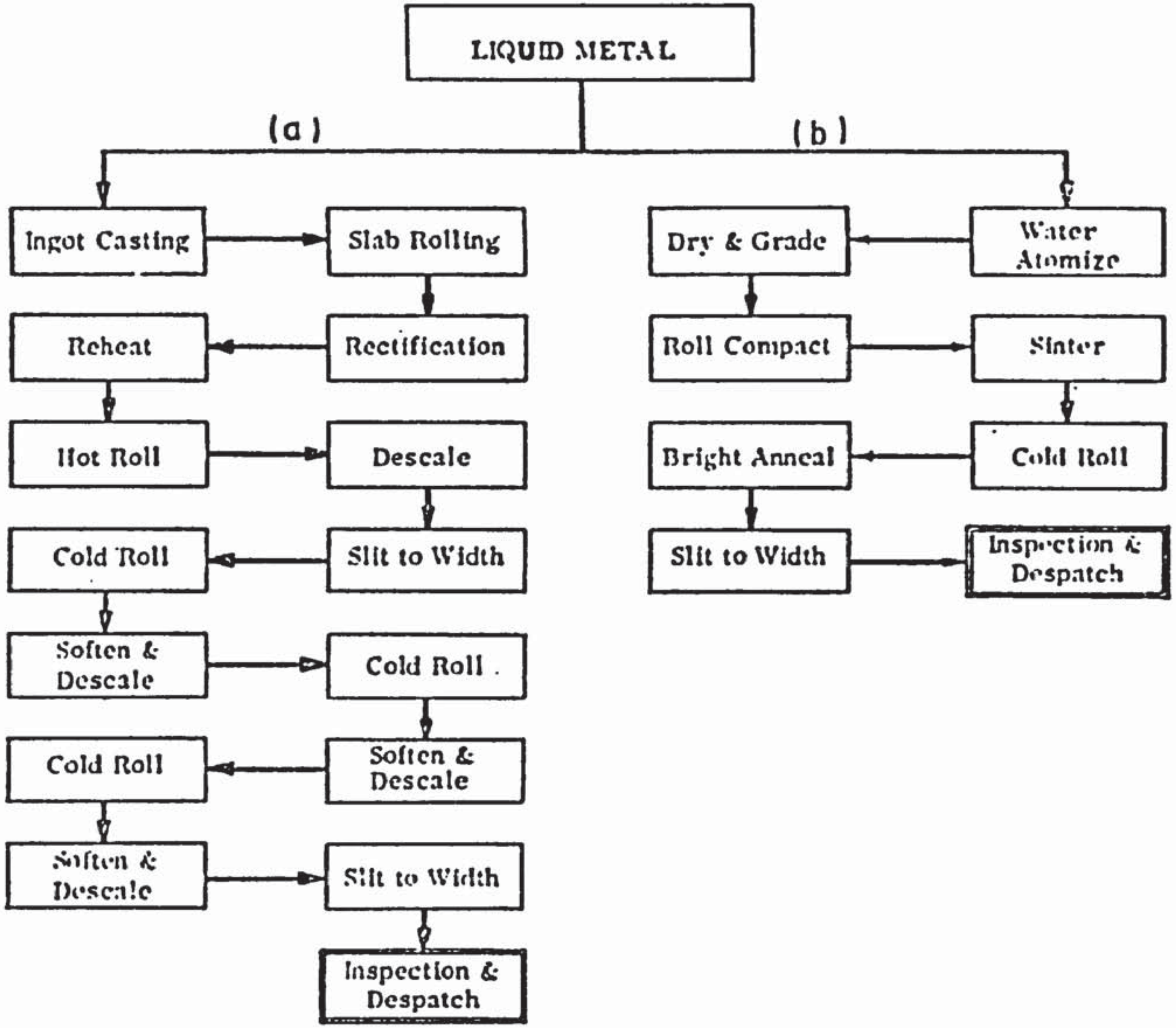


Fig.2. Conventional route (a). Powder route (b).

strip in sintered carbide[9] and in composite materials which can only be manufactured by the powder metallurgy technique, such as the neutron absorbing materials for atomic energy applications.[10] The powder metallurgy process also lends itself to the production of bimetallic and clad strip.

A comparison of the basic stages involved in the production of strip by the direct rolling and conventional routes, as shown in Figs2 and 3 suggest that the direct-rolling process, by eliminating such operations as melting, casting, ingot dressing and their break down before cold rolling should offer marked reductions in production costs.

Assuming that the engineering design of the product is suitable, an important procedure is to ensure that the processes used for making the product produce a minimum of scrap. In this respect powder metallurgy is particularly beneficial because scrap losses are generally low and the product is often made very close to the final required dimensions.[11]

Singer[12] noted that despite a lot of industrial development work, no process has yet been operated which has enabled iron powder to be produced at a sufficiently low cost that it can be converted into iron or steel strip comparable in price with strip produced by conventional methods.

Only in a few instances can it successfully compete with conventional production. Roll compaction of powder is already in

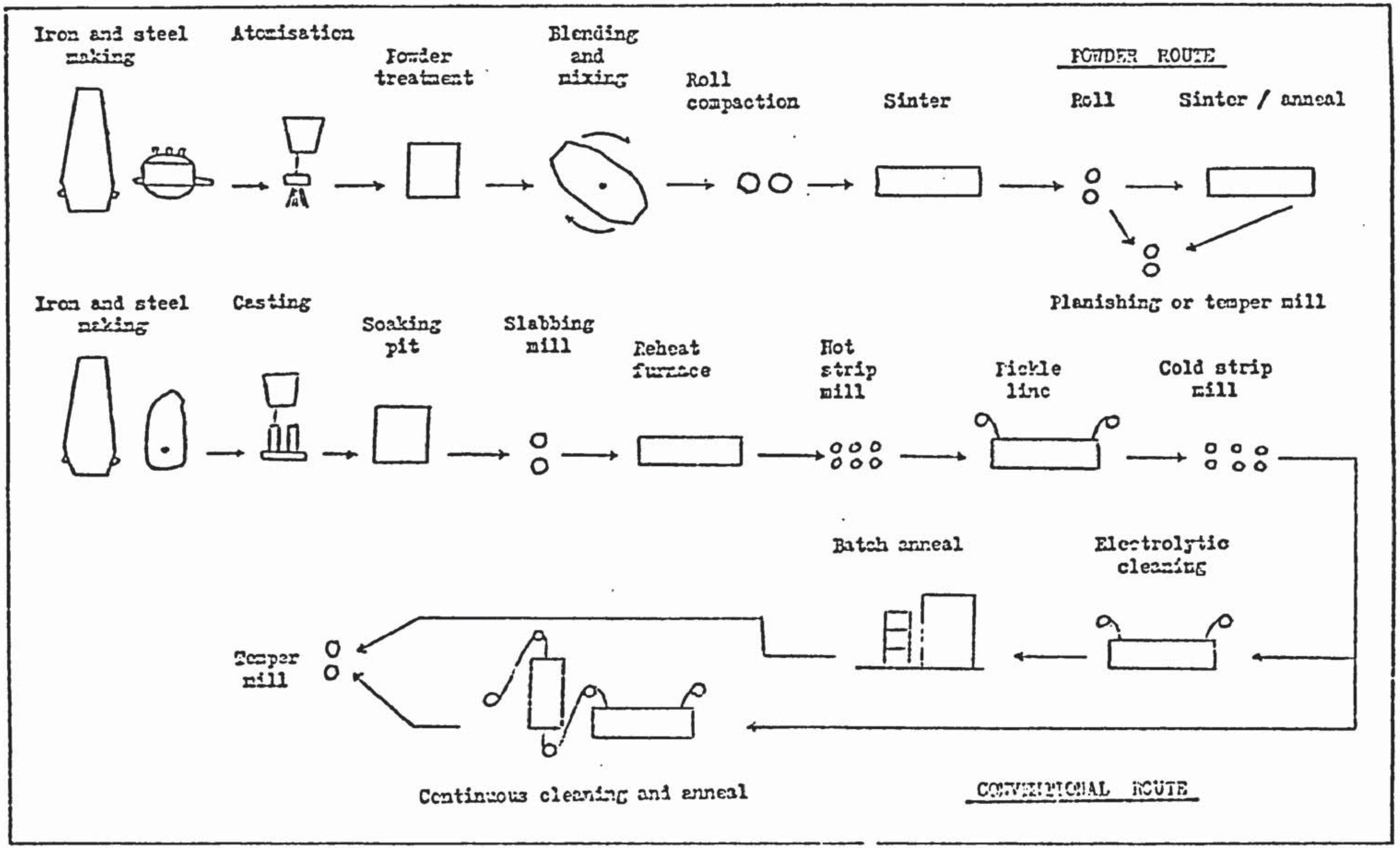


Fig.3. A comparison of strip production by powder rolling and conventional route.

commercial practice for nickel and cobalt strip. Experience with these plants has shown that high yields can be achieved, since little edge trimming is required. It should be noted,[13] however, that nickel and cobalt are readily available in suitable powder form at prices that make roll compaction favourable even on a small scale. Ferrous based powder materials which, for the development of new methods, are attractive because of their large scale application, are not yet available at a sufficiently low price level. Consequently, if steel strip is to be produced economically by powder metallurgical methods, low-cost powder production must be developed. Copper and nickel can claim such a success thanks to the advent of hydrometallurgical and carbonyl refining processes which give the refined metal already in the powder form.

At present, the cost of iron powder is prohibitive when compared to the cost of all strip except the thinnest, such as tinplate. However, Grant[14] has suggested that it might be possible to almost halve the cost of powder made from molten metal by melting in large electric furnaces. Because there are powder producers operating on an increasingly greater scale in North America and producers of significance in Sweden and Germany, there will tend to be pressure from various directions for powder prices to fall in the U.K.

It has been proposed by Gregory and Bridgwater[15] that iron powder can be made cheaply by chemical means rather than by existing pyrometallurgical methods. Also lower powder prices mean better prospects for powder forming techniques. Similarly, improved or significant new large scale powder forming techniques mean a greater probability of cheaper powder through increased needs.

One major technical draw-back at the moment is the low rolling speeds so far achieved. Speeds that have been reached are 63 ft/min (19 m/min) with 18-8 stainless steel powder,[16] 175 ft/min (53 m/min) with Cu powder,[17] 100 ft/min (30 m/min) with iron powder,[18] and 500 ft/min (152 m/min) for short lengths of film produced from a slurry of iron powder.[19] These rolling speeds are negligible when compared to the speeds achieved in modern mile-a-minute mills. Thus higher speeds would undoubtedly have to be achieved to make the direct-rolling process into an attractive proposition.

From the foregoing discussion it is apparent that the direct-rolling process is capable of very wide application, both as an alternative to conventional melting and casting methods, e.g. for the production of copper and nickel strip, and for the processing of unconventional materials which can only be produced by the powder metallurgy technique. The final assessment of the value of the process in any particular field depends, however, upon economic considerations, in particular, on the availability of suitable raw materials and achievement of suitable outputs.

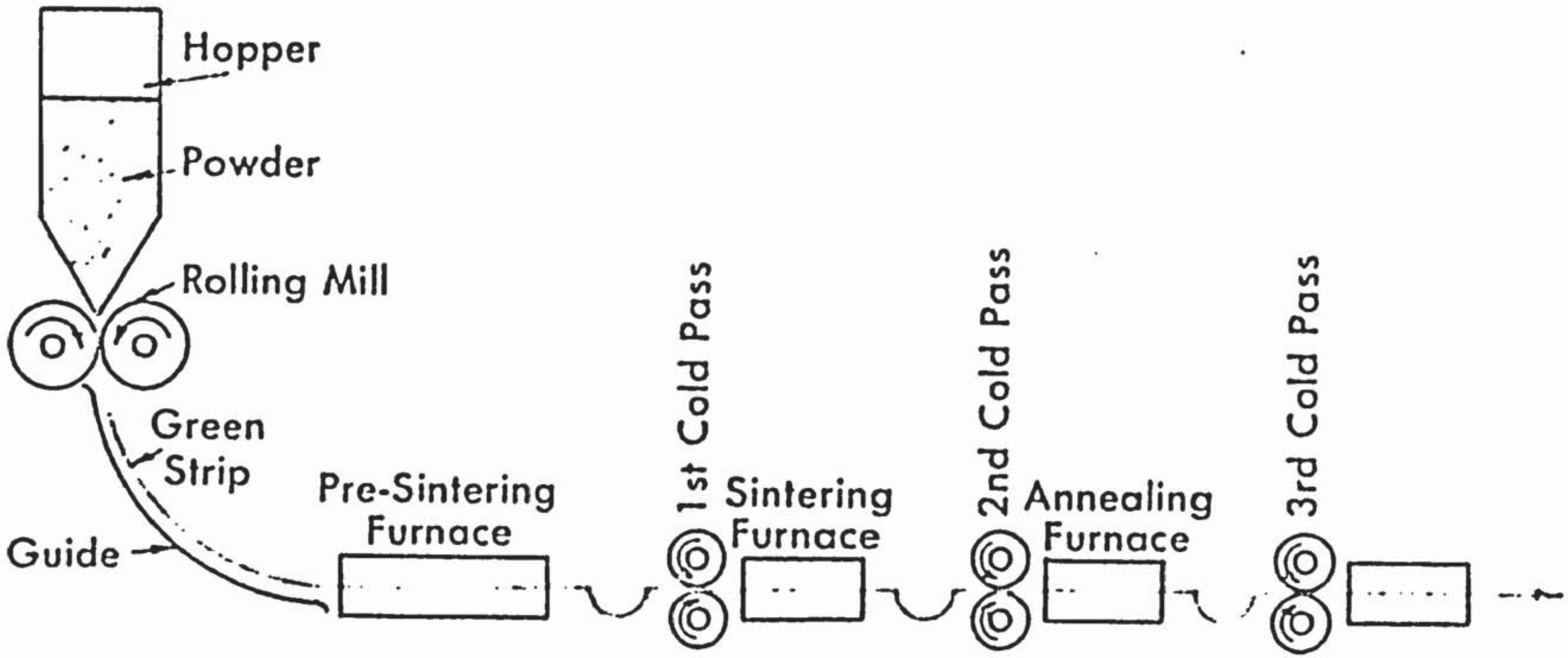


Fig.4. Schematic diagram of vertical equipment for the production of strip.

SECTION II.

LITERATURE REVIEW

2.0 METHODS OF COMPACTION

Since the original patent in 1902[1] and the process described by Naeser & Zirm,[4] many methods of producing strip have been suggested and recently reviewed.[2,3,20-26] There are five basic processes.

(1) Continuous compaction by cyclic pressing.
(2) Rolling of pre-sintered compacts.
(3) Compaction of powder supported on a temporary substrate.
(4) Compaction and sintering of powdered metal films.
(5) Direct roll compaction.

2.0.1. Cyclic compaction

Cyclic compaction was developed by Diebel et al[27] and reviewed in greater detail by Marshall et al.[28] The slab is produced by the compaction of powder in channel shaped containers using a punch with a heel parallel to the base of the channel and a nose portion inclined to the base at an angle of about 7°. The punch moves a distance of 1/8" - 1/2" horizontally along the channel with each stroke. Although the production rate could be greatly increased by employing equipment designed especially for the purpose, it is unlikely that rates greater than 1-2 ft/min (0.3-0.6 m/min) could be attained.

This process cannot be used for mass production.

2.0.2 Rolling pre-sintered compacts

The STORA[29] is perhaps the best example of this method. It involves combining the oxidation/reduction of a mixture of granulated pig iron and iron oxide, with a sintering operation in thin walled, perforated steel canisters to produce low carbon steel. The sintered slab, with the container, is subsequently compacted by hot-rolling before processing in a conventional manner to produce strip. The cost of this process discourages its industrial application.

A variation of this was developed by Matsumura[30] et al who produced strip by rolling reduced iron powder between two metal sheets.

2.0.3 Substrate supported compaction

In this method the powder is spread onto a substrate such as metal or paper strip,[31] in order to give the powder support while it is compacted into green strip via a rolling mill, Fig.4. The green strip peeled from the substrate and subjected to several sintering and rolling operations this principle appears to be feasible for continuous hot compaction of powder strip. A techno-economic study has been done by B.S.C.[32] and it has been shown to be uneconomic on present day powder prices.

2.0.4 Powder films

This technique uses slurry to form metal powder films. These slurries may contain upwards of 75% by weight of metal particles suspended in a dilute aqueous or alcoholic solution of a combustible organic binder and surface active agents. The slurries are deposited on a temporary substrate whilst they are fired. After drying, the film has sufficient strength to allow it to be peeled off and compacted in a mill. BSC has developed a variation of the slurry technique,[19] and has rolled short lengths of film at speeds up to 500 ft/min (152 m/min (now at BSC, Shotwick).

The problem posed by this method was the use of a special type of binder and the cost involved in thermal energy to dry the slurry.

2.0.5 Direct powder rolling

Interest and development of this method stems from the work by Naeser & Zirm.[4] The process consists of feeding metal powder into the throat of a standard or slightly modified rolling mill in order to compact the powder into green strip. The strip is afterwards sintered, and then hot and cold rolled down to size.

The direct-roll compaction of powder into strip appears to be the most applicable to quantity production and offers the greatest promise for large-scale commercial exploitation.

Fig.5 gives a graphical representation of the more likely techniques for the production of strip from metal powder.

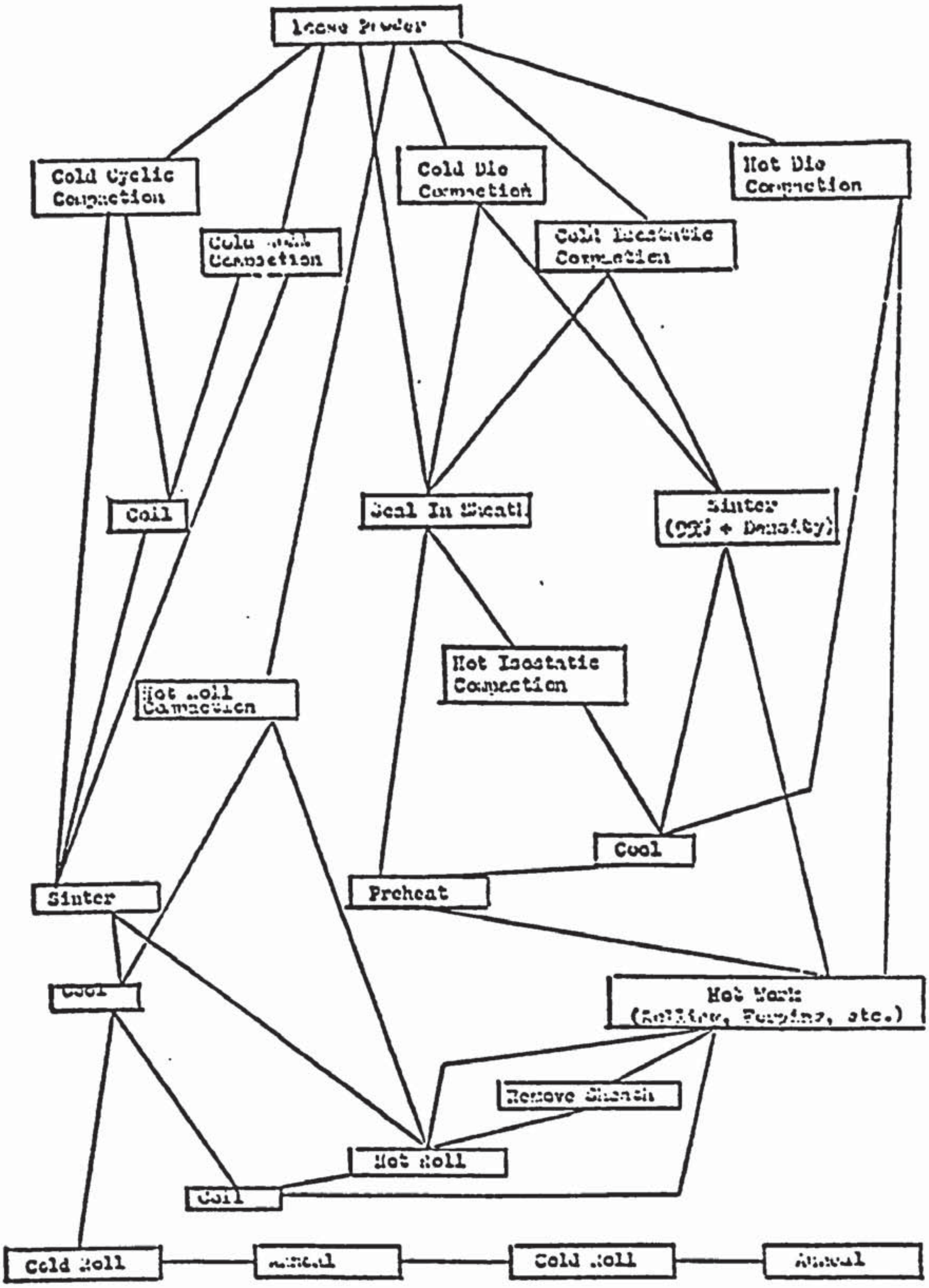


Fig.5. Technically-feasible routes for the consolidation of metal powder into fully-dense strip.

2.1 POWDER PROPERTIES

It is widely recognised that the simple production of powder product is in itself an inadequate demonstration of its commercial acceptability. For a given chemical composition the powder must meet certain specific property requirements before it is used in roll compaction processes.

The initial phase in direct roll compaction of powder into metal strip, involves supplying powder to the compaction zone between the rolls.

Individual particles are characterised by size, shape, specific area, surface texture, hardness and density, but the properties of the powder mass as a whole are also affected by chemical analysis, size distribution, mean particle size, apparent and tap densities and flow behaviour. Most of these properties are inter-related which makes the effect of any one variable on the process difficult to evaluate.

Several authors[17,33,49,50,71,34] have attempted to correlate the effects of various powder properties on the compaction process. Zapf[35] analysed the properties of eleven powders and observed seven parameters in each case, but despite such an examination, true separation of the effects of these inter-relations could not be achieved.

Hence for any chosen production route it will be essential, if a consistent and acceptable product is desired, to use a powder with a large number of properties controlled by specification.

2.2 COMPACTION CYCLE

In an attempt to study successive stages in roll compaction of metal powders, Evans & Smith[34] mounted and examined metallographically the taper section of coherent material existing in the compaction zone when rolling is stopped. Fig.6. They found that for copper powder the particles are first pressed into intimate contact and then if the pressure is sufficiently high, elongated in the rolling direction.

In die compaction, Seeling & Wulff[36] observed three different phases, viz: packing, elastic and plastic deformation and cold working with or without fragmentation. They further observed that these phases may overlap each other.

Evans & Smith[34] illustrated the existence of localised deformation during the compaction at the contact points between particles. As pressure exerted on the powder increases, the number of inter-particle contact points increases and the contact areas already present are enlarged by additional plastic deformation.[37] As the compacting pressure continues to increase intensive deformation occurs involving entire particles.[38] However, in the die compaction of commercial powders it has been claimed that this latter stage is never reached.[39]

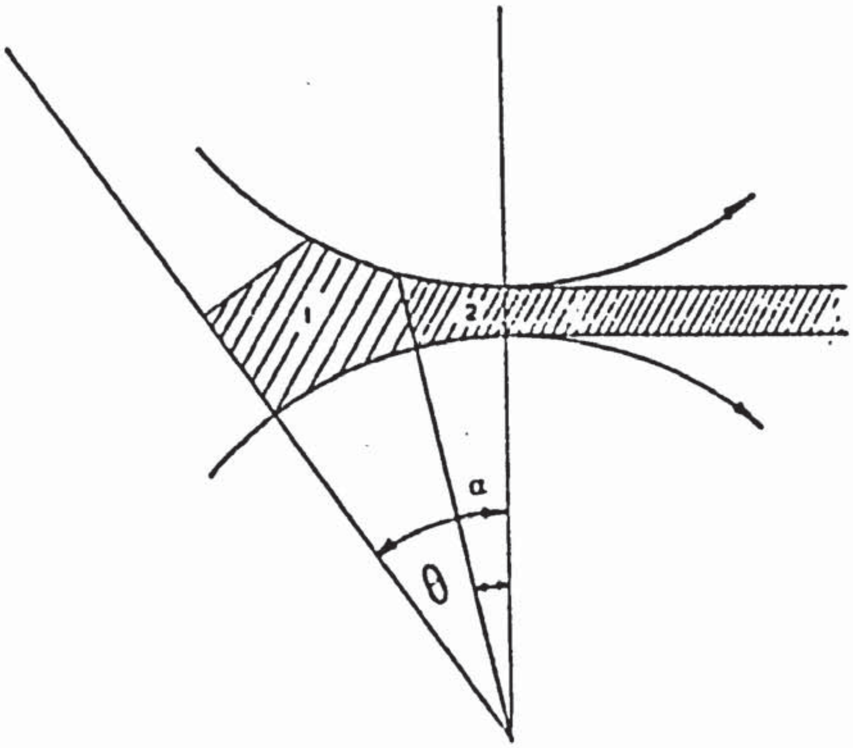


Fig.6. Schematic representation of state of powder in the roll gap. Zone 1 = incoherent powder; zone 2 = coherent powder.

In studying the pressing and rolling of metal powders Nikolaev[40] noted that powder deformation passes through the following stages.

1. The region of very small pressures. Elastic deformation of powder predominates. After load removal, the original powder volume is restored.
2. The volume decrease is irreversible and takes place as a result of deformation of projections and relative displacement of particles with respect to one another. This second stage manifests itself chiefly in rolling, and to a smaller extent in ordinary compacting.
3. The particles have been brought close together and large contact areas have been established between grains. The subsequent densification occurs as a result of particle metal flow into pores.

The above stages agree with the conclusions made by Sorokin.[41] These and other papers were reviewed by Tundermann[26] and he concluded that during the process the powder particles are:

(a) packed by restacking and re-orientation,

(b) locally deformed with the power asperities being deformed or possibly fractured to permit greater consolidation,

(c) deformed and particle material undergoes plastic flow.

It appears, however, that these stages overlap considerably and that at any stage during compaction several mechanisms may be operating at once.

Most of the many studies of powder compaction that have been made, have been concerned with the relationship between compacting pressure and density. There have been many formulas proposed but one of the most acceptable is that of Shapiro & Kolthoff[42] and Konopicky[43]

$$\ell n \ (1/1-D) = KP + \text{constant}$$

where P is the applied pressure, D the relative density and K a compaction constant. The curve has been applied by different investigators to a variety of materials and it has been found that the curve has characteristic regions as shown in Fig.7.

Kunin & Yurchenko[44] attribute the first region to the particles being brought closer together without undergoing deformation; the second region to brittle and plastic deformation; and the third to bulk compression. Heckel[45] makes a similar classification but he did not observe the third region since he was using relatively low compaction pressures.

Donachie & Burr[39] suggest that the first region is one of transitional restacking, the second corresponds to local plastic flow and the third to isostatic compression, both elastic and plastic.

Fig.7. Variation of $\ell n\, 1/1\text{-}D$ with compaction pressure for Atomet 28 iron powder.[46]

Recent work by Hewitt et al[46] using X-ray line broadening technique, concluded on the contrary that plastic deformation always occurs during consolidation and that extensive plastic deformation can take place during the first stage of powder compaction. Plastic deformation does not always cause consolidation as consolidation results from both mechanical interlocking and associated frictional welding, due to surface shear deformations. Thus, it is difficult to achieve consolidation in spherical powders, even after considerable plastic deformation.

2.3 HOT ROLL COMPACTION

In order to reduce the resistance to deformation of the metal powder during compaction and hence to increase bonding, Evans[47] conducted experiments on the rolling of copper powder heated to 300°C. He found that better strip properties could be obtained and therefore concluded that heating the powder definitely aided particle deformation and interparticle bonding. On a larger scale Republic Steel Corporation has a pilot plant which rolls steel powder at temperatures in the range 600-800° C.

A more recent paper by Sakai[53] contains a report of an attempt to reduce the sintering step by using resistance-heated graphite hot rolls through which the hot-rolled green strip was passed. The work involved several iron powders readily available in Japan and one was highlighted as having the best properties for the process suggested. Only the density values for the green strip and final product were given and no comment was made as to their mechanical and surface properties.

It can be concluded here that hot roll compaction will aid particle deformation at lower pressure and reduce sintering time.

2.4 GREEN STRIP

The green strip must leave the compaction zone with sufficient strength to permit handling, between the mill and the sintering furnace. The properties of most interest in the strip are density, thickness and strength and for proper control of these properties, it is necessary to know how rolling and powder variables affect them.

2.4.1 Microstructure

Evans & Smith[34] considered deformation of the particles in copper strip and found that if the rolling pressure is high enough, the powder particles will be elongated in the rolling direction. Tundermann & Singer[54] found a similar effect when rolling iron powders. This elongation was the principal difference between roll and die compaction.

2.4.2 Property variation

The properties of green strip may vary along its length and also across its width and thickness. Evans and Smith[34] noted, using oxidised powder, that resistance measurements were higher in the rolling direction than in the transverse direction. They concluded that the relative motion between particles in the rolling direction would tend to remove surface films from those parts of the particles parallel to the rolling direction, thus giving a greater number of metal-metal bonds per unit area. This would lead one to expect the strip to be stronger in the transverse direction, but Blore et al[55] found that the strip had the greatest strength in the rolling direction.

Density variation along the length, width and thickness have been noted by many workers[40,60,52,74] and the explanation offered is that since the apparent and tap densities of powder are much lower than the density of the metal, it follows that the powder must contain a large volume of air. When the loose powder enters the compaction zone of the rolls, its density begins to increase and its volume decreases. Fig.8. This forces the entrapped air away from the rolls and back through the powder.[75] At high roll speeds this back flow can cause severe turbulence, upsetting feed conditions and producing a variable strip. Grooving of the rolls has been suggested for avoiding density variation.[76]

Weaver et al[77] produced compacts from Easton atomized RZ365 iron powder at three compaction pressures: loosely spread powder to represent zero pressure; 117 N/mm^2 medium and 316 N/mm^2 high. The compacts, 3-4 mm thick x 76 mm long x 32 mm wide, were preheated to 850 and 1040°C for 5 min before being pulled through the roll gap. Although these were thinner compacts than those used in the present work, it is doubtful if they reached

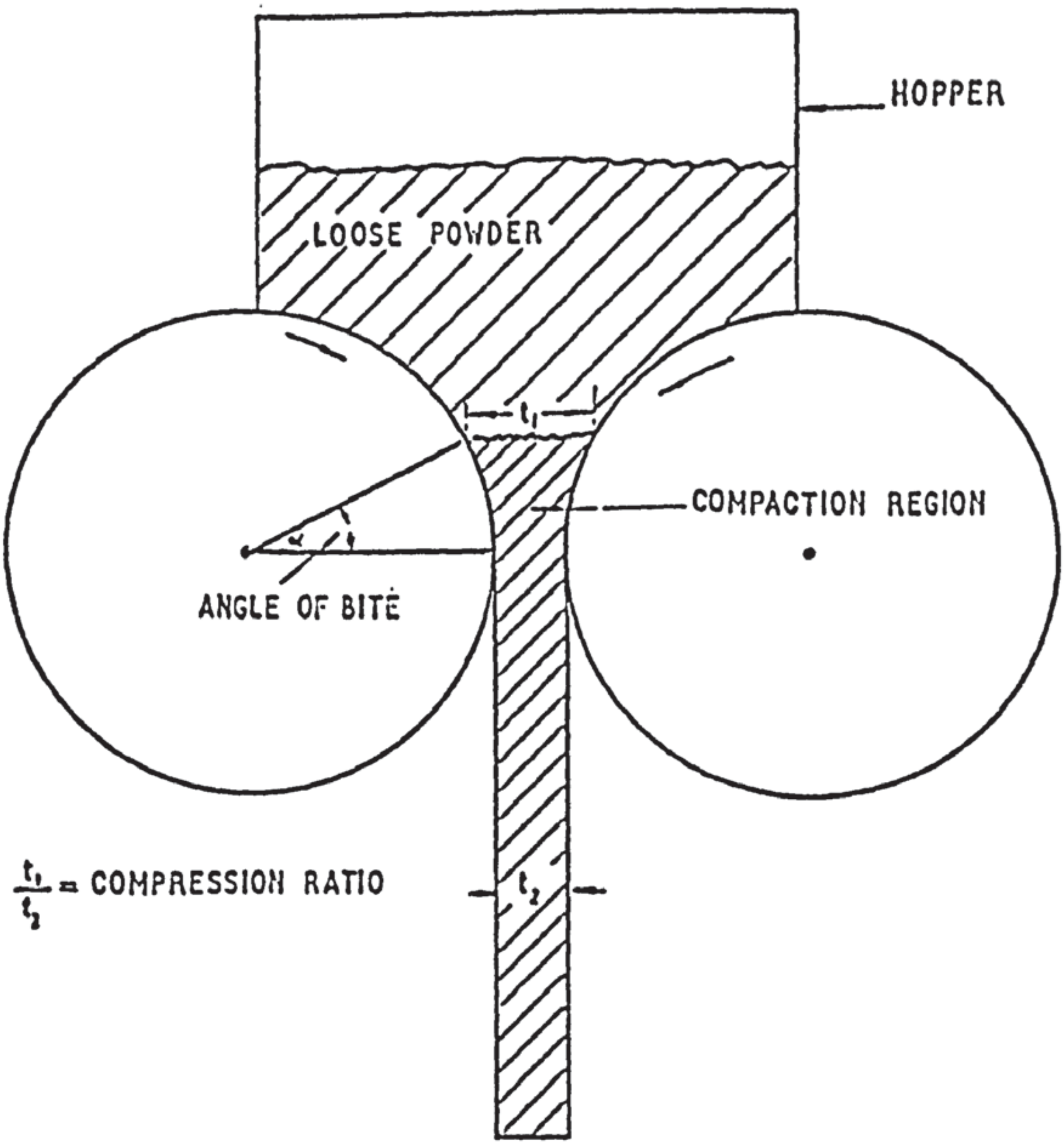


Fig.8. Roll compaction process.

the desired temperature throughout in 5 min. It was found that edge cracking was significant (up to 20% width) when reductions > 20% in area were used to achieve densities > 90% in one pass. Nevertheless, densities > 97% of solid metal could be obtained in a single pass, and no internal oxidation occurred when such compacts were reheated. It was shown that rolling loads were less at 850° than at 1040°C which is in agreement with data presented below. Weaver et al[77] have found the strength for a given reduction to increase with increasing sintering temperature within a range of 850 to 1040°C. They also claimed that hot rolled strip strength was independent of initial density. Daugherty[70] found that edge cracks were reduced by using smaller gaps.

2.4.3 Effect of powder properties

The effect on green strip properties of particle shape, size and size distribution is referred to by different authors. Naeser & Zirm[4] found that size distribution had some effect of maximum strip thickness and that finer powders produced thinner strips.[7, 34,74] Blore et al[55] found that coarse nickel powder produced a weak strip, whilst Evans & Smith found that coarse copper powder produced a strong strip. In general it appears that green strength increases with density,[48] Worn & Perks[59] found that irregular, fibrous nickel particles gave better strip properties than rounded particles.

2.4.4 Effect of roll surface

Naeser and Zirm stated that it is immaterial for the strip thickness whether the rolls are highly polished or roughened. Contrary to this several investigators have found that roll surfaces affect both strip thickness and density.[20,34] A number of workers have confirmed that strip thickness is increased by roughening the roll surface[34,16,17] and that rough areas or marks on rolls are transferred to the strip.[16]

2.4.5 Effect of the roll gap

The final strip thickness is dependent on the initial passive roll gap setting and also on the slack in the roll bearings and the elastic strain in the mill housing.[4,56] In general, green strip density and strength decrease with increasing roll gap and thickness increases.

The roll gap is adjustable over only a narrow range, beyond a certain opening the powder fails to compact and the strip disintegrates on leaving the rolls.[55]

2.4.6. The effect of roll speed

The effect of roll speed on strip density and thickness arises from the fact that at higher roll speeds the powder feed becomes a problem. As roll speed increases, strip density and thickness decreases, and Dougherty[57] noted that at high speeds the strip exhibited high density edges and low density centres. On subsequent rolling, such strip distorts by edge frilling or cupping.[20] Other workers[7,4,31] have similarly found that high speeds yield inferior quality strip. Evans[58] reasoned that decreased strip density due to high roll speeds could be ascribed partly due to the turbulence created by the escaping gases, and partly by the shorter times that the powder is subjected to pressure.

2.4.7 Strength of the strip

The tensile strength decreases with decreasing strip density and therefore with increasing roll gap.[4] Worn & Perks[59] found that the rupture strength of green nickel strip decreased with increasing roll speed and roll gap (decreasing strip density). In general, it appears that green strength is very dependent upon strip density and the variables which affect density will no doubt affect strength in the same manner.

2.4.8 Rolling load and strip density

Kimura et al[62] found that green strip density varied with rolling load. The rolling load decreased if the roll gap is increased at constant roll speed and also if the roll speed is increased at constant roll gap. Both these conditions adversely affect strip density.

They concluded that rolling load is an effective standard for predicting green strip density and that load measurements were indispensible in powder rolling studies.

Naeser & Zirm[4] and Crooks[18] produced graphs which related power consumption, strip density and roll gap. Both these works confirmed the views of Kimura et al.

2.4.9 Strip density and thickness

The relationship between green strip density and thickness has been studied by many workers. Worn & Perks[59] concluded that maximum thickness under given rolling conditions was limited by internal strain within the strip. If the strain exceeds a certain limit due to increase in density and thickness, then compacted material will disrupt. Storchheim et al[60] noted no such limit, but found thickness and density to be related. Worn[20] and others have shown that both strip density and strip thickness are closely related to roll diameter.

2.5 SINTERING THE STRIP

The sintering process is of importance to three separate disciplines: powder metallurgy, ceramics, and the agglomeration of ore fines. In industrial practice most iron powders are sintered in the austenite range, and fine iron powders sinter rapidly at temperatures below the transition point.

Sintering has been defined as the progressive transition without melting, from a state consisting of an agglomeration of metallic particles in simple juxtaposition to a massive state practically free from porosity.[61]

In a continuous process of this type the sintering time governs the relationship between production rate and sintering furnace length. Naeser & Zirm[4] and Storchheim[31] found that for sintering times approximately one minute the time dependence of sintering effect was more pronounced at temperatures above 1200°C.

Much work has been carried out into sintering conditions and resulting properties. Tundermann[26] provided a comprehensive list of references and the following workers have studied the sintering of iron.[4,62,40,63] Worn[20] recommended temperatures as close to the melting point of the material as possible and times of one minute or less. Experiments in the U.S.S.R.[64] have suggested that high frequency heating increases diffusion rates reducing overall sintering times. Sturgeon et al[65] also investigated the use of direct resistance heating but favoured radiation strip heating techniques.

2.6 PROTECTIVE ATMOSPHERES

During sintering the compacts must be prevented from oxidation. Roberts[66] used a refractory coating together with an argon atmosphere, which was successful. If hydrogen is to be used, it should be dried very carefully, Jones[2] to prevent oxidation reactions. (Biswas & Bashforth[67]) Often sintering in an atmosphere of cracked ammonia is carried out, and has proved to be successful in preventing oxidation. Japanese workers[68] have determined the nitrogen contents of iron powders, sintered in cracked ammonia, and have found that maximum nitrogen solubility occurs in the early stages of sintering at 1200°C, but decreases with decreasing temperature, the desorption being a maximum at 550°C.

2.7 HOT ROLLING

Hot rolling of powder has advantages over cold rolling in that there are no residual stresses in the strip afterwards, and also that volume of porosity is less. Storchheim et al[60] obtained poor quality strip after cold rolling sintered aluminium strip, whilst hot rolling gave up to 97% density in one pass and increased densification with further cold rolling. Evans & Smith[69] achieved considerably better properties from strip produced from copper powder rolled at 300°C than that rolled at room temperature. Kimura et al[62] considered two iron powders and found that after hot and cold rolling, the strip had comparable properties to conventionally rolled material.

Other workers,[17,55,71] gave favourable comparison between powder strip and conventional strips. Storchheim et al[16] and Storchheim[31] found marked variations in ultimate tensile strength between longitudinal and transverse direction in 18-8 stainless steel strip.

Storchheim et al[8] and Hunt & Eborall[17] attributed this variation to inclusions rather than textural orientations. Storchheim et al[16] used X-ray techniques and found that the samples exhibited no preferred orientation. These results were endorsed by Worn & Perks.[59]

2.8 STRIP PROPERTIES

Tamura & Noda[72] showed that tensile properties varied with sintering time. Only after a sintering time of one hour do the tensile properties of Tamura & Noda's material approach those of conventional stock, whereas BSC (who sintered in hydrogen rather than a vacuum) claim comparable figures with sintering times of five minutes. Storchheim et al[60] obtained tensile strengths very similar to wrought metal, which varied very little with testing direction. Their elongation figures, however, were low and showed a large variation between longitudinal (30%) and transverse (12-15%) directions.

It is interesting to note here that the anisotropy of properties observed in sheet produced from powders appears to be almost entirely due to the distribution of non-metallics. Evans & Smith[71] working with copper powders (which would contain very little non-metallic material, the oxide being readily reduced on sintering), found no significant variation in properties with direction of testing. Some preferred orientation was developed after a cold rolling reduction of 75%, but this was eliminated by annealing. Storchheim et al[60] claim that less than 5% preferred orientation was present in their strip even after five cold rolling passes. (They did not give the reduction).

2.9 COLD ROLLING

Cold rolling is a more accurate method of reduction than hot rolling. Hunt & Eborall[17] and Evans & Smith[56] found that copper strip could be cold reduced approximately 45% before cracking occurred. After annealing the strip showed an increase in tensile strength due to the inherent small grain size and increased density. By higher reductions the strength fell due to internal cracking of the strip. Another limitation was due to edge cracking which was quite severe at high reductions. Several workers[59] have suggested that the initial cold reductions must be limited to 20 per cent, but subsequent reductions could be greater.

Thus it appears that continuous cold reduction of sintered strip is limited and annealing operations must be performed at various stages during cold rolling. If this initial reduction could be increased without attendant adverse edge cracking effects it could, in an industrial plant, improve the economy of the process significantly by decreasing the number of passes.

2.10 ANNEALING

Annealing in powder metallurgy is carried out for similar reasons as in non-powder metallurgy, i.e. to remove the effects of cold work and increase plasticity for further working. Appoo[73] reported that after annealing, the strip showed an increase in tensile strength due to fine grain size and increased density. He also reported that relative rolled density increased with increasing annealing temperature, but had very little correlation with annealing time.

2.11 SURFACE FINISH

With respect to surface finish, the product of powder metallurgy route is likely to start with an advantage since it will not have gone through the stages at which surface defects are most likely to appear. Small slag inclusions can be present in the powder and there seems to be fine dispersion of a small amount of oxide in the structure. However, material produced at BSC has been given a polished surface which appears to be the equal of anything that could be produced on a conventionally made stainless steel sheet.

2.12 ECONOMIC ASPECTS

The economic aspects of powder rolling as a source of steel strip have been considered by a number of workers. Sturgeon et al[65] commented on the fact that marginal increases in conventional strip manufacture usually necessitate multi-million pound investments. This usually leads to under-utilization of plant, with consequent increase in production costs. With powder process it may be practicable to operate smaller units economically making possible more gradual expansion and hence higher overall plant utilization. Davies et al[19] suggested that such units to manufacture blackplate could economically produce 100,000 tons per annum compared with 500,000 tons per annum for the conventional route. They assumed a mill speed of 500 ft/min (152 m/min), a 95% yield and a strip thickness of 0.2 mm, and calculated that strip from powder would be at least as cheap as conventional strip and give a 30% saving on capital cost.

Since the compaction is the slowest stage in producing strip from powder, it has been suggested that it would be more economic to produce high density thick green strip, followed by sintering and cold rolling to size. However as the gauge is reduced so the price of the strip increases. (Fig.1.). The greatest economic advantage may be gained by rolling the powder direct to thin strip requiring the minimum reduction to final gauge consistent with required strip properties. The type of plant envisaged for industrial use would be simple in construction and operating with unit strands.

First estimates indicate that capital investment per annual tonne should be lower than with conventional plant. A single strand plant would be slightly smaller than a large conventional non-ferrous installation and much smaller than a high tonnage steel strip plant.

The reduction of unit strand size would be regarded as an important feature. Experience of industrial production shows that with an existing technological process, increase in size brings rewards in terms of reduced cost per tonne standard. Installed plant size and cost therefore increases with time at the expense of flexibility and adaptability. Beyond a certain point in time. new technological processes begin to challenge the old and step change in plant size occurs when the older process can no longer adapt to a new situation. Some of the traditional processes in the metal strip industry are probably near to this point. The smaller unit size of a powder rolling plant, may therefore be beneficial. Certainly it facilitates the introduction of the new process alongside conventional plants as additional capacity. Ayers[51] claimed to have manufactured powder strip at much lower cost than the conventional steel strip. However, specific details and process parameters are not available.

2.13 The present work

It has been shown that considerable work has been done on iron powder rolling, dealing primarily with consolidation of the powders during hot rolling and final properties of the strip produced by hot and cold rolling. The deformation mechanisms of iron powder preforms in the roll gap during hot rolling had not been satisfactorily explained.

There is a general lack of data concerning the properties of the strip at different process stages. A wider range of variables and production stages should also be studied in order to examine and test the products formed at each stage and thus determine the variables which control the properties and quality of the final strip. In addition, from a utilisation point of view, a comparative study of various types of finishes available in conventional strips should be examined.

SECTION III

3.0 EXPERIMENTAL PROCEDURES

The initial intention of the experimental work was to determine the mechanisms by which consolidation of preforms occurred during the hot rolling of iron powder.

Die compaction was used to produce the green compacts. The compacts were then hot rolled after which they were metallographically examined in order to determine how consolidation had been achieved.

A further study was undertaken to examine the effect of six variable stages in the production of finished strip. These stages are outlined in Table 1 with the variables shown at the levels investigated.

The choice of variables was made with commercial practice in mind and with reference to work done by previous investigators.[73,77] It was thought that the factors given in Table 1 were those most likely to affect the properties measured.

In this investigation, it was aimed to use procedures and materials readily available commercially, so that the results could be translated easily into commercially profitable operations.

Samples were tested for U.T.S., elongation, hardness and surface finish. The influence of the different process variables on the properties were obtained by statistical methods using a computer. Finally, it was aimed to find which combination of

TABLE 1. PRODUCTION STAGES

3 POWDERS (ASC 100, NC 100, MP 32)

↓

COMPACTION (155, 232, 310, 386 N,mm^{-2})
(10, 15, 20, 25 T, in^{-2})

↓

PREHEATING (700, 800, 900, 1000°C)
for 20 mins

↓

End of Stage I. — HOT REDUCTION (20, 30, 40, 50, 60%)

↓

End of Stage II. — ANNEALING (650, 800, 900, 1100°C
for 20, 30, 40, 60 mins)

↓

End of Stage III. — COLD REDUCTION (20, 30, 40, 50%)

↓

End of Stage IV — ANNEALING (650, 800, 950, 1100°C
for 20 and 60 mins)

↓

End of Stage V. — COLD REDUCTION 20% (ASC 100 only)

↓

End of Stage VI — ANNEALING (950°C for 20 and 40 mins) process variables produced the most satiafactory properties in the strip.

3.1 Raw Materials

In ferrous powder metallurgy there is a very wide choice of powders available which can be categorised according to their methods of manufacture, their shape, their chemical composition, surface activity, and their compressibility performances.

Höganäs and Domtar powders tend to be porous and have fairly high residual oxygen levels due to their method of production.

An expensive but commonly used powder ASC 100 made by Höganäs using a water atomisation process was chosen for the main part of the investigation. It yielded compacts with adquate green strength even at low compaction pressures, and gave higher density compacts under increased loads without any trouble. The other two powders used were the direct sponge type NC 100, and Rospol water atomised type MP 32.

The powder properties are shown in Tables 2 and 3. Stereoscan photographs of the powder particles are illustrated in Fig. 9-11.

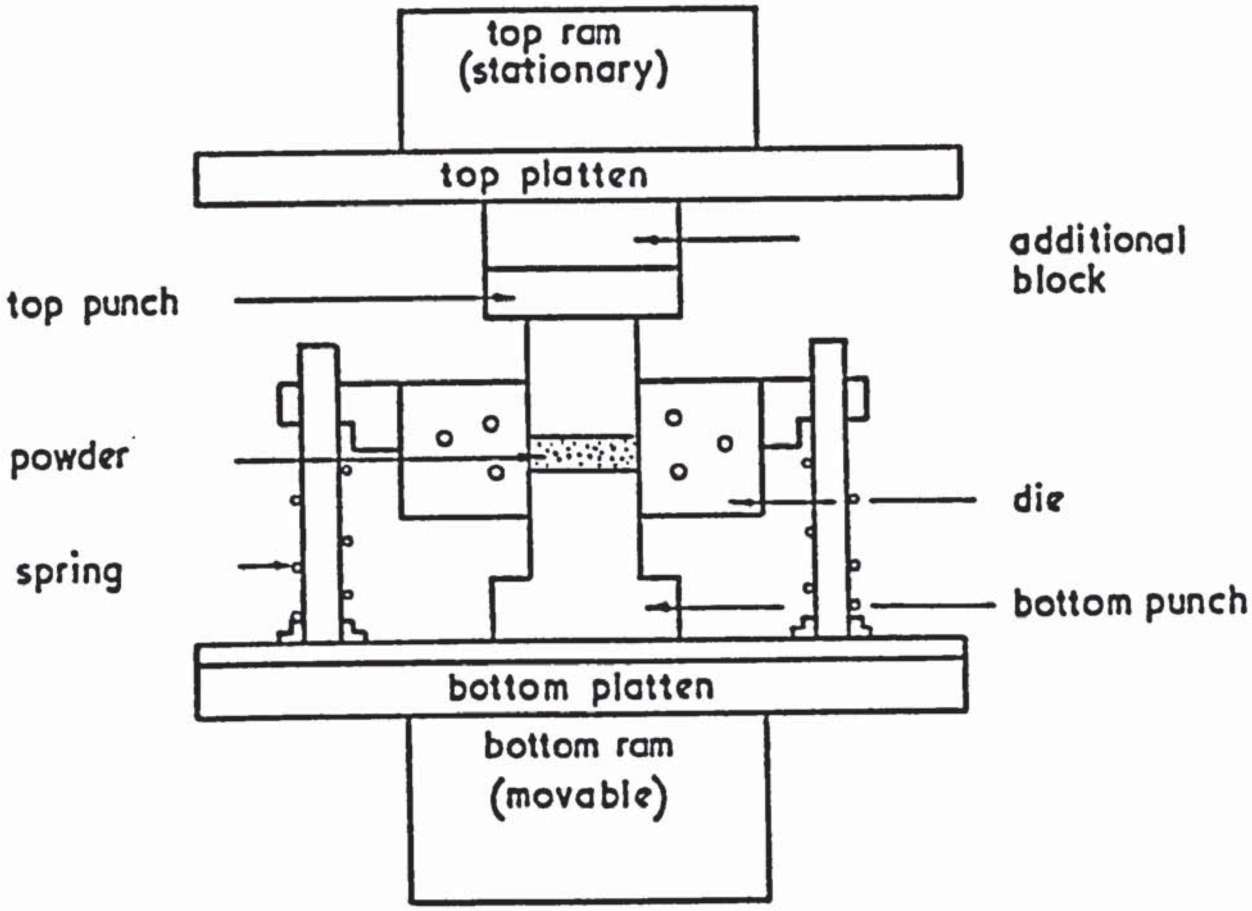
3.2 Compaction method

Green compacts (76 x 13 x 4-6 mm thick) were produced on a 300 tonne Dennison single acting press using a rectangular die cavity (76 x 13 mm). The floating die assembly used, shown in Fig.12, gave results similar to those that would have been obtained on a double acting press, i.e. compaction proceeded from the top and bottom surfaces towards the middle.

The die was arranged upon the bottom platten of a Dennison hydraulic compression machine. The bottom platten was built onto a spherical bearing so that any slight misalignment between bottom and top plattens was automatically removed during compaction. The resulting compacts were then substantially parallel along their length with no more than ± 0.5 mm discrepancy from end to end.

No admixed lubricant was used but a 5% solution of stearic acid in diethyl ether was sprayed on the die walls. The amount of powder used for each compact was weighed on a pendulum type balance with a top pan with an accuracy of ± 0.5 gm.

To prevent the segregation of the particles, the die housing was compressed until the botton punch was nearly level with the top surface. Then by slowly and carefully introducing the powder via a glass tube containing the requisite amount, and simultaneously allowing the die housing to return to its original position, the powder had only a little distance to fall, and was consequently much less segregated. Finally the top surface of the powder was levelled with a straight edge flush with the top surface of the die, Fig 12 Compacting assembly



and the load removed. The top punch was inserted, and the load applied slowly via an oil bypass valve to the value required and a dwell time of about two seconds was allowed to ensure that the correct pressure was attained throughout the compact before reducing to zero. The whole compaction cycle from start to finish took approximately twenty seconds.

With the top punch removed, the compact was ejected smoothly. During the pressing operation it was noticed that lubricant particles became entrapped in the surface of the compacts. All compacts were numbered immediately after pressing.

3.2.1. Green density of the compacts

The average green density of the compacts was found from their dimensions and mass. The length and the width of the compacts were taken to be those of the die cavity and the thickness was obtained by measuring at three different points along the specimen and taking the average. The compacts were weighed and the density calculated (Table 4). A graph of green density versus compaction pressure was plotted for three iron powders (Fig.13).

3.2.2 Microhardness measurement of compacts

A microhardness scan across the thickness of two ASC 100 green compacts was produced for two pressures. Fig.14[73] illustrates the typical density distribution obtained. A Vickers microhardness tester was used, with a diamond indentor. Indentations were made at intervals of about 1 mm starting at about 0.5 mm from the surface

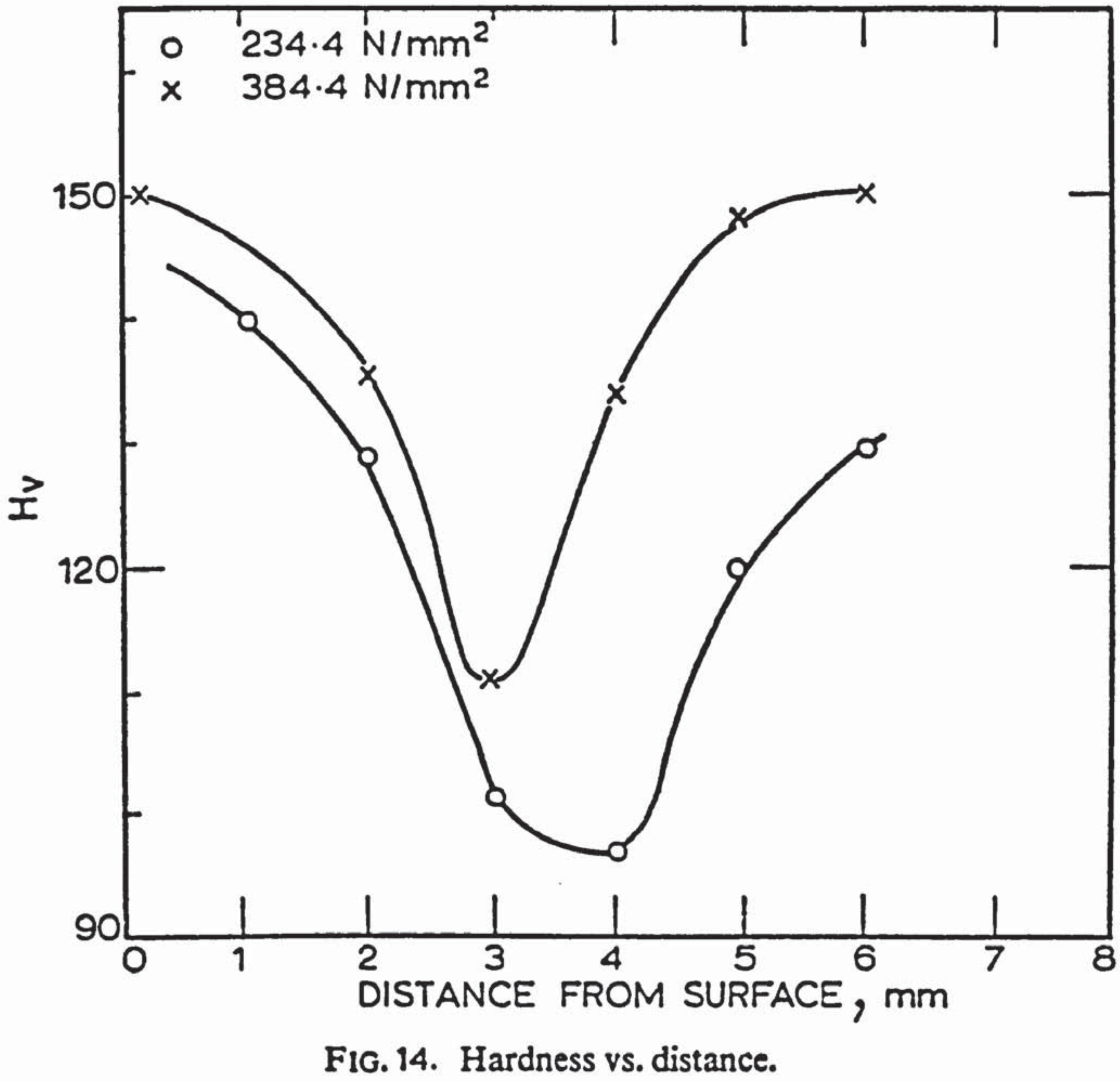


FIG. 14. Hardness vs. distance.

and mid-way along the length. The variation in hardness can be taken as a measure of the variation in compaction that takes place. The lowest values occurred at the centre of the compact, showing that the least compaction took place there. This effect causes a limiting thickness for a useful compact that can be produced.

3.3 Sintering

A series of experiments were designed to determine the effect of sintering temperature upon the mechanical properties of three powder compacts after sintering in 90% N_2 10% H_2 for various times. The results can be seen in Tables 5 - 7. The sintering furnace employed in the experimental work is illustrated in Fig.15. It consisted of an Inconel tube 80 mm in diameter and 3 mm thick. Six silicon carbide heating elements were used, three above and three below the tube. This gave a hot zone 150 mm long $\pm 15^{\circ}C$ at a temperature of $900 - 1100^{\circ}C$. The ends were sealed with rubber bungs protected internally with circular asbestos discs. Glass tubes on the inlet side enabled the gas to enter from cylinders via the drying train. This train consisted of a 50 mm diameter glass tube containing a hydrogen catalyst which converted any oxygen present to water vapour. Then came a section of silica gel, and finally a section of magnesium perchlorate on the furnace side. The three sections were separated by wads of dried cotton wool. The outlet rubber bung contained two glass tubes, one leading via a flowmeter to the outlet pipe, and the other containing the Inconel wire with which the boat was pulled into the hot zone after adequate gas purging of the tube. The glass tube

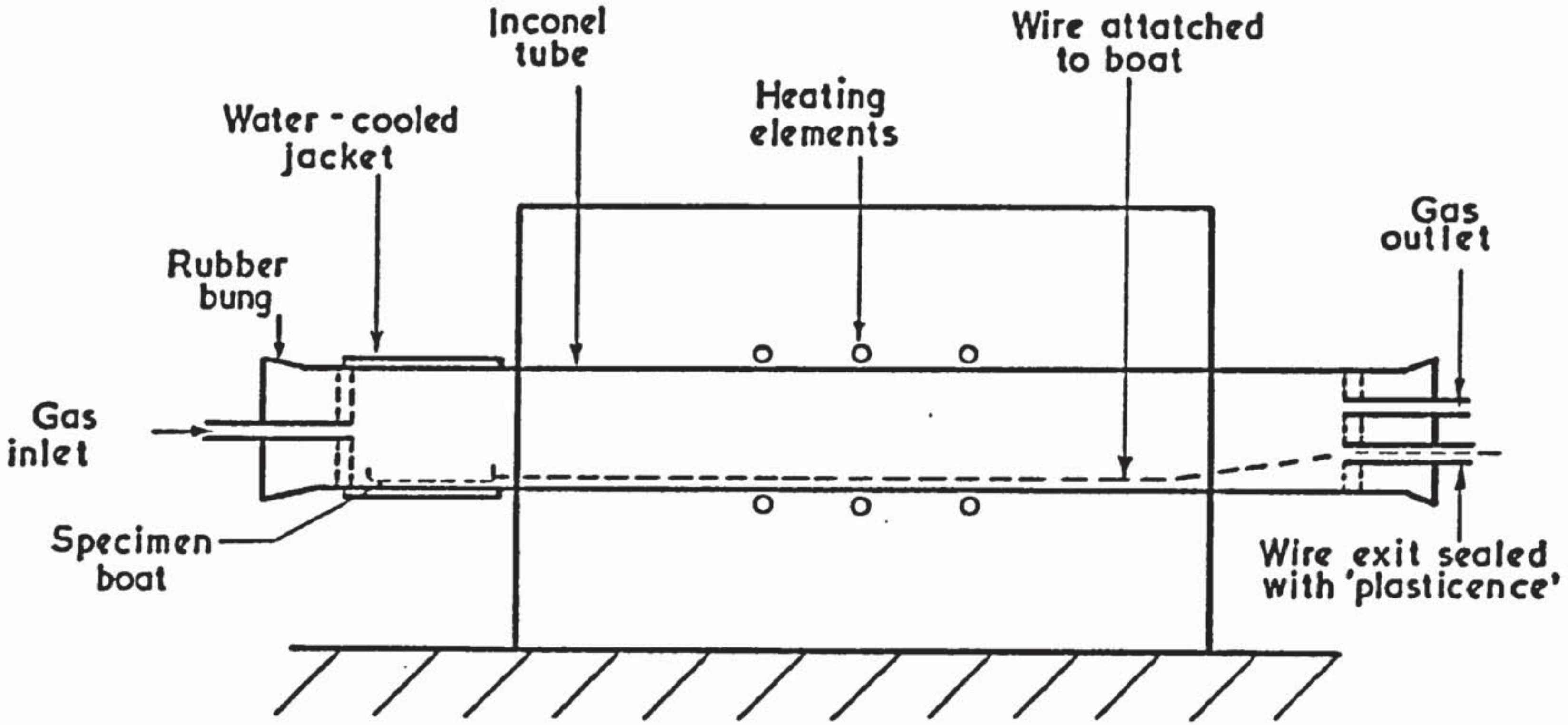


Fig.15. Sintering furnace

was sealed with plasticene enabling the boat to be pulled into a hot zone without ingress of air. The heating elements were controlled by a variable tap transformer, and a transitrol control unit enabling a temperature ± $5^{\circ}C$ of that required to be obtained. A separate Pt/Pt : 13% Rh thermocouple was used in conjunction with a potentiometer to set the hot zone temperature accurately before sintering commenced.

After sintering, the boat was pulled into the cold zone of the furnace, which was water cooled. A time of 20 - 30 minutes was required in the cold zone to cool the sample down to room temperature. The drying train removed oxygen and water, and the flow meter controlled how much gas passed per unit time. A water bubbler at the outlet gave a slight positive gas pressure, and if the gas was momentarily turned off, the positive pressure would fall very slowly indicating that the bungs were a very good fit and that very little air, if any, could gain access to the inside of the furnace. A 90% N_2 10% H_2 atmosphere was used.

3.4 Specimen temperature during rolling

Trials were made to measure both the temperatures at the surface and the centre of the compacts during rolling. Thicker compacts were produced at a compaction pressure of $386 N, mm^{-2}$ so as to give enough strength in the green compacts to enable them to be machined and which would be big enough to accommodate the thermocouple.

For the surface measurement, a groove 3 x 3 x 35 mm long was machined in the surface, in order to house the thermocouple and its

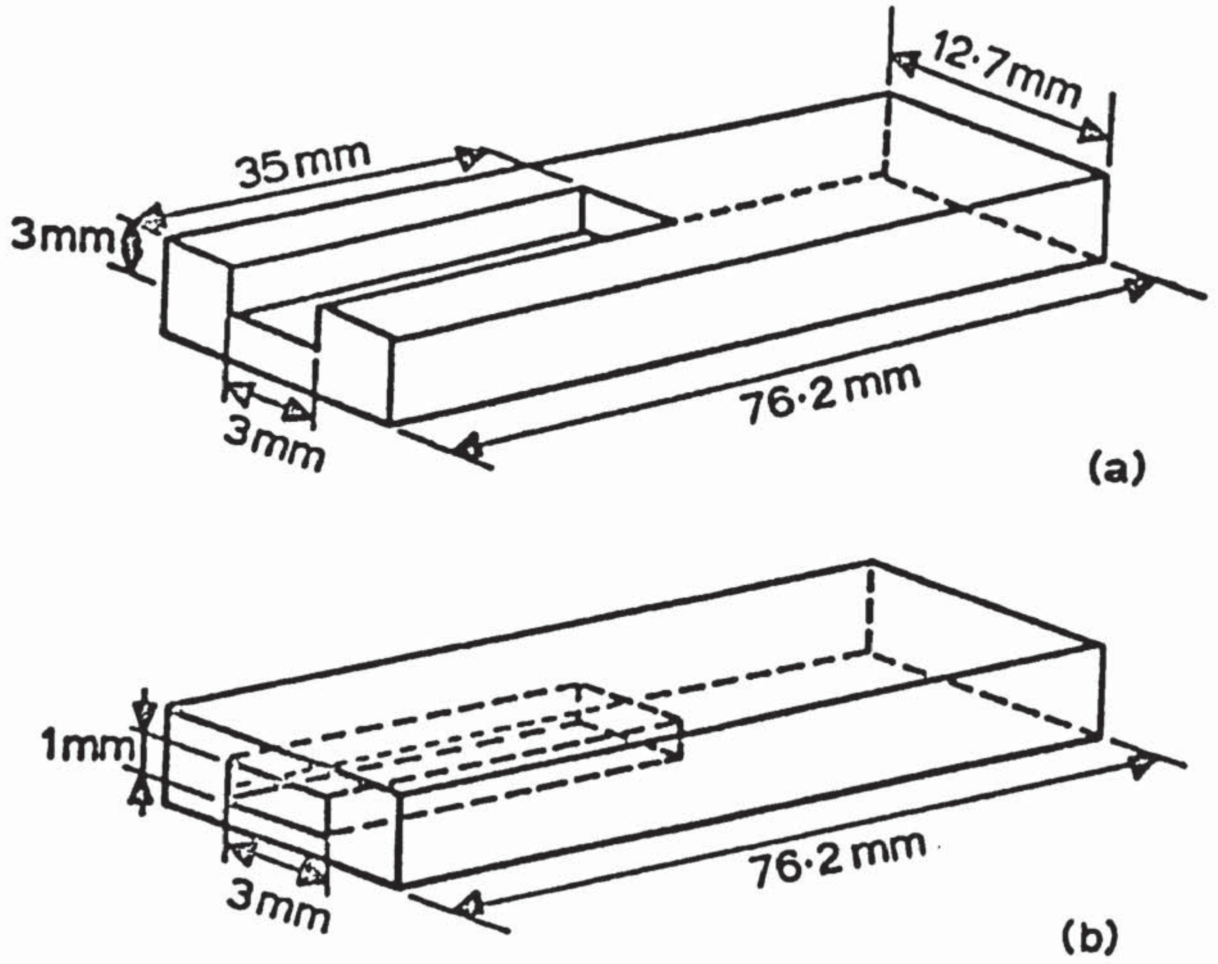


FIG. 16 Machined specimens for measurement of (*a*) surface temperature and (*b*) internal temperature.

sheaths. This is shown in Fig.16a. For the temperature measurements at the centre a hole 3 x 1 x 35 mm was machined into the specimen, as shown in Fig.16b. Fine chromel-alumel wire was used so as to obtain a rapid response to temperature changes, and was coupled along with compensating leads to a Servoscribe 2S pen recorder in order to obtain a record of the temperature changes. A chart scale of 0 - 50 mv was selected and a chart speed of 600 mm/hr used while the specimen was being heated. It was found that the twelve minutes allowed by previous workers for compacts of this thickness to reach temperatures was correct for the surface but the centre took longer to achieve the required temperature, approximately 18 minutes. From this point all compacts were preheated for 20 minutes to ensure that they had reached the desired temperature. When the specimens were withdrawn from the furnace and rolled, the chart speed was changed to 600 mm/min in order to measure the temperature changes more accurately. The compacts were given only 10% reduction, as any greater reductions destroyed the thermocouple and no information could be collected. The recorded temperature drops are given in Table 8.

3.5 Half rolling of powder compacts

Early work carried out using the NC 100 powder[80] yielded a series of results which are illustrated graphically in Figs. 17 - 19. Some powder compacts were half rolled and this was achieved by stopping the rolls as the compact entered the roll gap. A lower rolling speed of 20 r.p.m. was used so that the rolls would stop before all of the compact was rolled. The compact was released from the rolls as quickly as possible to enable them to finish cooling under 90% N_2 10% H_2 within the usual hoods to minimize oxidation, but this was not completely successful. Further, it must be realised that the surface temperature of these half rolled specimens during rolling was less than normal owing to the slower speed of the mill. This difference, it is estimated, could have been double the normal. When cold, the compacts were sectioned longitudinally and examined metallographically in order to follow the changes that occurred during rolling.

The rolling data is shown in Tables (9 - 42). Metallographic structures of half rolled specimens using ASC 100 powder are shown in Figs. 20-22.

3.6 Hot rolling of compacts

A general view of the rolling mill and related equipment is shown in Fig.23. The compacts were preheated to a predetermined temperature in a muffle furnace under a 90% N_2 - 10% H_2 reducing atmosphere to prevent oxidation. The furnace characteristics were investigated and the hot zone located.

The method used to get the compacts in and out of the furnace was by using a mild steel strip with a slot 15 mm wide x 240 mm long. The samples were placed in the slot and held in position by wrapping thin nichrome wire around the sample and steel strip. With larger reductions it was found that the wires were impressed into the compacts forming grooves when the compacts were rolled. Twelve minutes was allowed for the specimen to heat up and then a further three minutes for them to soak before they were rolled. These times were

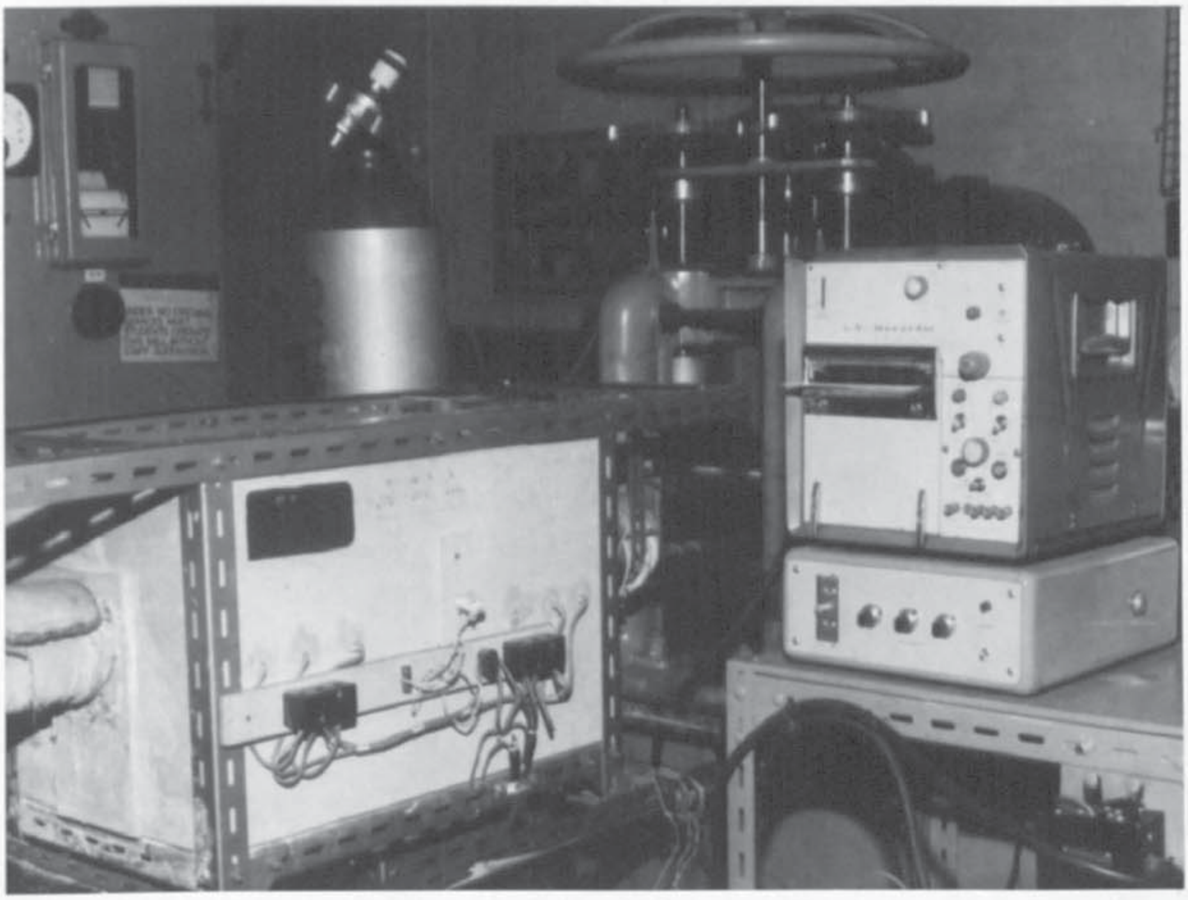


Fig.23. General view of Furnace/rolling mill equipment

used by previous workers.[73] They were later revised to 20 mins after temperature measurements had been carried out. The N_2/H_2 gas mixture was allowed to flow through the furnace at an appreciable rate. The gases were dried by passing through silica gel. Branch lines were used to feed gas to two hoods on the exit side of the rolls. The compacts were covered with these hoods after rolling and this protected them from oxidation during cooling. Another auxiliary line was employed to obtain a jet of gas through a fish-tailed glass tube on the entry side of the mills. These precautions were adequate to prevent excessive oxidation of the compacts.

All the reductions were carried out in a single pass and the load developed during rolling was measured on an ultra-violet recorder connected to load cells fitted to the mill. The roll gap was adjusted by using slip blocks, allowing for elastic springback. Initially, the amount allowed for this was done by trial and error until sufficient data had been collected. A graph of active roll gap against the passive roll gap was then plotted and this was used to obtain the correct roll setting. A plot of this graph is shown in Fig.24.

When cold, the specimens were re-numbered and their thickness measured. Hence the reduction and roll pressure could be calculated. This was the end of the stage I as shown in Table 1. The results obtained for all three powders are shown in Tables 9 - 42.

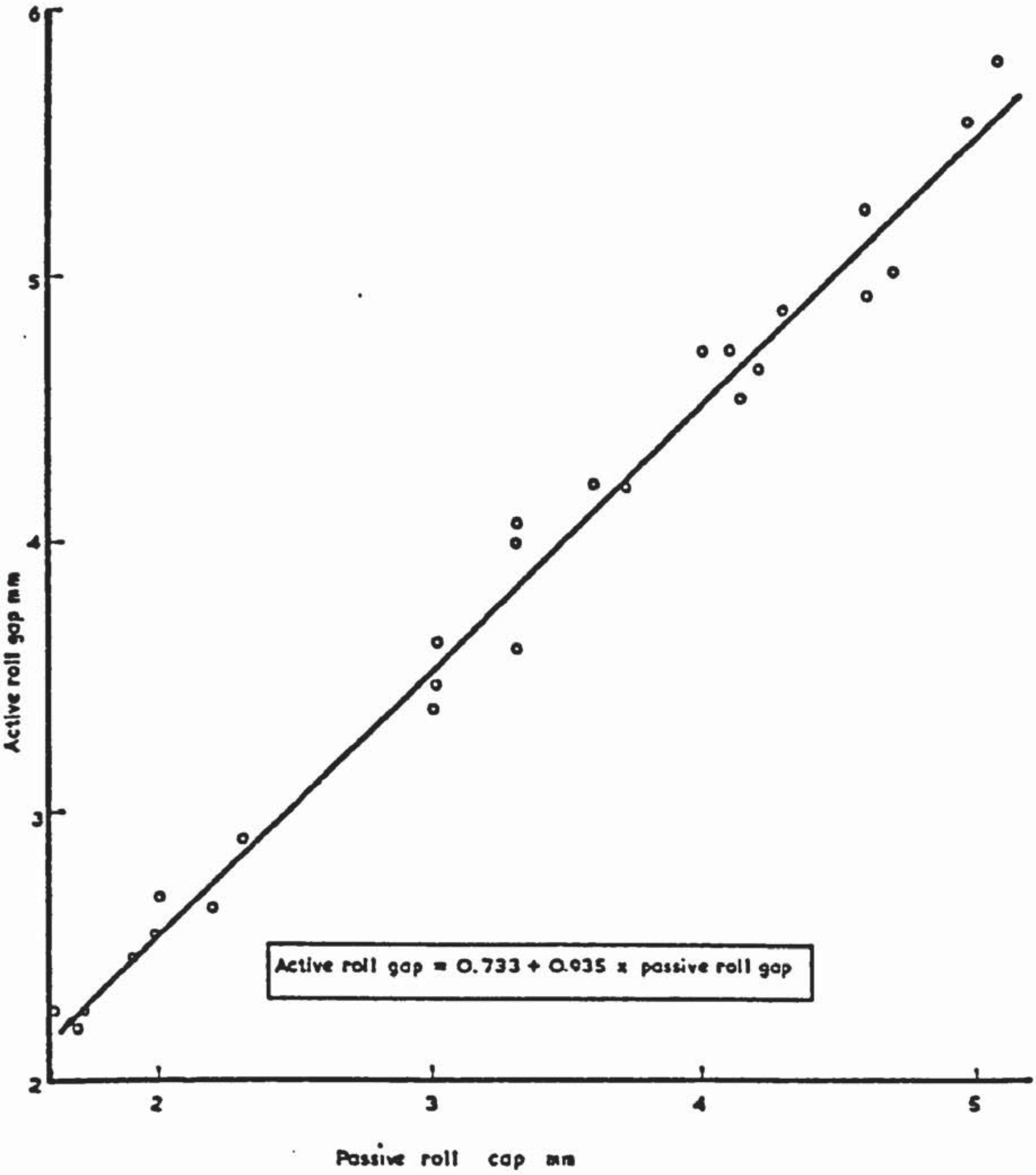


Fig.24. Active roll gap vs passive roll gap

The hot rolls measured 152.4 mm in diameter x 203 mm and a rolling speed of 40 r.p.m. was employed, giving a linear velocity of ∿ 20 m/min.

3.6.1 Annealing of hot rolled strip

Annealing of hot rolled compacts was carried out in a muffle furnace with a metal tube, Fig.15. A 90% N_2/10% H_2 gas was used to provide a reducing atmosphere and this was dried by passing through silica gel before entering the furnace. The reason for this choice was that this atmosphere corresponded more closely to the type of atmosphere which would be used industrially, for instance cracked ammonia. No powder metallurgy producer employs pure hydrogen as a reducing atmosphere. For the results obtained for three powders at the end of this stage see Tables 9 - 42.

3.7 Cold rolling of compacts

Between the hot and cold rolling stages the mill rolls were changed but the roll speed was kept at 40 rev/min. The cold rolls were lubricated with oil. It was found that 40 - 50% reduction could be achieved in a single pass during cold rolling. Difficulties were experienced with the bending of specimens during rolling, especially when the strips were thin. However, this phenomenon is not expected to occur when continuous lengths of strip are rolled with correct tensions applied. After rolling the faces and edges of the samples were examined, the thickness of the strip measured and the specimens re-numbered to prevent mixing and loss in handling.

To achieve consistent properties in the final product, the cold rolled band was further processed by annealing. This was the end of stage four. The improved properties at the end of stages III and IV are shown in Tables (9-42) compared with those at the end of stages I and II.

As may be seen from Tables 14, 15, the properties for stages V and VI for ASC 100 powder were so similar to those obtained at the end of stages III and IV, that it was decided not to continue with further work on the other two powders NC 100 and Rospol MP 32 beyond stage IV.

3.8 Edge cracking

Throughout this work edge cracking did not pose any problems with the three powders used. In the majority of cases edge cracking was negligible and no trimming was required.

Some minor edge cracking is inevitable because the frictional conditions at the edge of the strip during rolling are such that lateral (perpendicular to rolling direction) spread can take place. This is especially so for specimens which had undergone these very heavy reductions with 700°C preheat temperature but only amounted to 2 mm maximum.

3.8.1 Examination of the hot rolled strip

3.8.2 Mounting, polishing and etching

The specimens were sectioned and impregnated with araldite under vacuum. The technique was an excellent one provided that the araldite wetted the surface and impregnated the pores. Each specimen was then ground sequentially on grades 100, 220, 320, 400 and 600 silicon carbide paper with an adequate supply of running water, polishing was completed using 6 and 1 micron diamond abrasives. Samples were etched in 2% nital and then repolished on the 6 and 1 micron diamond abrasives before given a final etch in 2% nital.

3.8.3. Q.T.M. Measurements

3.8.4. Metallographic examination

The rolled and half rolled specimens were sectioned longitudinally and examined metallographically. (Figs. 17 - 22.) Porosity distribution within them was measured on a Quantimet (Quantitative Television Microscope Model B) and for the half-rolled specimens changes in density were traced as rolling progressed. Absolute porosity values are not claimed but relative changes for two of the half-rolled specimens are shown in Figs. 25 - 26. These were related to the different structures observed during metallographic examination.

Calibration of the Quantimet was achieved by using green compact specimens whose density had been previously determined and an estimate was made for the almost fully dense rolled material. Oxide layers on the surface were easily identified and ignored. The oxide particles within the specimens were difficult to distinguish from porosity but where larger inclusions were encountered the measurements made were discarded.

3.8.5. Tensile testing

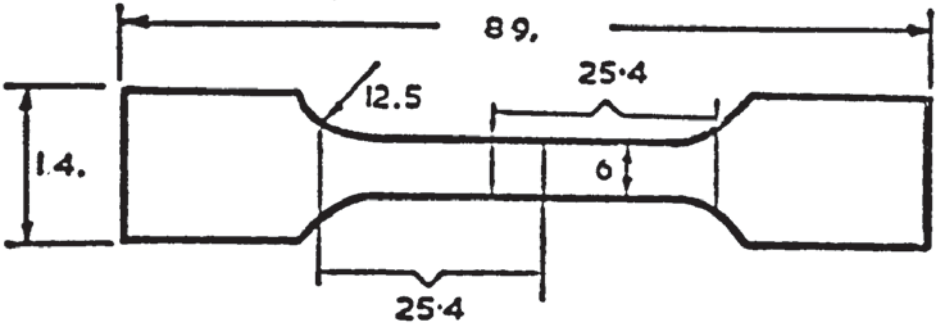
Tensile test specimens were machined with dimensions shown in Fig.27. It must be noted here that the thickness of specimens was not always the same due to the previous compacting and rolling schedules and therefore their dimensions were not standard. However, they were in the same geometrical ratio to those of a standard Hounsfield test piece and so the results would be expected to differ only slightly from the standard. The results obtained should have been less for the test specimens due to grain size effect. To prove this a few larger green compacts (110 x 25 mm) were produced and rolled. Two tensile test pieces were cut from each strip, one with standard dimensions and the other non-standard, as used in the experimental work. Results given in Table 43 show that tensile strengths obtained using standard test pieces were higher than non-standard ones. Therefore ultimate tensile strength results presented would have been marginally higher if standard test pieces had been used.

The specimens were tested on a Hounsfield Tensometer with a 1 ton maximum load beam and cross head speed of 1/16 in. per minute.

3.8.6 Elongation measurement

Elongation measurements were made on the same test specimens. The gauge length chosen was one inch. Two gauge lengths were marked on the specimen as shown in Fig.27.

This overlap meant that a meaningful reading could be obtained wherever the sample fractured during testing.



Dimensions in mm

Fig.27. Tensile test specimen

3.8.7 Hardness measurement

The Vickers Diamond Pyramid test was used with a load of 10 Kg.

Vickers measurements were made on the tensile test specimens at both hot and cold rolled stages. Seven readings were taken at random positions on each strip. The lowest and highest values were discarded and the mean of five readings were taken as a representative value. Hardness values increased with cold working as expected, due to strain hardening, but the effect was accentuated on the edges. Annealing of cold rolled strip creates hardness consistency throughout the strip. (Table 44).

3.8.8 Determination of oxygen (Exhalograph)

This apparatus (Fig. 28) measures the oxygen content of metallic powders by dissolving them into a molten nickel bath contained in a carbon crucible held at a temperature of 1800°C, whereupon the dissolved oxygen present reacts with carbon to form CO.

The amount of CO evolved was measured by an infra-red analyser and converted into wt % oxygen content of the powders.

Loose powders were compacted into samples about 1 - 2 gm in weight in a screw press prior to testing. Rolled samples were cut directly from the specimens. The size of the samples was dependent upon the expected oxygen content to keep within the limits of the equipment. Results for powders and strip can be seen in Tables 2 and 45.

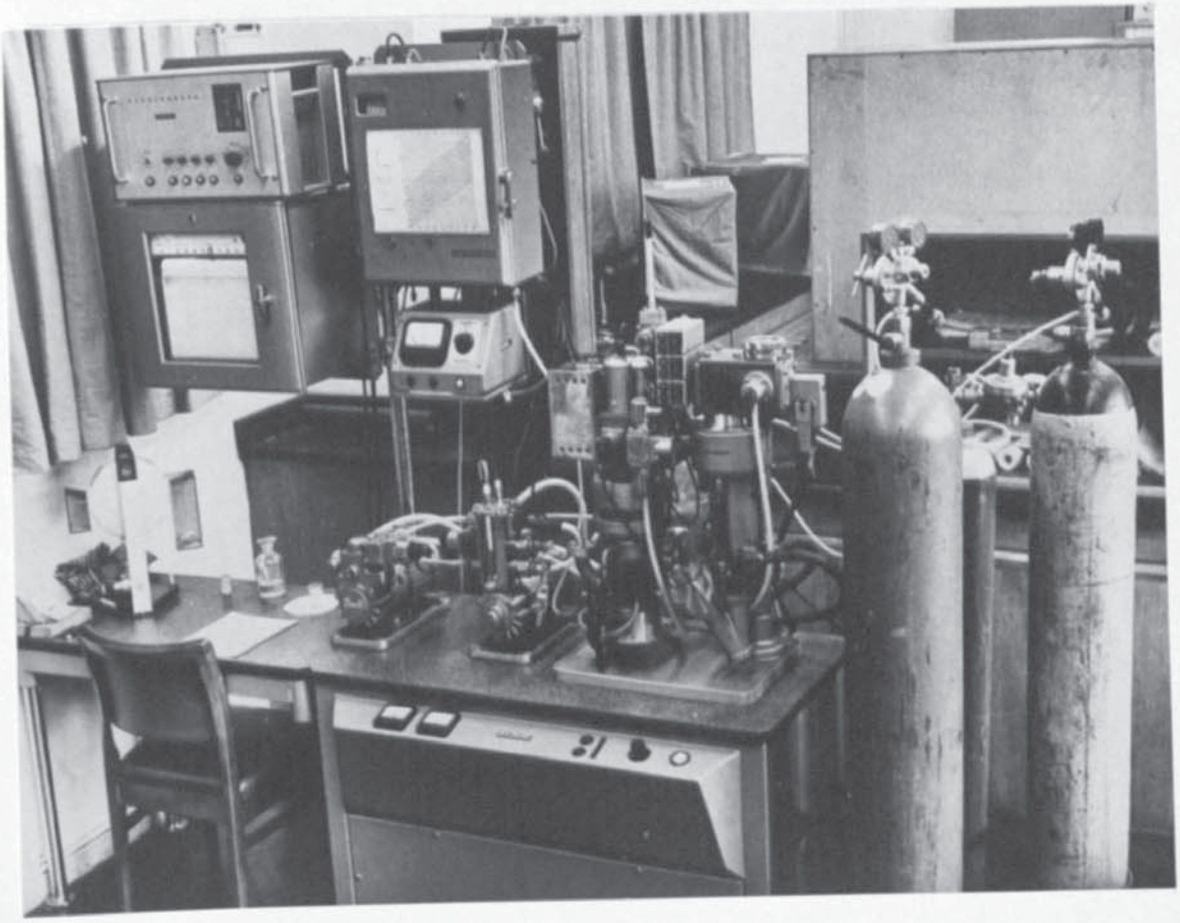


Fig.28. Exhalograph for oxygen determination

SECTION IV

4.0 EXPERIMENTAL RESULTS

TABLE 2. Chemical Analyses of Powders

Designation	POWDERS		
	Höganäs ASC 100	Höganäs NC 100	Rospol MP 32
Method of Manufacture	Atomization	Reduction.	Atomization
Composition			
C	0.014%	<0.01%	0.073%
Mn	Trace	<0.01%	0.12%
Si	Trace	0.068%	0.04%
P	0.003%	0.006%	0.01%
S	0.003%	0.001%	Trace
O	0.096%	0.459%	0.2%
Apparent density g, cm^{-3}	3.02	2.4	2.51
Tap density g, cm^{-3}	3.92	3.28	3.23

TABLE 3. Screen analyses of powder

Particle size µm	Höganäs ASC 100 %	Höganäs NC 100 %	Rospol MP 32 %
+ 180	1.46	<0.001	0.22
149 - 180	12.5	9.1	3.03
104 - 149	20.0	26.3	21.6
74 - 104	24.7	28.4	32.5
53 - 74	23.0	21.8	25.7
<53	18.3	13.9	17.0
Average size µm	76	79	73

TABLE 4. Green and relative densities of powder compacts

Powders	CP N,mm^{-2}	Green Density g,cm^{-3}	Relative Density %	Relative Density (D)	$\left(\frac{1}{1-D}\right)$	$\ln\left(\frac{1}{1-D}\right)$
ASC 100	155	5.55	70.52	0.7052	3.39	1.22
	232	6.04	76.75	0.7675	4.30	1.46
	310	6.50	82.59	0.8259	5.74	1.75
	386	6.70	85.13	0.8513	6.72	1.91
	Apparent density g,cm^{-3}	3.02	38.37	0.3837	1.62	0.48
	Tap density g,cm^{-3}	3.92	49.81	0.4981	1.99	0.69
NC 100	155	5.06	64.29	0.643	2.80	1.03
	232	5.67	72.05	0.7205	3.58	1.27
	310	6.11	77.64	0.7764	4.47	1.50
	386	6.40	81.32	0.8132	5.35	1.68
	Apparent density g,cm^{-3}	2.40	30.50	0.305	1.44	0.36
	Tap density g,cm^{-3}	3.28	41.68	0.4168	1.71	0.54
MP 32	155	5.34	67.85	0.6785	3.11	1.13
	232	5.85	74.35	0.7435	3.90	1.36
	310	6.24	79.29	0.7929	4.83	1.57
	386	6.50	82.59	0.8259	5.74	1.75
	Apparent density g,cm^{-3}	2.51	31.89	0.3189	1.47	0.38
	Tap density g.cm^{-3}	3.23	41.04	0.4104	1.70	0.53

TABLE 4. Green and relative densities of powder compacts

Powders	CP N,mm^{-2}	Green Density g,cm^{-3}	Relative Density %	Relative Density (D)	$\left(\frac{1}{1-D}\right)$	$\ln\left(\frac{1}{1-D}\right)$
ASC 100	155	5.55	70.52	0.7052	3.39	1.22
	232	6.04	76.75	0.7675	4.30	1.46
	310	6.50	82.59	0.8259	5.74	1.75
	386	6.70	85.13	0.8513	6.72	1.91
	Apparent density g,cm^{-3}	3.02	38.37	0.3837	1.62	0.48
	Tap density g,cm^{-3}	3.92	49.81	0.4981	1.99	0.69
NC 100	155	5.06	64.29	0.643	2.80	1.03
	232	5.67	72.05	0.7205	3.58	1.27
	310	6.11	77.64	0.7764	4.47	1.50
	386	6.40	81.32	0.8132	5.35	1.68
	Apparent density g,cm^{-3}	2.40	30.50	0.305	1.44	0.36
	Tap density g,cm^{-3}	3.28	41.68	0.4168	1.71	0.54
MP 32	155	5.34	67.85	0.6785	3.11	1.13
	232	5.85	74.35	0.7435	3.90	1.36
	310	6.24	79.29	0.7929	4.83	1.57
	386	6.50	82.59	0.8259	5.74	1.75
	Apparent density g,cm^{-3}	2.51	31.89	0.3189	1.47	0.38
	Tap density $g.cm^{-3}$	3.23	41.04	0.4104	1.70	0.53

TABLE 5. **The dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 5 min)**

Compaction pressure N,mm^{-2}	Sintering Temperature ^{o}C	ASC 100		NC 100		MP 32	
		Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}
155	900	5.6	44.3	5.1	30.5	5.4	44.6
	900		36.7		28.3		53.9
	1000		65.6		55		53
	1000		64.7		52.9		54.6
	1100		69.2		57.9		69.2
	1100		72.8		62.4		72.3
232	900	6.1	48.8	5.7	41.7	5.9	56.5
	900		56.3		31.6		55.8
	1000		86.6		56		80.8
	1000		86.9		55.6		81.7
	1100		109.1		100.2		101.1
	1100		100.2		91		106.5
386	900	6.8	66.5	6.4	45.6	6.5	60.6
	900		58.6		74.1		62.3
	1000		101.6		76.6		110.5
	1000		106.6		79.9		116.6
	1100		155.4		134.9		164.2
	1100		150.2		122.2		162.6

TABLE 6. Dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 20 min)

Compaction pressure N,mm^{-2}	Sintering Temperature ^{o}C	ASC 100		NC 100		MP 32	
		Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}
155	900	5.6	60.9	5.1	44.2	5.3	49.8
	900		61.2		47.8		51.9
	1000		66.3		54.4		57.8
	1000		65.8		54.6		54.5
	1100		71.6		64.8		72.6
	1100		74.5		61.2		69.4
232	900	6.0	89.8	5.7	81.7	5.9	85.9
	900		84.3		80.3		92.2
	1000		86.1		85.9		99.3
	1000		89.1		83.9		95.5
	1100		106.9		92.5		104.1
	1100		104.6		101.1		108.9
386	900	6.7	134.7	6.4	133.0	6.5	150.2
	900		122.0		123.9		135.0
	1000		146.0		126.2		147.0
	1000		142.6		137.5		154.3
	1100		172.8		153.5		185.9
	1100		157.8		161.4		172.3

TABLE 7.. Dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 60 min)

Compaction pressure N,mm^{-2}	Sintering Temperature ^{o}C	ASC 100		NC 100		MP 32	
		Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N,mm^{-2}
155	900	5.6	62.2	5.1	48.1	5.4	56.9
	900		68.2		43.5		61.0
	1000		78.3		69.9		87.4
	1000		94.5		60.8		94.2
	1100		133.3		101.1		125.1
	1100		128.7		110.0		127.4
232	900	6.1	89.6	5.7	82.5	5.9	76.2
	900		89.2		79.2		98.2
	1000		108.6		88.9		98.9
	1000		98.2		81.4		99.9
	1100		184.0		132.2		157.5
	1100		182.4		120.2		149.9
386	900	6.8	128.7	6.4	129.9	6.5	124.2
	900		133		129.2		143
	1000		138.8		138.3		126.6
	1000		149.9		132.2		144.2
	1100		203.9		160.2		159.9
	1100		196.9		157		170.5

TABLE 8. Temperatures during rolling

Preheat Temp. °C	T/C Position	Average Temp.Drop °C	Actual rolling Temp. °C (95% Conf. Limits)
900	Surface	50	850 ± 7
900	Centre	20	880 ± 4
1000	Surface	77	923 ± 6
1000	Centre	36	964 ± 3

TABLE 9. Stage I, ASC 100. Preheat Temperature 1000°C.

Compaction Press. N,mm^{-2}	Thickness of Green Compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling pressure N,mm^{-2}	Effic. of densification %
155	4.38	5.54	35	7.30	93.2	35	280	90	64.2
155	4.3	5.56	40	7.48	95.5	12	323	117	61.3
155	4.46	5.56	66	7.72	98.6	17	373	209	41.8
155	4.44	5.55	66	7.72	98.6	16	401	186	42.0
155	4.46	5.56	46	7.62	97.3	20	376	112	57.2
232	4.59	6.08	37	7.54	96.3	13	323	109	50.4
232	4.4	6.09	41	7.57	96.7	25	350	148	46.1
232	4.4	6.09	66	7.79	99.5	22	411	248	32.9
232	4.44	6.04	66	7.75	99.0	19	386	198	33.1
232	4.70	6.08	29	7.16	91.4	5	228	79	47.6
232	5.87	6.08	40	7.51	95.9	14	294	117	45.7
232	5.9	6.09	40	7.53	96.2	17	291	123	46.0
310	4.3	6.52	48	7.71	98.5	18	410	158	31.7
310	4.41	6.53	43	7.67	98.0	5	433	162	33.9
310	4.37	6.52	42	7.64	97.6	19	370	111	34.1
310	4.39	6.53	38	7.44	95.0	17	368	94	30.6

TABLE 9 (Contd.) STAGE I, ASC 100. Preheat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness of Green Compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling pressure N,mm^{-2}	Effic. of densification %
386	5.16	6.72	37	7.60	97.1	27	385	118	30.4
386	4.52	6.77	63	7.77	99.2	31	350	233	20.3
386	4.49	6.70	63	7.75	99.0	33	384	221	21.3
386	4.52	6.77	40	7.66	97.8	20	352	156	28.4
386	4.52	6.77	48	7.70	98.3	5	430	133	24.7
386	4.75	6.79	8	7.04	89.9	5	183	55	39.9

TABLE 10. Stage II, ASC 100. Preheat Temperature 1000°C

Compaction Press. N,-mm^{-2}	Thickness of Green Compact mm	Green Density g,cm^{-3}	H.R. %	Anneal. Temp. °C	Anneal. Time Min.	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.62	5.58	35	1100	30	7.31	93.4	44	240
155	4.57	5.55	39	1100	30	7.46	95.3	46	281
155	4.48	5.56	45	650	20	7.58	96.8	19	301
155	4.46	5.56	66	900	40	7.75	99.0	25	365
232	5.67	6.07	40	900	40	7.59	96.9	37	291
232	5.76	6.08	40	650	60	7.56	96.5	17	287
232	5.74	6.04	39	1100	20	7.49	95.7	44	291
386	4.6	6.7	37	1100	30	7.61	97.2	47	281
386	4.57	6.7	37	1100	30	7.59	96.9	46	293
386	4.58	6.66	47	1100	20	7.69	98.2	50	330

TABLE 11. STAGE III, ASC 100. Preheat Temperature 1000°C.

Compaction Pressure N,mm^{-2}	Thickness of green Compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}
155	4.32	5.56	48	800	40	45	7.81	99.7	6	565
155	4.34	5.58	39	1100	20	24	7.73	98.7	10	428
155	4.30	5.59	40	900	30	35	7.74	98.8	10	511
155	4.36	5.55	45	900	20	38	7.75	99.0	6	550
155	4.34	5.54	50	1100	20	28	7.78	99.4	10	455
232	5.94	6.08	48	1100	20	28	7.71	98.5	10	488
232	5.13	6.07	52	1100	20	44	7.8	99.6	7	625
232	4.34	6.06	50	1100	30	31	7.75	99	10	516
232	4.35	6.04	46	800	30	34	7.78	99.4	6	521
232	4.28	6.06	44	800	30	26	7.61	97.2	6	450
310	4.30	6.51	36	900	60	56	7.82	99.9	6	691
310	4.29	6.52	54	1100	60	48	7.79	99.5	10	642

TABLE 11. (Contd.) STAGE III, ASC 100. Preheat Temperature 1000°C

Compaction Pressure N, mm^{-2}	Thickness of green Compact mm	Green Density g, cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g, cm^{-3}	Relative Density %	UTS N, mm^{-2}	Rolling Pressure N, mm^{-2}
310	4.32	6.52	42	900	60	51	7.82	99.9	7	650
310	4.32	6.52	40	900	60	52	7.79	99.5	8	663
386	5.8	6.71	50	650	60	41	7.80	99.6	5	562
386	5.82	6.70	44	650	40	22	7.78	99.4	3	424
386	5.88	6.72	38	900	30	48	7.81	99.7	9	619
386	5.20	6.68	43	900	30	24	7.74	98.8	8	431
386	5.20	6.72	41	900	40	48	7.83	100.0	7	638

TABLE 12. STAGE IV. ASC 100. Preheat Temperature 1000°C

Compaction pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time Min	C.R. %	Annealing Temp. °C	Annealing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.48	5.55	46	1100	20	24	950	60	7.72	98.6	29	339
155	4.33	5.57	45	1100	20	27	950	20	7.74	98.8	29	359
155	4.41	5.54	47	900	30	37	950	20	7.73	98.7	27	384
232	5.18	6.04	45	900	30	28	1100	20	7.79	99.5	33	360
232	5.10	6.06	40	900	30	30	1100	20	7.71	98.5	28	373
232	4.34	6.05	47	800	40	31	950	20	7.8	99.6	28	385
232	4.32	6.08	54	900	40	42	1100	20	7.83	100	31	415
386	5.17	6.79	35	1100	20	38	1100	20	7.81	99.7	35	381
386	5.24	6.67	50	900	40	32	1100	20	7.79	99.5	31	380
386	5.19	6.76	52	900	20	43	950	20	7.81	99.7	25	415
386	4.47	6.77	48	800	30	45	800	60	7.78	99.4	23	435

TABLE 13. STAGE V. ASC 100. Preheat Temperature 1000°C

Compaction Pressure N,mm^{-2}	Thickness of Green Compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	El. %	UTS N,mm^{-2}
155	5.16	5.56	50	1100	20	23	950	60	21	7.77	99.2	13	590
155	3.63	5.55	38	950	30	20	800	60	19	7.72	98.6	12	419
232	4.28	6.04	43	800	20	21	650	60	20	7.82	99.9	6	475
232	4.58	6.08	48	950	40	22	800	20	21	7.69	98.2	11	564
232	4.42	6.07	51	650	60	23	1100	20	22	7.8	99.6	13	581
386	4.36	6.71	48	1100	20	22	800	60	21	7.78	99.4	11	585
386	4.30	6.7	34	800	20	19	1100	20	18	7.79	99.5	13	384
386	4.36	6.7	42	900	30	27	950	20	21	7.83	100.0	11	606

TABLE 14. STAGE VI, ASC 100. Preheat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness of Green Density mm	Green Density $g.cm^{-3}$	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min.	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.35	5.55	48	900	40	23	1100	20	22	950	20	7.69	98.2	30	375
155	4.38	5.55	42	1100	20	23	650	60	21	950	40	7.70	98.3	26	360
232	4.45	6.10	43	900	20	19	800	60	20	950	40	7.81	99.7	29	340
232	4.53	6.10	52	800	60	22	950	20	21	950	20	7.79	99.5	31	370
386	4.40	6.70	38	650	60	22	800	20	19	950	20	7.74	98.8	27	331
386	4.35	6.71	47	800	40	23	1100	20	22	950	40	7.83	100.0	30	381

TABLE 15. STAGE I. ASC 100. Preheat Temperature 900°C

Compaction pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %	Hardness HV
155	4.40	5.54	35	7.29	93.1	22	250	63	63.9	88
155	4.44	5.55	45	7.38	94.2	8	274	108	51.9	114
155	4.43	5.53	45	7.59	96.9	31	320	106	58.5	124
155	4.47	5.54	56	7.71	98.5	25	367	131	49.5	131
155	6.44	5.56	45	7.60	97.1	46	285	118	57.9	112
155	4.48	5.55	66	7.70	98.3	32	319	175	41.6	145
155	4.61	5.57	43	7.51	95.9	32	311	120	57.6	126
155	4.46	5.56	48	7.62	97.3	21	350	130	54.8	110
155	4.46	5.54	13	6.2	79.2	0	92	43	64.8	66
155	4.61	5.60	54	7.69	98.2	26	396	111	49.4	138
232	4.33	6.05	43	7.64	97.6	20	307	121	47.2	138
232	4.36	6.07	62	7.74	98.8	25	308	203	34.4	148

TABLE 15. (Contd.) STAGE I. ASC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %	Hardness HV
232	4.44	6.04	62	7.70	98.3	26	384	168	34.2	164
232	4.40	6.04	45	7.70	98.3	29	342	98	47.1	144
232	4.26	6.09	45	7.67	98.0	25	350	134	44.8	123
232	4.41	6.06	67	7.77	99.2	13	437	168	32.6	179
232	4.26	6.05	65	7.75	99.0	22	415	148	33.4	155
232	4.52	6.08	67	7.81	99.7	29	435	152	33.0	160
232	4.38	6.10	21	6.97	89.0	3	158	75	52.9	77
232	4.41	6.09	41	7.62	97.3	47	283	98	47.7	113
232	4.48	6.10	47	7.68	98.1	22	410	155	42.9	145
310	4.32	6.55	41	7.56	96.5	14	312	107	31.5	128
310	4.31	6.55	45	7.67	97.9	24	360	134	31.8	148
310	3.59	6.51	50	7.71	98.5	24	365	151	30.6	148

TABLE 15. (Contd.) STAGE I. ASC 100. Preheat Temperature 900°C

Compaction pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %	Hardness HV
310	4.40	6.51	66	7.81	99.7	21	408	204	25.2	169
310	4.37	6.51	64	7.78	99.4	20	409	186	25.3	151
310	4.38	6.52	67	7.80	99.6	19	430	155	24.4	133
310	4.44	6.50	66	7.73	98.7	21	430	176	23.8	173
386	5.25	6.74	32	7.51	95.9	42	299	69	30.7	142
386	4.49	6.76	60	7.69	98.2	25	394	142	19.8	159
386	4.49	6.76	38	7.58	96.8	44	315	75	27.6	150
386	5.13	6.73	66	7.80	99.6	19	320	270	20.7	173
386	4.54	6.70	67	7.79	99.5	32	369	211	20.8	167
386	4.97	6.79	43	7.64	97.6	22	359	94	25.2	138

TABLE 15. (Contd.) STAGE I. ASC 100. Preheat Temperature 900°C

Compaction pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %	Hardness Hv
386	4.55	6.70	47	7.70	98.3	7	296	161	27.2	148
386	4.43	6.76	29	7.53	96.2	25	275	62	33.9	117
386	5.25	6.72	63	7.74	98.8	24	429	193	20.7	170
386	4.46	6.78	23	7.40	94.5	22	248	106	34.4	91
386	4.47	6.77	47	7.69	98.2	37	310	170	25.0	128
386	4.43	6.76	54	7.70	98.3	25	363	141	22.2	145

TABLE 16. STAGE II. ASC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
155	4.43	5.57	37	1100	30	7.50	95.8	30	288	83
155	4.44	5.54	43	1100	30	7.55	96.4	30	327	89
155	4.31	5.57	48	1100	20	7.64	97.6	31	335	114
155	4.46	5.56	51	900	60	7.66	97.8	25	364	118
155	4.62	5.60	64	650	60	7.72	98.6	18	412	125
155	4.43	5.57	66	900	40	7.71	98.5	31	290	135
155	4.62	5.60	51	900	60	7.69	98.2	19	413	153
232	4.34	6.04	44	900	40	7.65	97.7	27	305	113
232	4.32	6.07	43	1100	20	7.60	97.1	29	312	107
232	4.35	6.07	40	900	40	7.48	95.5	27	315	111

TABLE 16. (Contd.) STAGE II. ASC 100 Preheat Temperture 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Anneal-ing Temp. °C	Anneal-ing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
232	4.44	6.08	44	1100	30	7.50	95.8	28	329	102
232	4.41	6.04	42	900	30	7.59	96.9	24	327	110
232	4.52	6.09	62	800	20	7.76	99.1	22	374	126
232	4.52	6.10	55	900	60	7.71	98.5	23	376	142
310	4.29	6.51	45	650	60	7.70	98.3	23	341	165
310	4.47	6.55	59	800	40	7.75	99	24	379	145
310	3.54	6.53	60	650	60	7.74	98.8	23	386	110
310	4.45	6.54	62	800	20	7.74	98.8	24	400	130
310	4.40	6.51	64	900	20	7.77	99.2	26	429	102
386	4.36	6.76	32	1100	20	7.56	96.5	33	288	100

TABLE 16. (Contd.) STAGE II. ASC 100 Preheat Temperature 900°C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Anneal-ing Temp. °C	Anneal-ing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
386	4.37	6.76	39	1100	30	7.58	96.8	33	300	112
386	4.45	6.68	38	650	20	7.57	96.7	24	300	121
386	4.44	6.68	40	1100	30	7.63	97.4	30	327	114
386	4.41	6.76	60	800	60	7.73	98.7	23	390	153
386	4.37	6.72	36	1100	60	7.58	96.8	33	303	101

TABLE 17. STAGE III. ASC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
155	4.28	5.54	42	900	20	51	7.81	99.7	9	635	207
155	4.34	5.57	44	900	20	48	7.77	99.2	7	583	186
155	4.28	5.55	48	800	30	41	7.77	99.2	7	541	179
232	4.34	6.04	54	1100	30	45	7.82	99.9	7	630	220
232	4.32	6.08	44	1100	30	43	7.73	98.7	7	589	215
232	4.37	6.07	44	1100	30	20	7.69	98.2	10	459	154
232	4.39	6.05	45	900	40	49	7.73	98.7	9	600	217
232	4.38	6.08	44	1100	30	32	7.71	98.5	8	527	192
310	4.36	6.54	47	900	40	48	7.78	99.4	8	626	209
310	4.44	6.53	50	1100	40	46	7.77	99.2	9	614	207

TABLE 17. (Contd.) STAGE III. ASC 100. Preheat Temperture 900^{o}C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. ^{o}C	Annealing Time min	C.R %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
310	4.39	6.52	46	800	30	48	7.76	99.1	9	602	212
386	4.44	6.65	46	650	60	49	7.79	99.5	8	615	224
386	4.38	6.64	51	1100	20	35	7.75	99.0	7	505	192
386	4.33	6.68	49	1100	40	48	7.76	99.1	7	635	221
386	4.29	6.67	46	1100	30	26	7.72	98.6	7	456	170

TABLE 18. STAGE IV. ASC 100. Preheat Temperature 900° C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elongn. %	UTS N,mm^{-2}	Hardness HV
155	4.54	5.56	61	900	40	23	950	20	7.79	99.5	26	325	105
155	4.47	5.54	60	900	60	25	950	20	7.78	99.4	25	335	108
155	4.49	5.55	44	800	60	25	650	60	7.72	98.6	18	329	102
232	4.33	6.04	47	1100	20	29	1100	20	7.80	99.6	29	353	92
232	4.31	6.05	43	650	40	39	650	60	7.79	99.5	12	388	110
232	4.33	6.07	47	800	30	39	650	60	7.79	99.5	18	408	118
386	5.18	6.68	43	900	20	31	950	60	7.77	99.2	25	352	107
386	4.34	6.70	43	650	60	32	800	60	7.80	99.6	23	368	132
386	4.41	6.68	45	900	30	42	800	20	7.78	99.4	21	396	119
386	4.48	6.63	50	900	20	46	1100	20	7.82	99.9	23	413	140

TABLE 19. STAGE V. ASC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongn. %	UTS N,mm^{-2}	Hardness HV
155	4.36	5.54	51	900	40	24	1100	20	22	7.77	99.2	10	563	192
155	5.16	5.56	49	1100	20	23	950	20	21	7.82	99.9	11	548	185
232	4.30	6.07	48	900	30	22	650	60	21	7.68	98.1	10	530	182
232	4.42	6.06	39	800	60	21	800	60	20	7.73	98.7	10	394	181
386	4.58	6.68	48	650	60	23	1100	20	22	7.79	99.5	11	553	188
386	4.36	6.67	38	900	20	20	950	20	19	7.76	99.1	10	363	178
386	4.36	6.66	53	1100	30	25	800	60	22	7.80	99.6	10	569	193

TABLE 20. STAGE VI. ASC 100. Preheat Temperature 900°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green density g,cm^{-3}	H.R. %	Annealing Temp. C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}	Hardness HV
155	4.40	5.54	50	1100	20	23	950	60	22	950	20	7.76	99.1	28	350	109
232	4.53	6.08	51	1100	30	22	950	20	23	950	40	7.71	98.5	28	358	112
232	4.38	6.04	39	900	60	22	1100	20	21	950	20	7.80	99.6	30	323	106
386	3.65	6.70	32	800	40	21	800	60	21	950	20	7.62	97.3	24	333	105
386	4.35	6.68	48	650	60	24	800	20	23	950	20	7.78	99.4	24	366	134

TABLE 21. STAGE I. ASC 100. Preheat Temperature 800°C

Compaction Press. N,mm^{-2}	Thickness or green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic. of Densification %
155	4.34	5.51	30	6.80	86.8	2	137	62	54.90
155	6.19	5.57	41	7.24	92.5	9	179	78	52.0
155	4.40	5.54	45	7.52	96.0	23	230	109	56.2
155	6.59	5.59	62	7.70	98.3	16	251	172	43.5
155	6.44	5.60	57	7.69	98.2	12	262	119	46.8
155	4.40	5.51	59	7.69	98.2	4	262	195	47.2
232	4.39	6.07	28	7.05	90.0	6	190	81	44.7
232	4.34	6.08	47	7.66	97.8	32	260	174	42.9
232	4.37	6.07	65	7.74	98.8	20	319	270	32.8
232	4.37	6.07	62	7.74	98.8	17	325	141	34.4
232	5.87	6.12	23	6.84	87.4	3	152	75	40
232	6.00	6.10	59	7.78	99.4	44	261	156	36.4
310	4.35	6.51	22	7.35	93.9	6	214	83	48.8
310	4.30	6.54	33	7.40	94.5	15	251	103	33.3
386	4.43	6.77	24	7.05	90.0	11	260	79	14.9
386	4.35	6.77	26	7.38	94.2	6	214	98	30.0
386	4.44	6.77	14	7.07	90.3	6	245	62	27.4
386	4.30	6.64	45	7.72	98.6	15	251	143	30.6
386	4.42	6.77	43	7.75	99.0	42	253	167	29.1
386	5.25	6.64	60	7.78	99.4	12	323	172	24.3
386	4.43	6.77	63	7.83	100.0	30	378	245	21.5
386	5.25	6.80	64	7.81	99.7	41	282	238	20.1

TABLE 22. STAGE I. ASC 100. Preheat Temperature 700°C

Compaction Press. N,mm^{-2}	Thickness or green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic.of Densification %
155	4.41	5.57	19	6.57	83.9	3	115	51	67.2
155	6.42	5.55	40	7.22	92.2	4	140	83	53.3
155	6.54	5.52	57	7.42	94.8	6	167	126	42.6
155	4.44	5.57	45	7.62	97.3	5	335	166	58.2
155	6.27	5.59	65	7.73	98.7	1	362	270	42.0
155	6.27	5.61	59	7.73	98.7	2	337	169	45.9
232	4.45	6.09	17	6.63	84.7	1	155	81	40.6
232	5.81	6.10	40	7.40	94.5	9	201	86	41.5
232	5.99	6.10	53	7.76	99.1	20	228	218	40.0
232	5.65	6.10	47	7.56	96.5	21	274	165	39.7
232	4.40	6.09	37	7.36	94.0	5	320	137	43.8
232	5.90	6.10	72	7.79	99.5	16	370	366	30.0
310	4.59	6.52	29	7.47	95.5	14	325	165	41.8
310	4.24	6.48	20	7.19	91.8	3	260	81	45.3
386	4.52	6.75	29	7.50	95.8	3	305	147	33.0
386	5.13	6.73	40	7.61	97.2	20	300	164	28.1
386	5.17	6.69	68	7.69	98.2	12	331	271	18.8
386	4.46	6.77	43	7.71	98.5	20	338	277	27.9
386	4.49	6.77	43	7.70	98.3	16	352	253	27.6
386	4.97	6.65	51	7.72	98.6	20	361	298	26.8
386	5.25	6.69	61	7.74	98.8	20	396	342	22.0

TABLE 23. STAGE I. NC 100. Pre-heat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness or green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic. of Densification %
155	4.70	5.06	21	6.76	86.3	2	116	25	103.4
155	4.67	5.06	67	7.63	97.4	17	372	118	49.0
155	4.57	5.09	49	7.33	93.6	8	321	69	58.4
155	4.56	5.06	59	7.46	95.3	14	281	78	52.0
155	4.61	5.08	39	7.30	93.2	13	274	36	72.7
232	4.59	5.67	24	6.71	85.7	2	148	35	55.3
232	4.65	5.66	47	7.49	95.7	11	288	66	49.7
232	4.76	5.69	49	7.55	96.4	8	343	87	48.5
232	4.58	5.70	49	7.54	96.3	13	313	100	48.0
232	4.71	5.67	53	7.60	97.1	14	313	104	46.5
232	4.76	5.68	64	7.58	96.8	20	337	126	37.9
232	4.59	5.66	51	7.52	96.0	15	308	71	46.6
232	4.64	5.67	57	7.58	96.8	12	303	113	42.8
386	4.55	6.35	64	7.57	96.7	20	340	144	24.3
386	4.58	6.42	38	7.45	95.1	9	295	68	34.6
386	4.58	6.41	26	7.15	91.3	5	227	57	36.3
386	4.61	6.38	38	7.50	95.8	8	302	73	37.6
386	4.56	6.40	51	7.53	96.2	9	372	100	28.3
386	4.60	6.38	52	7.54	96.3	11	330	117	28.5
386	4.58	6.35	46	7.50	95.8	8	334	89	31.9
386	4.78	6.42	40	7.45	95.1	16	317	78	32.9
386	4.59	6.37	39	7.44	95.0	12	287	71	35.0
386	4.62	6.33	50	7.59	96.9	20	326	106	32.2
386	4.70	6.38	54	7.49	95.7	11	330	128	26.2

TABLE 24. STAGE II, NC 100. Preheat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.72	5.05	37	1100	30	7.17	91.6	28	243
155	4.62	5.10	41	1100	40	7.21	92.1	29	285
155	4.47	5.10	42	650	60	7.28	93.0	17	286
232	4.44	5.68	37	1100	20	7.21	92.1	25	275
232	4.48	5.68	40	900	30	7.49	95.7	27	287
232	4.33	5.67	39	1100	20	7.48	95.5	31	279
232	4.70	5.67	52	800	60	7.61	97.2	19	322
386	4.68	6.40	64	1100	20	7.69	98.2	28	329
386	4.59	6.43	41	900	30	7.55	96.4	26	298
386	4.55	6.38	37	1100	20	7.30	93.2	27	301
386	4.61	6.35	42	650	60	7.56	96.5	19	299

TABLE 25. STAGE III, NC 100. Preheat Temperature 1000°C

Compaction Pressure N,mm^{-2}	Thickness of green Compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}
155	4.72	5.10	46	800	30	24	7.31	93.4	3	389
155	4.46	5.10	42	900	30	35	7.47	95.4	6	429
155	4.97	5.08	46	650	30	38	7.65	97.7	2	507
232	4.49	5.65	50	900	20	34	7.47	95.4	5	476
232	4.48	5.71	38	900	30	44	7.64	97.6	6	495
232	4.60	5.71	53	800	60	44	7.60	97.1	7	516
232	4.52	5.71	39	1100	30	32	7.56	96.5	7	412
386	4.55	6.40	44	1100	40	40	7.61	97.2	5	473
386	4.44	6.40	45	1100	20	52	7.70	98.3	4	533
386	4.52	6.38	41	900	20	32	7.52	96.0	5	409
386	4.38	6.40	44	900	40	38	7.58	96.8	9	468

TABLE 26. STAGE IV. NC 100. Preheat Temperature 1000°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	5.64	5.09	33	900	40	25	1100	20	7.46	95.3	26	314
155	5.80	5.10	34	800	40	20	950	30	7.49	95.7	23	273
155	4.43	5.08	28	800	40	31	1100	20	7.56	96.5	28	337
155	4.48	5.06	44	900	30	42	800	60	7.61	97.2	25	364
232	4.59	5.64	33	900	40	25	800	30	7.47	95.4	24	301
232	4.55	5.61	41	900	60	24	650	40	7.41	94.6	20	315
232	4.61	5.63	31	800	60	28	650	60	7.49	95.7	19	319
232	4.24	5.67	47	1100	20	41	1100	20	7.77	99.2	31	358
386	4.25	6.45	52	900	30	23	1100	20	7.58	96.8	29	303
386	4.61	6.46	44	1100	20	45	950	20	7.70	98.3	32	389
386	4.55	6.41	38	900	40	32	1100	30	7.58	96.8	29	333
386	4.50	6.40	39	650	60	40	800	40	7.61	97.2	26	345

TABLE 27. STAGE I. NC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %
155	4.80	5.06	61	7.42	94.8	9	308	69	49.4
155	4.52	5.10	66	7.54	96.3	12	314	102	47.2
155	4.61	5.08	53	7.39	94.4	8	260	68	55.7
155	4.54	5.05	29	6.66	85.1	3	128	33	70.9
155	4.52	5.06	40	7.20	91.9	9	207	41	68.3
155	4.71	5.08	40	7.19	91.8	11	180	32	67.4
155	4.50	5.05	41	7.06	90.2	5	252	90	62.6
155	4.60	5.02	41	7.30	93.2	9	202	39	71.0
155	4.70	5.06	65	7.55	96.4	20	289	103	48.9
232	4.62	5.59	49	7.43	94.9	17	303	100	48.0
232	4.53	5.67	49	7.47	95.4	7	293	86	47.0

TABLE 27. (Contd.) STAGE I. NC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %
232	4.65	5.60	40	7.34	93.7	15	235	57	55.6
232	4.59	5.60	64	7.60	97.1	22	309	125	39.9
232	4.70	5.62	49	7.45	95.1	10	281	72	47.7
232	4.47	5.64	53	7.51	95.9	14	294	80	45.1
232	4.48	5.67	17	6.51	83.1	2	119	42	63.1
232	4.59	5.64	53	7.48	95.5	11	285	68	44.3
232	4.54	5.60	65	7.59	96.9	13	314	108	39.1
232	4.50	5.69	60	7.60	97.1	7	304	90	40.7
232	4.62	5.67	58	7.53	96.2	10	304	79	41.0
310	4.74	6.11	53	7.56	96.5	20	321	107	34.9
386	4.59	6.40	42	7.50	95.8	8	301	68	33.4

TABLE 27. (Contd.) STAGE I. NC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^{-2}	Efficiency of Densification %
386	4.50	6.41	56	7.57	96.7	15	330	140	26.5
386	4.52	6.35	20	7.07	90.3	6	196	46	46.0
386	4.48	6.38	40	7.51	95.9	7	311	66	36.1
386	4.61	6.37	43	7.51	95.9	9	314	73	33.9
386	4.47	6.35	38	7.47	95.4	16	264	89	37.6
386	4.62	6.34	64	7.56	96.5	25	296	117	24.3
386	4.48	6.39	38	7.38	94.2	11	290	68	33.3

TABLE 28. **STAGE II.** **NC 100.** **Preheat Temperature 900°C**

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}
155	4.70	5.04	37	1100	20	7.21	92.1	26	234
155	4.67	5.10	41	650	60	7.33	93.6	24	244
155	4.59	5.06	41	1100	20	7.38	94.2	28	260
232	4.55	5.68	51	900	60	7.48	95.5	27	284
232	4.58	5.65	60	1100	20	7.56	96.5	27	291
232	4.57	5.65	40	900	30	7.48	95.5	23	274
232	4.44	5.69	39	1100	20	7.50	95.8	28	265
310	4.72	6.11	52	900	60	7.65	97.7	25	304
386	4.62	6.38	43	800	40	7.51	95.9	17	287
386	4.58	6.40	55	650	60	7.67	98	18	280
386	4.48	6.41	33	650	60	7.38	94.2	18	187

TABLE 29. STAGE III. NC 100. Preheat Temperature 900°C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g,cm $^{-3}$	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm $^{-3}$	Relative Density %	Elongation %	UTS N,mm $^{-2}$
155	4.7	5.06	44	650	60	18	7.46	95.3	4	285
155	4.68	5.08	42	800	30	22	7.48	95.5	3	302
155	4.71	5.11	45	800	40	34	7.48	95.5	5	418
232	4.62	5.64	33	650	60	18	7.30	93.2	1	264
232	4.61	5.64	54	900	30	41	7.67	98	8	508
232	4.60	5.68	51	1100	20	39	7.56	96.5	6	456
232	4.62	5.66	48	1100	20	22	7.32	93.5	5	315
386	4.49	6.40	54	900	30	22	7.42	94.8	3	300
386	4.53	6.38	51	1100	20	44	7.68	98.1	11	503
386	4.54	6.42	44	800	60	36	7.54	96.3	8	403
386	4.55	6.40	50	1100	20	42	7.58	96.8	14	495

TABLE 30. STAGE IV. NC 100. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong %	UTS N,mm^{-2}
155	4.70	5.06	38	900	30	27	950	20	7.42	94.8	25	312
155	4.66	5.08	33	650	60	21	800	60	7.37	94.1	24	261
155	4.72	5.10	30	800	40	38	950	20	7.58	96.8	27	329
232	4.58	5.64	38	900	20	25	800	20	7.48	95.5	31	284

TABLE 30. (Contd.) **STAGE IV.** **NC 100.** **Preheat Temperature 900°C**

Compaction Pressure $N.mm^{-2}$	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong %	UTS N,mm^{-2}
232	4.62	5.62	43	800	60	28	650	60	7.50	95.8	23	305
232	4.57	5.68	40	1100	20	30	1100	20	7.49	95.7	27	331
232	4.59	5.73	42	900	40	32	1100	20	7.48	95.5	28	338
310	4.73	6.06	53	800	40	38	950	60	7.65	97.7	22	360
310	4.63	6.11	45	800	20	48	950	20	7.69	98.2	22	337
386	4.51	6.47	39	800	40	29	950	20	7.38	94.2	26	291
386	4.53	6.49	41	1100	20	29	950	20	7.45	95.1	29	303
386	4.49	6.42	54	900	30	47	800	20	7.69	98.2	27	386
386	4.53	6.40	51	800	40	38	800	20	7.54	96.3	27	333

TABLE 31. STAGE I. NC 100. Preheat Temperature 800°C

Compaction press. N,mm^{-2}	Thickness of Green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic: of densification %
155	4.50	5.04	19	6.16	78.7	2	108	20	75.3
155	4.30	5.04	35	6.67	85.2	4	140	25	59.5
155	4.51	5.06	41	7.20	91.9	8	178	59	66.7
155	4.50	5.05	66	7.53	96.2	16	272	119	48.0
155	4,52	5.07	57	7.38	94.2	9	260	92	51.8
232	4.44	5.66	42	7.31	93.4	5	238	79	50.2
232	4.60	5.68	36	7.06	90.2	6	170	33	49.0
232	4.52	5.67	40	7.32	93.5	4	205	69	52.7
232	4.61	5.69	45	7.41	94.6	11	254	87	48.8
232	4.62	5.68	66	7.58	96.8	20	281	150	36.8
232	4.57	5.62	38	7.30	93.2	7	223	57	56.5
232	4.38	5.64	48	7.46	95.3	9	278	119	48.4
386	4.44	6.45	25	7.16	91.4	5	179	112	36.3
386	4.67	6.46	35	7.29	93.1	10	209	50	30.3
386	4.49	6.46	65	7.59	96.9	20	285	153	22.2
386	4.61	6.40	39	7.43	94.9	12	279	108	33.7
386	4.58	6.42	38	7.43	94.9	8	272	99	33.9
386	4.49	6.44	36	7.40	99.5	15	273	68	34.1

TABLE 32. STAGE I. NC 100. Preheat Temperature 700°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic: of densification %
155	4.52	5.04	23	6.33	80.8	2	96	24	71.6
155	4.55	5.03	43	6.80	86.8	3	158	52	52.6
155	4.61	5.06	45	7.13	91.1	7	229	79	58.7
155	4.57	5.04	66	7.61	97.2	17	277	148	49.7
155	4.58	5.03	59	7.35	93.9	11	260	108	50.2
232	4.65	5.64	25	6.60	89.3	2	146	37	49.0
232	4.62	5.60	40	7.10	90.7	4	201	83	47.9
232	4.57	5.62	40	7.09	90.5	6	225	78	46.9
232	4.67	5.68	42	7.14	91.2	3	195	63	44.4
232	4.62	5.69	41	6.98	89.1	7	198	86	40.2
232	4.66	5.68	65	7.58	96.8	17	279	135	37.3
386	4.32	6.36	21	6.92	88.4	4	171	36	32.8
386	4.55	6.45	36	7.26	92.7	9	223	71	28.7
386	4.44	6.45	62	7.61	97.2	17	301	146	23.9

TABLE 33. STAGE I. MP 32. Preheat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic: of Densification %
155	4.73	5.34	19	6.28	80.2	0	122	37	63.2
155	4.69	5.34	48	7.52	96.0	8	332	78	58.0
155	4.71	5.38	62	7.64	97.6	16	373	145	46.5
155	4.62	5.33	64	7.65	97.7	7	458	152	46.3
155	4.59	5.34	51	7.56	96.5	8	407	96	55.6
232	4.68	5.84	50	7.58	96.8	6	368	151	44.4
232	4.57	5.82	38	7.35	93.9	2	327	74	51.4
232	4.53	5.85	44	7.47	95.4	6	307	68	47.0
232	4.57	5.75	20	6.67	85.2	2	179	37	58.7
232	4.62	5.85	38	7.26	92.7	0	176	87	47.4
232	4.58	5.85	39	7.29	93.1	0	290	121	47.2
310	4.50	6.25	48	7.61	97.2	8	363	149	36.2
310	4.52	6.22	39	7.49	95.7	3	341	98	41.6
386	4.51	6.51	42	7.56	96.5	8	244	115	31.9
386	4.48	6.50	43	7.65	97.7	0	280	109	34.2
386	4.45	6.52	26	7.31	93.4	4	287	66	38.8
386	4.49	6.53	48	7.71	98.5	17	373	124	31.4
386	4.49	6.50	49	7.70	98.3	12	397	142	31.3

TABLE 34. STAGE II. MP 32. Preheat Temperature 1000°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Anneal. Temp. °C	Anneal. Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.54	5.35	35	1100	30	7.25	92.6	24	299
155	4.55	5.34	41	1100	40	7.42	94.8	18	317
155	4.53	5.34	49	650	60	7.57	96.7	17	377
155	4.59	5.33	62	800	60	7.68	98.1	16	432
232	4.53	5.82	36	900	40	7.31	93.4	25	327
232	4.51	5.83	45	1100	20	7.53	96.2	28	432
232	4.44	5.82	61	900	20	7.71	98.5	26	471
232	4.51	5.81	67	800	40	7.77	99.2	19	427
386	4.57	6.53	20	900	30	7.04	89.9	22	179
386	4.48	6.50	29	650	60	7.38	94.2	18	294
386	4.49	6.51	34	1100	40	7.45	95.1	30	307
386	4.50	6.52	36	1100	40	7.50	95.8	39	357

TABLE 35. STAGE III. MP 32. Preheat Temperture 1000^{o}C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g,cm $^{-3}$	H.R. %	Annealing Temp. ^{o}C	Annealing Time min	C.R. %	Rolled Density g,cm ^{3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.52	5.37	49	900	30	37	7.81	99.7	3	472
155	4.49	5.33	42	800	40	39	7.79	99.5	7	501
155	4.48	5.34	52	1100	20	38	7.80	99.6	8	511
155	4.57	5.33	49	1100	20	48	7.83	100.0	5	604
232	4.49	5.84	20	650	60	18	7.46	95.3	0	289
232	4.53	5.80	50	1100	20	35	7.77	99.2	4	460
232	4.61	5.82	62	1100	40	34	7.71	98.5	5	462
232	4.52	5.83	48	900	20	37	7.83	100.0	4	475
232	4.59	5.81	50	1100	20	36	7.80	99.6	6	471
386	4.50	6.54	38	650	60	21	7.62	97.3	0	278
386	4.48	6.53	48	650	30	27	7.66	97.8	7	360
386	4.49	6.51	60	900	60	47	7.81	99.7	1	598
386	4.52	6.50	49	800	30	33	7.78	99.4	3	399

TABLE 35. STAGE III. MP 32. Preheat Temperture 1000°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Rolled Density g,cm^{3}	Relative Density %	Elong. %	UTS N,mm^{-2}
155	4.52	5.37	49	900	30	37	7.81	99.7	3	472
155	4.49	5.33	42	800	40	39	7.79	99.5	7	501
155	4.48	5.34	52	1100	20	38	7.80	99.6	8	511
155	4.57	5.33	49	1100	20	48	7.83	100.0	5	604
232	4.49	5.84	20	650	60	18	7.46	95.3	0	289
232	4.53	5.80	50	1100	20	35	7.77	99.2	4	460
232	4.61	5.82	62	1100	40	34	7.71	98.5	5	462
232	4.52	5.83	48	900	20	37	7.83	100.0	4	475
232	4.59	5.81	50	1100	20	36	7.80	99.6	6	471
386	4.50	6.54	38	650	60	21	7.62	97.3	0	278
386	4.48	6.53	48	650	30	27	7.66	97.8	7	360
386	4.49	6.51	60	900	60	47	7.81	99.7	1	598
386	4.52	6.50	49	800	30	33	7.78	99.4	3	399

TABLE 36. STAGE IV, MP 32. Preheat Temperature 1000°C

Compation Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time Min	C.R. %	Annealing Temp. °C	Annealing Time Min	Rolled Density g,cm^{-3}	Relative Density %	Elong %	UTS N,mm^{-2}
155	4.49	5.34	34	900	40	18	650	60	7.63	97.4	21	256
155	4.44	5.30	51	800	60	35	950	20	7.80	99.6	23	415
155	4.51	5.34	49	1100	20	47	1100	20	7.82	99.9	29	536
155	4.40	5.33	42	800	60	39	950	20	7.78	99.4	28	394
232	4.44	5.86	30	650	40	19	800	40	7.60	97.1	18	229
232	4.52	5.84	34	1100	20	36	950	30	7.72	98.6	27	399
232	4.51	5.83	42	900	30	40	800	40	7.77	99.2	24	435
232	4.43	5.81	48	1100	20	33	1100	20	7.82	99.9	26	403
232	4.48	5.80	48	900	30	27	950	30	7.78	99.4	25	333
386	4.44	6.52	51	900	40	41	800	40	7.76	99.1	23	472
386	4.49	6.52	41	900	40	41	1100	20	7.83	100.0	27	489
386	4.52	6.53	38	900	30	44	800	30	7.80	99.6	22	519
386	4.58	6.50	32	800	20	36	800	30	7.71	98.5	21	423
386	4.46	6.52	50	800	60	48	650	60	7.82	99.9	16	626

TABLE 37. STAGE I. MP 32. Preheat Temperature 900°C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g,cm $^{-3}$	H.R. %	Rolled Density g,cm $^{-3}$	Relative Density %	Elongation %	UTS N,mm $^{-2}$	Rolling Pressure N,mm $^{-2}$	Efficiency of Densification %	Hardness HV
155	4.43	5.27	16	6.10	77.9	0	93	30	66.2	39
155	4.51	5.34	51	7.46	95.3	2	341	91	53.1	96
155	4.54	5.34	62	7.59	96.9	8	362	144	46.3	118
155	4.61	5.30	65	7.62	97.3	7	480	161	45.6	124
155	4.60	5.32	54	7.50	95.8	6	402	101	51.6	108
232	4.53	5.78	48	7.34	93.7	3	356	87	41.5	135
232	4.46	5.78	11	6.49	82.9	0	112	36	82.4	41
232	4.59	5.78	38	7.18	91.7	4	284	75	47.0	115
232	4.66	5.77	62	7.65	97.7	14	374	175	38.7	148
232	4.58	5.85	49	7.43	94.9	2	293	133	41.2	140
232	4.68	5.77	64	7.68	98.1	11	433	179	38.1	150
310	4.62	6.25	46	7.67	98.0	16	438	119	39.4	144

TABLE 37. (Contd.) STAGE I. MP 32. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Rolling Pressure N,mm^2	Efficiency of Densification %	Hardness HV
385	4.47	6.48	63	7.67	98.0	3	387	160	24.1	139
386	4.41	6.47	46	7.61	97.2	14	366	111	31.6	124
386	4.41	6.47	63	7.70	98.3	20	523	166	24.9	158
386	4.46	6.44	24	7.17	91.6	2	242	60	38.8	83
386	4.51	6.51	40	7.56	96.5	6	284	100	33.5	138
386	4.49	6.53	48	7.68	98.1	2	348	118	30.6	139

TABLE 38. STAGE II. MP 32. Preheat Temperature 900°C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g.cm $^{-3}$	H.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm $^{-3}$	Elongation %	UTS N,mm $^{-2}$	Relative Density %	Hardness HV
155	4.59	5.34	37	800	60	7.15	19	289	91.3	91
155	4.47	5.28	46	900	40	7.51	23	346	95.9	124
155	4.62	5.31	56	1100	20	7.66	22	391	97.8	113
232	4.51	5.81	46	1100	20	7.59	28	366	96.9	109
232	4.59	5.79	21	650	60	6.83	15	193	87.2	73
232	4.58	5.80	37	900	20	7.31	18	301	93.4	94
232	4.66	5.75	53	1100	20	7.68	20	433	98.1	138
310	4.67	6.22	50	900	60	7.71	19	415	98.5	135
386	4.52	6.39	50	1100	20	7.74	22	392	98.8	125
386	4.47	6.48	46	900	40	7.68	21	323	98.1	111
386	4.51	6.50	42	1100	20	7.64	26	361	97.6	101

TABLE 39. STAGE III. MP 32. Preheat temperature 900°C

Compaction Pressure N,mm $^{-2}$	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Anneal-ing Temp. °C	Anneal-ing Time min	C.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS N,mm^{-2}	Hardness HV
155	4.61	5.32	34	800	30	25	7.52	96.0	1	311	169
155	4.55	5.34	52	1100	20	34	7.69	98.2	0	433	191
155	4.58	5.36	46	800	30	29	7.79	99.5	2	344	187
232	4.51	5.81	40	1100	20	42	7.74	98.8	3	483	215
232	4.52	5.82	38	900	20	32	7.73	98.7	4	380	203
232	4.44	5.80	37	800	60	37	7.52	96.0	2	430	213
232	4.54	5.79	51	900	20	40	7.80	99.6	5	479	228
386	4.48	6.48	40	650	60	22	7.67	98.0	7	284	177
386	4.45	6.52	53	1100	20	44	7.81	99.7	1	511	225
386	4.49	6.48	45	900	30	50	7.83	100.0	3	592	233

TABLE 40. STAGE IV. MP 32. Preheat Temperature 900°C

Compaction Pressure N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Annealing Temp. °C	Annealing Time min	C.R. %	Annealing Temp. °C	Annealing Time min	Rolled Density g,cm^{-3}	Relative Density %	Elong. %	UTS N,mm^{-2}	Hardness HV
155	4.62	5.34	50	1100	20	40	800	30	7.77	99.2	19	485	118
155	4.68	5.31	40	800	40	21	950	20	7.64	97.6	22	325	93
155	4.58	5.37	47	650	60	44	1100	20	7.80	99.6	28	463	108
232	4.57	5.83	50	1100	20	28	950	30	7.63	97.4	26	355	95
232	4.53	5.81	39	900	40	37	800	30	7.62	97.3	25	380	112
232	4.49	5.79	48	650	60	41	950	20	7.76	99.1	22	421	126
310	4.59	6.25	51	600	20	46	650	20	7.75	99.0	11	752	141
310	4.61	6.23	49	600	40	37	950	60	7.76	99.1	23	396	107
386	4.62	6.53	50	900	20	48	1100	30	7.83	100.0	26	494	119
386	4.58	6.54	54	1100	20	32	1100	20	7.75	99.0	27	407	102
386	4.47	6.51	50	650	60	36	800	30	7.70	98.3	21	393	108
386	4.50	6.50	40	800	20	21	950	20	7.67	98	23	307	88

TABLE 41. STAGE I. MP 32. Preheat Temperature 800°C

Compaction Press.	Thickness of green compact	Green Density	H.R.	Rolled Density	Relative Density	Elongation	UTS	Rolling Pressure	Effic: of Densification
$n.mm^{-2}$	mm	g,cm^{-3}	%	g,cm^{-3}	%	%	N,mm^{-2}	N,mm^{-2}	%
155	4.38	5.28	21	6.71	85.7	0	135	33	87.0
155	4.38	5.29	39	6.95	88.7	2	235	43	54.4
155	4.41	5.28	45	7.28	93.0	3	259	73	56.8
155	4.35	5.30	64	7.65	97.7	11	415	149	46.9
232	4.45	5.80	26	7.01	89.5	2	232	41	59.4
232	4.51	5.77	45	7.39	94.4	6	301	68	46.0
232	4.50	5.77	66	7.68	98.1	14	431	187	37.0
386	4.53	6.45	16	7.11	90.8	0	227	34	52.7
386	4.55	6.48	38	7.54	96.3	14	323	61	35.6
386	4.49	6.49	63	7.71	98.5	16	420	185	24.7

TABLE 42. STAGE I. MP 32. Preheat Temperature 700°C

Compaction Press. N,mm^{-2}	Thickness of green compact mm	Green Density g,cm^{-3}	H.R. %	Rolled Density g,cm^{-3}	Relative Density %	Elongation %	UTS. N,mm^{-2}	Rolling Press. N,mm^{-2}	Effic. of Densification %
155	4.46	5.30	15	5.99	76.5	0	94	31	58.7
155	4.42	5.28	40	6.91	88.2	0	220	70	52.0
155	4.25	5.37	58	7.61	97.2	5	405	281	49.3
232	4.68	5.77	21	6.78	86.6	0	221	50	61.4
232	4.50	5.77	45	7.51	95.9	3	453	174	49.4
232	4.48	5.79	64	7.67	98.0	14	492	236	37.5
386	4.43	6.46	21	7.12	90.9	0	299	59	40.1
386	4.50	6.39	30	7.44	95.0	2	358	100	44.7
386	4.50	6.39	61	7.68	98.1	12	423	233	27.0

TABLE 43. Comparison between standard and non-standard specimens

Specimens	Compaction pressure N,mm^{-2}	Sintering Temperature ^{o}C	Hot Reduction %	Rolling Pressure N,mm^{-2}	Elong. %	U.T.S. N,mm^{-2}
Standard	232	900	62.5	168	28.1	388
Non-standard	232	900	62.5	168	26.0	384
Standard	386	900	66.6	211	43.8	401
Non-standard	386	900	66.6	211	32.0	369
Standard	386	1000	63.5	221	43.7	416
Non-standard	386	1000	63.5	221	32.8	384

TABLE 44. Vickers Hardness Measurements (Hv)

No.	Middle of the Strip Hv	Middle of the Strip Hv	Middle of the Strip Hv	Edge of the Strip Hv	Edge of the Strip Hv	Averages Hv
1	105	103	107	102	108	105
2	105	110	105	104	115	108
3	115	78	108	99	109	102
4	93	92	87	91	98	92
5	112	109	108	113	108	110
6	123	116	117	114	119	118
7	104	108	109	104	109	107
8	127	133	130	129	141	132
9	122	116	118	121	117	119
10	139	144	140	135	142	140
11	106	109	110	109	111	109
12	112	109	112	113	114	112
13	110	104	105	104	107	106
14	104	105	104	107	99	104
15	136	132	133	130	139	134

TABLE 45. **Oxygen and Carbon content of rolled strip**

No.	Powders	Carbon	Oxygen
1	ASC 100	<.01	0.0628
2		<.01	0.0680
3		N/D	0.0580
4		N/D	0.0526
5		<0.01	0.0699
6		<0.01	0.0655
7		N/D	0.0472
8		N/D	0.0560
9	NC 100	N/D	0.3429
10		<0.01	0.3432
11		N/D	0.3109
12		<0.01	0.3195
13		N/D	0.2969
14		<0.01	0.3137
15	MP 32	0.013	0.1702
16		0.017	0.1586
17		0.02	0.1605
18		0.018	0.1900
19		0.016	0.1590
20		0.014	0.1569

TABLE 46. Rolling load for hot reductions

Powders →		ASC 100			NC 100			MP 32		
C.P. N,mm^{-2}	S.T. ^{o}C	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}
155	900	45	108	274	41	39	202	51	91	341
155	900	66	175	319	65	103	289	62	144	362
155	1000	46	112	376	59	78	281	48	78	332
155	1000	66	186	401	39	36	274	62	145	373
232	900	41	98	283	49	86.5	293	48	87	356
232	900	62.5	168	384	64	125	309	62	175	374
232	1000	37.5	109	323	49	100	313	38	74	327
232	1000	66	198	386	64	126	337	44	68	307
386	900	47	161	296	38	89	264	45.6	111	366
386	900	66.6	211	369	64	117	296	63.5	160	387
386	1000	63.5	221	384	50	106	326	26.5	65.7	287
386	1000	40	156	352	64	143.5	340	48.5	123.5	373

Table 47. British Standard 1449, Part I 1972 Steel Strip

Material Grade	Quality	Tensile Strength N,mm^{-2}	Elongation percent on 50 mm gauge	C %	Mn %	S %	P %
HS1	Extra deep drawing	290	34	0.08	0.45	0.03	0.02
HS2	" "	290	34	0.08	0.45	0.035	0.03
HS3	Deep drawing	290	28	0.1	0.50	0.04	0.04
HS4	Drawing & forming	280	25	0.12	0.16	0.05	0.05
CS12	Rimmed	310	28	0.1-0.15	0.4-0.6	0.05	0.05
CS17	Rimmed	340	26	0.15-0.2	0.4-0.6	0.05	0.05
CS22	Rimmed	370	25	0.2-0.25	0.4-0.6	0.05	0.05

TABLE 48. Surface Finish

Mag.	1 reading C.L.A.	2 reading C.L.A.	3 reading C.L.A.	Average roughness height	
				C.L.A. micron	microinch
2000	0.2	0.12	0.11	0.14	5.51
	0.11	0.11	0.11	0.11	4.33
	0.2	0.3	0.2	0.23	9.06
	0.25	0.17	0.38	0.27	10.63
	0.2	0.2	1.8	0.73	28.74
	0.22	0.4	0.36	0.33	12.99
	0.2	1.6	0.35	0.72	28.74
	0.2	0.3	0.15	0.22	8.66
	0.19	0.21	0.15	0.18	7.09
	0.3	0.35	0.21	0.29	11.42
	0.1	0.1	0.15	0.12	4.72
	0.8	0.1	0.1	0.33	12.99
	0.35	0.4	0.3	0.35	13.78
	0.18	0.4	0.4	0.327	12.87
	0.24	0.18	0.2	0.207	8.15
	0.2	0.38	0.2	0.26	10.24
	0.15	0.16	0.18	0.163	6.42
	0.18	0.1	0.1	0.13	5.12
	0.4	0.28	0.2	0.29	11.42
	0.12	0.1	0.22	0.15	5.91
	0.2	0.28	0.22	0.23	9.06
	0.16	0.26	0.3	0.24	9.45
	0.35	0.32	0.4	0.36	14.17
	0.3	0.15	0.2	0.22	8.66
	0.46	0.18	0.11	0.25	9.84
	0.2	0.2	0.28	0.23	9.06
	0.2	0.4	0.15	0.25	9.84
	0.05	0.1	0.1	0.08	3.15
	0.18	0.18	0.22	0.19	7.48
	0.08	0.3	0.35	0.24	9.45
	0.12	0.2	0.12	0.15	5.91

TABLE 48. (Contd.)

Mag.	1 reading C.L.A.	2 reading C.L.A.	3 reading C.L.A.	Average roughness height	
				C.L.A. micron	microinch
	0.22	0.14	0.18	0.18	7.09
	0.03	0.21	0.7	0.31	12.2
	0.2	0.6	0.35	0.38	14.96
	0.35	0.28	0.15	0.26	10.24
	0.2	0.3	0.1	0.2	7.87
	0.16	0.3	0.6	0.35	13.78
	0.12	0.15	0.1	0.12	4.72
	0.2	0.4	0.48	0.36	14.17
Mean				0.26	10.15

C.L.A. = Central line Average

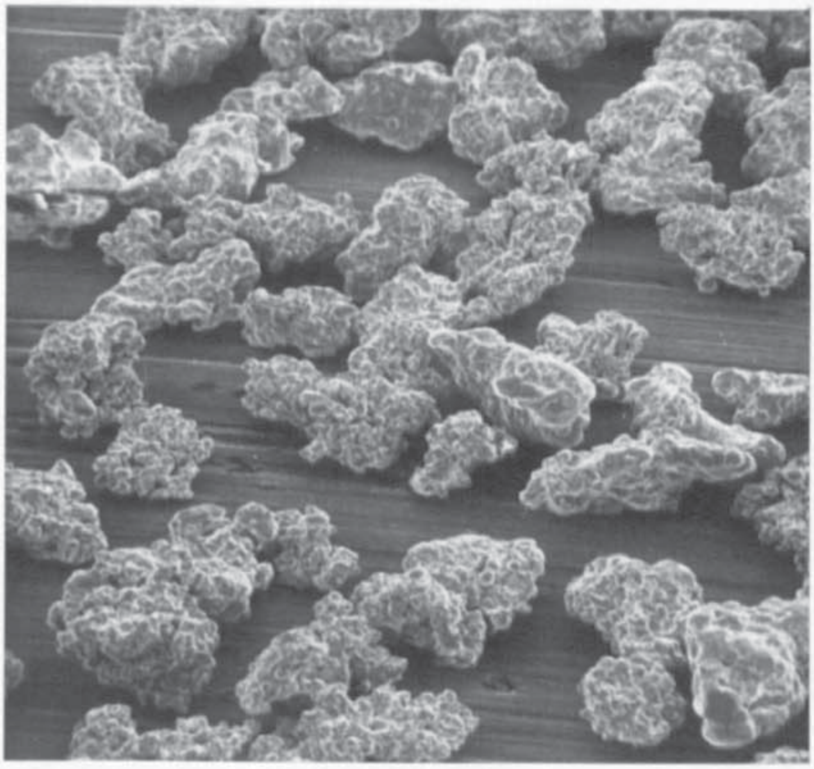


Fig.9a. Höganäs ASC 100 Iron Powder. x 100

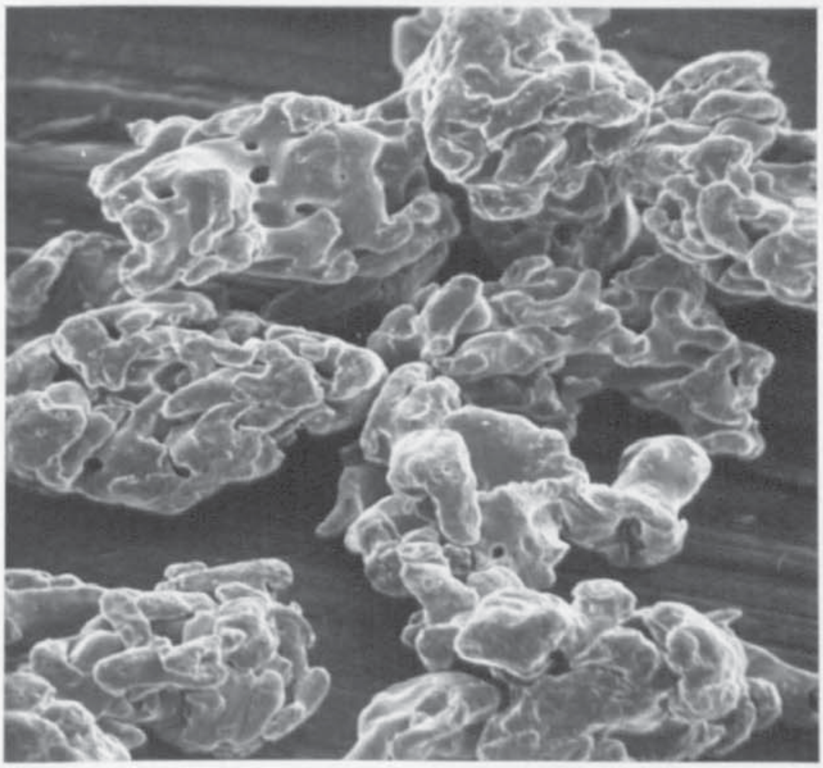


Fig.9b. Höganäs ASC 100 Iron Powder. x 500

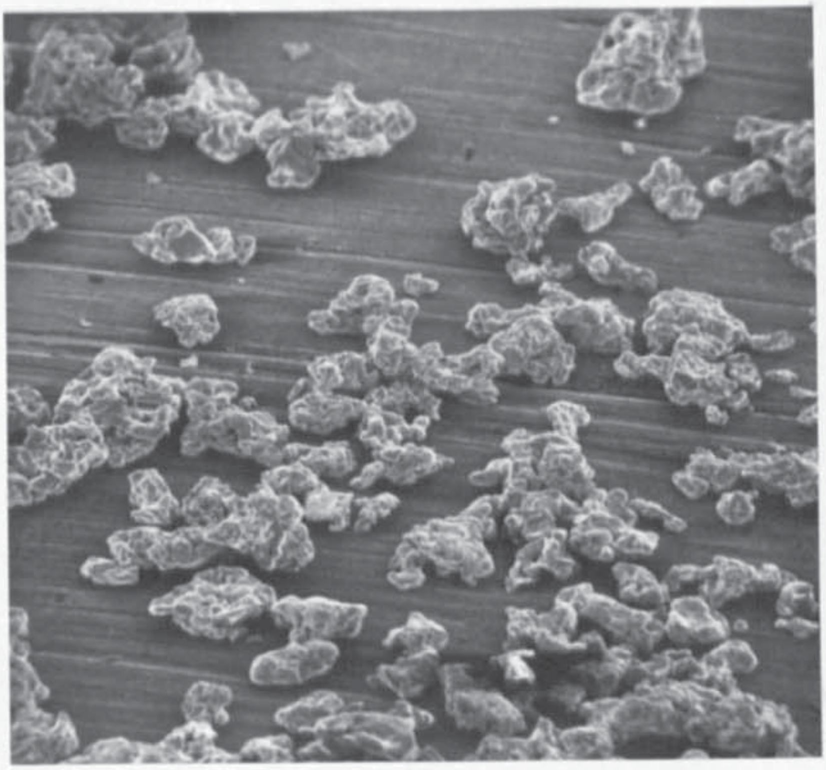


Fig.10a. Höganäs NC 100 Iron Powder. x 100

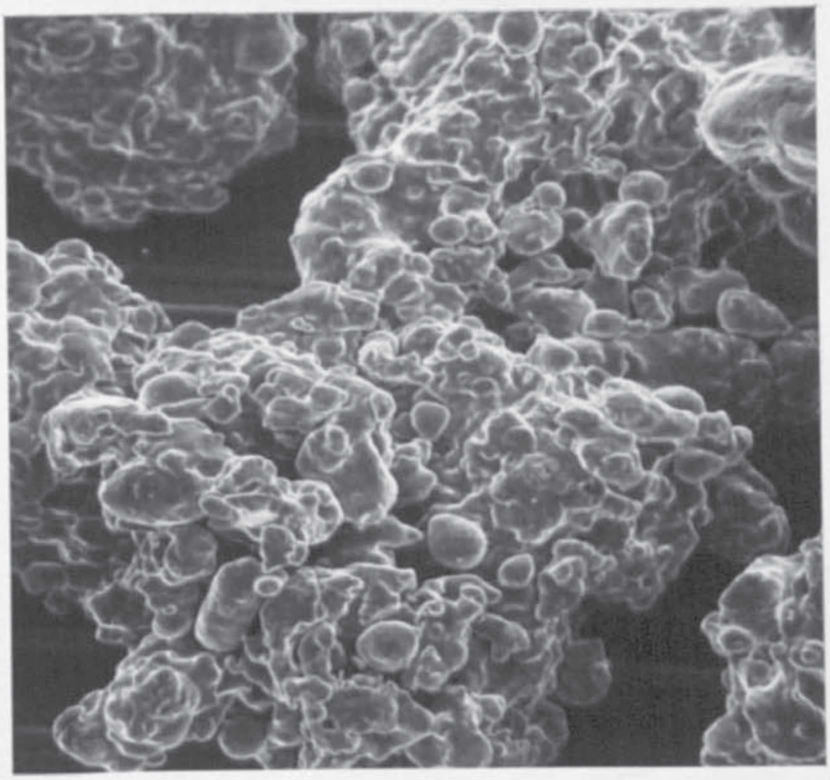


Fig.10b. Höganäs NC 100 Iron Powder. x 500

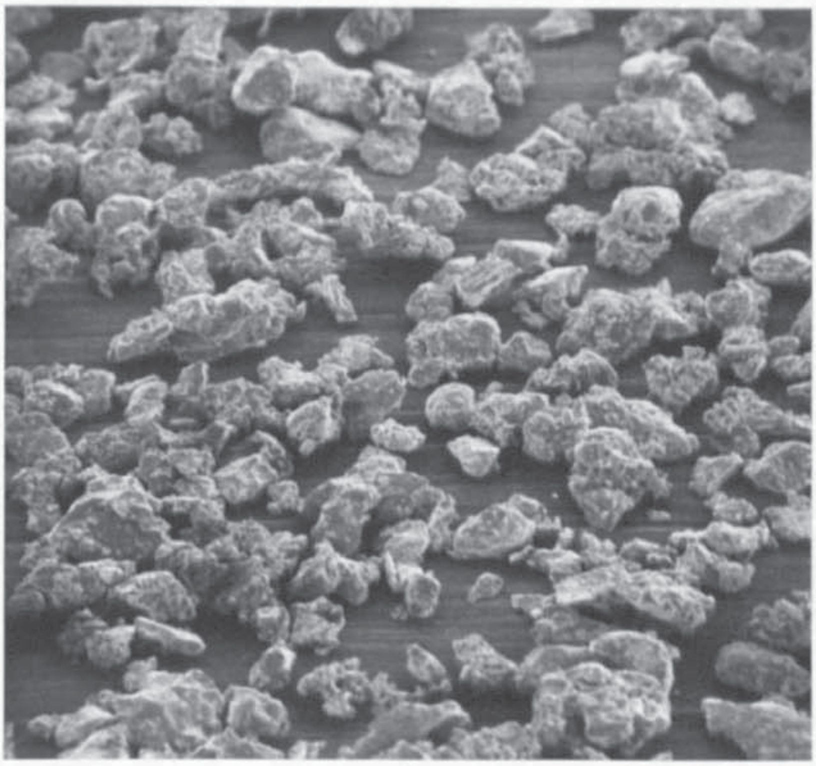


Fig.11a. Rospol Mp 32 Iron Powder x 100

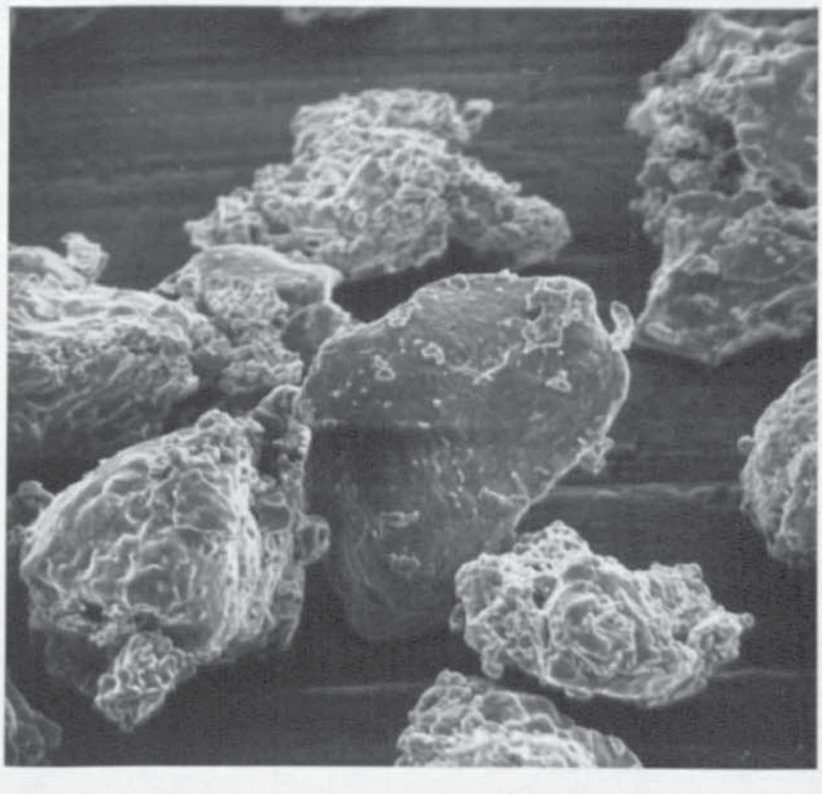


Fig.11b. Rospol Mp 32 Iron Powder x 500

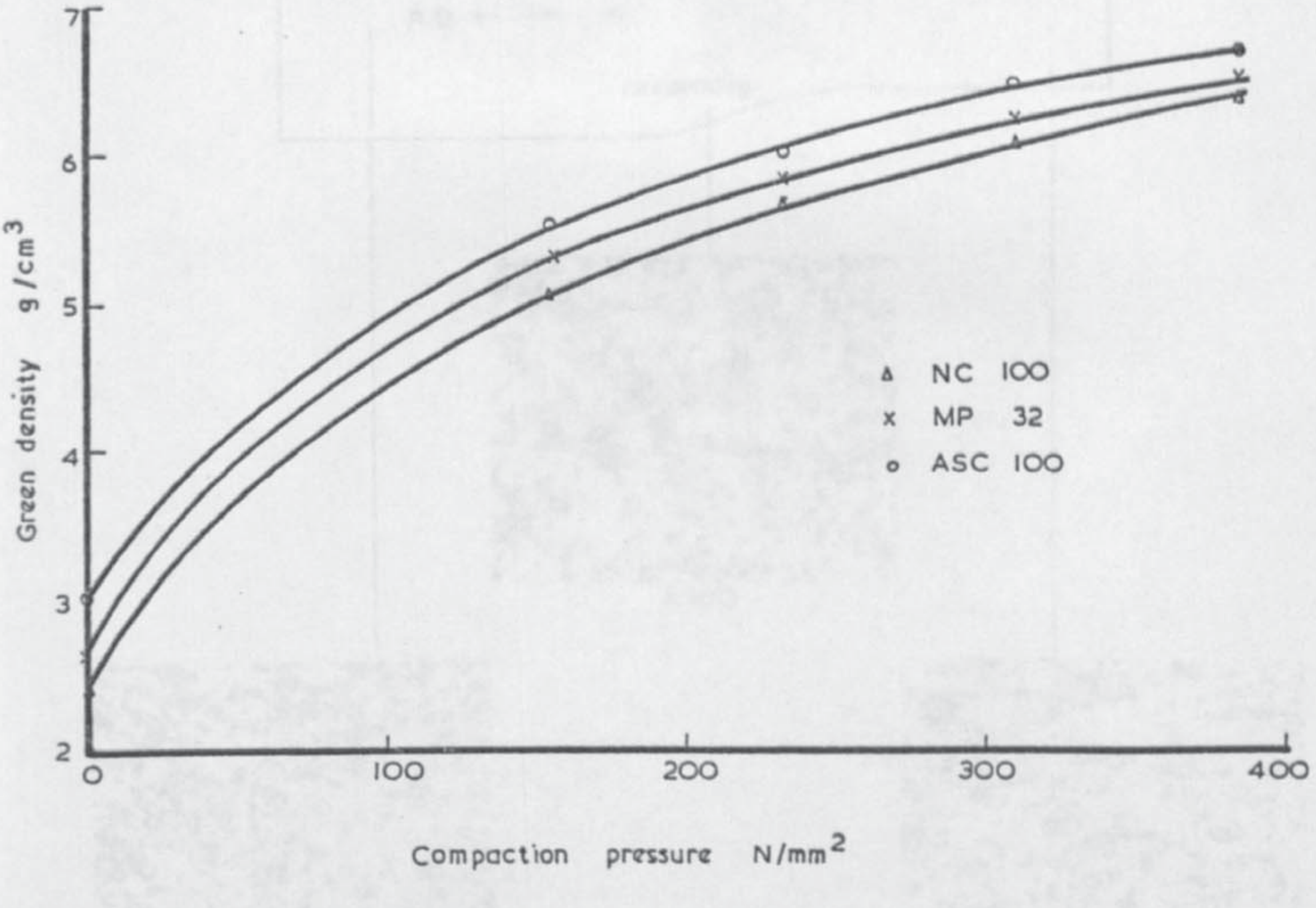


Fig.13. Green density vs Compaction pressure for three iron powders

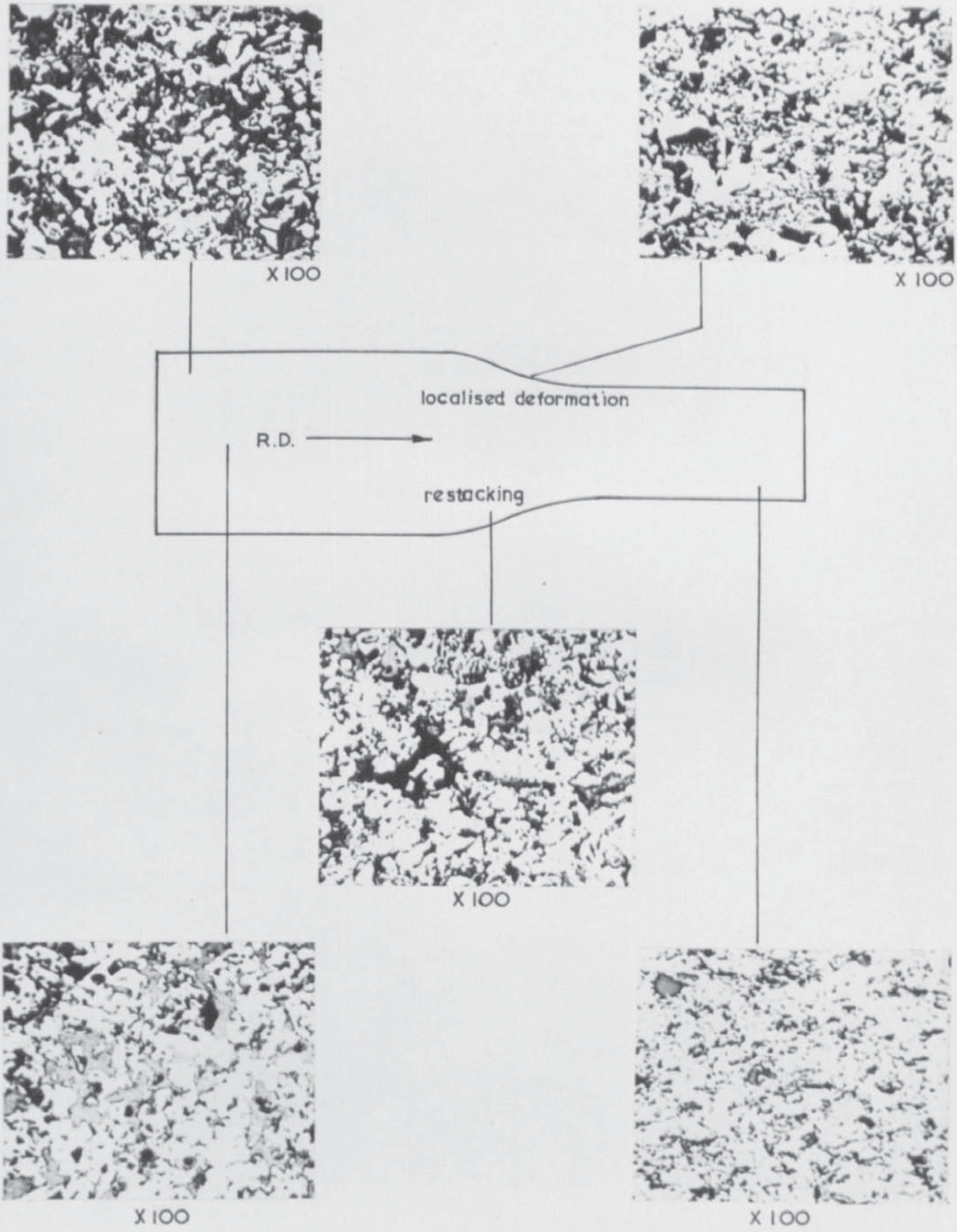


Fig. 17. Microstructure in half-rolled specimen for NC100 (treatment 155/900/59)

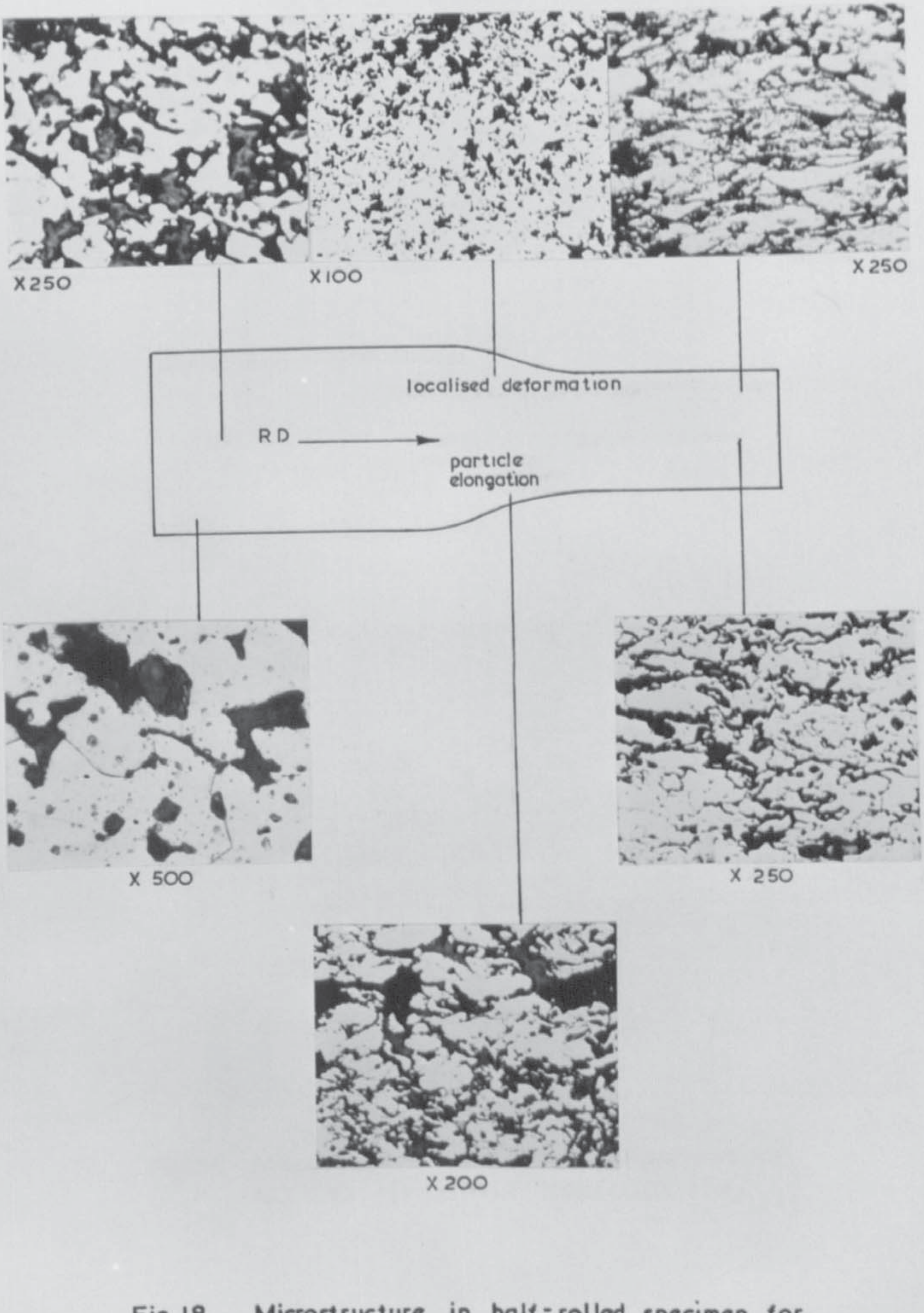


Fig. 18. Microstructure in half-rolled specimen for NC 100 (treatment 232/900/56)

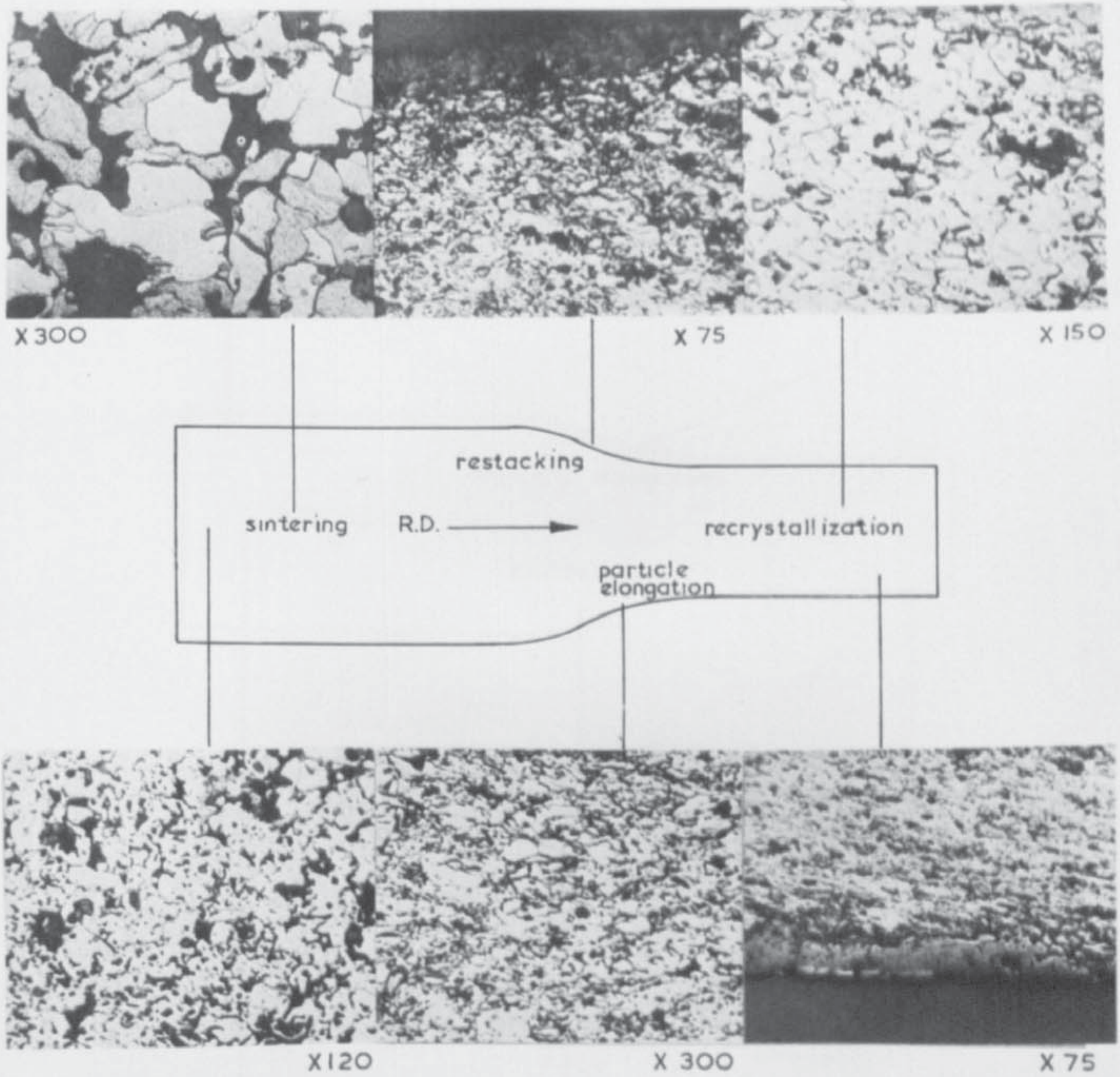


Fig. 19. Microstructure in half-rolled specimen for NC 100 (treatment 386/1000/58)

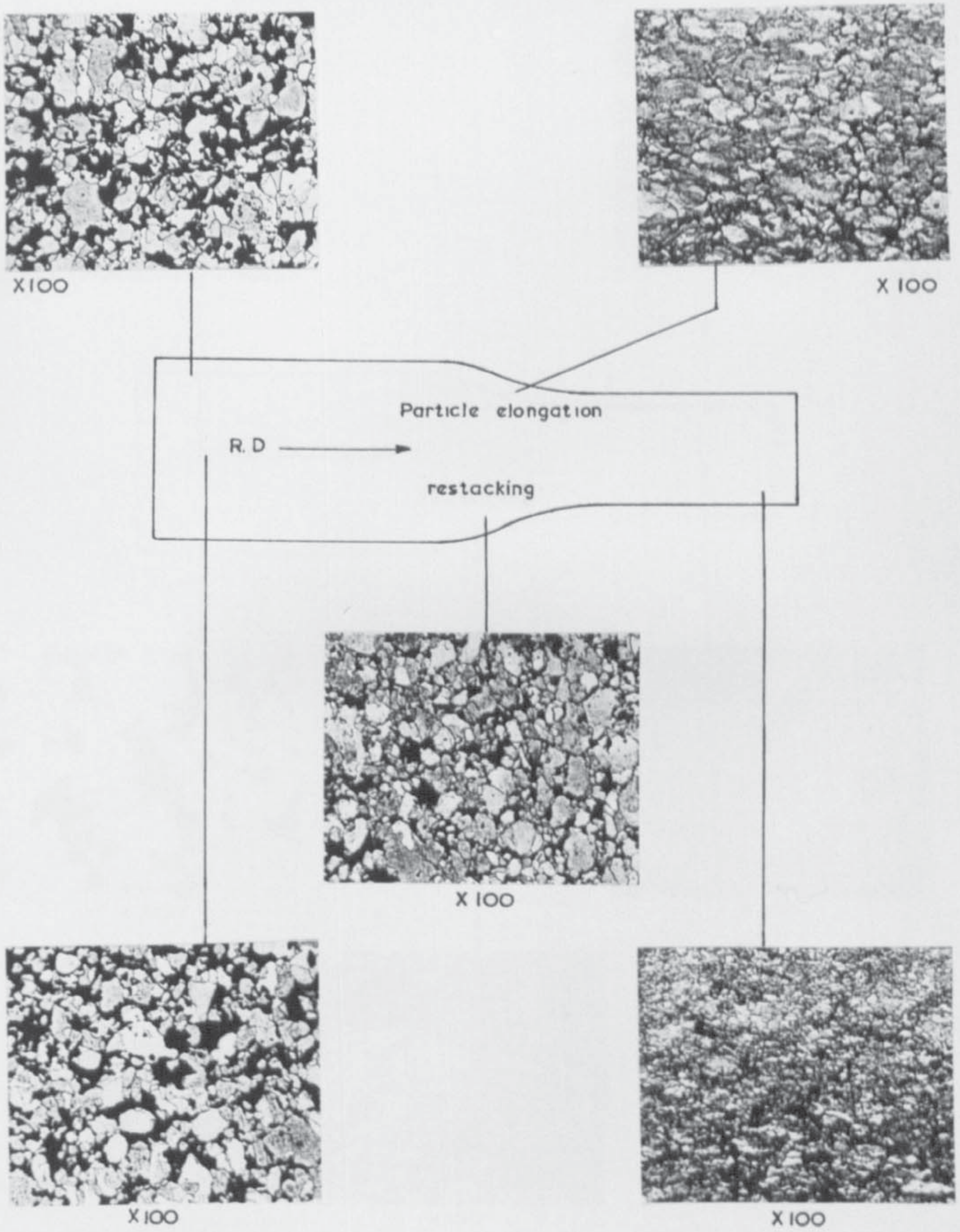


Fig. 20. Microstructure in half-rolled specimen for ASC 100 (treatment 155/900/60)

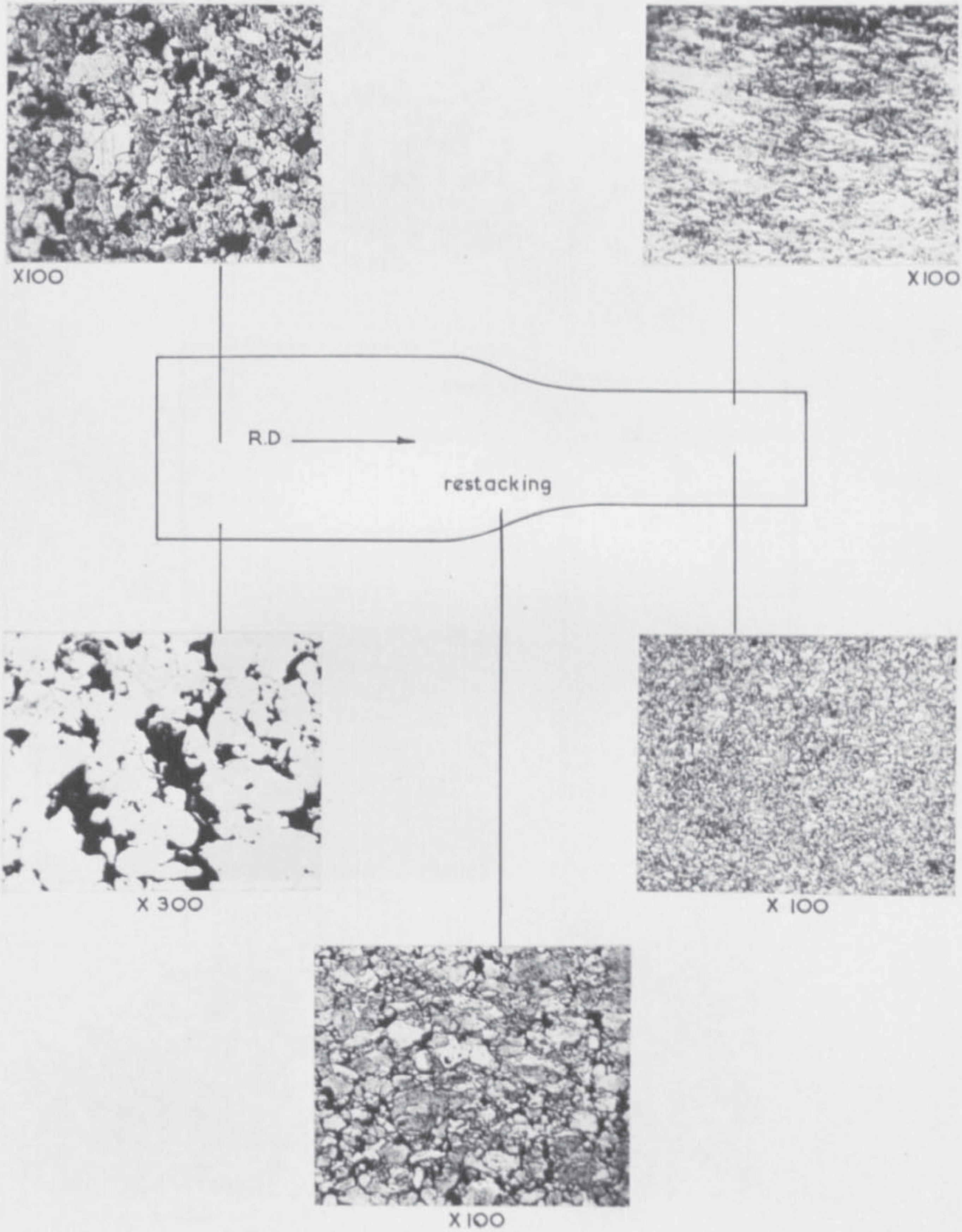


Fig. 21. Microstructure in half-rolled specimen for ASC 100 (treatment 232/1000/57)

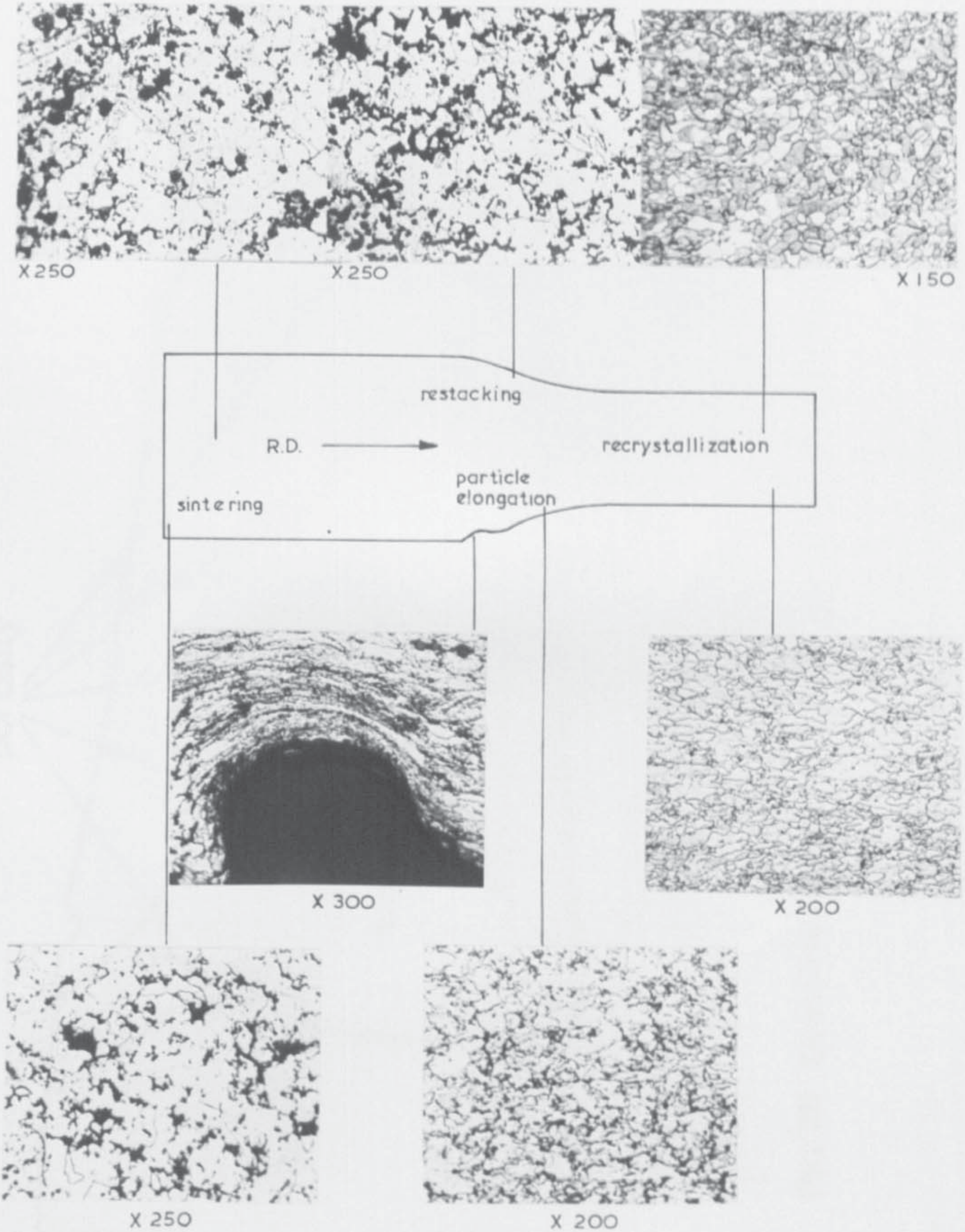


Fig. 22. Microstructure in half-rolled specimen for ASC 100 (treatment 386/1000/59.)

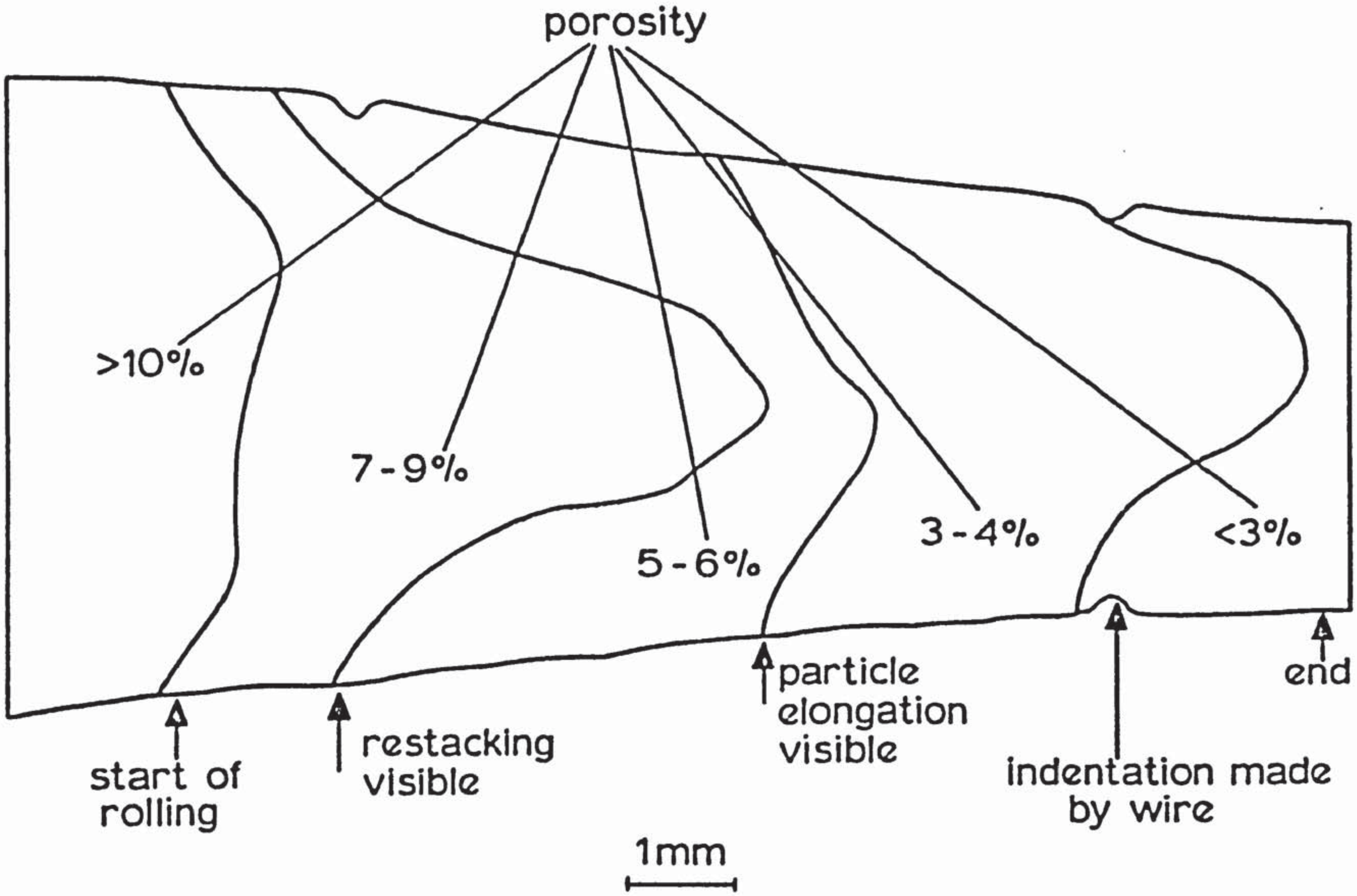


FIG. 25. Quantimet results for half-rolled specimen (treatment 386/1000/40·7).

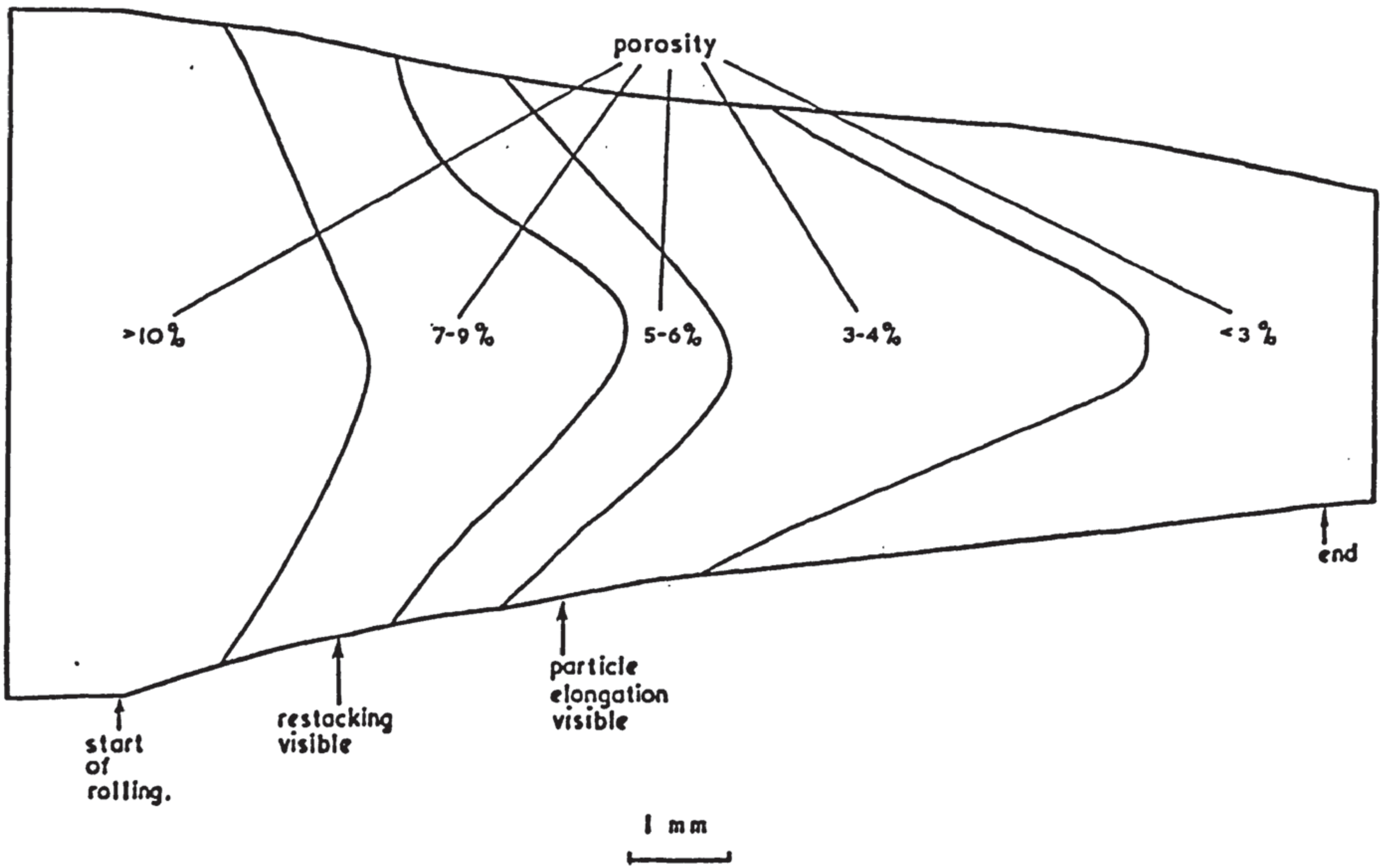


Fig. 26. Quantimet results for half-rolled specimen (treatment 386/1000/57)

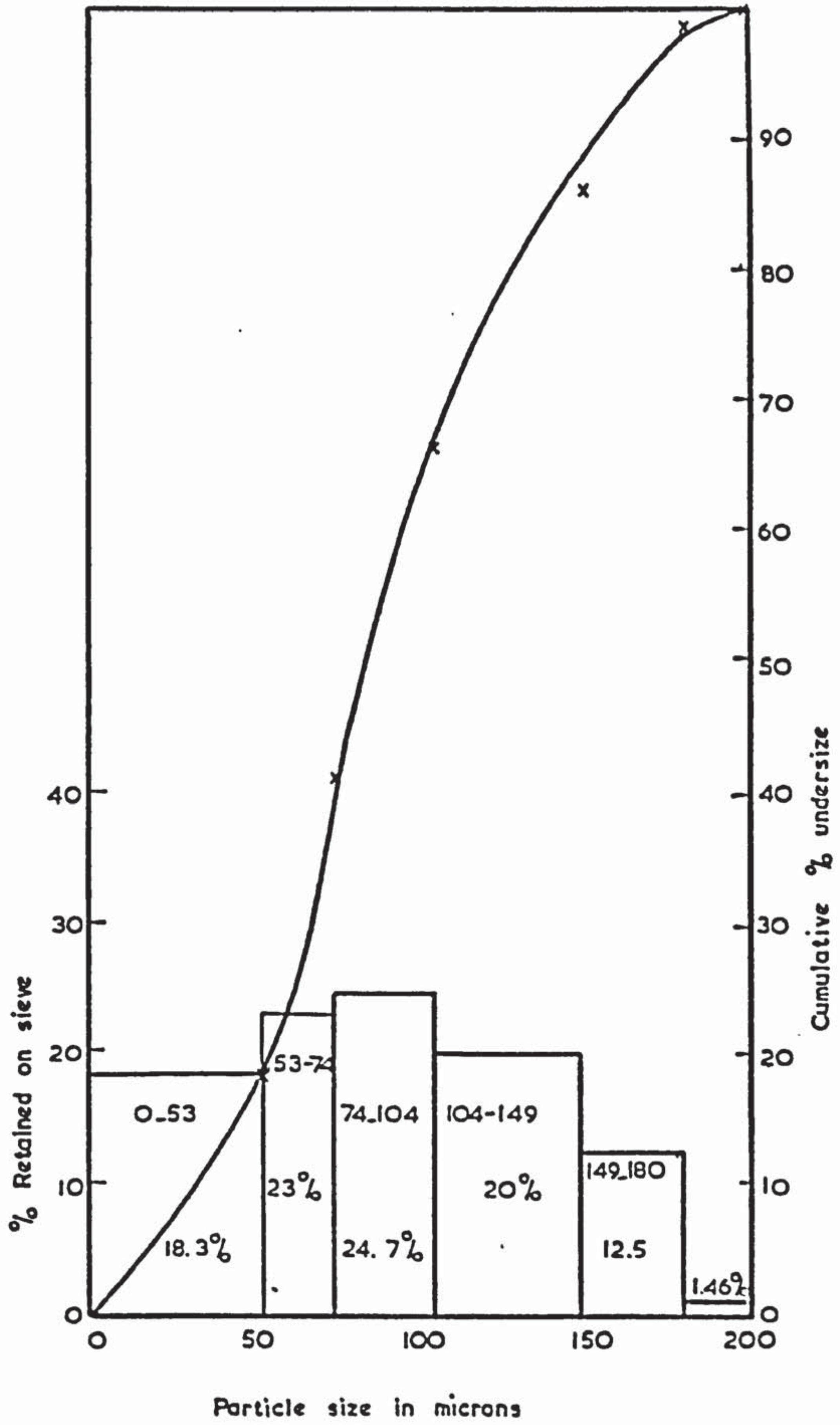


Fig.29 Sieve analysis of ASC 100

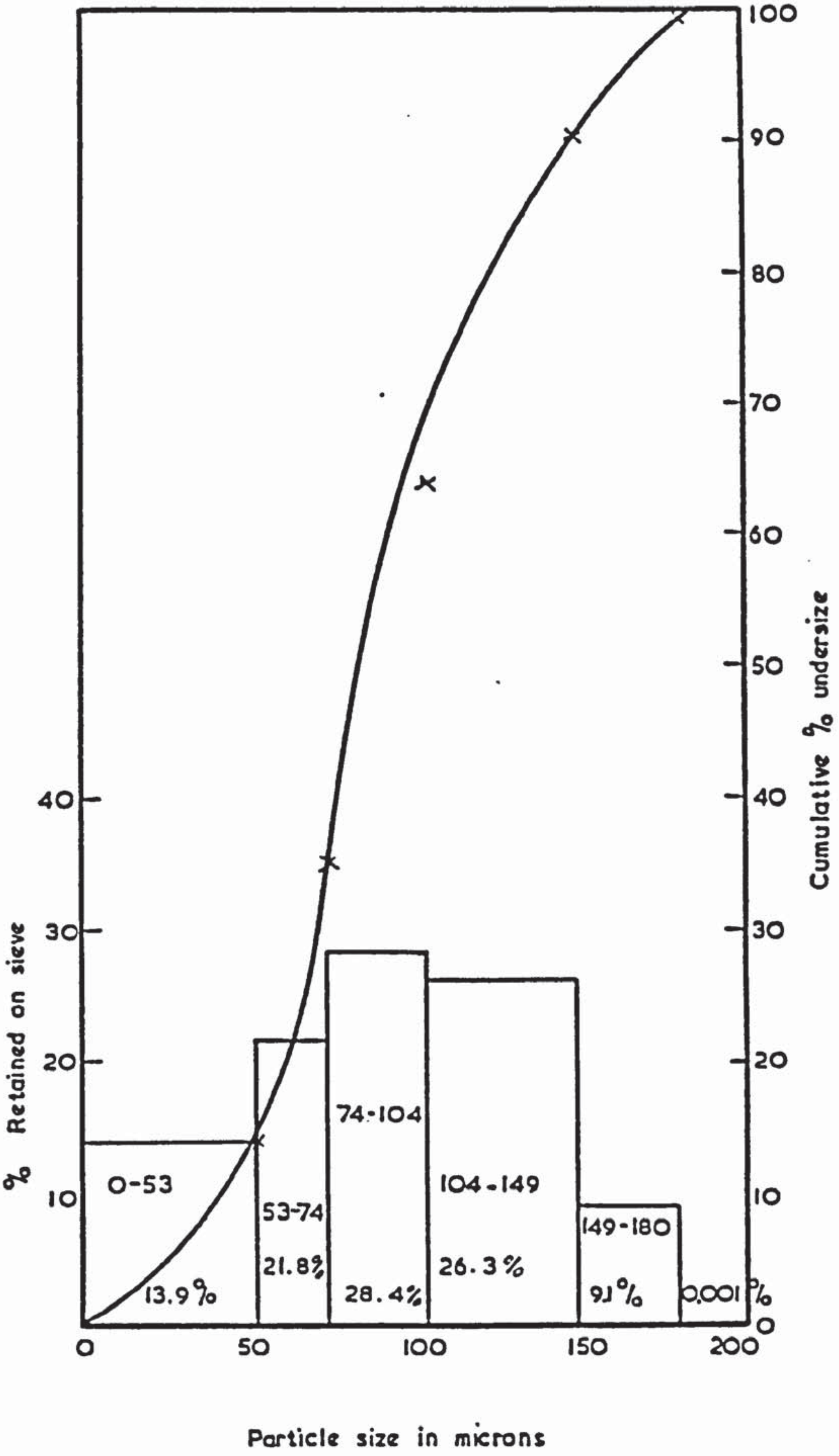


Fig.30. Sieve analysis of NC 100

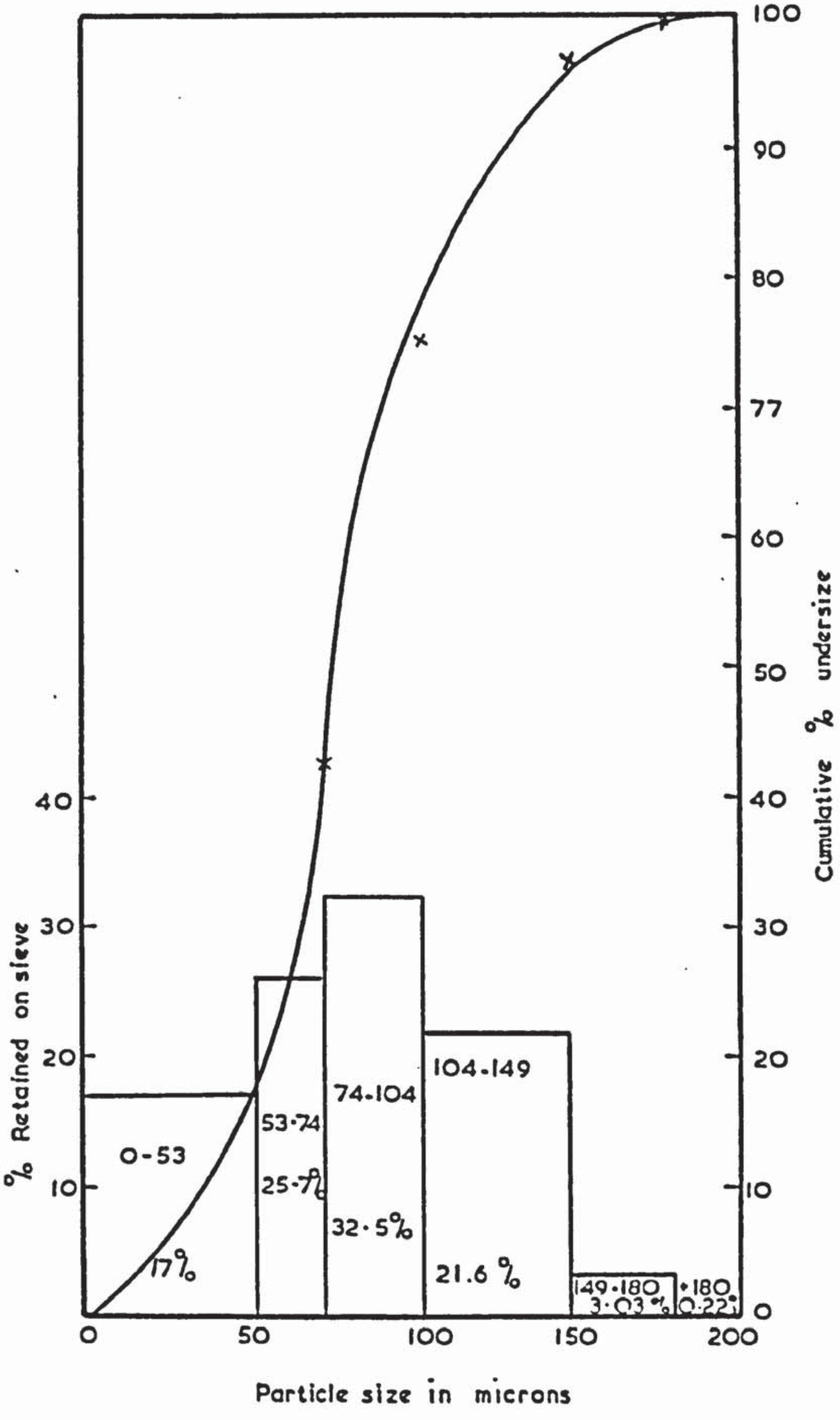


Fig.31. Sieve analysis of Mp 32

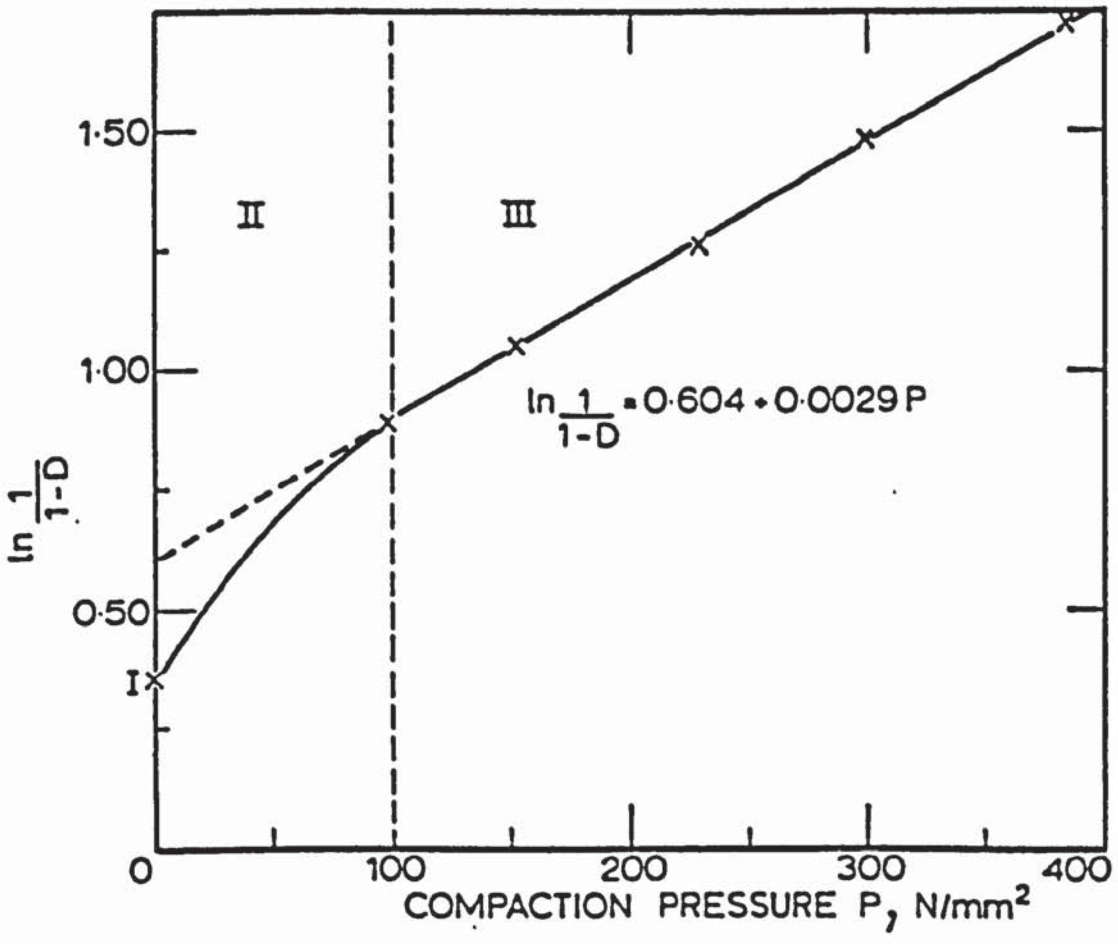


FIG. 32. Heckel equation for Höganäs NC100 iron powder.

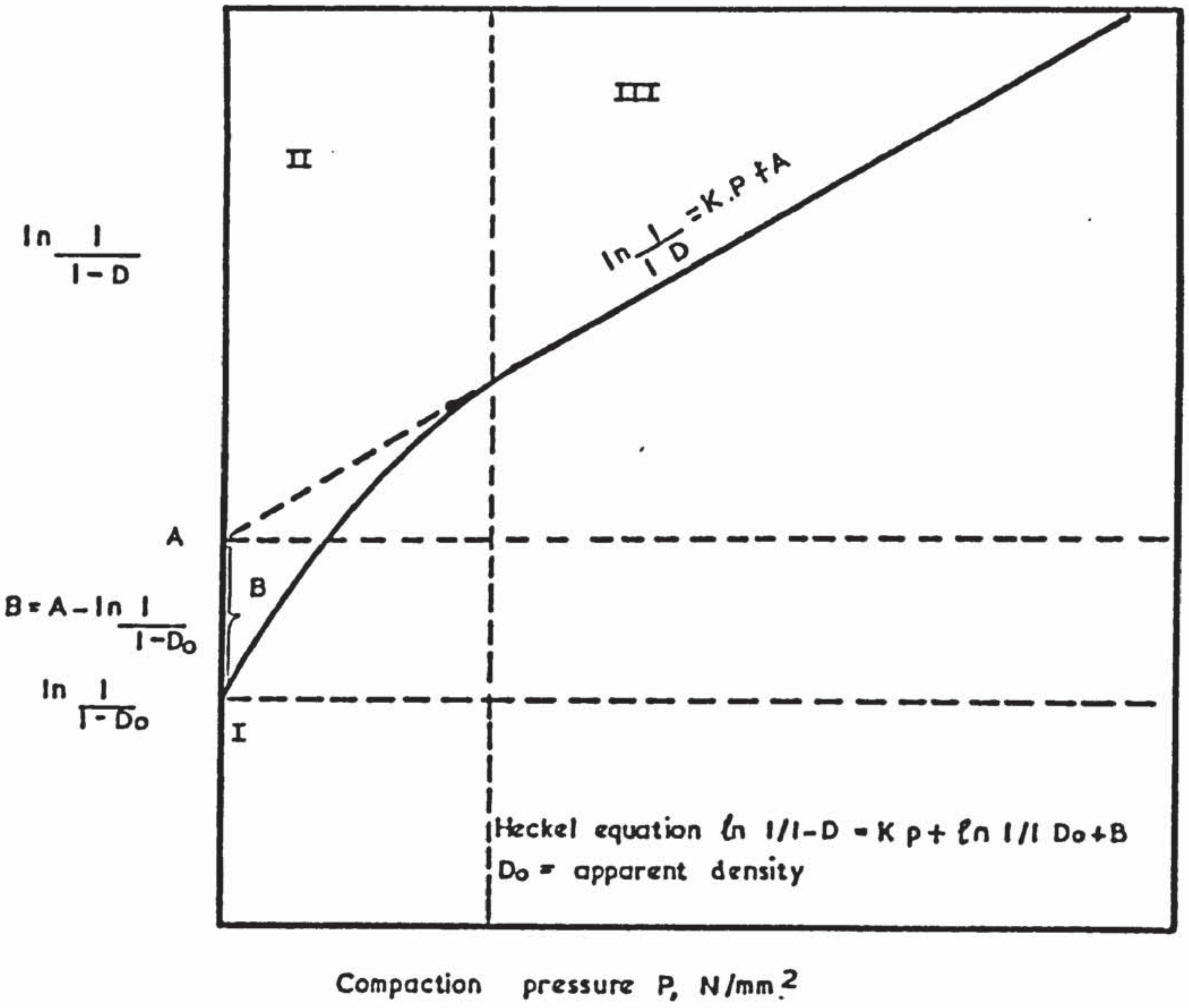


Fig.33. Compaction pressure vs ℓn 1/1-D

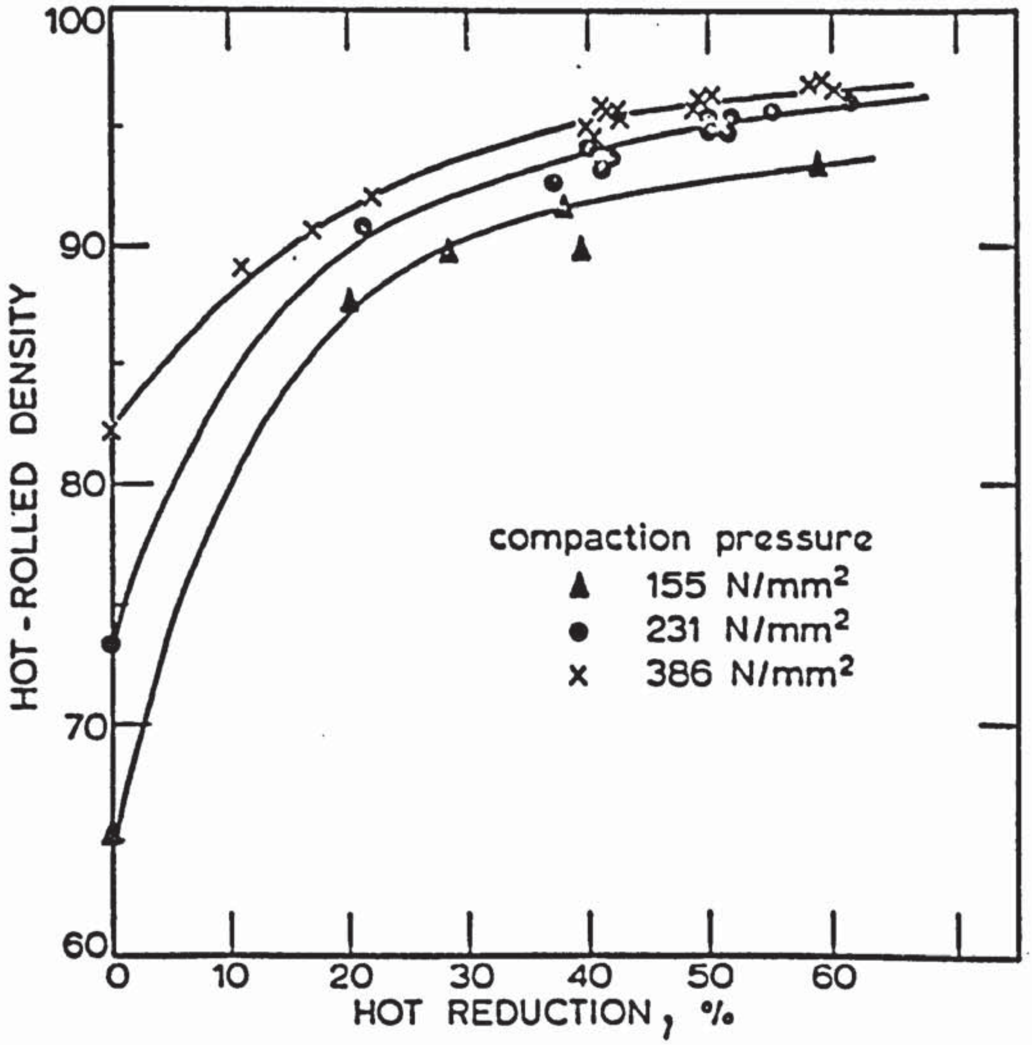


FIG. 34 Hot-rolled density vs. hot reduction (points include results at both 900° and 1000°C).

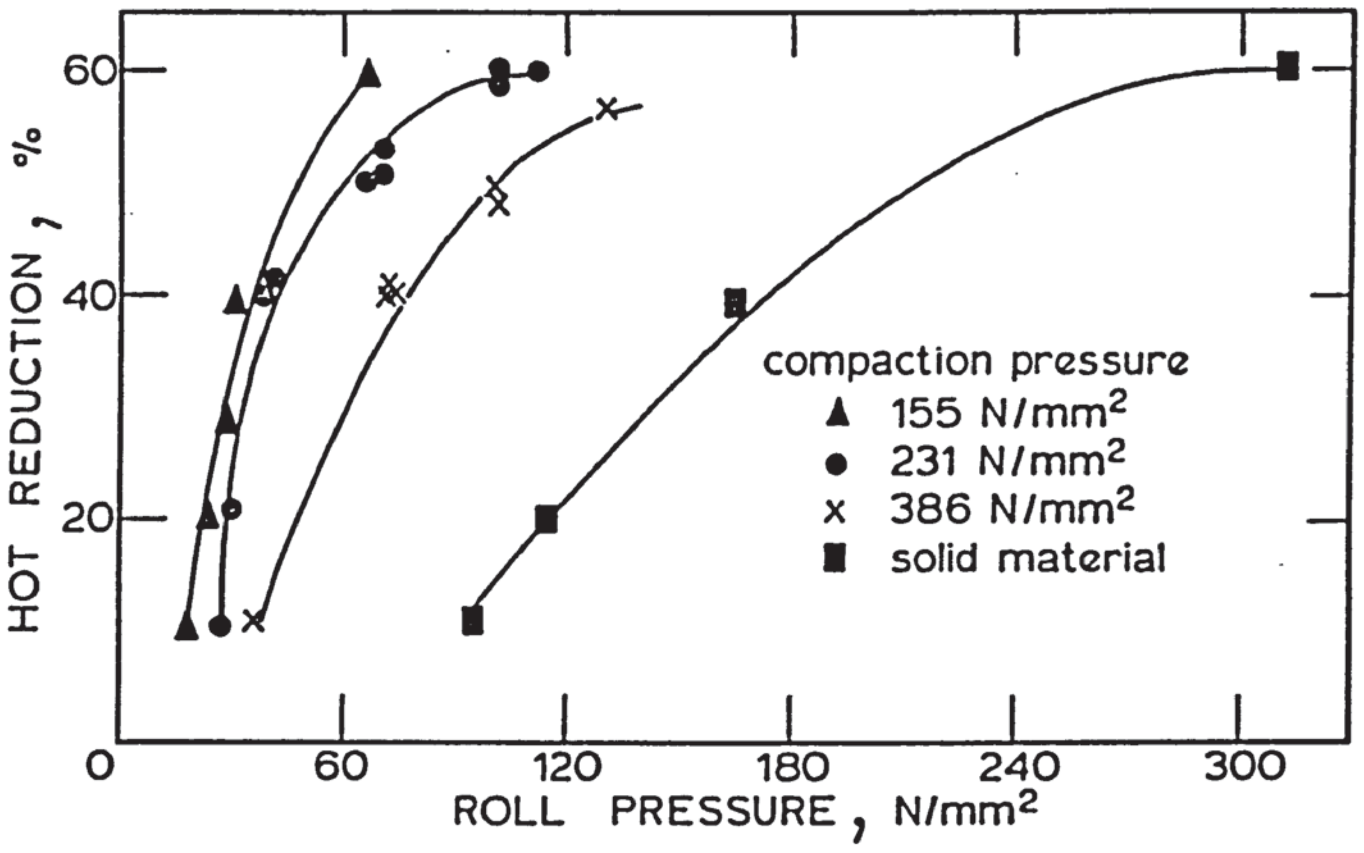


FIG. 35 Hot reduction vs. roll pressure.

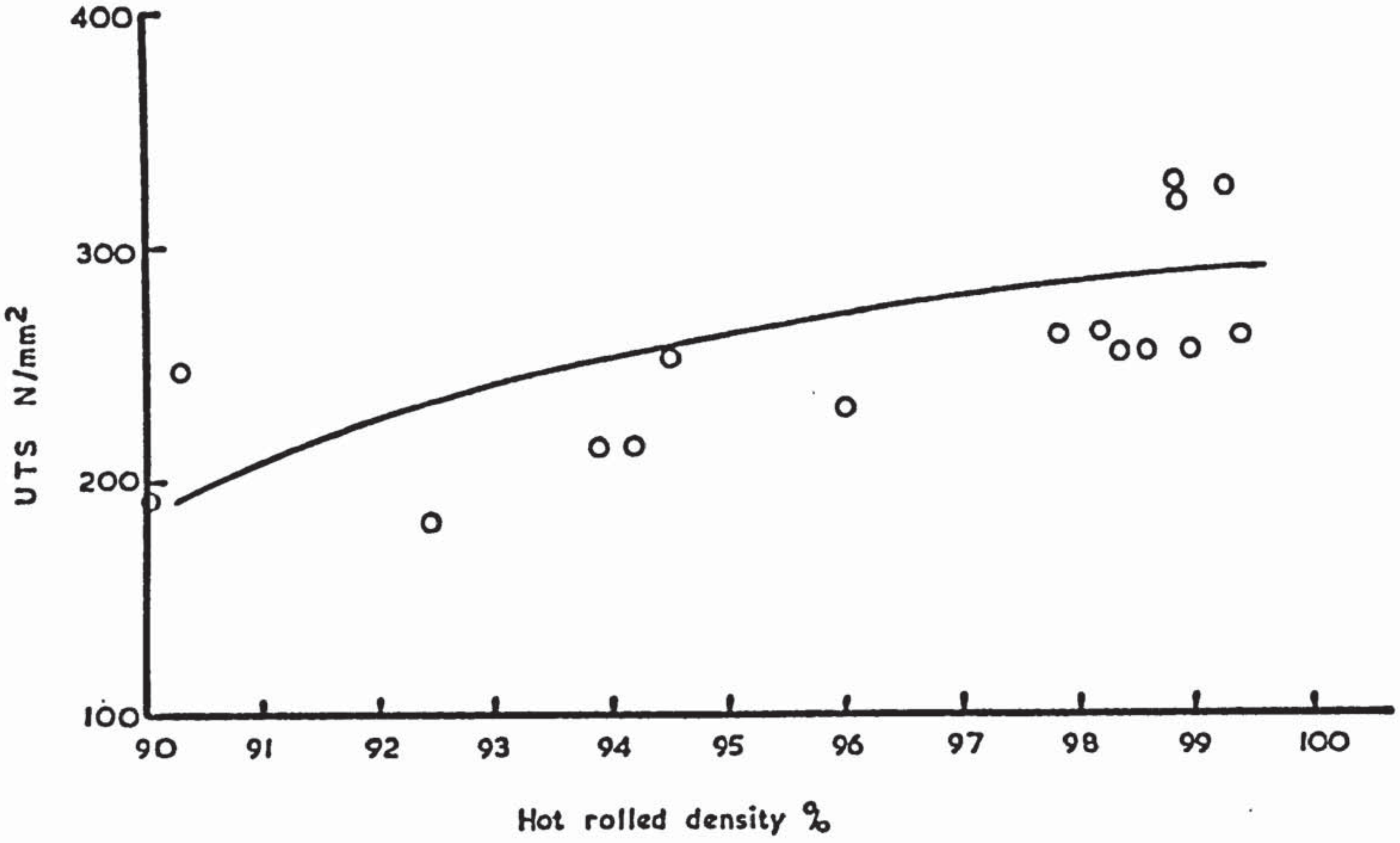


Fig.36. U.T.S. vs Hot rolled density of Hot-rolled strip for ASC 100.
(Points include results at 800° C and three compaction pressure)

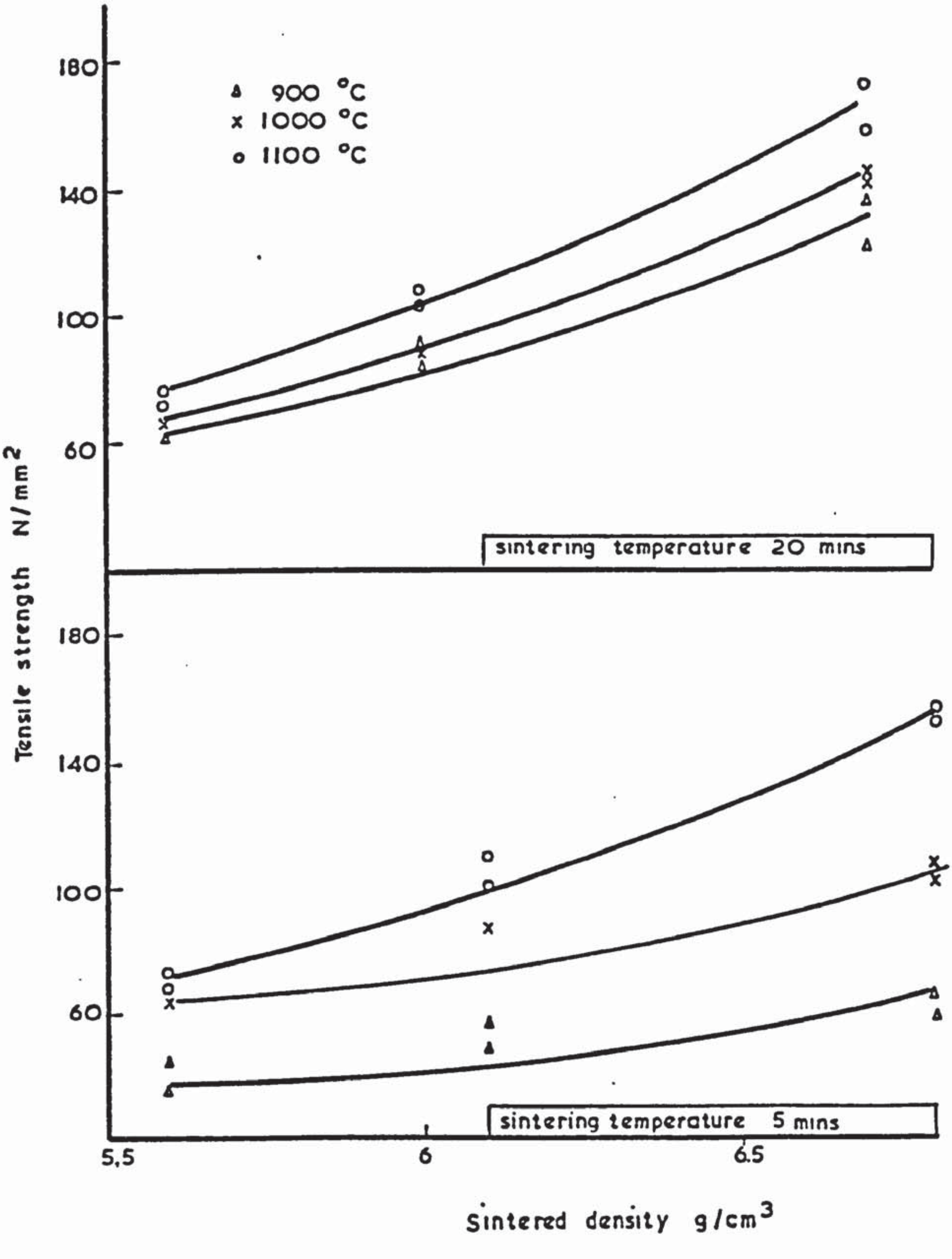


Fig.37. Tensile strength vs sintered density for ASC 100 iron powder

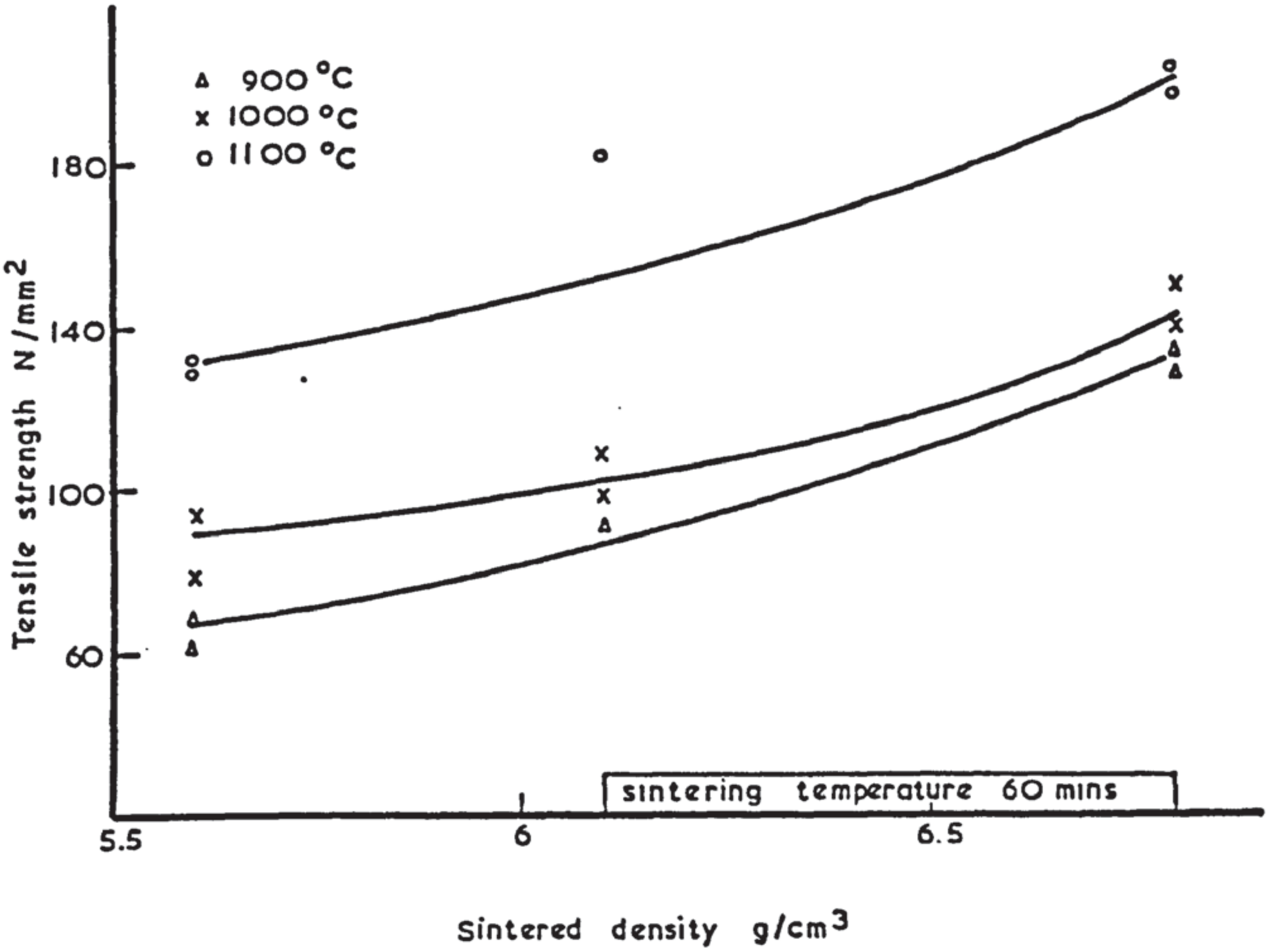


Fig.38. Tensile strength vs sintered density for ASC 100 Iron Powder

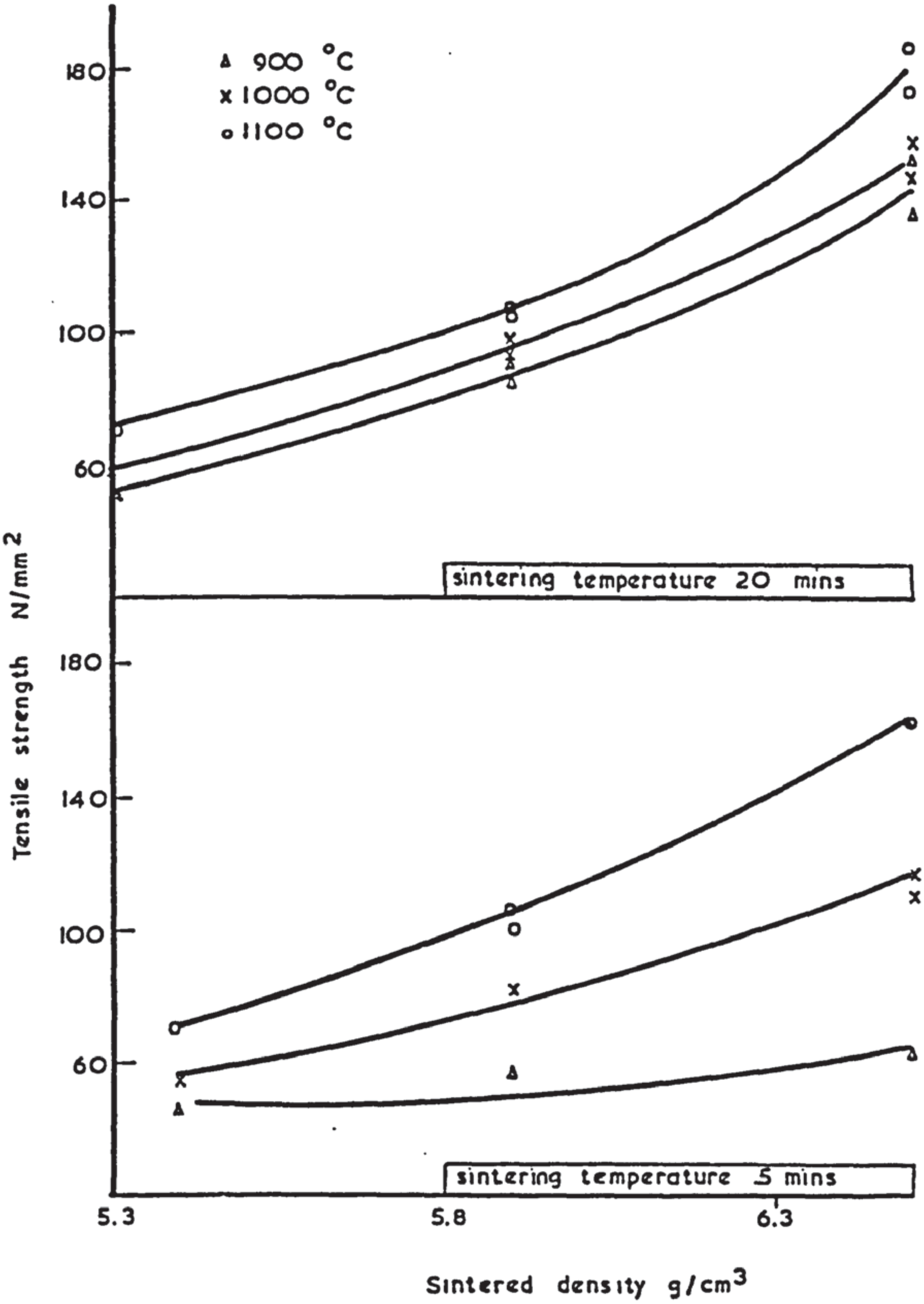


Fig.39. Tensile strength vs sintered density for Rospol Mp 32 iron powder

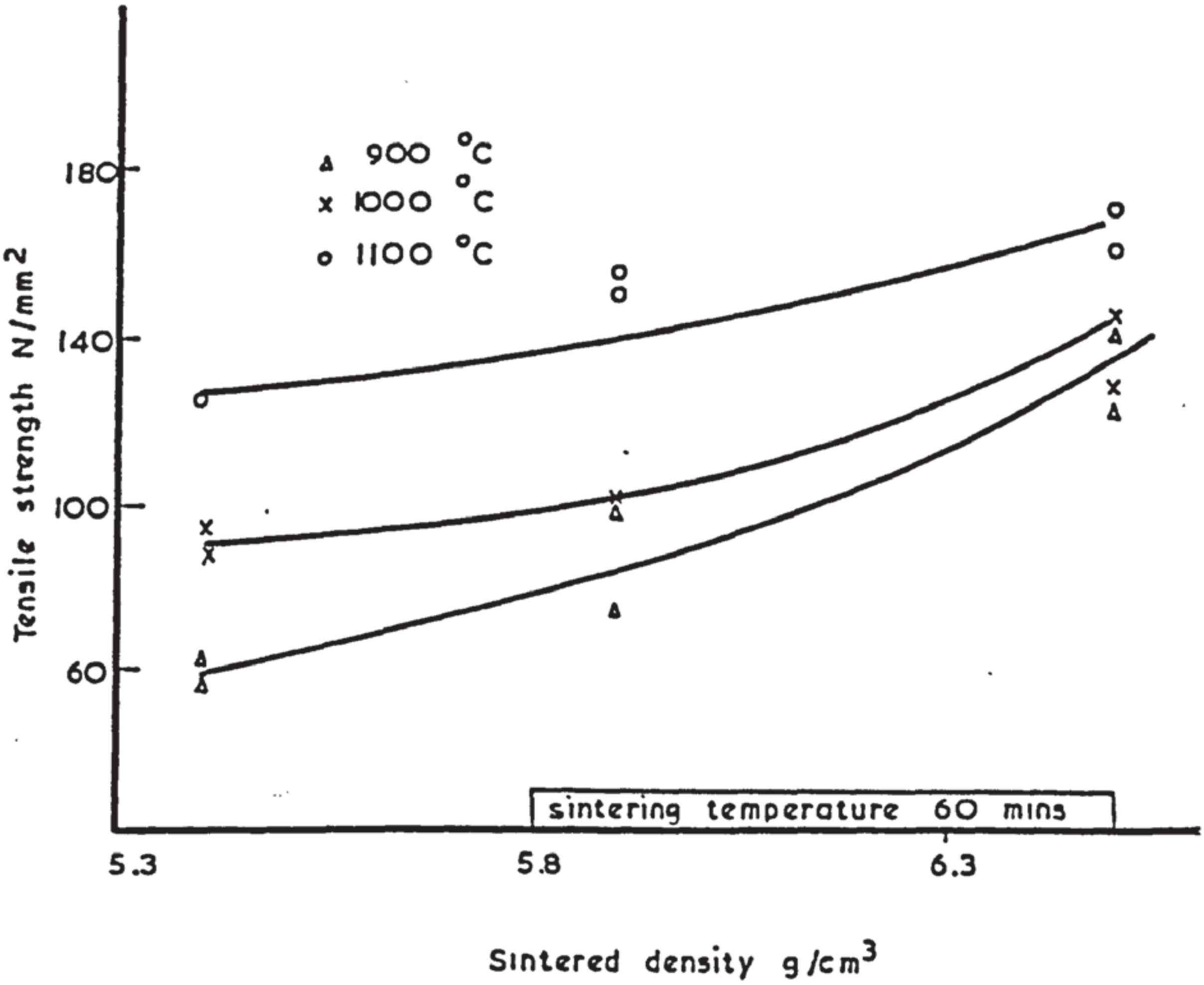


Fig.40. Tensile strength vs Sintered density for Rospol Mp 32 iron powder

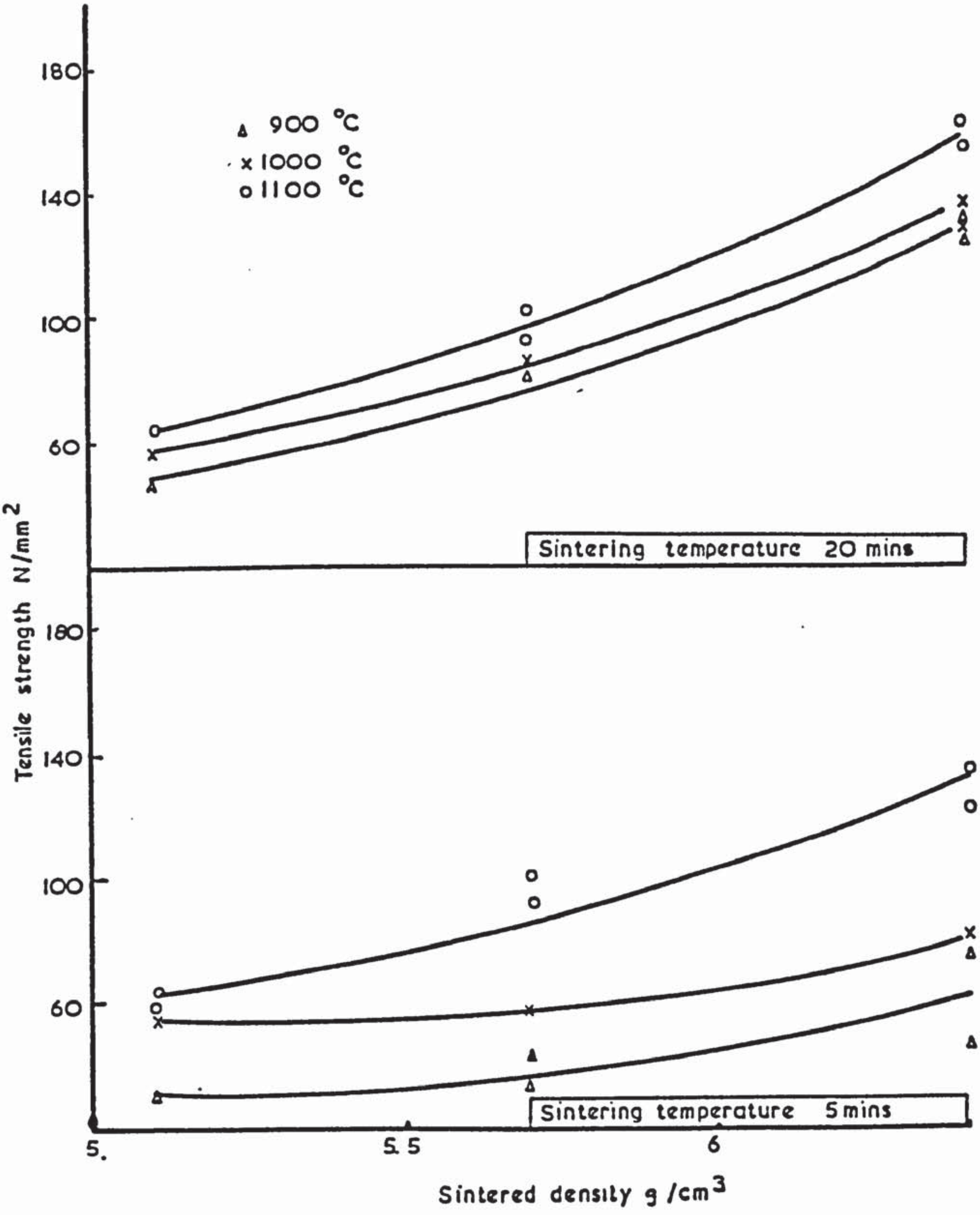


Fig.41. Tensile strength vs sintered density for NC 100 iron powder

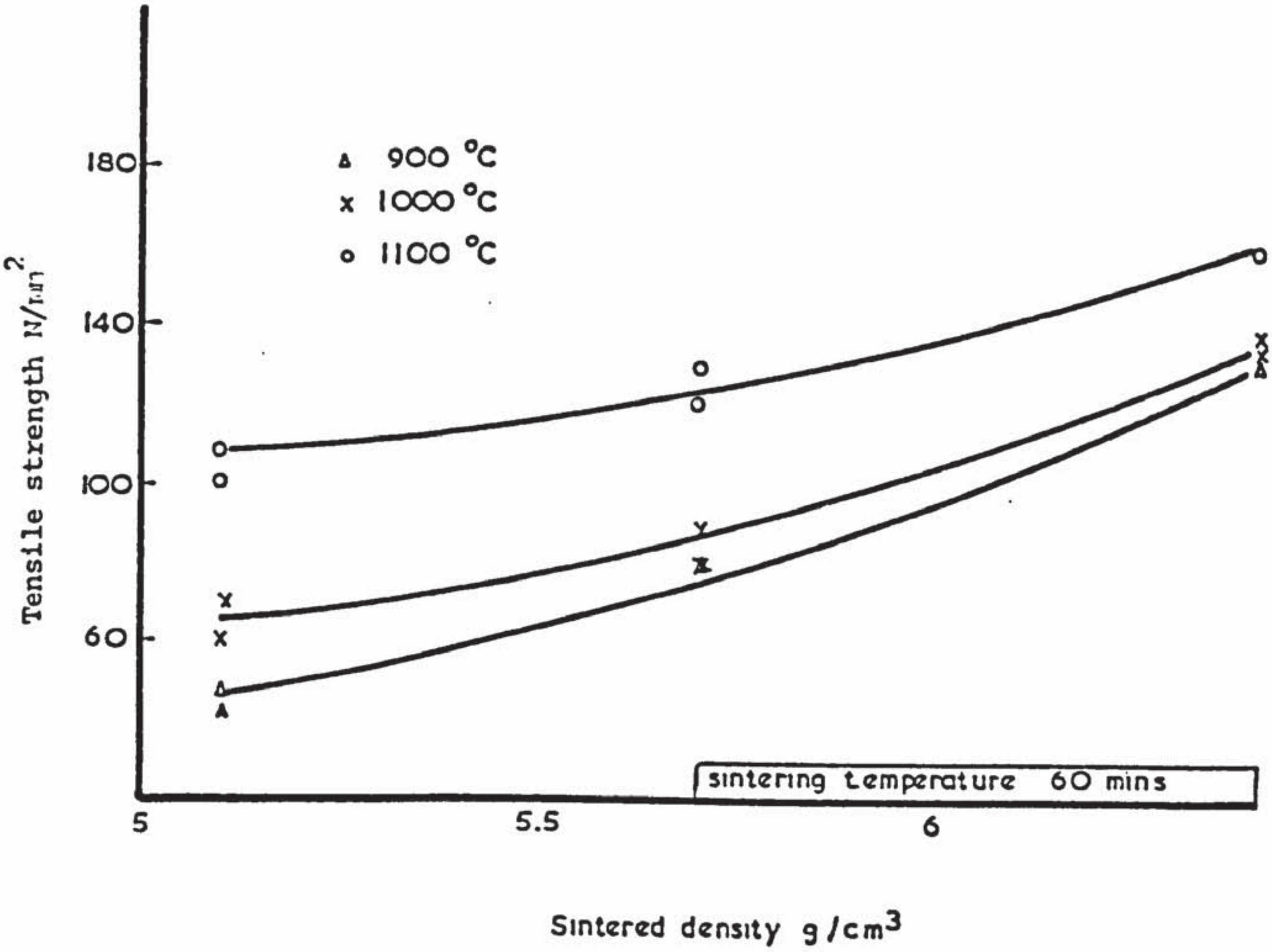


Fig.42. Tensile strength vs Sintered density for NC 100 iron powder

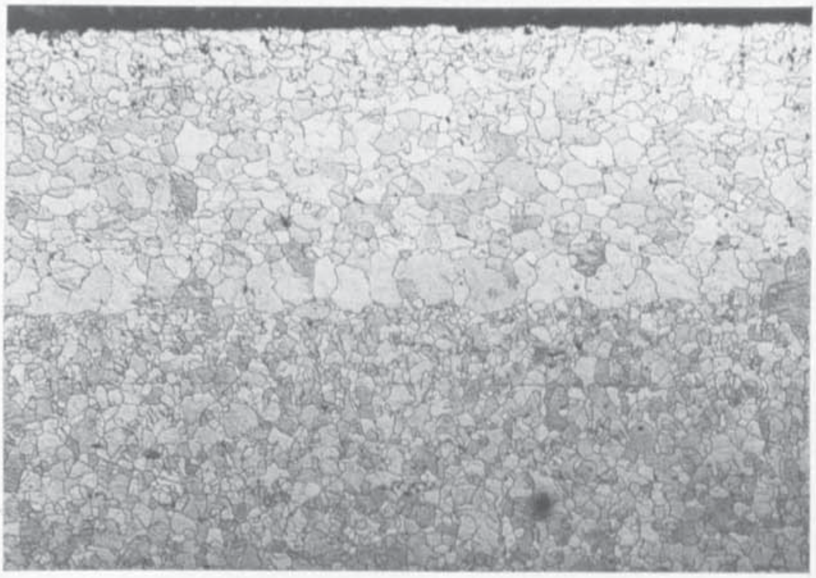


Fig.43a. Chilling effect of rolls.
ASC 100. ST 1000° C HR 60% x 50

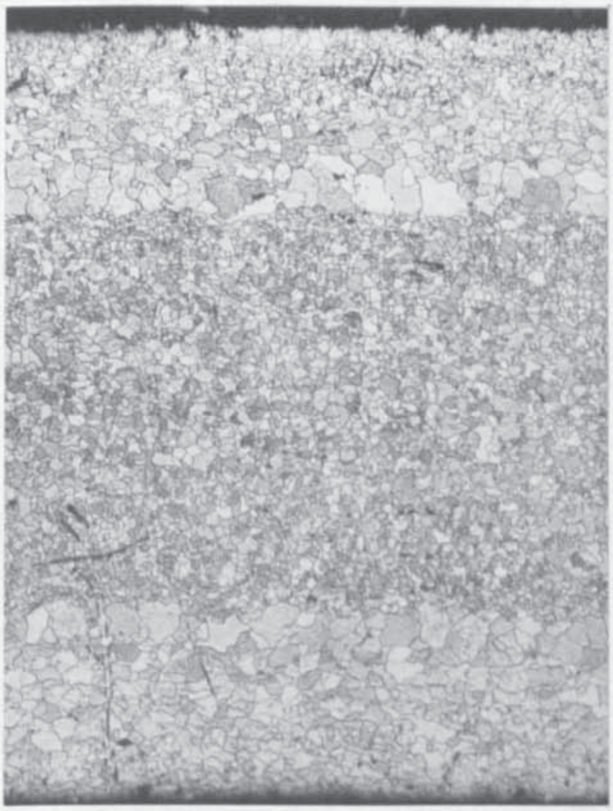


Fig.43b. Chilling effect of rolls
ASC 100. ST 1000° C. HR 60%
x 25

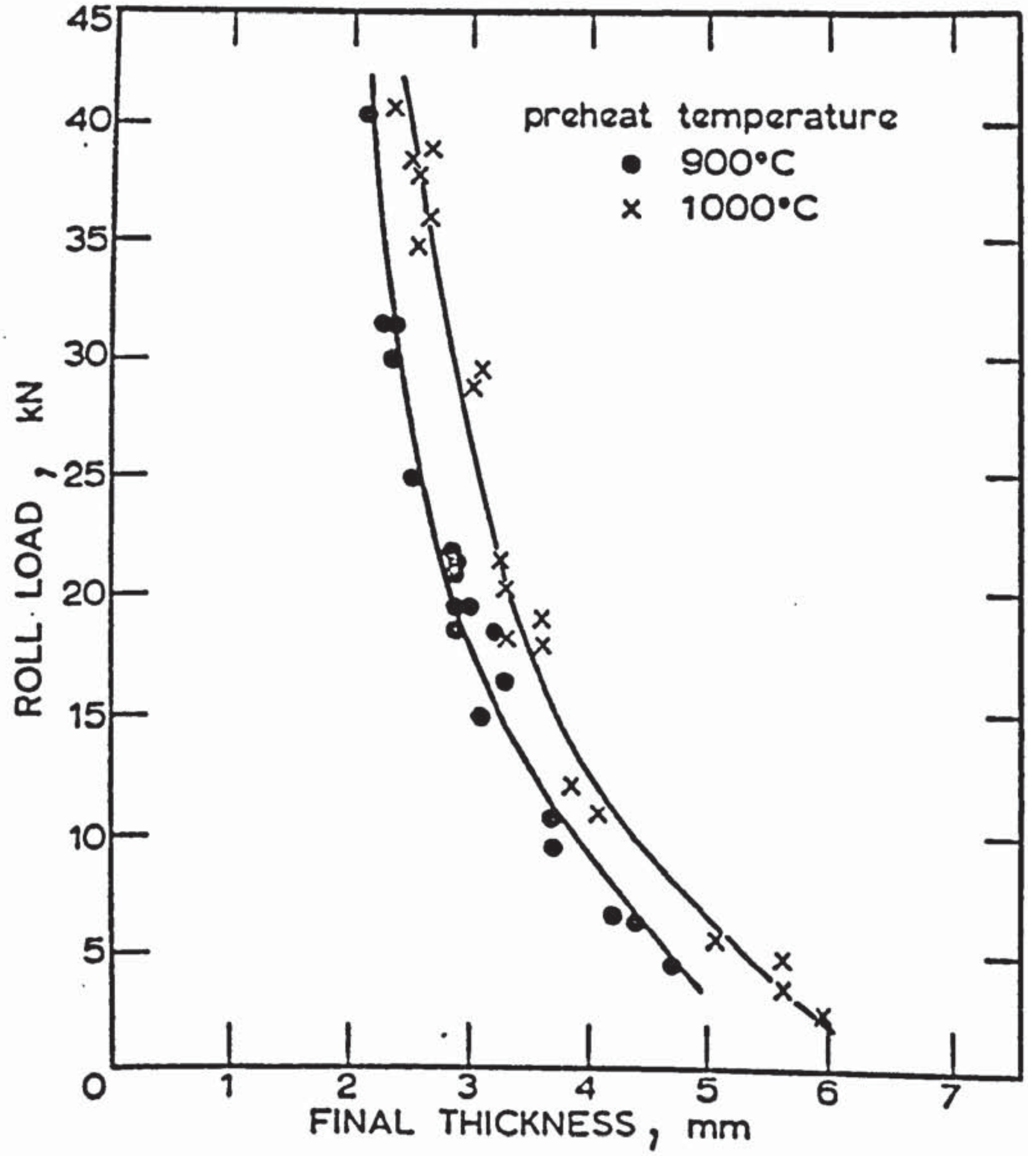


FIG.44. Roll load vs. final thickness.

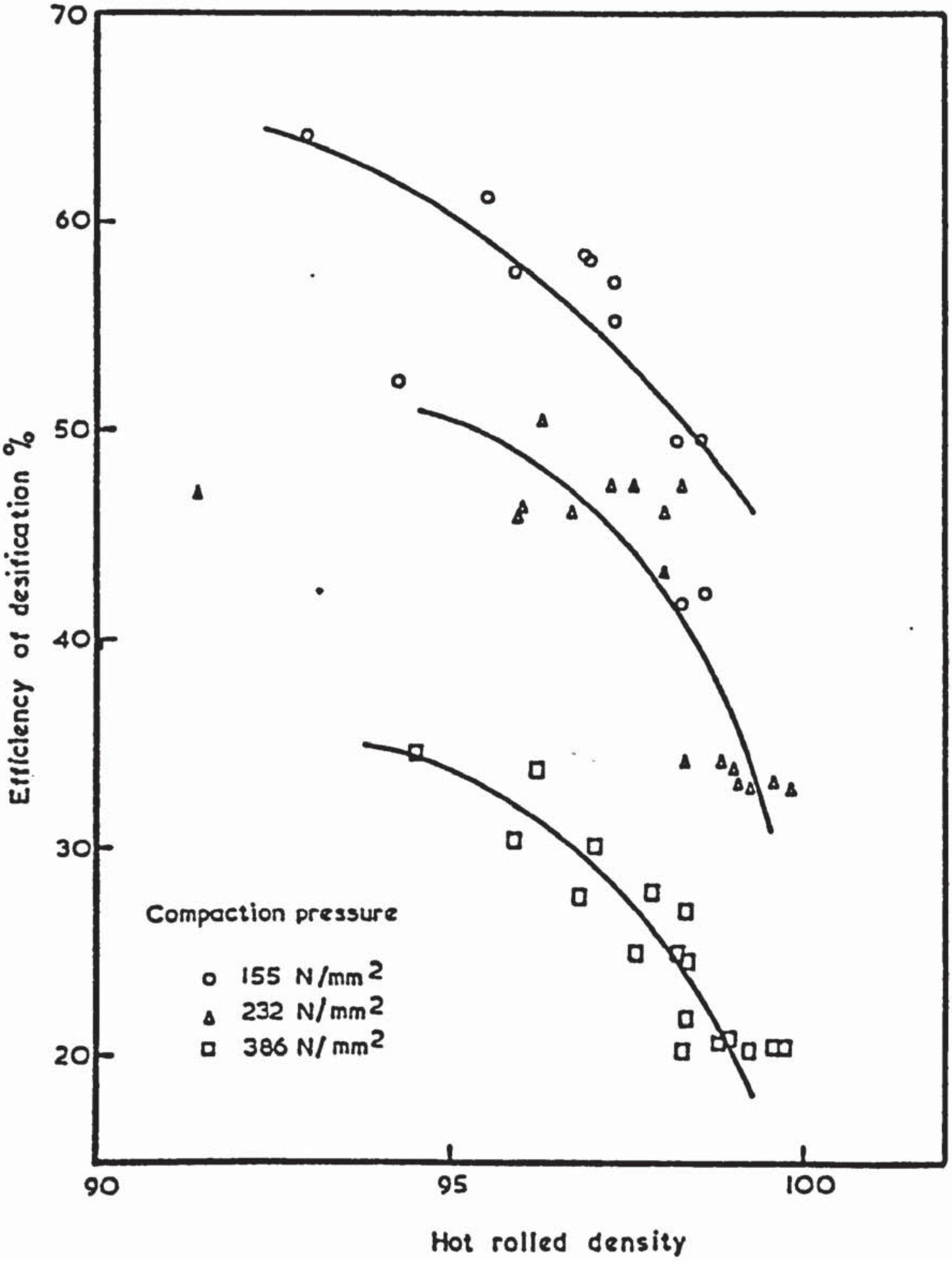


Fig.45. Efficiency of densification vs Hot Rolled density for ASC 100 at 900 and 1000° C.

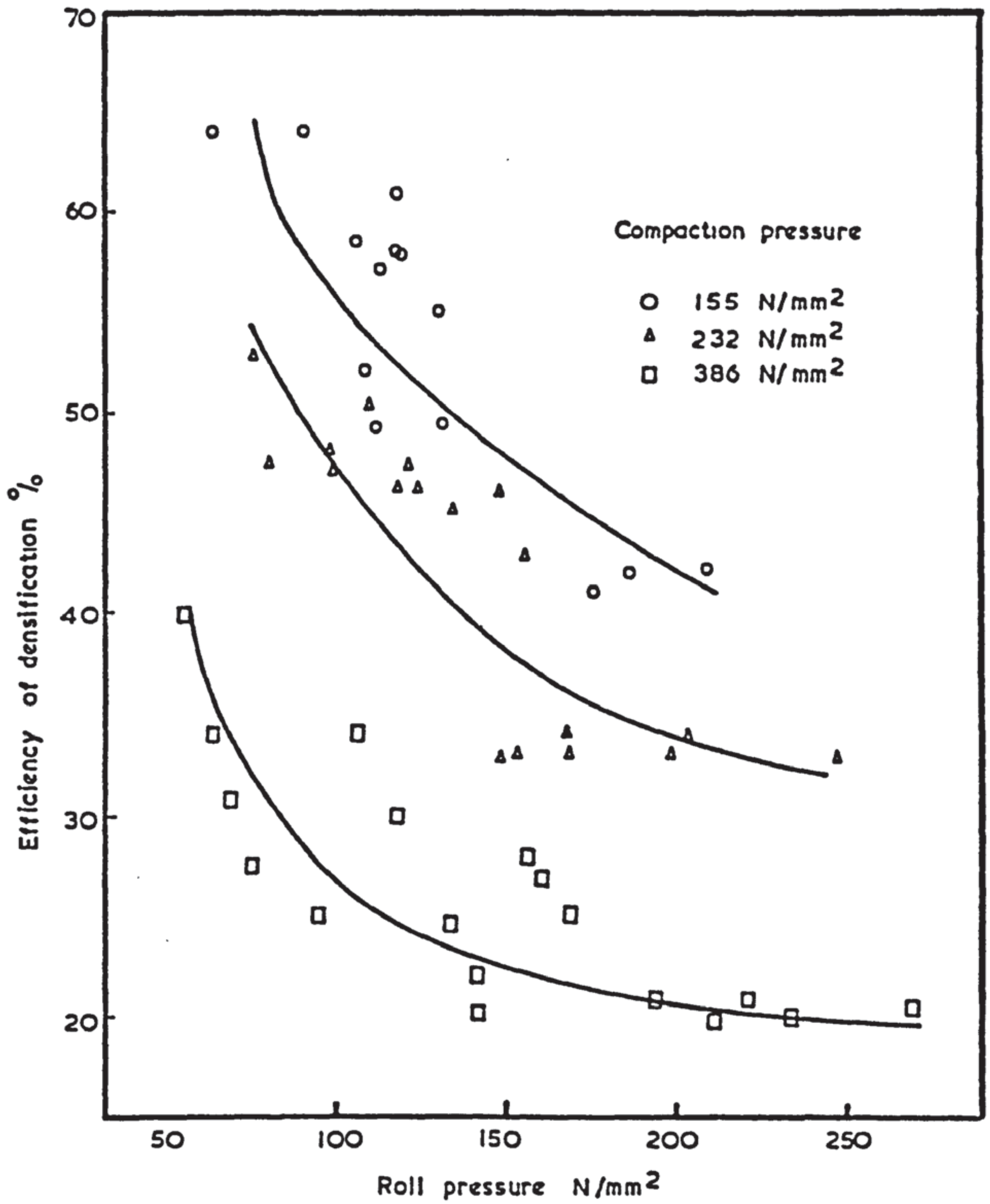


Fig.46. Efficiency of Densification vs Roll pressure for ASC.100 at 900 and 1000° C.

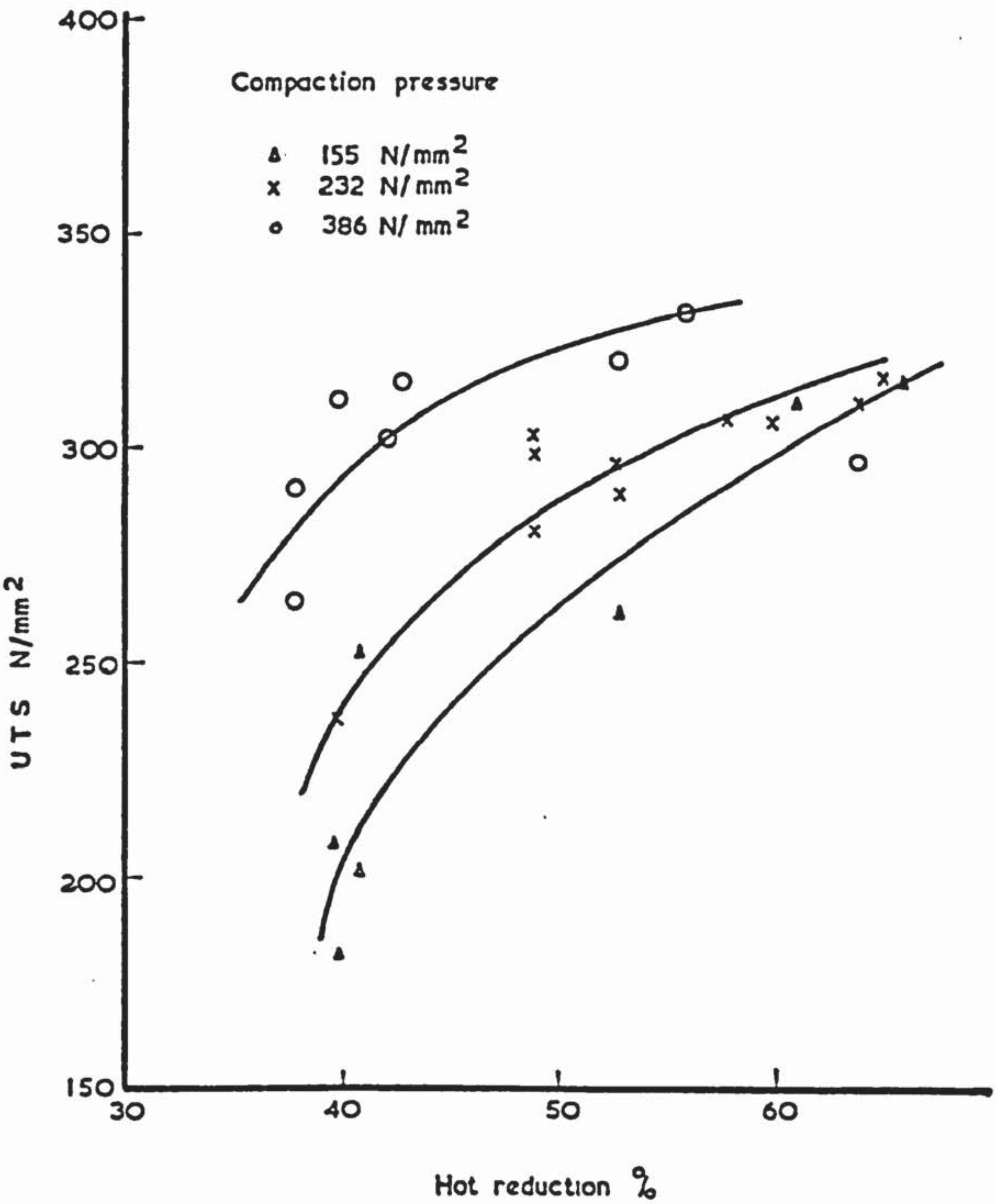


Fig.47. U.T.S. vs Hot Reduction of hot-rolled strip for NC 100 at 900° C.

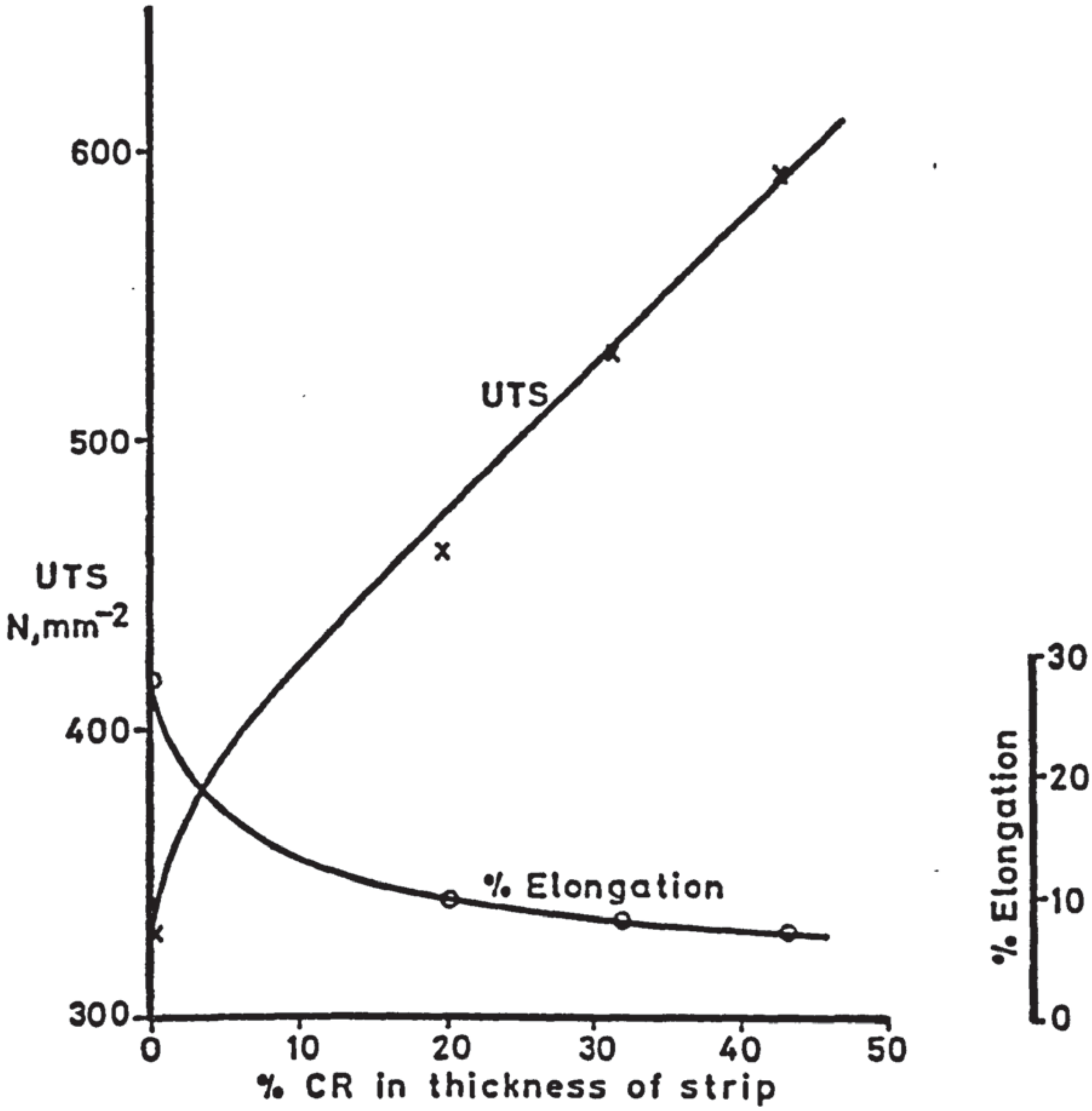


Fig.48. Effect of cold rolling on U.T.S. and elongation of hot rolled strip

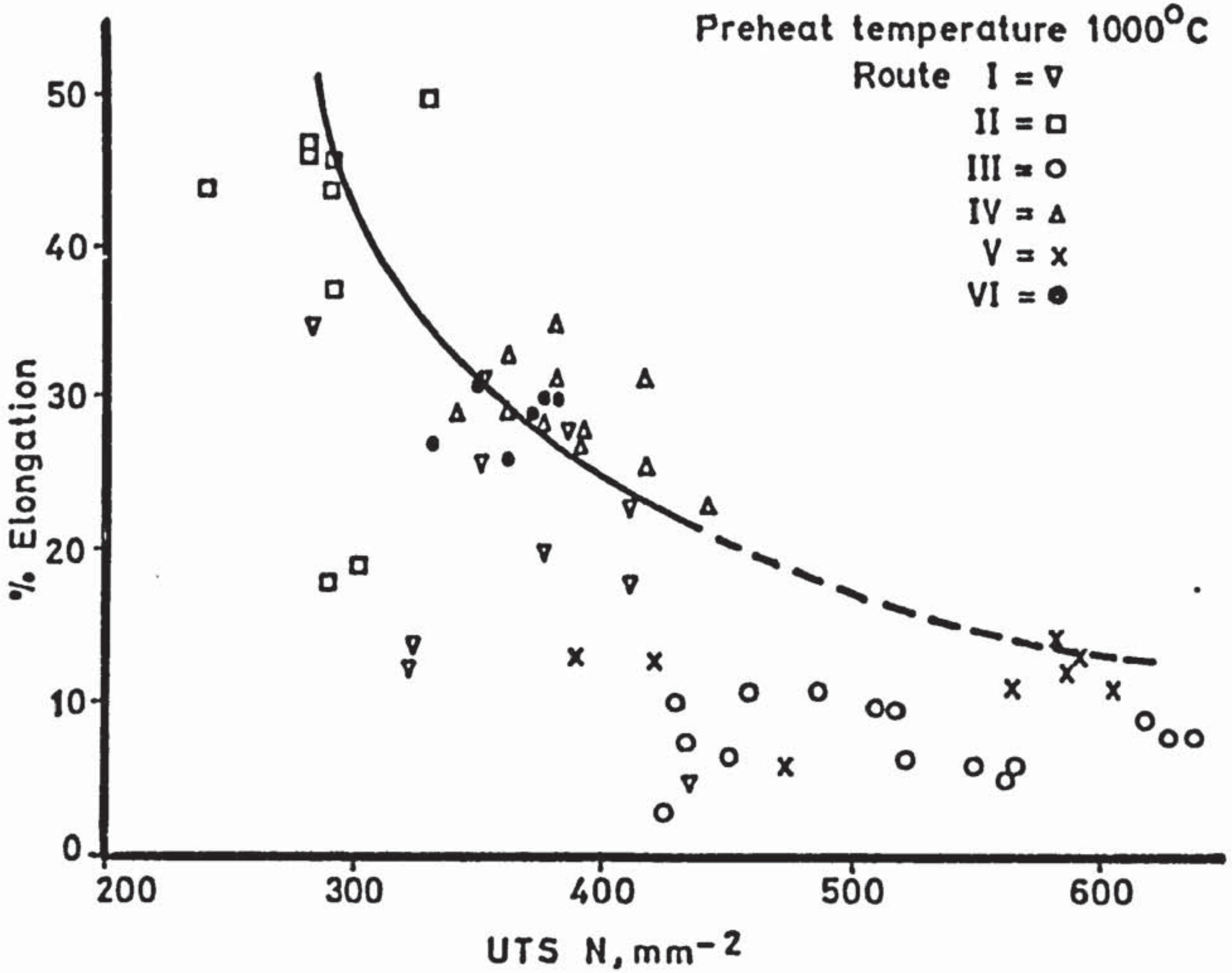


Fig. 49 UTS vs Elongation for ASC 100

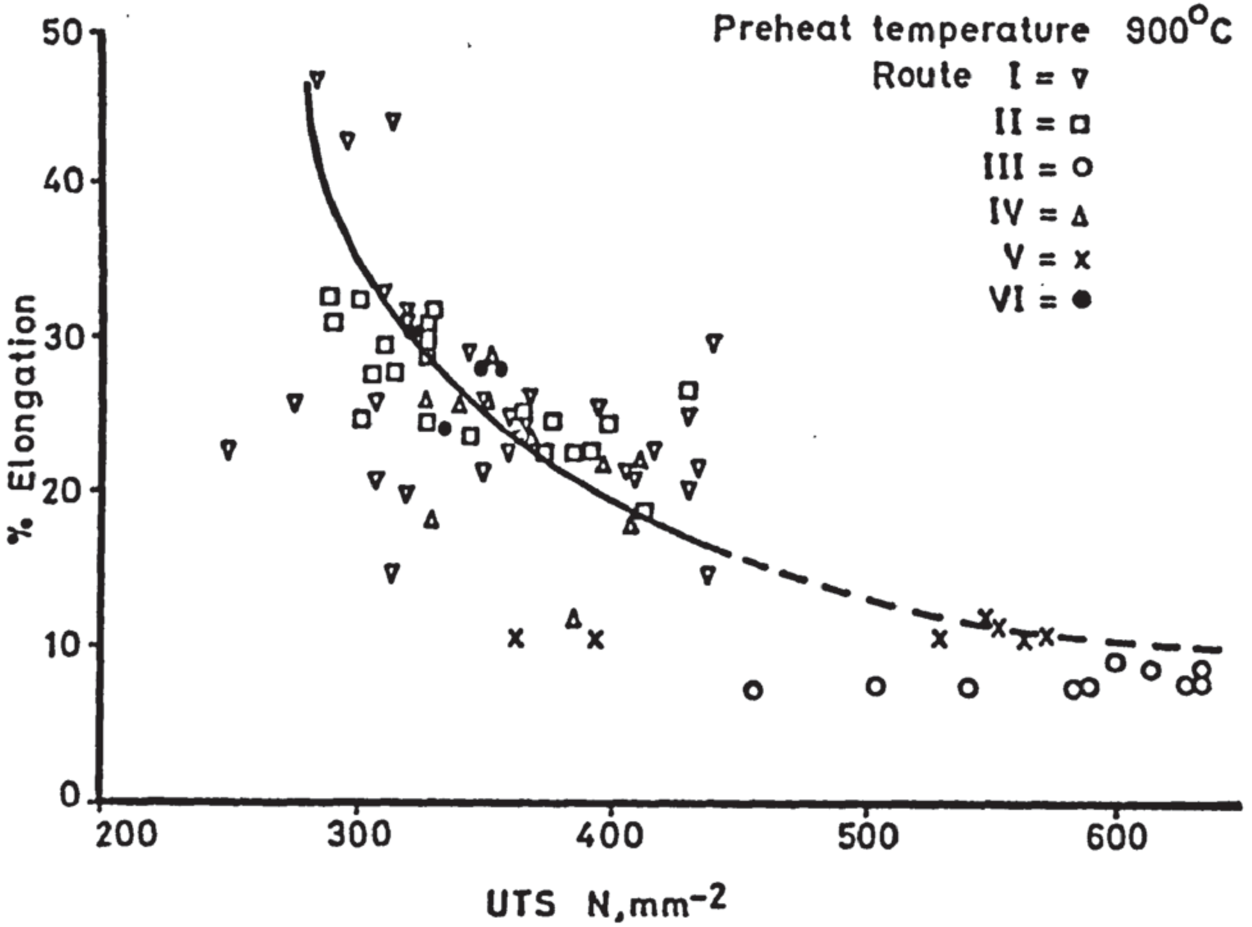


Fig. 50 UTS vs Elongation for ASC 100

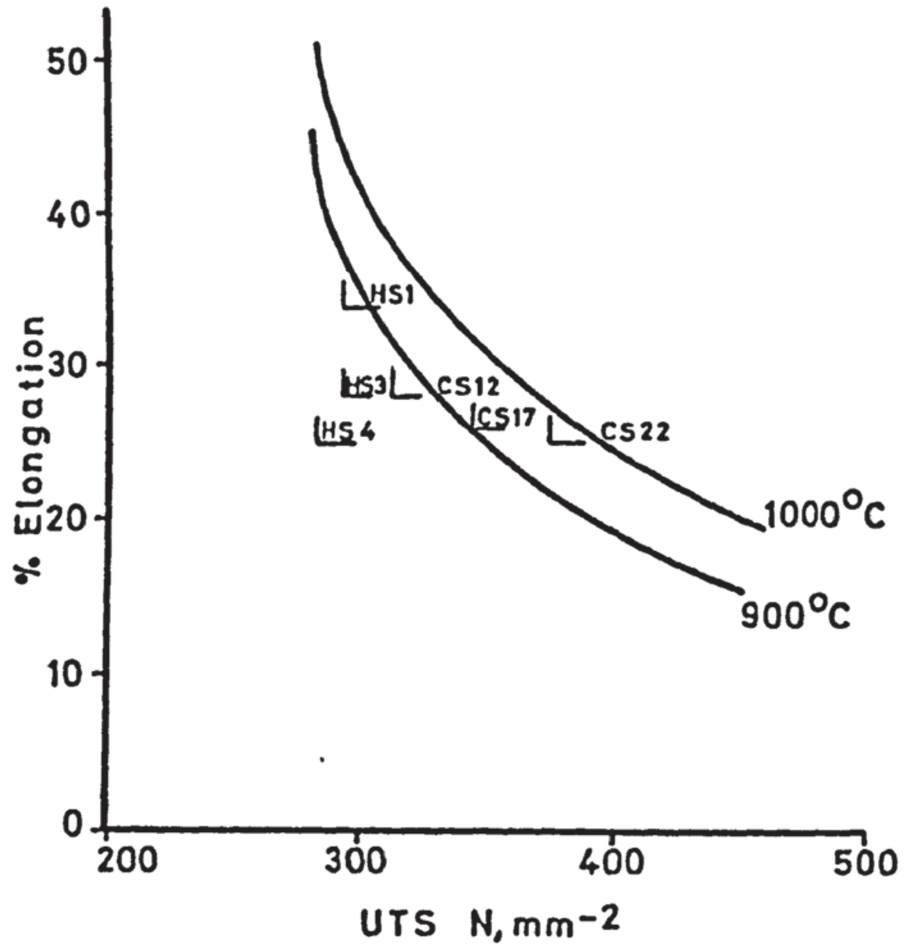


Fig.51 UTS vs Elongation for ASC 100

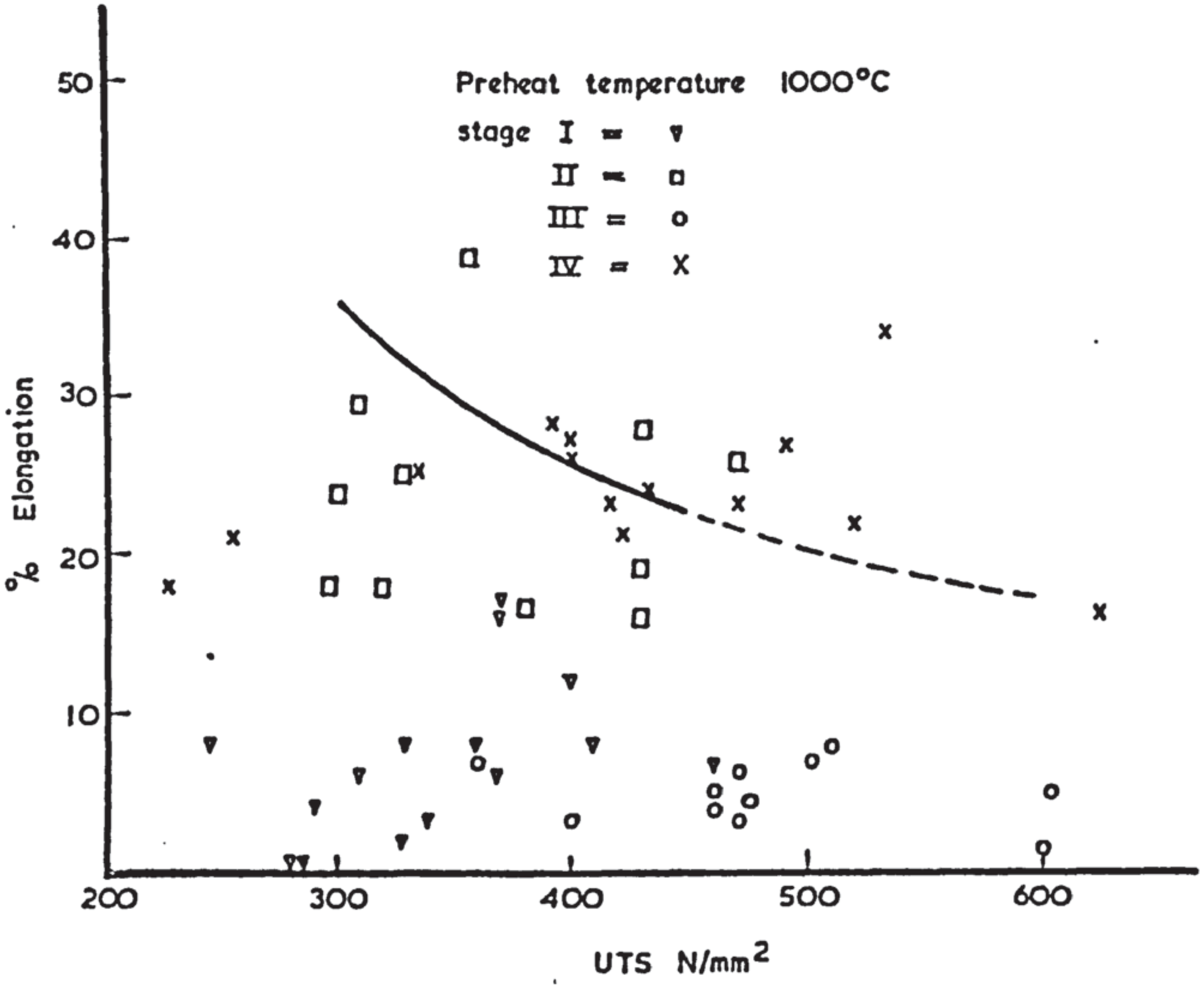


Fig.52. U.T.S. vs Elongation for Mp 32

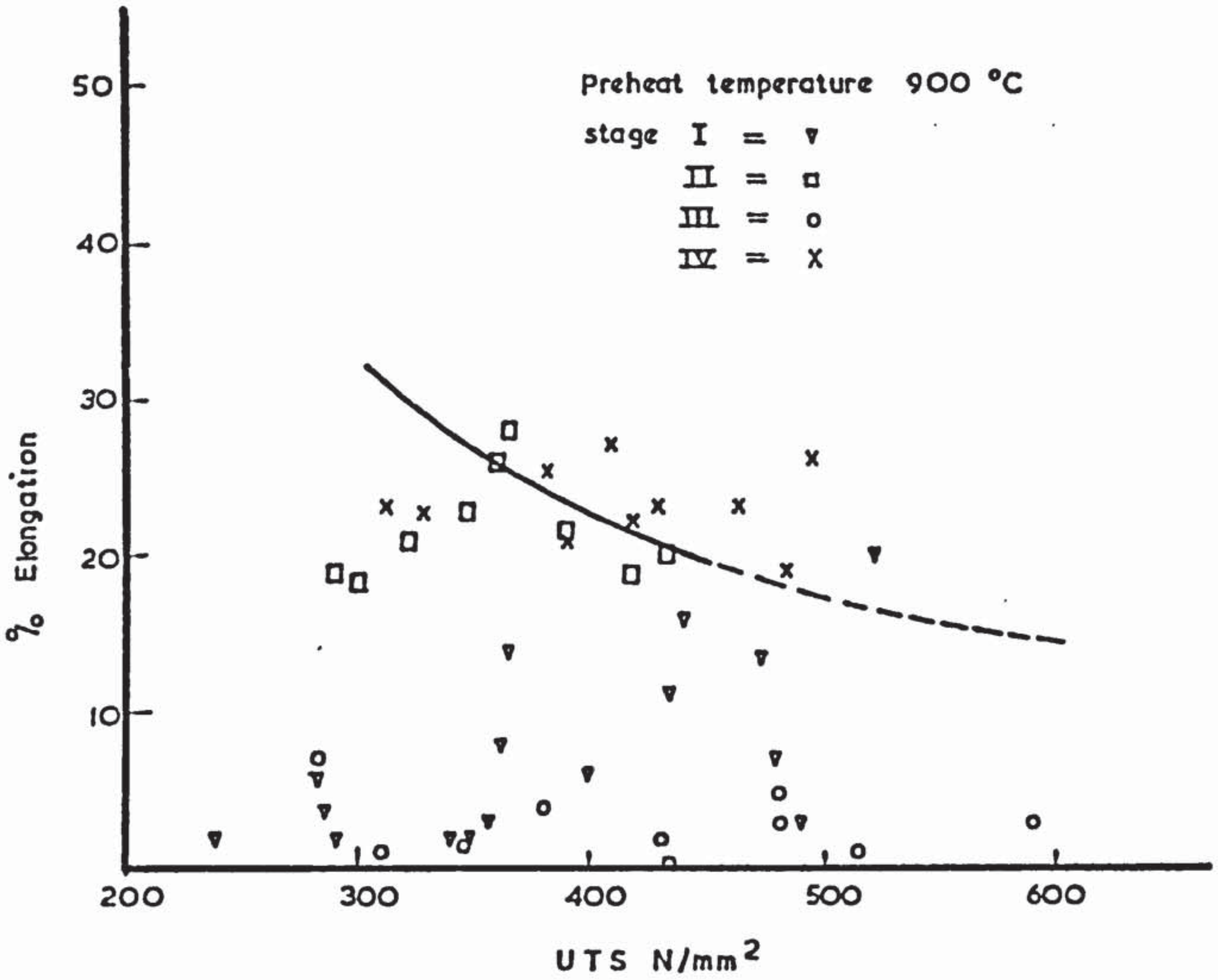


Fig.53. U.T.S. vs Elongation for Mp 32

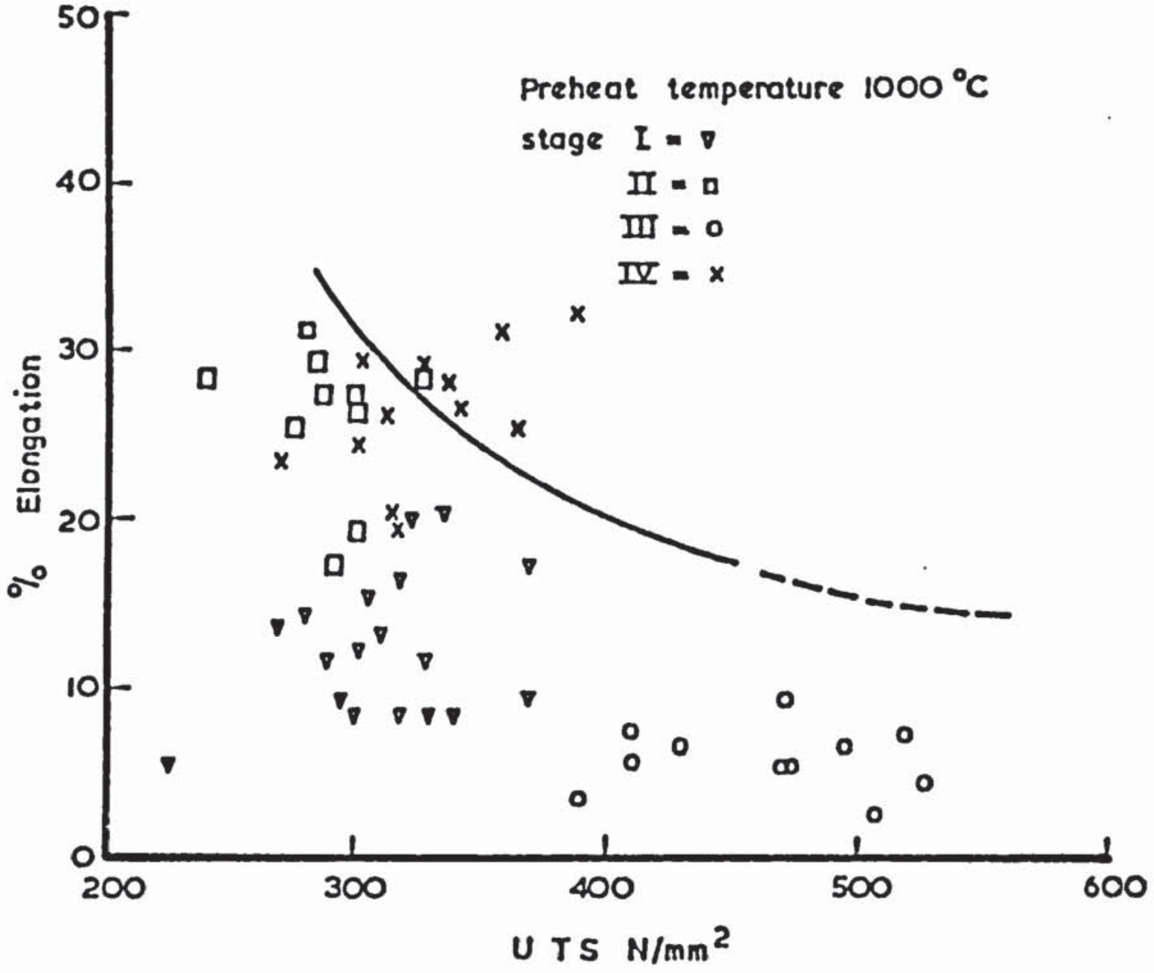


Fig.54. U.T.S. vs Elongation for NC 100

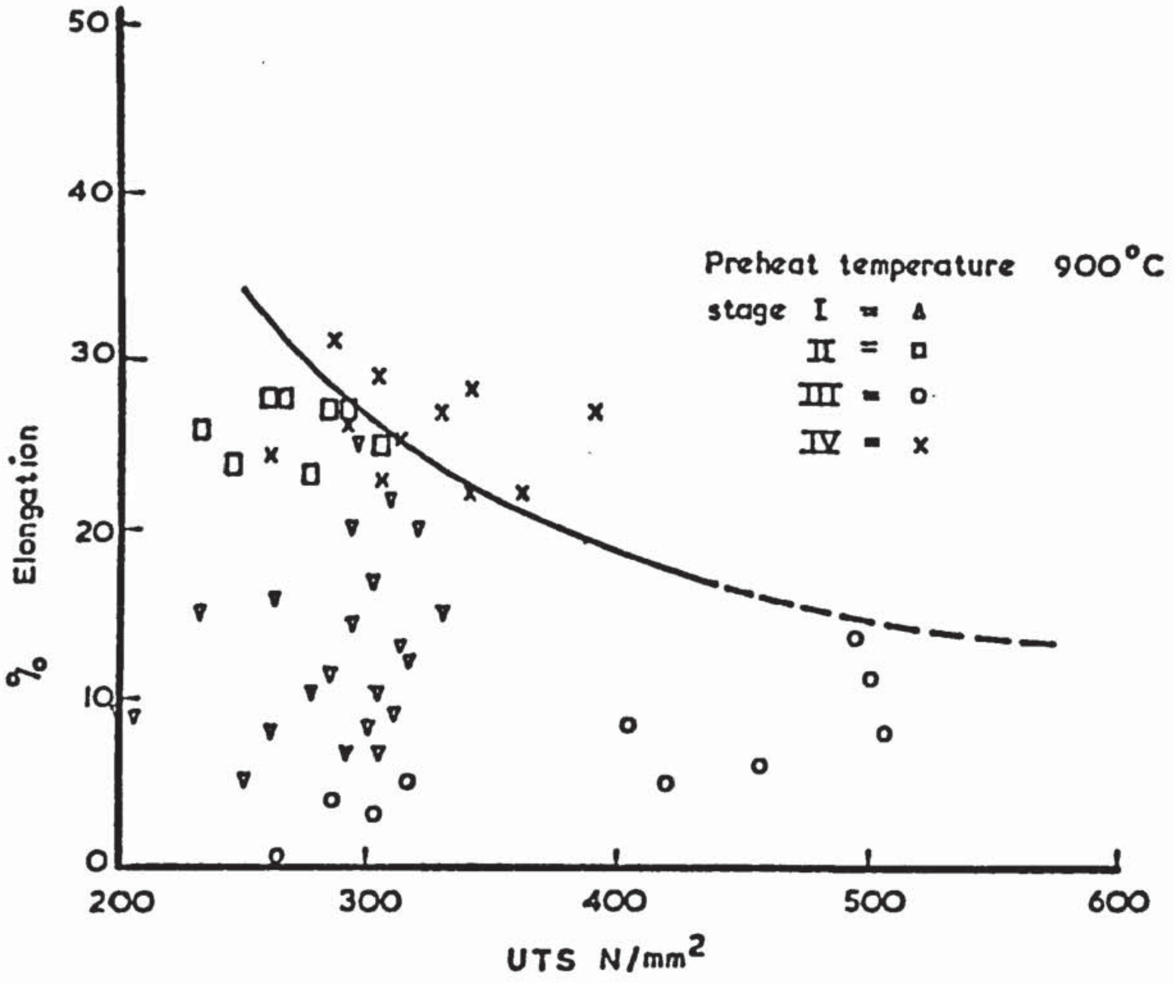


Fig.55. U.T.S. vs Elongation for NC 100·

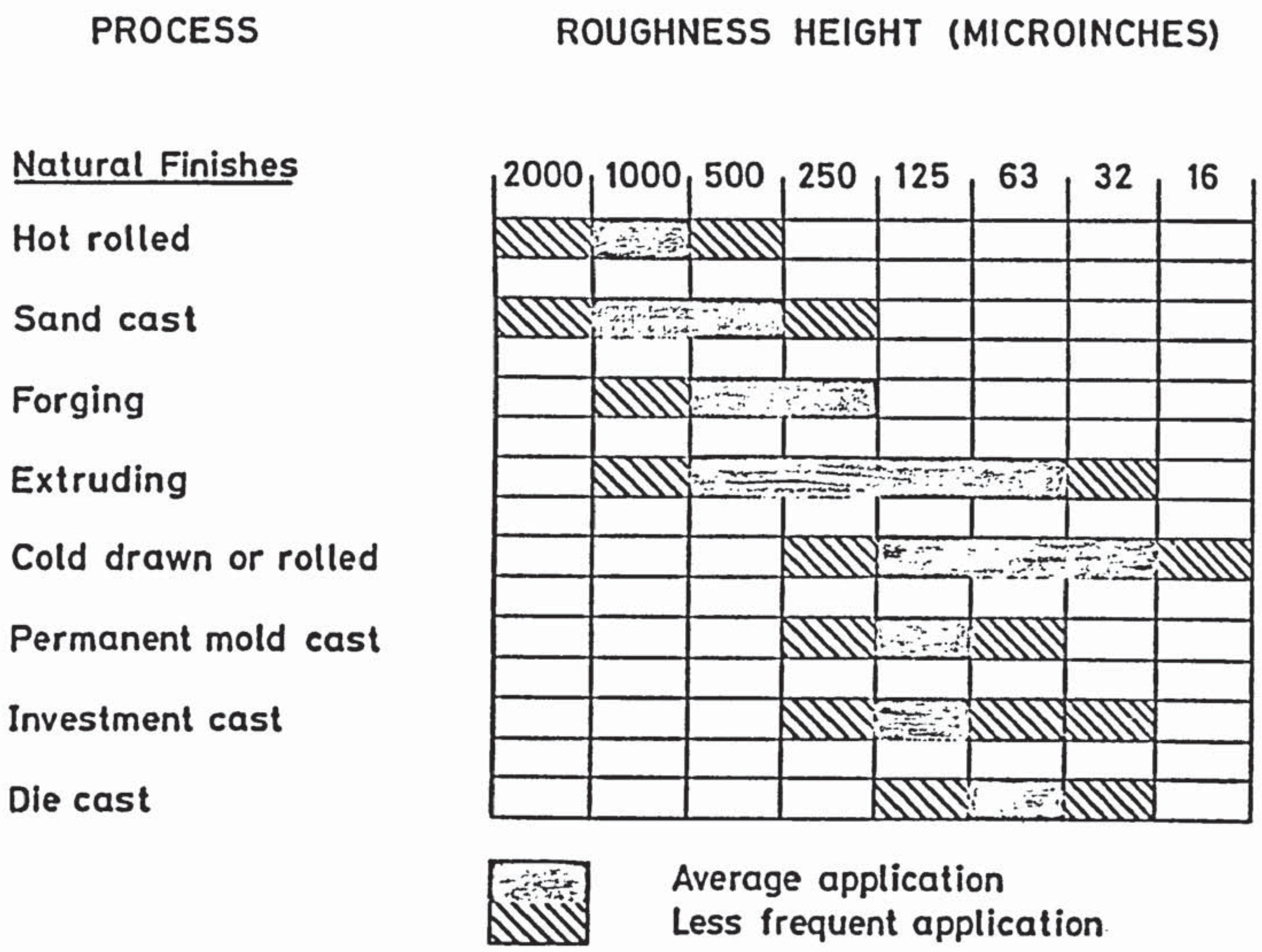


FIG 56 SURFACE ROUGHNESS PRODUCED BY COMMON PRODUCTION METHODS

SECTION V.

5.0 DISCUSSION

The process of hot rolling powder preforms can be divided into five stages viz:

a) the cold compaction to produce original performs,

b) preheating prior to rolling,

c) hot rolling reduction,

d) annealing of hot band,

e) cold rolling and annealing to final strip.

As shown in Table 1 the six stages chosen allowed the products formed at each stage to be examined and tested and thus determine those variables which control the properties and quality of the final strip.

The initial intention was to test the feasibility of hot rolling commercially available iron powders starting with precompacted specimens. To understand the mechanism of the hot rolling process interrupted rolling was used.

5.1 Compaction

The compressibility of Höganäs NC 100 powder as can be seen from Fig.13 is not as high as that of the other two powders. This is probably due to the high impurity content and also the shape of its particles. Figs. 9-11 show Stereoscan photographs of the three powders, Höganäs ASC 100 (atomised, super-compressibility), MP 32 (atomised, high compressibility) and NC 100 (Sponge reduced, normal compressibility).

The NC 100 powder is a directly reduced iron powder and has to be milled after reduction to break up the sponge iron. This would lead to the folding over and breaking off of asperities as well as disintegration of the sponge iron. The powder is then annealed, which removes the local strains, but it does not restore the original structure. Thus NC 100 is spongy and more porous than the water atomised ASC 100, and has a greater oxygen content. These factors tend to reduce the apparent density of the compact. In the case of MP 32, the presence of 0.12% manganese, higher carbon, and intermediate oxygen content might be the cause of density differences compared with the other two powders. The effect of the manganese on strain hardening could result in a higher pressure necessary for deformation. The compressibility of ASC 100 is naturally very high and this has been attributed to its favourable size distribution although there is no significant difference between it and NC 100, (Figs. 29-31), and its physical and chemical properties. (Tables 2-3). The latter features would appear to be the more significant. Bonding during compaction was mainly due to cold welding taking place between clean metal to metal contacts produced by the shearing off of surface irregularities of the particles. For all the green compacts, densities were determined and their relative densities determined as shown in Table 4.

A plot of ℓn (1/1-D) against compaction pressure for NC 100 powder is shown in Fig.32 and the regression equation for the assumed straight-line part of the graph corresponds to a Heckel-type[45] equation, viz:

$$\ln (1/1-D) = Kp + \ln (1/1-Do) + B$$

$$\ln (1/1-D) = 0.0029p + 0.364 + 0.24$$

$$\ln (1/1-D) = 0.0029p + 0.604 \qquad r = 0.999$$

where D = relative density, p = Compaction pressure in N,mm^{-2}

Do = relative apparent density

B = densification occurring during second stage,

r = regression coefficient

Heckel noted three stages during compaction: the first (denoted by I) being the filling of the die cavity, the amount of densification indicated by Do; the second (II) characterised by individual particle movement and rearrangement; and the third stage (III) the proportional rate of change of density with pressure. (Fig.33).

The change during stage II cannot be accounted for merely by rearrangement because the intercept term 0.604 does not coincide with the tap density $\ln (1/1-D) = 0.54$, which is the best density achieved at zero applied pressure. Hewitt et al[46] claimed that some local plastic deformation did occur during Stage II which was detected by X-ray line broadening measurements, and that stage III commenced when plastic flow became homogeneous and not local.

Therefore, it is believed that during stage II restacking of particles occurs and tap density is achieved at low pressures. Higher pressures cause localised deformation, e.g. shearing-off and folding-over of asperities as particles move relative to each other to achieve denser packing. This is shown in the micrograph at x 300 magnification (Fig.19) representing the undeformed region where an asperity is seen to have been bent over. At low compaction pressures the contact area between particles is small, being at asperities only. As these become folded over a greater contact area is produced which leads to cold welding as particles attempt to continue their slide past each other. When interparticle bonding becomes appreciable Heckel's stage III commences and deformation is more homogeneous. The mechanisms which occur in stages II and III overlap with the predominance changing from localised homogeneous plastic flow as the compaction pressure is increased. The latter process, it is believed, is operative chiefly above 95% density. The Heckel equation for the other two powders are:

$$\text{ASC 100} \quad \ln\left(\frac{1}{1-D}\right) = 0.0029\,p + 0.8 \qquad r = 0.999$$

$$\text{Mp 32} \quad \ln\left(\frac{1}{1-D}\right) = 0.0025\,p + 0.765 \qquad r = 0.997$$

The differences between compaction behaviour of the three powders is due to the differences in the extent of stages I and II. This must be due to the differences between the particle characteristics and chemical composition.

Once stage III is reached by all three powders they behave in a similar manner. In stage III, bulk deformation is the predominant mechanism. The slopes for this stage in all cases are almost identical.

5.2 Half-rolled specimens

These were examined metallographically and by Quantimet. (Figs. 17-22). Sintering was present only in the surface layers of the 1000°C compacts, confirming the time required to heat up the specimens. Reductions of 40% or more destroyed any bonding which may have been formed during sintering. All changes in structure started at the surface and were transmitted to the centre as rolling progressed. The extent of the changes was dependent on the initial density and percentage reduction given. The first noticeable change that occurred in all compacts was restacking and localised plastic flow of material into the voids. Deformation of the particles increased as the pore volume decreased, until the particles elongated in the direction of rolling. These elongated particles were present in the surface layers of compacts produced at 232 and 386 N,mm^{-2} and given 40% reduction, and also in all compacts given 60% or more reduction. The commencement of particle elongation occurred earlier for ASC 100 as the initial density of this powder was higher. As would be expected, it appears that there was a limiting density before the compacts began to behave as 100% dense material and exhibit elongation of grains in the direction of rolling.

When the Quantimet measurements in Figs. 25-26 are related to the photomicrographs in Fig.19 it can be seen that density at the centre lags behind the density of the surface layers. This is due to the mechanism of pressure transfer discussed above.

However, when particle elongation begins at the surface a rapid change in density at the centre is seen and this is due to the fact that the now 'solid' material at the surface is able to transmit pressure from the rolls more efficiently towards the centre. Comparing the changes that occur using different reductions, they take place faster with increasing reductions (Figs. 25 and 26) although there is not much difference in the final densities because it is difficult to remove the last 5 per cent of porosity. In fact, it may not be possible to remove all the porosity in one pass and obtain 100% dense material because once the material reaches 95% relative density the compacts begin to behave like solid material, with particles deforming in the rolling direction rather than filling in the pores. Weaver et al[77] state that in both hot rolling and forging processes it may be technically impracticable, and quite unnecessary, to obtain a 100 per cent product in a single hot working strip.

Density changes are rapid in the first part of the deformation zone (86-95%) and slow in the latter part of the zone (95-97%). This confirms how difficult further densification becomes once particle elongation occurs. These principles are illustrated in Fig.34. The photomicrograph of the area around the indentation made by the wire (Fig.22) shows how material flowed around the wire as it was impressed by rolls into the compact, causing a localised increase in pressure which was sufficient to cause particle elongation to occur much earlier in the deformation zone than throughout the rest of the compact.

From Figs. 34 and 35 it can be seen that for a constant reduction, the high density green compacts gave a higher final density and a much greater roll pressure was needed to achieve that density. However, for a given reduction the roll pressure is very much larger for solid wrought material.

To compare the roll pressures with those for hot rolling solid mild steel plate the following experiment was made. Mild steel plate was cut into the same dimensions as the compacts. The pieces were then stress-relieved by heating to 900°C for 1 hr and furnace cooled under a protective atmosphere of argon. Hardness measurements were taken on each specimen to ensure that they were fully stress relieved. The variation of roll pressure with percentage hot reduction for these solid mild steel specimens is illustrated in Fig.35 for a preheat temperature of 1000°C.

This shows that the deformation occurring during the rolling of powder compacts is much easier than for wrought material. However, a rapid increase in roll pressure is given but not to the rolling loads for solid, when the final density reaches ∿ 95%, coinciding with the Quantimet results, which show that at about this density the material in the roll gap elongates and behaves more and more like 100% solid material Further densification would be desirable only to improve the mechanical properties of the hot band. This lower working load for powder compacts suggests that a porosity of 3 - 5% allows easier deformation without comparable decreases in final properties. Thus, it seems that low strength strip may be produced of much lower energy input by the powder route than by the conventional ingot reduction process.

In Fig.36 the improvement in ultimate tensile strength with increasing hot rolled density is illustrated and confirms the point that little improvement in strength is obtained by increasing density beyond 95%. It is possible that the required dimensions and mechanical and surface properties of the finished strip can be achieved during cold rolling schedules using a hot band of <100% solid. If this is proven possible then the energy input and thus cost of hot rolling could be reduced very considerably owing to the much smaller capital expenditure on the early cogging and blooming mills.

5.3 Hot rolled strips

To determine the effect of preheating temperature and time on the final properties of the hot band a series of tests were made at 900, 1000 and 1100°C for 5, 20 and 60 mins. The results are given in Tables 5-7. The values at 5 mins preheat show that initial sintering was less, due to incomplete heating through the specimens. The properties obtained at 20 mins were not significantly lower than those at 60 mins. (Figs. 37-42). This suggests that 20 mins sintering time is enough to achieve the required strength.

Tables (5-7) indicate the differences in the preheated compact properties and reflect the original powderproperties. Since these compact properties changed considerably during subsequent processing it might be useful to compare the powders with their as sintered properties. The advantageous compressibility of ASC 100 powder compared with NC 100 and MP 32 is reflected in the original compact green density and at low compaction pressures. This higher density resulted in higher sintered properties. However, it should be noted that the advantages of ASC 100 as a starting material were reduced as mechanical work, i.e. compaction pressure, is increased. MP 32 appeared to be the best powder when final strength is taken as the determining factor. In all cases NC 100 was lower in final strength which may be due to its higher oxygen and oxide content compared with ASC 100 and additionally, lower carbon and manganese than MP 32.

During hot rolling the rolls were not preheated and therefore they always had a chilling effect upon the strip being rolled. This is shown in Figs. 43(a) and (b) for the rolling of ASC 100 compacts preheated to 1000°C and given a reduction of 60%. From Table 45 it would seem that some decarburisation of the compact may have occurred during processing. However, for the ASC 100 powder compacts the original carbon was only 0.014% and, therefore, the effect shown in Figs. 43 (a) and (b) is unlikely to have been effected by decarburisation and should be a structural change.

The centre of the microstructure is obtained from recrystallisation of γ iron during rolling while the outside is due to chilling by the rolls and high strain effect. The intermediate zone with larger grain size is controlled by the higher temperature there and lower strain due to rolling.

Fig.44 shows that for a given final thickness the roll load is higher at 1000°C than at 900°C. This can be seen from equations 2, 4 and 5. This is the opposite to what would be expected because the yield stress of the iron powders is lower at 1000°C and ought to roll at a lower load. The reason for the unexpectedly low loads may be in the structure being rolled. A consequence of the actual temperatures of rolling is that compacts preheated to 1000°C would be entirely austenitic during rolling but those preheated at 900°C must have had a mixed ferritic and austenitic structure. This may account for the rolling loads at 1000°C being greater than for compacts nominally at 900°C, a phenomenon which has been observed by previous workers. 73,77. The manganese in the powders is very low (Table 2) and this will not be conducive to the stabilisation of γ iron. Ferrite is a body-centred cubic material, whereas austenite is face-centred cubic. Cross-slip, a thermally activated process, is aided by stacking fault energy. Therefore, cross-slip will be easier in body-centred cubic material (i.e. ferrite) than in face-centred cubic material (austenite). This will lead to a lower rate of work-hardening in b.c.c. as dislocations are more able to overcome obstacles in their path. Lower work hardening rates lead to lower rolling loads and hence material consisting of α and γ will deform at lower loads than γ material at the same temperature and so the compacts preheated to 900°C will generate lower rolling loads than compacts preheated to 1000°C (Table 46).

A question raised by this theory is how far into the $\alpha + \gamma$ or α only region rolling can occur before increasing the rolling loads. It would be industrially useful to find the lowest temperature with the smallest rolling loads. This would save energy on both preheating and rolling and thereby make the process more economically attractive. The practical conditions of the present work aided the low rolling loads because the working rolls were cold and therefore cooled the surfaces of the compacts. This meant that more α was likely to be present at the place where most of the deformation occurred. This condition was most pronounced for material of lowest density and receiving the minimum reductions.

Efficiency of densification was defined[77] as $\frac{Pf - Po}{Ps \times R} \times 100$ where Pf is the hot rolled density, Po the original compact density, Ps maximum density attainable, (Ps was taken as 7.83 g, cm^{-3}, this being the highest density achieved after rolling) and R per cent reduction. The efficiency of densification is plotted against final hot rolled density in Fig. 45. Roll compaction is more efficient for compacts of a lower starting density, and the nearer to full density the strip approached, the less the efficiency becomes. As can be seen from Table 4 the low density compacts have about 35% porosity before they are rolled. Interparticle bonding is starting to become significant but there is still a large pore volume present. This will allow some rearrangement and localised deformation of particles. The higher density compacts have a starting porosity of about 20%. This is still a large volume but rearrangement of particles will not be possible. There is not enough pore volume to allow simple movement of particles, and for densification material will have to be extruded into the pores.

As the compacts reach the plane of entry of the rolls, the normal roll pressure will be low because the resistance of the hot porous compacts will be low. For small amounts of deformation, in these initial stages of rolling, and especially for the low density compacts, compaction takes place by rearrangement and by extrusion of materials into voids. The greater the porosity the more dominant is the rearrangement of particles. Under these conditions compaction is efficient because there is high density material further ahead in the roll gap which prevents longitudinal movement of the particles. Most of the energy expended is able to go into densification. As the neutral plane is approached, the pore volume is reduced and densification proceeds by plastic flow and extrusion of material into voids. The resistance to compaction and hence the roll load increases. With low initial density compacts, larger reductions are necessary to obtain high density and the contact arc between the rolls and compact is greater. Fig.46 shows that, for a given roll load, densification is more efficient for a compact having a low green density.

The improvement in the strengths of the hot band with increased reduction during rolling is shown in Fig.47, and as would be expected the low density compacts increase their strengths relatively more than the higher density ones. However, this does lead to a significant point; that it is possible to take very low density iron powder compacts and by correct processing to produce high quality strip irrespective of the original powder.

A standard statistical programme was used in the ICL 1905 E computer to obtain multiple regression analysis. This yielded the following equations summarising the effect of independent variables on dependent variables. The properties investigated were ultimate tensile strength, percentage elongation and rolled density.

<u>key</u>

GD = green density, g,cm^{-3}
PHT = preheat temperature, $^{\circ}C$
HR = % hot reduction
AT = annealing temperature after HR, $^{\circ}C$
At = annealing time after HR, min
CR = % cold reduction
ANT = annealing temperature after CR, $^{\circ}C$
ANt = annealing time after CR, min
γ = correlation oceffícient
reg. eq. = regression equation

Roll Pressure (N,mm^{-2})

		Y
1	Roll pressure = 38.38 (GD) - 3.23 (PHT) + 3.39 (HR) + 0.0018 $(PHT)^2$ + 1177.9 Values of 't' for GD = 5.61, PHT = 5.86, HR = 15.9, $(PHT)^2$ = 5.56 ASC 100 Stage I.	0.869
2	Roll pressure = 19.54 (GD) + 0.2058 (PHT) + 2.979 (HR) - 318.8 Values of 't' for GD = 2.99, PHT = 3.24, HR = 13.90 ASC 100 Stage I, for PHT 900 and 1000°C	0.882
3	Roll pressure = 24.95 (GD) - 0.445 (PHT) + 2.156 (HR) + 0.00023 $(PHT)^2$ + 42.45 Values of 't' for GD = 7.35, PHT = 1.46, HR = 15.7, $(PHT)^2$ = 1.31 NC 100 Stage I.	0.88
4	Roll pressure = 23.507 (GD) + 1.95 (HR) + 0.000026 $(PHT)^2$ - 170.57 Values of 't' for GD = 6.2, HR = 12.43, $(PHT)^2$ = 1.28 NC 100 Stage I for PHT 900 and 1000°C	0.886

		γ
5	Roll pressure = $20.37\ (GD) + 2.63\ (HR) + 0.0000039\ (PHT)^2 - 134.398$ Values of 't' for $GD = 3.25$, $HR = 12.82$, $(PHT)^2 = 0.13$ MP 32 Stage I for PHT 900 and 1000°C	0.919
U.T.S. (N,mm^{-2})		
6	U.T.S. = $30.23\ (GD) + 0.286\ (PHT) + 3.9\ (HR) - 302.1$ Values of 't' for $GD = 2.67$, $PHT = 2.61$, $HR = 10.52$ ASC 100 Stage I.	0.819
7	U.T.S. = $47.029\ (GD) + 3.7\ (HR) + 0.0001\ (PHT)^2 - 277.97$ Values of 't' for $GD = 8.71$, $HR = 16.94$, $PHT = 7.93$ NC 100 Stage I.	0.922
8	U.T.S. = $4.259\ (GD)^2 + 0.237\ (PHT) + 3.914\ (HR) - 270.029$ Values of 't' for $(GD)^2 = 6.73$, $PHT = 3.14$, $HR = 12.97$ NC 100 Stage I.	0.90

		γ
9	$U.T.S. = 332.94\,(GD) - 25.166\,(GD)^2 + 3.746\,(HR) - 0.42\,At - 0.0159\,(AT) - 921.957$ Values of 't' for $GD = 0.97$, $(GD)^2 = 0.9$, $(HR) = 8.42$, $At = 1.17$ $AT = 0.65$ ASC 100 Stage II	0.976
10	$U.T.S. = 10.736(CR) + 0.41\,(At) + 0.047\,(AT) - 20.271(GD) + 0.79\,(GD)^2 + 0.167\,(HR) + 0.00018\,(PHT)^2 - 77.605$ Values of 't' for $CR = 20.85$, $At = 1.53$, $AT = 1.30$, $GD = 0.08$, $(GD)^2 = 0.04$, $HR = 0.32$, $(PHT)^2 = 5.41$ MP 32 Stage III	0.998
11	$U.T.S. = 460.06\,(GD) - 36.63\,(GD)^2 + 0.72\,(HR) + 0.0001\,(PHT)^2 + 3.39\,(CR) - 0.034\,(ANT) - 1272.54$ Values of 't' for $GD = 4.32$, $(GD)^2 = 4.28$, $HR = 2.83$, $(PHT)^2 = 6.29$, $CR = 12.9$, $ANT = 3.18$ ASC 100 Stage IV	0.998

		γ
12	U.T.S. = 3.149 (CR) + 513.47 (GD) - 40.788 $(GD)^2$ + 0.336 (HR) + 0.422 (At) + 0.022 (AT) - 0.0937 (ANT) - 0.09 (ANt) - 1282.07 Values of 't' for CR = 6.53, GD = 1.71, $(GD)^2$ = 1.69, (HR) = 0.65, At = 0.84, AT = 0.46, ANT = 1.95, ANt = 0.49 ASC 100 Stage IV	0.994
13	U.T.S. = 3.34 (CR) + 591.2 (GD) - 47.31 $(GD)^2$ - 0.77 (ANT) - 1488.97 Values of 't' for CR = 9.96, GD = 4.21, $(GD)^2$ = 4.17, ANT = 3.66 ASC 100 Stage IV	0.989
14	U.T.S. = 10.55 (CR) - 0.1586 (ANT) + 191.03 Values of 't' for CR = 8.61, ANT = 2.11 MP 32 Stage IV	0.871
<u>Hot rolled density</u> (g,cm^{-3})		
15	Hot rolled density = 0.177 (GD) + 0.0158 (HR) + 5.7 Values of 't' for GD = 5.44, HR = 15.67 ASC 100 Stage I	0.849

		γ
16	Hot rolled density = 0.254 (GD) + 0.0198 (HR) + 4.954 Values of 't' for GD = 8.27, HR = 15.87 NC 100 Stage I	0.883
17	Hot rolled density = 0.36 (GD) + 0.02 (HR) + 4.36 Values of 't' for GD = 6.41, HR = 13.36 MP 32 Stage I	0.929
18	Hot rolled density = 0.003 (AT) + 0.204 $(GD)^2$ + 0.25 (HR) + 74.673 Values of 't' for AT = 2.33, $(GD)^2$ = 5.05, HR = 13.42 MP 32 Stage II	0.956
Elongation (%)		
19	Elong. = 0.034 (AT) + 0.345 $(GD)^2$ + 0.0976 (PHT) - 106.64 Values of 't' for AT = 8.33, $(GD)^2$ = 2.79, PHT = 6.26 ASC 100 Stage II	0.899
20	Elong. = 0.0000198 $(PHT)^2$ - 0.158 (CR) + 0.0235 (ANT) - 6.147 Values of 't' for $(PHT)^2$ = 3.58, CR = 2.45, ANT = 6.87 ASC 100 Stage IV	0.934

A few examples of substitution of data in regression equations are given below.

Data used for ASC 100 powder are:

CP = 155 N,mm^{-2} (GD = 5.55 g,cm^{-3}), HR = 50%, PHT = 900°C

Data used for NC 100 powder are:

CP = 232 N,mm^{-2} (GD = 5.67 g,cm^{-3}), HR = 60%, PHT = 900°C

Data used for MP 32 powder are:

CP = 232 N,mm^{-2} (GD = 5.85 g,cm^{-3}), HR = 50%, PHT = 900°C

Reg. eq. 2: Roll pressure = 19.54 (GD) + 0.2058 (PHT)
+ 2.979 (HR) - 318.8

Roll pressure = 19.54(5.55) + 0.2058 (900) + 2.979 (50) - 318.8

Roll pressure = 124 N,mm^{-2}

Reg. eq. 4: Roll pressure = 101 N,mm^{-2}

Reg. eq. 5: Roll pressure = 119 N,mm^{-2}

Reg. eq. 6: U.T.S. = 318 N,mm^{-2}

Reg. eq. 15 HR relative density = 95%

Reg. eq. 16 HR relative density = 97%

Reg. eq. 17 HR relative density = 95%

Summarising this work it can be said that it is possible to produce a quality rolled strip in several ways using many different conbinations of variables. However, the important factor is the total energy requirement. Industry is always looking for the quickest and cheapest methods of producing strip. The important energy components are preheating temperature, compaction and hot reduction. Therefore from an energy point of view it may be best to produce compacts for NC 100 powder at 232 N,mm^{-2} and give a reduction of about 60 per cent after preheating to 900°C. In the case of ASC 100 and MP 32 compaction pressures of 155 and 232 N,mm^{-2} respectively are recommended together with hot reduction of 50 per cent and 900°C for both powders. Thus in Stage I the energy would be minimised in compacting, preheating and rolling as well as a saving of time in preheat stage. This treatment will give a strip at the end of the hot rolled stage with a density of more than 95% of solid density.

For the hot rolled strips (Stage I) it can be seen from equations 6-8 that the main effective variables controlling ultimate tensile strength are hot reduction, green density and preheat temperature. The roll pressure as shown by equations (1-5) is also dependent on the above variables. However, hot reduction has very little effect on elongation. (Table 33). This is because of the fact that recrystallisation takes place only in the centre portion of the strip and near the edges the chilling effect of the rolls inhibits recrystallisation.

The present elongation can be increased in stage II by giving annealing treatment. Annealing eliminates the elastic distortion of the crystal lattice (i.e. recovery). At higher annealing temperatures, new grains form (recrystallisation) and grow. Due to this recovery and recrystallisation the strip is softened and the elongation of the hot band is increased.

Annealing was investigated at temperatures of 650°C, 800°C 900°C and 1100°C; the first being in the ferrite/cementite region just below A1, the second in the austenite/ferrite region, the third under austenite and austenite/ferrite boundary, and the fourth in the austenite region. Annealing times were also varied as can be seen from table 1. It can be seen from table (9-42) that increased annealing temperature increased the percentage elongation while at the same time it decreased the U.T.S., because with the higher annealing temperature the softer the material becomes and this is turn decreased the U.T.S. value. Mechanical properties of thehot rolling strip after annealing at 1100°C were a U.T.S. of about 300 N,mm^{-2} coupled with elongation of 40-45%. These properties, as may be seen in Table 10 and by putting in data to equations (9-19), can be improved by adjusting the process variables, are similar to those for low carbon mild steel strip. The density after the annealing treatment, as shown in equation 18, is a function of hot reduction, green density and annealing temperature, with density increasing with increasing annealing temperature. This is due to greater sintering activity leading to a higher density and interparticle bond strength.

There are many applications, such as tin plate, and in fabrication of many appliances, where full deep drawing quality strip is not necessary or desirable economically. In these areas the powder fabricated product could well be used. However, the major uses in the industrialised countries are in the automobile industry and so the importantproperties are, not only mechanical properties, but deep drawing and surface finish. Of course, the final properties of the strip must be adapted to meet the demands of the markets for which it is intended. Never the less from the results obtained by stage II it could be useful to investigate the possibility of producing and using it in a developing country for lower quality applications.

5.4. Cold rolled strip

To achieve consistent properties and good surface finish in the final product, hot rolled and annealed strip produced from stage II should be further processed, preferably by cold rolling. The results of stage III for three powders are shown in Table (9-42). The effect of cold working (Fig.48) is shown to increase U.T.S. and decrease elongation values.

A similar statistical programme to that used for the hot rolling experiment was used to obtain regression equations for cold rolling. From equation 10 it can be seen that the strength of the cold rolled strip was mainly dependent upon the cold reduction and sintering temperature. It was only slightly dependent on green density, possibly because hot and cold reductions caused breakdown and reformation of interparticle bonds. The annealing temperature and time also affected the strength of the cold rolled strip. The cold reduction can be increased, without internal cracking occurring, by using a higher annealing temperature and a longer annealing time.

It was found that 40-50% cold reduction could be achieved in a single pass without any adverse edge cracking effects. This could, in an industrial plant, improve the economy of the process significantly by decreasing the number of passes. The present work does not therefore agree with the workers[4,59] who previously have suggested that the initial cold reduction must be limited to 20% although subsequent reductions could be greater. In stage III the profound effect of cold working on the U.T.S. can be seen. The limitation of the product at this stage is the low elongation.

To improve the elongation values annealing at different temperatures was carried out for various times. The results of annealing after cold working indicate that elongation values can be increased considerably. (Tables 9-42) This is confirmed by equation 20 which shows the positive effect of annealing temperature upon elongation.

Also it is evident from equations 11-14 that increasing annealing temperature after cold reduction reduces the ultimate tensile strength of cold roll strip. When the hot rolled and annealed strip was given 30% cold reduction followed by a final anneal at 1100°C (Stage IV), the mechanical properties of 31% elongation coupled with a U.T.S. of nearly 350 N,mm^{-2} were obtained, which were similar to those of conventional low carbon mild steel strip. This route offers the additional advantage of hardness consistency across the strip.

From the four stages examined for all powders, stage IV can be highlighted as giving good mechanical, surface and hardness properties although an investigation of the behaviour of the strip when used for pressing and drawing has not yet been carried out. Also its commercial development must await the availability of lower cost powder raw materials.

The results obtained from stages V and VI for ASC 100 were approximately equivalent to those from stages III and IV. (Tables 9-42). Therefore these last two stages were not followed in later experiments with MP 32 and NC 100.

The properties determined for all three powders were ultimate tensile strength and percentage elongation as these are the two properties specified most frequently and therefore would dictate the selection of a suitable process route for manufacture of steel strip using a given powder.

Referring to Figs. 49,50, in which the ultimate tensile strength and elongation values are plotted for the six stages for ASC 100 a general trend can be drawn considering only the results from stages II and IV and this is reproduced in Fig.51. This shows that an increase in preheat temperature will increase the ultimate tensile strength and elongation values depending upon the process stage. It will be noted that the trend lines on Figs. 49, 50 have been extended tentatively beyond the valid results for the ultimate tensile strength obtained from stages II and IV, but in Fig.51 only the valid portions of the two lines have been reproduced. Also plotted on Fig.51 are the properties specified in BS.1449 Pt.I 1972 for steel strip as recorded in Table 47. The results for 900°C are slightly lower but do satisfy the properties required in BS 1449 for some of the deep drawing and rimmed qualities, whereas the strips finished at the higher rolling temperatures appear to satisfy all six qualities specified given the correct process route to the final product. This means that it should be possible to manufacture hot and cold rolled strip specified from conventional strip properties by preheating at the designated temperature and following a suitable route. Furthermore, on the basis of the data available (Tables 9-42), it should be possible to get the required final properties. Any one of the powders can be used even using low compaction pressure to prevent die wear. However, one has to alter the process route to achieve the final strip.

From Table (9-42) there appears to be a significant difference between the ultimate tensile strength values of the hot band of ASC 100 and MP 32 (Figs. 52-53) on the one hand and NC 100 (Figs. 54-55) on the other, which is reproduced after an annealing treatment. There seems to be no reason why NC 100 should be low except for the oxygen content. If this is present mainly as inclusions then it is possible that they could weaken the matrix. Oxygen content as determined by vacuum fusion analysis is the sum of oxide in inclusion (FeO) form, plus the oxide on the particle surfaces. No oxygen results from oxygen solubility in γ iron ($O_2 < 0.005\%$). Sintering of the compacts in a N_2/H_2 atmosphere will remove some of the surface oxygen, but will have no effect on the oxygen in inclusion form. Thus it is possible that the powder compacts with highest total oxygen content after sintering, are those with the higher inclusion content. $O_2\%$ NC 100 > MP 32.

The great difference between the two Höganäs powders is the greater compressibility of ASC 100 material which always gives a much higher green density than NC 100 due to its higher purity and closer quality control. The density of MP 32 green compacts is intermediate. During the preheating and hot rolling operations the densities of the MP 32 and ASC hot bands become very similar and therefore the strengths become much more alike but after cold rolling and annealing ASC 100 powder gives higher values for elongation and lower values for ultimate tensile strength. The reason for this may be due to the presence of 0.2% oxygen in MP 32 which if distributed finely throughout the strip may pin down the grain growth resulting in low elongation. The higher ultimate tensile strength values are more likely to be due to the presence of higher carbon and manganese content of this powder.

5.5. Hardness

It has been found that hardness (V.H.N) remained constant across the strip samples obtained from the process route in which annealing after cold working was involved. (Table 44)

5.6. Surface finish

With respect to this property the product from a powder metallurgy route is likely to start with an advantage, as it will not have gone through the process stages at which surface defects are most likely to occur in the conventional production routes. Only small slag inclusions are present in the powder and oxide particles appear as a fine dispersion throughout the structure. Forty specimens were examined by Talysurf Model 3 at three points on their surfaces and the mean for these measurements was obtained (Table 48), 0.26 µm (= 10.15 microinches). It can be seen from Table 48 that they varied from 29 microinches at the worst to less than 5 microinches in some cases and were, therefore, within the most rigorous requirements for cold rolled strip (Fig.56),[79] hence plating and painting on these surfaces should be no problem.

The main function of cold working in powder strip is the same as in conventional steel strip, i.e. to get the required final gauge, shape and surface finish. As can be seen from Fig.36 above 95 percentage density there is no significant increase in ultimate tensile strength and therefore the required strength can be obtained by cold rolling.

6.0 CONCLUSIONS

1. There are three stages in the deformation of preforms by hot rolling.

    1) Restacking and rearrangement of particles during entry to the mill.
    2) Local plastic deformation and particle folding-over.
    3) Bulk plastic flow leading to elongation and recrystallisation of grains.

    These stages overlap and their onset depends upon the original density of the compact. Densification occurs throughout the rolling process, becoming increasingly difficult as the 100% solid state is approached. The centre of the hot band lags behind the density of the surface layers. It would seem advantageous from the point of view of rolling loads to roll powder compacts at the lowest possible temperature compatible with the increasing strength of the ferrite matrix.

2. The ASC 100 powder was found to give the highest green densities for a given compaction pressure.

3. Lower rolling loads are generated at 900°C than 1000°C because of the presence of ferrite and austenite, rather than only austenite.

4. Preheating time of 20 minutes is needed for these sized compacts to ensure that a uniform temperature is reached throughout the specimen.

5. Efficiency of densification is higher starting from lower green densities.

6. The conventional standards of ultimate tensile strength, elongation and surface finish in the final product can be obtained by adjusting the process route and the amount of cold reduction irrespective of powder used.

7. Green density can be kept low to save energy and die wear at the compacting stage.

8. Factors contributing most to strength of hot rolled strip are hot reduction, green density and preheat temperature. Further it is observed that strength varied with density up to 95%.

9. It is possible to achieve 95% density in one pass for all three powders at the hot rolling stage.

10. The roll pressure is dependent mainly on the hot reduction and green density and also on preheat temperature.

11. Beyond 95 per cent hot rolled density the tensile properties are flattening off and little improvement in ultimate tensile strength is obtained.

12. At the end of Stage II when the hot band was annealed, high elongation values were achieved. Elongation at this stage was a function of annealing temperature, preheat temperature and green density.

13. The tensile strength of the cold rolled strip is mainly dependent upon the cold reduction and preheat temperature. The annealing temperature and time also affect the strength of the cold rolled strip. The higher the annealing temperature and the longer the time, the higher the cold reduction which can be applied.

14. It was found that 40-50% reduction could be achieved in a single pass during cold rolling.

15. Cold reduction has a negative effect on the elongation.

16. Annealing after cold reduction creates high elongation and consistency of hardness throughout the strip.

7.0 RECOMMENDATIONS

1. Texture study should be done to determine whether in hot rolled strip the transformation to ferrite on cooling occurred from deformed austenite or from recrystallised austenite.

2. Deep drawing tests on powder strip should be done to ascertain its industrial application.

3. The behaviour of impurities and their effect on longitudinal and transverse strip properties should be studied.

4. The effect of oxide film and inclusions present in the iron powder should be studied.

5. An investigation into the effect of oxide content on rolled properties is required.

6. An investigation into the effect of different powder particle size on rolled mechanical properties can be examined.

7. The effect of roll speed variation should be studied.

8. The exact account of energy consumption should be investigated.

8.0 APPENDIX

Rolling pressure

$$\text{Rolling pressure} = \frac{\text{Roll Load}}{\text{Contact area}}$$

The roll load was measured from the ultra violet recorder and the contact area found from width and contact length data.

$$\text{Rolling pressure} = \frac{\text{Roll Load}}{\text{Contact length x contact width}}$$

therefore

$$\text{Roll pressure} \quad \boxed{P = \frac{L}{R(ho - hf)^{\frac{1}{2}} \times b}}$$

where L = roll load, R = roll radius

ho = initial thickness, hf = final thickness

b = contact width

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PROPERTIES OF HOT AND COLD ROLLED STRIP FROM IRON POWDERS

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PROPERTIES OF HOT AND COLD ROLLED STRIP FROM IRON POWDERS

ABSTRACT

The investigation is an extension of earlier work[1] (Powder Metallurgy, 1975, Vol.18, No.36 P.323) which described the deformation during hot rolling of iron powder compacts. This new paper discusses the effect of several variables of the powder rolling process, including compaction, pre-heating, hot reduction, cold reduction and annealing on the final properties of the finished product. Six different routes with three commercially available powders, Höganäs NC 100 and ASC 100, and Rospol MP 32, have been investigated and the results show that ultimate tensile strength, elongation and surface finish are attainable comparable to those of conventional strip but they are dependent on the process route employed. Variables which most affect the mechanical properties are sintering temperature, percentage hot reduction and percentage cold reduction. Hardness is shown to be constant across the strip and a very good surface finish is obtained.

INTRODUCTION

In recent years the steel industry has been attempting to find new methods of producing thin strip. The powder processing routes appear to be very versatile and possibly economic because they eliminate ingot casting, hot rolling of ingot and slab, and much of the cold rolling as well as intermediate annealing processes. Roll compaction of powder is already in commercial practice for nickel and cobalt strip. Experience with these plants has shown that high yields can be achieved, since little edge trimming is required.

It should be noted,[2] however, that nickel and cobalt are readily available in suitable powder form at prices that make roll compaction favourable even on a small scale. Ferrous based powdered materials which, for the development of new methods, are attractive because of their large scale applications, are not yet available at a sufficiently low price level. Consequently, if steel strip is to be produced economically by powder metallurgical methods, low-cost powder production must be developed.

Singer[3] noted that despite a lot of industrial development work, no process has yet been operated which has enabled iron powder to be produced at a sufficiently low cost that it can be converted into iron or steel strip comparable in price with low carbon steel strip produced by conventional methods. The aim of the present work is to study the strip properties obtained by hot and cold rolling of iron powder compacts. Weaver et al[4] have found the strength for a given reduction to increase with increasing sintering temperature within a range of 850 to 1040°C. They also claimed that hot rolled strip strength was independent of initial density. Several workers[5,6] have suggested that the initial cold reduction must be limited to 20% but subsequent reductions could be greater. If this initial reduction could be increased without attendant adverse edge cracking effects it could, in an industrial plant, improve the economy of the process significantly by decreasing the number of passes.

MATERIALS USED

Three powders - Höganäs water atomised type, ASC 100 and direct reduced type NC 100, and Rospol water atomised type MP 32 were used in this work. The powder properties are shown in Tables 1 and 2. Stereoscan photographs of the powder particles are shown in Fig. 1(a-f).

EXPERIMENTAL METHOD

Six routes, outlined in Table 3, were selected for study. There were six main variables, viz. compacting pressure, pre-heat temperature, hot reduction, annealing temperature and time, and cold reduction at the values shown in Table 3.

The iron powder green compacts (76 x 13 x 4-6 mm thick) were produced on a 300 ton Dennison single acting press using a rectangular die cavity (76 mm x 13 mm). The floating die assembly used, shown in Fig.2 gave results similar to those that would have been obtained on a double acting press, i.e. compaction proceeded from the top and bottom surfaces towards the middle. Pressing was carried out at the predetermined pressures and a dwell time of about two seconds was allowed to ensure that the correct pressure was attained. The average green density of the compacts was found from their dimensions and mass. The length and width of the compacts were taken to be those of the die cavity and the thickness was obtained by measuring at three different points along the specimen and taking the average. The compacts were weighed and the density calculated. In Table 4 green densities of the three powders have been compared.

The compacts were pre-heated at the required temperatures and hot rolled in one pass. The general view of the rolling mill and other related apparatus is shown in Fig.3. Annealing was achieved in 10% hydrogen/nitrogen gas atmosphere. For various routes different annealing schedules as shown were used.

Between hot and cold rolling stages the mill rolls (154 mm diameter x 203 mm width) were changed and the roll speed was kept at 40 rev/min (i.e. $\sim$ 20 m, min^{-1}). The cold rolls were lubricated with oil. It was found that 40-50% reduction could be achieved in a single pass during cold rolling. Difficulties were experienced with the bending of specimens during rolling, especially when the strips were thin. However, this phenomenon is not expected to occur when continuous lengths of strip are rolled with correct tensions applied.

Annealing of hot rolled compacts were carried out in a muffle furnace with a metal tube. A H_2/N_2 gas mix was used to provide a reducing atmosphere and this was dried by passing through silica gel crystals before entering the furnace.

TENSILE TESTING

Throughout this work edge cracking did not pose any problems with the three powders used. In the majority of cases no edge trimming was required even when hot reducing by 60% in thickness and only for specimens which had undergone these very heavy reductions with 700°C pre-heat did significant cracking occur (up to 0.6 mm for ASC 100 and NC 100 and up to 2 mm for MP 32).

The tensile test specimens were machined with the dimensions shown in Fig.4.

It must be noted here that the thickness of specimens was not always the same due to the previous compacting and rolling schedules and therefore their dimensions were not standard. The specimens were tested on a Hounsfield tensometer. Their dimensions were in the same geometrical ratio to those of a standard Hounsfield est piece and so the results would be expected to differ only slightly from the standard. The results obtained should have been less for the test specimens due to grain size effect. To prove this a few larger green compacts (110 x 25 mm) were produced and rolled. Two tensile test-pieces were cut from each strip, one with standard dimensions and the other non-standard, as used in the experimental work. Results given in Table 5 show that tensile strengths obtained using standard test pieces were higher than non-standard ones. Therefore ultimate tensile strength results presented would have been marginally higher if standard test pieces had been used.

EXPERIMENTAL RESULTS

Some 400-500 experiments were made during this work and therefore only means of several tests have been plotted on the following diagrams and statistical analysis has been applied to obtain overall effects of the variables on the final properties. Thus, on Figures 5 and 6 each point represents the mean of three results for the ultimate tensile strength and elongation percentage at each stage of the process.

In the initial work ASC 100 powder was used to test all six routes but it was found that the final properties obtained from routes V and VI were approximately equivalent to those from routes III and IV. Therefore these routes were not used in later experiments with NC 100 and MP 32. The results shown in Table 6 which include all six variables demonstrated the overall values obtained within 95% confidence limits for strip greater than 94% dense.

DISCUSSION

The process of hot rolling powder preforms can be divided into five stages viz:

a) the cold compaction to produce the original preforms,

b) preheating prior to rolling,

c) hot rolling reduction,

d) annealing of hot band,

e) cold rolling and annealing to final strip.

As shown in the experimental design the six routes chosen allowed the products formed at each stage to be examined and tested and thus determine those variables which control the properties and quality of the final strip.

The compressibility of Höganäs NC 100 powder (see Table 4) is not as high as that of the other two powders. This is probably due to the high impurity content and also the shape of its particles. Figs 1(a-f) show Stereoscan photographs of the three powders - Höganäs ASC 100 (atomised, super compressibility), MP 32 (atomised, high compressibility) and NC 100 (sponge reduced, normal compressibility). The NC 100 powder is more angular and will not pack as well as the more spherical ASC 100 particles. Also NC 100 is a directly reduced iron powder which is spongy and more porous than the water atomised ASC 100, and has a greater oxygen content and these factors will tend to reduce the apparent density. In the case of MP 32, the presence of 0.12% manganese and higher carbon might be the cause of density differences due to the effect of manganese on strain hardening resulting in a higher pressure required for deformation. The compressibility of ASC 100 is naturally very high and this has been attributed to its favourable size distribution and its physical and chemical properties. Bonding during compaction was mainly due to cold welding taking place by the shearing off of surface irregularities of the particles, thus providing clean metal to metal contact. The difference between the compaction behaviour of the three powders as described in earlier work[1] is due to the difference in the extent of Stages I and II of the compacting process. The first stage (I) being the filling of the die cavity, the second (II) characterised by individual particle movement and re-arrangement. This must have been due to the differences between the particle properties and chemical composition. Once Stage III[1] (mainly bulk deformation) has been reached the three powders behave in a similar manner. As the particles slide past one another they deform, but at the same time they are being re-arranged.

To determine the correct pre-heating temperature and the required time to heat completely through the green compacts a series of sintering tests were made at 900, 1000 and 1100°C for 5, 20 and 60 mins. In Tables 7(a-c) the strength (U.T.S.) of cooled compacts are given at 5, 20 and 60 mins. The values at 5 mins sintering were slightly lower due to incomplete heating through the specimens and those at 60 mins were significantly higher than those at 20 mins. However, it was not the aim of this work to produce a very high strength in the pre-heated compacts and therefore the time for pre-heating was fixed at 20 mins. This time had also been determined as described in the previous paper[1] by inserting thermocouples in the compacts and the actual rolling temperatuure was achieved by applying the necessary correction to the pre-heat temperature. Table 7 indicates the difference in the pre-heated compact properties (albeit determined at room temperature) and reflect the original powder properties. Since these compact properties change considerably during subsequent processing it might be useful to compare the powders with their as sintered properties. The advantageous compressibility of ASC 100 powder compared with NC 100 and MP 32 is reflected in the original compact green density and at low compaction pressures this higher density is reflected in higher sintered properties. However, it should be noted that the advantages of ASC 100 as a starting material are reduced as mechanical work (i.e. compaction) is increased and MP 32 then appears in general better when final strength is taken as the determining factor. In all cases NC 100 is lower in final strength which may be due to its high oxygen content compared with ASC 100 and additionally, lower carbon and manganese than MP 32. A significant feature was observed in the rolling loads at 900 and 1000°C (see Table 8), those at 900°C were lower than at 1000°C. This is the opposite to what would be expected from yield stress considerations for the iron powders. A lower yield stress at 1000°C ought to give lower rolling loads than at 900°C. The reason for this may be in the material being rolled. From the temperature measurements the compacts pre-heated to 900°C will consist of ferrite and austenite whilst the compact pre-heated at 1000°C will consist entirely of austenite. Ferrite is a body-centred cubic material, whereas austenite is face-centred cubic. Cross-slip which occurs in rolling is a thermally activated process, and is also aided by a high stacking fault energy. Therefore cross-slip will be easier in body-centred cubic materials at temperature, than in face-centred cubic. Therefore body-centred cubic material will deform more easily at temperature than face-centred cubic.

It can be seen from (Figure7) that an increase in pre-heat temperature will increase the ultimate tensile strength values.

During hot rolling the rolls were not pre-heated and therefore they had a chilling effect upon the strip being rolled. This is shown in Figures 8(a) and (b) for the rolling of ASC 100 powder compacts pre-heated to 1000°C. It can be seen that the roll chilling inhibited recrystallisation at the surface of the strip and this extended to about one quarter of the thickness from each surface.

It was shown in the previous work that hot compaction in the roll gap consists of three main stages which may overlap.

1. Restacking and rearrangement of particles during entry to the mill.
2. Local plastic deformation and particles folding over.
3. Bulk plastic flow leading to elongation and recrystallisation of grains.

From the microstructure of the cooled hot band it was shown that above 95% density the material in the roll gap elongates and behaves more and more like 100% solid material, and it was suggested that further densification would be desirable only to improve the mechanical properties of the hot band. In Fig.9 the improvement in U.T.S. with increasing hot rolled density is illustrated and confirms the point that little improvement in properties is obtained by increasing density beyond 95%.

It can be seen from Fig.10 that an increase in green density of the compacts achieved by higher compacting pressures and an increase in hot reduction can increase the ultimate tensile strength of the rolled strip.

Annealing of the hot band improves its ductility due to the elimination of the elastic distortion of the crystal lattice (i.e. recovery). At higher annealing temperatures, new grains form (recrystallisation) and grow. Due to this recovery and recrystallisation the strip is softened and increases its ductility.

Annealing was investigated at temperatures of 650°C, 800°C, 900°C and 1100°C; the first being in the ferrite-cementite region just below A_1, the second in the austenite-ferrite region, the third on the austenite and austenite-ferrite boundary, and the fourth in the austenite region. Annealing times were also varied as can be seen from Table 3. The compacts were left to cool in the furnace to about 300°C before they were cooled in air. The percent elongation of the hot band was increased by giving an annealing treatment. From the results obtained by route II it can be seen that it is technically possible to get equivalent tensile properties of steel strip to BSS 1449 (shown in Table 9) but from the final surface finish point of view it will not be practicable to use annealed hot band directly obtained from route II. Nevertheless it could be useful to investigate the possibility of producing and using it in a developing country.

To achieve consistent properties and good surface finish in the final product, hot rolled and annealed strip produced from route II should be further processed, preferably by cold rolling. The results of route III are shown in Fig. 11 which shows the effect of cold working on increasing ultimate tensile strength and decreasing the elongation values.

It was found that 40-50% cold reduction could be achieved in a single pass without any adverse edge cracking effects. This could, in an industrial plant, improve the economy of the process significantly by decreasing the number of passes. The present work does not therefore agree with several workers[5,6] who previously have suggested that the initial cold reduction must be limited to 20% although subsequent reductions could be greater.

As far as cold rolled strip is concerned green density does not exhibit a significant effect. The main variable controlling the ultimate tensile strength of the cold rolled strip is final cold reduction (Fig.11).

To improve the elongation values, process route III was followed by annealing at different temperature for various times. The results of annealing after cold working indicates that elongation values can be increased considerably.

The results obtained from routes V and VI for ASC 100 were approximately equivalent to those from routes III and IV (see Table 6). Therefore these last two routes were not followed in later experiments with MP 32 and NC 100.

The properties determined for all three powders were ultimate tensile strength and percentage elongation as these are the two properties specified most frequently and therefore would dictate the selection of a suitable route for manufacture of steel strip using a given powder. It must be borne in mind that the tensile strength and elongation values are subject to inaccuracies, due to tearing of the specimens in the grips during testing, to oxidation at the surface and to defects caused during rolling and machining. Referring to Figs.5, 6, in which the ultimate tensile strength and elongation values are plotted for the six routes for ASC 100 a general trend can be drawn considering only the results from routes II and IV and these are reproduced in Fig.7. This shows that an increase in preheat temperature will increase the ultimate tensile strength and elongation values depending upon the process route. It will be noted that the trend lines on Figs. 5 and 6 have been extended tentatively beyond the valid results for the U.T.S. obtained from routes II and IV, but in Fig. 7 only the valid portions of the two lines have been reproduced. Also plotted on Fig. 7 are the properties specified in B.S.1449 Pt I 1972 for steel strip as recorded in Table 9. This means that it should be possible to manufacture hot and cold rolled strip specified from conventional strip properties by preheating at the designated temperature and following a suitable route. Furthermore, on the basis of the data available (table 6), it should be possible to get the required final properties. Any one of the powders can be used even using low pressure for compaction. However, one has to alter the process route to achieve the final strip.

From Table 6 there appears to be a significant difference between the ultimate tensile strength values of the hot band of ASC 100 and MP 32 on the one hand and NC 100 on the other which is reproduced after an annealing treatment. There seems to be no reason why NC 100 should be low except for the oxygen content. If this is present mainly as inclusions then it is possible that they could weaken the matrix but it must be admitted they should have a similar depressing effect upon the elongation values. The great difference between the two Höganäs powders is the greater compressibility of ASC 100 material which always gives a much higher green density than

NC 100 but the densities of MP 32 green compacts is intermediate. During the preheating and hot rolling operations the densities of the MP 32 and ASC 100 hot bands become very similar and therefore the strengths become much more alike but after cold rolling and annealing ASC 100 powder gives higher values for elongation and lower values for ultimate tensile strength. The reason for this may be due to the presence of 0.2% oxygen in MP 32 which if distributed finely throughout strip may pin down the grain growth, resulting in low elongation. The higher ultimate tensile strength values are more likely to be due to the presence of higher carbon and manganese content of this powder.

HARDNESS

It has been found that hardness (V.H.N.) remained constant across the strip samples obtained from a particular process route in which intermediate annealing and cold working were involved.

SURFACE FINISH

With respect to this property the product from a powder metallurgy route is likely to start with an advantage, as it will not have gone through the process stages at which surface defects are most likely to occur in the conventional production routes. Only small slag inclusions are present in the powder and oxide particles appear as a fine dispersion throughout the structure. Forty specimens were examined by Talysurf Model 3 at three points on their surfaces and the mean for these measurements was obtained (Table 10) - 0.26 μm (≡ 10.15 micro-inches) which is a very good surface finish and appears to be equivalent to anything that can be produced by conventional production of strip, Fig.12[7], hence plating and painting on these surfaces should be no problem.

The main function of cold working in powder steel strip is the same as in conventional steel strip, i.e. to get the required final gauge, shape and surface finish. As it is clear from Fig.9 beyond a level of about 95 percentage density there is no significant increase in U.T.S. and therefore the required strength can be obtained by cold rolling.

CONCLUSIONS

In the production of strip from iron powders:

1. The conventional standards of U.T.S., elongation and surface finish in the final product can be obtained by adjusting the process route and the amount of cold reduction, irrespective of powder used.
2. Green density can be kept low to save energy and die wear at the compacting stage.
3. Pre-heat temperature before hot rolling is significant in the achievement of final properties.
4. The main process variables of tensile strength for the hot rolled strip were sintering temperature and hot reduction. Further it was observed that strength varied with density up to 95%.
5. It is possible to achieve 95% density in one pass for all three powders at the hot rolling stage.
6. The U.T.S. of cold rolled strip was mainly dependent upon the sintering temperature and cold reduction and

unlike hot rolled U.T.S. it was nearly independent of green density.

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TABLE 1. Chemical Analyses of Powders

Designation	POWDERS		
	Höganäs ASC-100	Höganäs NC-100	Rospol MP-32
Method of Manufacture →	Atomization	*Reduction*	Atomization
Composition			
C	0.014%	<0.01%	0.073%
Mn	Trace	<0.01%	0.12%
Si	Trace	0.068%	0.04%
P	0.003%	0.006%	0.01%
S	0.003%	0.001%	Trace
O	0.096%	0.459%	0.2%
Apparent density g,cm^{-3}	3.02	2.4	2.51
Tap density g,cm^{-3}	3.92	3.28	3.23

TABLE 2. Screen Analyses of Powder

Particle size µm	Höganäs ASC-100 %	Höganäs NC-100 %	Rospol MP-32 %
+ 180	1.46	<0.001	0.22
149 - 180	12.5	9.1	3.03
104 - 149	20.0	26.3	21.6
74 - 104	24.7	28.4	32.5
53 - 74	23.0	21.8	25.7
<53	18.3	13.9	17.0
Average size µm	76	79	73

TABLE 3.

PRODUCTION ROUTES

	3 POWDERS (ASC 100, NC 100, MP 32)
	↓
	COMPACTION (155, 232, 310, 386 N, mm^{-2}) (10, 15, 20, 25 T, in^{-2})
	↓
	PRE-HEATING (700, 800, 900, 1000°C) for 20 mins
	↓
End of Route I.	HOT REDUCTION (20, 30, 40, 50, 60%)
	↓
End of Route II.	ANNEALING (650, 800, 900, 1100°C for 20, 30, 40, 60 mins)
	↓
End of Route III.	COLD REDUCTION (20, 30, 40, 50%)
	↓
End of Route IV.	ANNEALING (650, 800, 950, 1100°C for 20 and 60 mins)
	↓
End of Route V.	COLD REDUCTION 20% (ASC 100 only)
	↓
End of Route VI.	ANNEALING (950°C for 20 and 40 mins)

TABLE 4. Green Density of Powder Compacts (g, cm^{-3})

	Compacting Pressure (N, mm^{-2})		
Powder	155	232	386
ASC 100	5.55	6.04	6.7
NC 100	5.06	5.67	6.4
MP 32	5.34	5.85	6.5

TABLE 5. Comparison between standard and non-standard specimens

Specimens	Compaction pressure N, mm^{-2}	Sintering Temperature °C	Hot Reduction %	Rolling Pressure N, mm^{-2}	Elong: %	U.T.S. N, mm^{-2}
Standard	232	900	62.5	168	28.1	388
Non-standard	232	900	62.5	168	26	384
Standard	386	900	66.6	211	43.8	401
Non-standard	386	900	66.6	211	32	369
Standard	386	1000	63.5	221	43.7	416.5
Non-standard	386	1000	63.5	221	32.8	384

TABLE 6. U.T.S. and Elongation Data for the six routes

Properties	Route I Die Compaction→preheating→hot reduction		
	POWDERS		
	ASC 100	NC 100	MP 32
U.T.S. N,mm^{-2} (95% Conf.Limits)	349 ± 18	287 ± 17	345 ± 28
Elongation % (95% Conf.Limits)	18 ± 2	16 ± 3	9 ± 3

Properties	Route II Die Compaction→preheating→hot reduction →annealing		
	POWDERS		
	ASC 100	NC 100	MP 32
U.T.S. N,mm^{-2} (95% Conf.Limits)	320 ± 16	276 ± 15	327 ± 14
Elongation % (95% Conf.Limits)	25 ± 4	23 ± 3	19 ± 2.5

Properties	Route III Die Compaction→preheating→hot reduction →annealing→cold reduction		
	POWDERS		
	ASC 100	NC 100	MP 32
U.T.S. N,mm^{-2} (95% Conf.Limits)	524 ± 21	452 ± 19	485 ± 28
Elongation % (95% Conf.Limits)	8 ± 0.7	5 ± 1	3 ± 1

Properties	Route IV Die Compaction→preheating→hot reduction →annealing→cold reduction→annealing		
	POWDERS		
	ASC 100	NC 100	MP 32
U T.S. N,mm^{-2} (95% Conf.Limits)	346 ± 23	294 ± 16	376 ± 18
Elongation% (95% Conf.Limits)	31 ± 3.4	27 ± 2	25.4± 2

TABLE 6. (Contd.)

Route V ASC 100 only	
Die Compaction→pre-heat→hot reduction→annealing→cold reduction →annealing→cold reduction	
U.T.S. N,mm^{-2} (95% Conf.Limits)	501 ± 34
Elongation % (95% Conf.Limits)	10 ± 2

Route VI ASC 100 only	
Die Compaction→pre-heat→hot reduction→annealing→cold reduction →annealing →cold reduction→annealing	
U.T.S. N,mm^{-2} (95% Conf.Limits)	348 ± 16
Elongation % (95% Conf.Limits)	29 ± 2

TABLE 7a. **The dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 5 min)**

Compaction pressure N, mm^{-2}	Sintering Temperature ^{o}C	ASC 100		NC 100		MP 32	
		Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}
155	900	5.6	44.3	5.1	30.5	5.4	44.6
	900		36.7		28.3		53.9
	1000		65.6		55		53
	1000		64.7		52.9		54.6
	1100		69.2		57.9		69.2
	1100		72.8		62.4		72.3
232	900	6.1	48.8	5.7	41.7	5.9	56.5
	900		56.3		31.6		55.8
	1000		86.6		56		80.8
	1000		86.9		55.6		81.7
	1100		109.1		100.2		101.1
	1100		100.2		91		106.5
386	900	6.8	66.5	6.4	45.6	6.5	60.6
	900		58.6		74.1		62.3
	1000		101.6		76.6		110.5
	1000		106.6		79.9		116.6
	1100		155.4		134.9		164.2
	1100		150.2		122.2		162.6

TABLE 7b. Dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 20 min)

Compaction pressure N, mm^{-2}	Sintering Temperature ^{o}C	ASC 100		NC 100		MP 32	
		Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}	Sintered Density g cm^{-3}	U.T.S. N, mm^{-2}
155	900	5.6	60.9	5.1	44.2	5.3	49.8
	900		61.2		47.8		51.9
	1000		66.3		54.4		57.8
	1000		65.8		54.6		54.5
	1100		71.6		64.8		72.6
	1100		74.5		61.2		69.4
232	900	6.0	89.8	5.7	81.7	5.9	85.9
	900		84.3		80.3		92.2
	1000		86.1		85.9		99.3
	1000		89.1		83.9		95.5
	1100		106.9		92.5		104.1
	1100		104.6		101.1		108.9
386	900	6.7	134.7	6.4	133.0	6.5	150.2
	900		122.0		123.9		135.0
	1000		146.0		126.2		147.0
	1000		142.6		137.5		154.3
	1100		172.8		153.5		185.9
	1100		157.8		161.4		172.3

TABLE 7c. Dependence of U.T.S. on sintering temperature for constant sintered density (sintering time 60 min)

Compaction pressure N,mm^{-2}	Sintering Temperature ^oC	ASC 100		NC 100		MP 32	
		Sintered Density $g\ cm^{-3}$	U.T.S. N,mm^{-2}	Sintered Density $g\ cm^{-3}$	U.T.S. N,mm^{-2}	Sintered Density $g\ cm^{-3}$	U.T.S. N,mm^{-2}
155	900	5.6	62.2	5.1	48.1	5.4	56.9
	900		68.2		43.5		61.0
	1000		78.3		69.9		87.4
	1000		94.5		60.8		94.2
	1100		133.3		101.1		125.1
	1100		128.7		110.0		127.4
232	900	6.1	89.6	5.7	82.5	5.9	76.2
	900		89.2		79.2		98.2
	1000		108.6		88.9		98.9
	1000		98.2		81.4		99.9
	1100		184.0		132.2		157.5
	1100		182.4		120.2		149.9
386	900	6.8	128.7	6.4	129.9	6.5	124.2
	900		133		129.2		143
	1000		138.8		138.3		126.6
	1000		149.9		132.2		144.2
	1100		203.9		160.2		159.9
	1100		196.9		157		170.5

TABLE 8. Rolling load for hot reductions

Powders →		ASC 100			NC 100			MP 32		
C.P. N,mm^{-2}	S.T. ^{o}C	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}	H.R. %	Roll Pressure N,mm^{-2}	U.T.S. N,mm^{-2}
155	900	45	108	274	41	39	202	51	91	341
155	900	66	175	319	65	103	289	62	144	362
155	1000	46	112	376	59	78	281	48	78	332
155	1000	66	186	401	39	36	274	62	145	373
232	900	41	98	283	49	86.5	293	48	87	356
232	900	62.5	168	384	64	125	309	62	175	374
232	1000	37.5	109	323	49	100	313	38	74	327
232	1000	66	198	386	64	126	337	44	68	307
386	900	47	161	296	38	89	264	45.6	111	366
386	900	66.6	211	369	64	117	296	63.5	160	387
386	1000	63.5	221	384	50	106	326	26.5	65.7	287
386	1000	40	156	352	64	143.5	340	48.5	123.5	373

Table 9. British Standard 1449, Part I 1972 Steel Strip

Material Grade	Quality	Tensile Strength N,mm^{-2}	Elongation percent on 50 mm gauge	C %	Mn %	S %	P %
HS1	Extra deep drawing	290	34	0.08	0.45	0.03	0.02
HS2	" "	290	34	0.08	0.45	0.035	0.03
HS3	Deep drawing	290	28	0.1	0.50	0.04	0.04
HS4	Drawing & forming	280	25	0.12	0.16	0.05	0.05
CS12	Rimmed	310	28	0.1-0.15	0.4-0.6	0.05	0.05
CS17	Rimmed	340	26	0.15-0.2	0.4-0.6	0.05	0.05
CS22	Rimmed	370	25	0.2-0.25	0.4-0.6	0.05	0.05

TABLE 10. Surface Finish

Mag.	1 reading C.L.A.	2 reading C.L.A.	3 reading C.L.A.	Average roughness height	
				C.L.A. micron	microinch
2000	0.2	0.12	0.11	0.14	5.51
	0.11	0.11	0.11	0.11	4.33
	0.2	0.3	0.2	0.23	9.06
	0.25	0.17	0.38	0.27	10.63
	0.2	0.2	1.8	0.73	28.74
	0.22	0.4	0.36	0.33	12.99
	0.2	1.6	0.35	0.72	28.74
	0.2	0.3	0.15	0.22	8.66
	0.19	0.21	0.15	0.18	7.09
	0.3	0.35	0.21	0.29	11.42
	0.1	0.1	0.15	0.12	4.72
	0.8	0.1	0.1	0.33	12.99
	0.35	0.4	0.3	0.35	13.78
	0.18	0.4	0.4	0.327	12.87
	0.24	0.18	0.2	0.207	8.15
	0.2	0.38	0.2	0.26	10.24
	0.15	0.16	0.18	0.163	6.42
	0.18	0.1	0.1	0.13	5.12
	0.4	0.28	0.2	0.29	11.42
	0.12	0.1	0.22	0.15	5.91
	0.2	0.28	0.22	0.23	9.06
	0.16	0.26	0.3	0.24	9.45
	0.35	0.32	0.4	0.36	14.17
	0.3	0.15	0.2	0.22	8.66
	0.46	0.18	0.11	0.25	9.84
	0.2	0.2	0.28	0.23	9.06
	0.2	0.4	0.15	0.25	9.84
	0.05	0.1	0.1	0.08	3.15
	0.18	0.18	0.22	0.19	7.48
	0.08	0.3	0.35	0.24	9.45
	0.12	0.2	0.12	0.15	5.91

TABLE 10. (Contd.)

Mag.	1 reading C.L.A.	2 reading C.L.A.	3 reading C.L.A.	Average roughness height	
				C.L.A. micron	microinch
	0.22	0.14	0.18	0.18	7.09
	0.03	0.21	0.7	0.31	12.2
	0.2	0.6	0.35	0.38	14.96
	0.35	0.28	0.15	0.26	10.24
	0.2	0.3	0.1	0.2	7.87
	0.16	0.3	0.6	0.35	13.78
	0.12	0.15	0.1	0.12	4.72
	0.2	0.4	0.48	0.36	14.17
Mean				0.26	10.15

C.L.A. = Central line Average

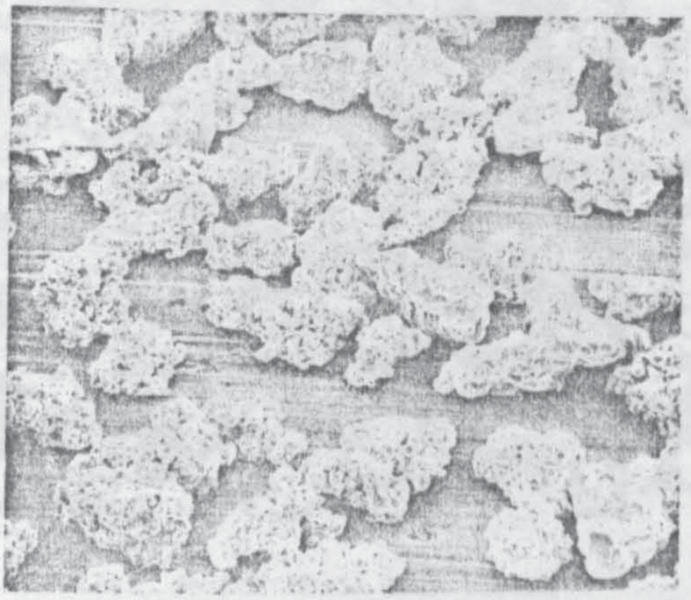


Fig.1a. Hoganas ASC-100 Iron Powder x 100

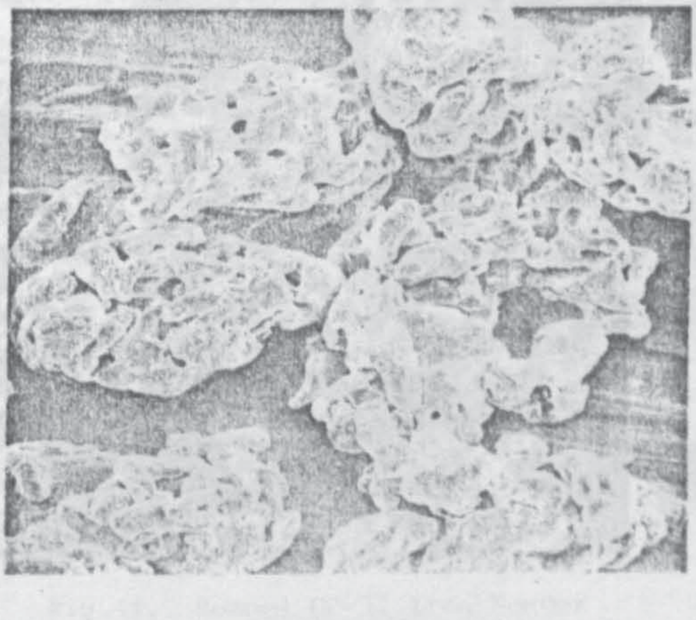


Fig.1b. Hoganas ASC-100 Iron Powder x 500

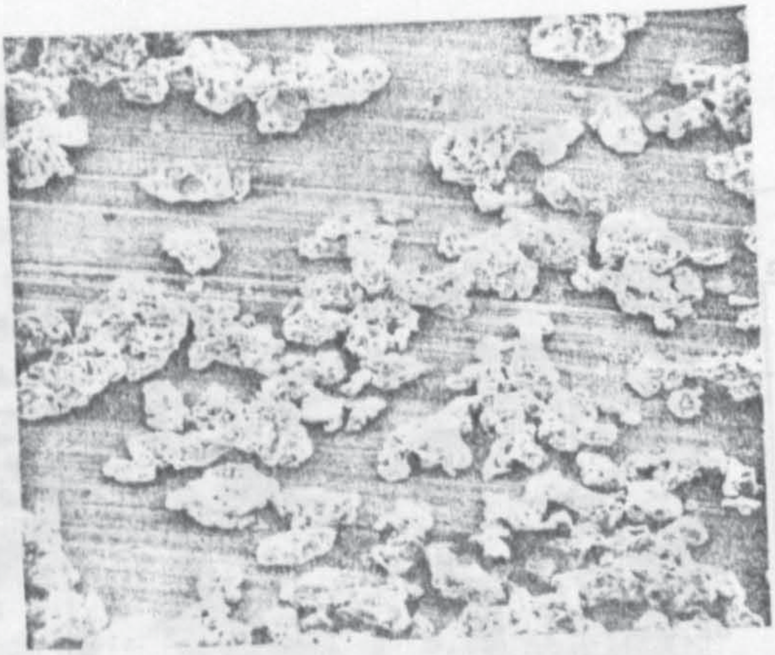


Fig.1c. Hoganas NC-100 Iron Powder x 100

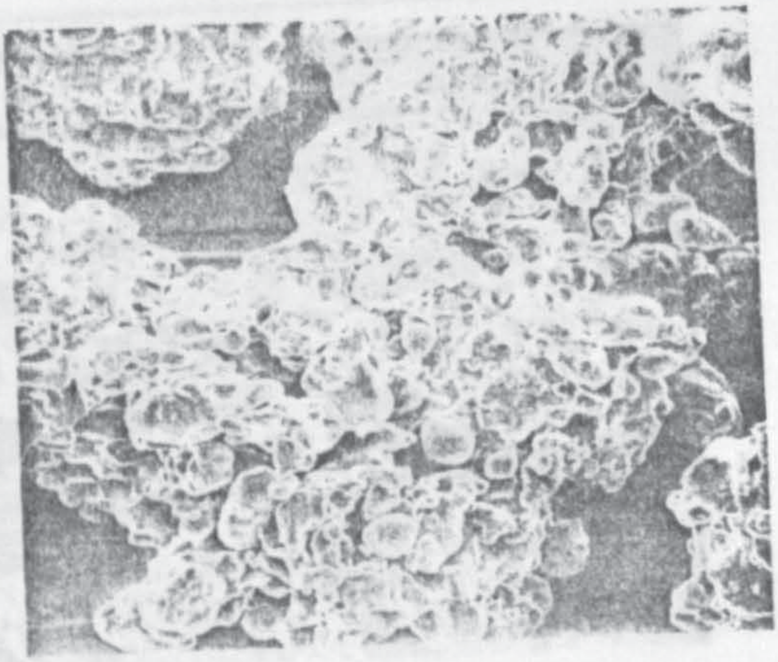
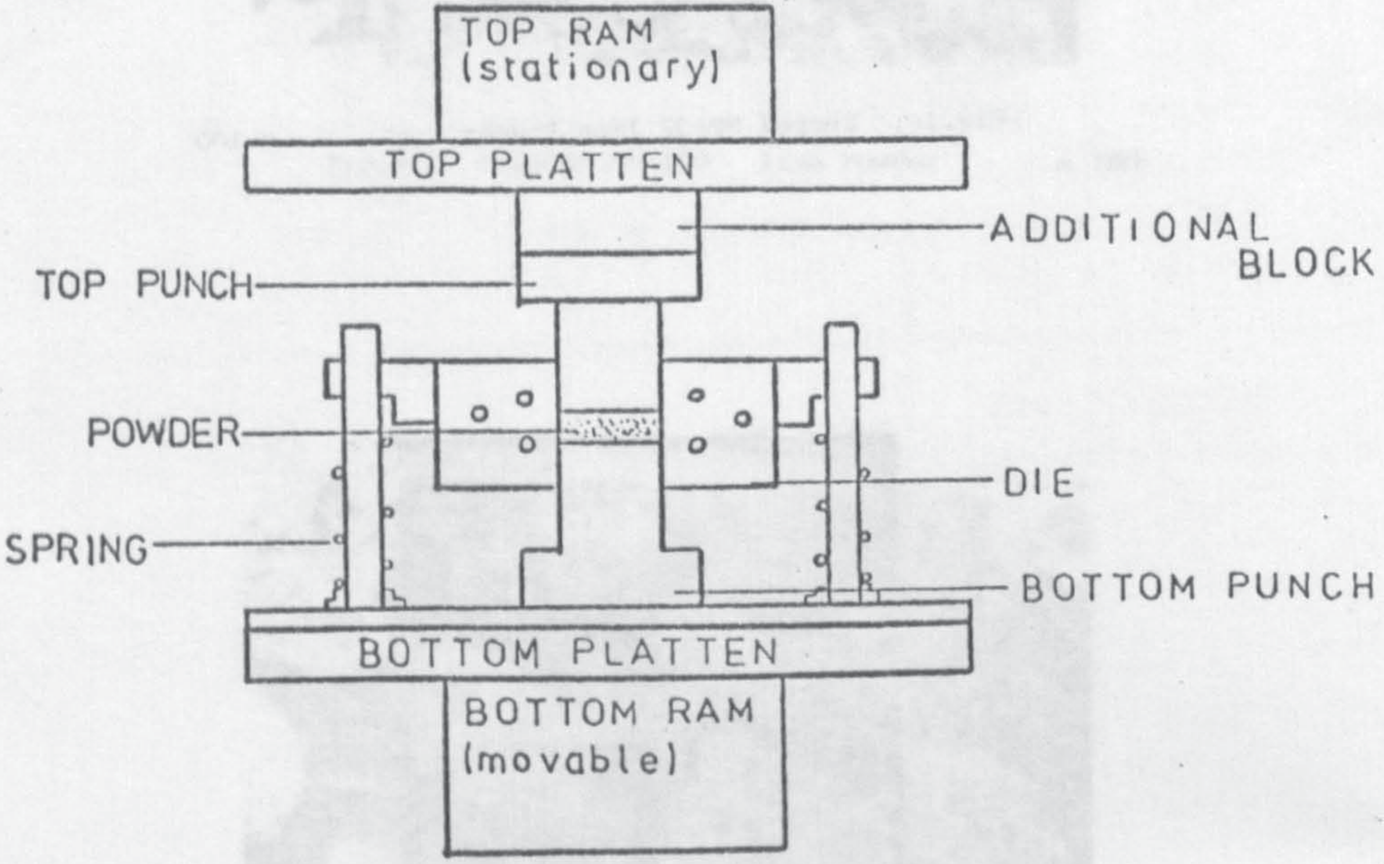


Fig.1d. Hoganas NC-100 Iron Powder x 500

Fig.1e. Rospol MP-32 Iron Powder x 100

Fig.1f. Rospol MP-32 Iron Powder x 500

FIG.2 COMPACTING ASSEMBLY



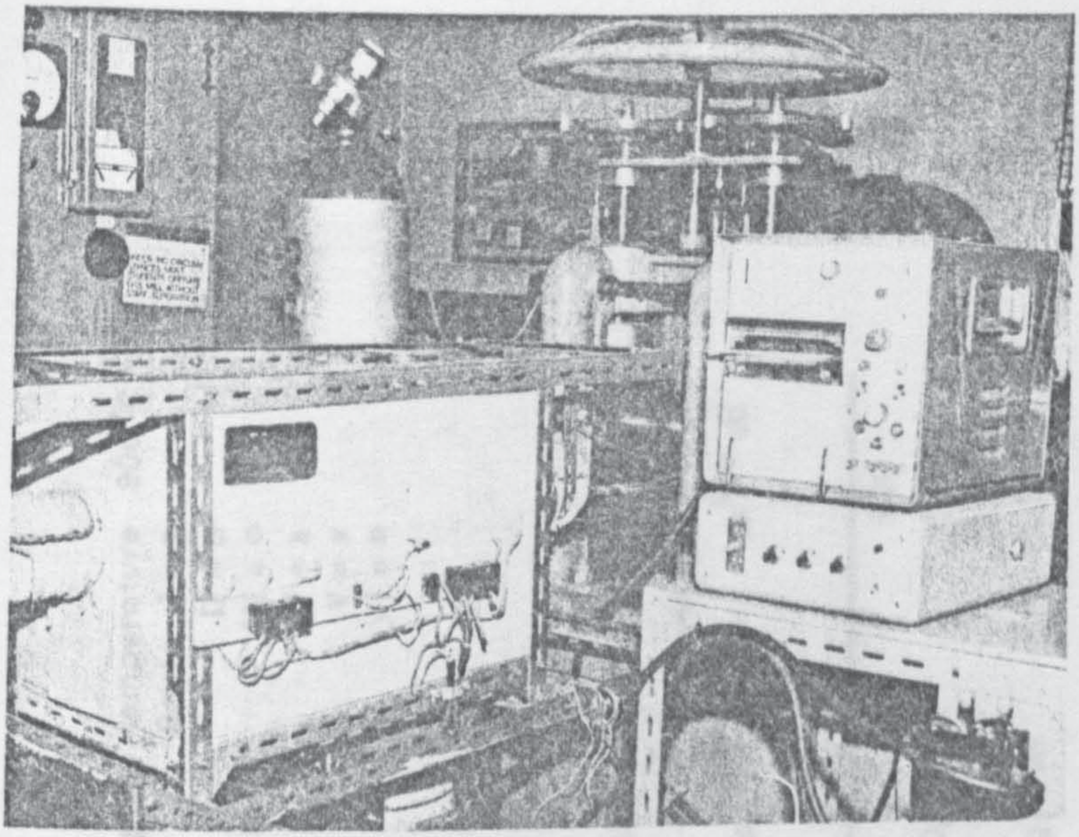
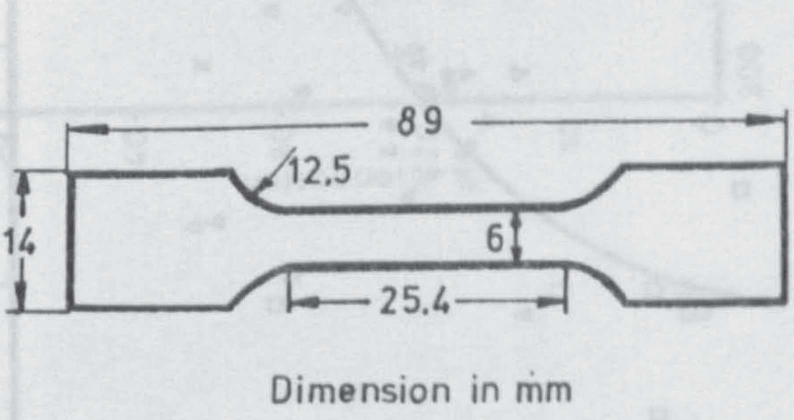


Fig.3. General View of Furnace/Rolling Mill Equipment

FIG.4 TENSILE TEST SPECIMEN



Dimension in mm

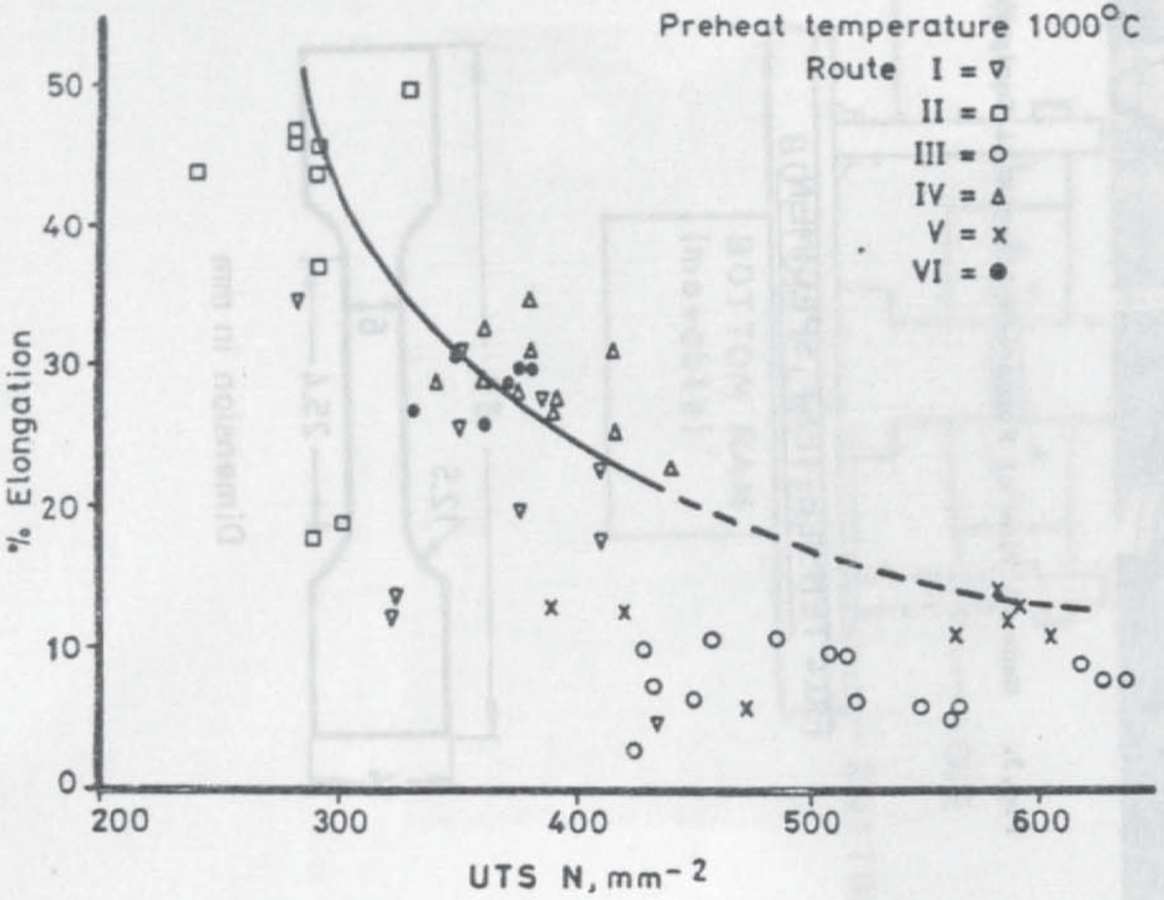


Fig 5 UTS vs Elongation

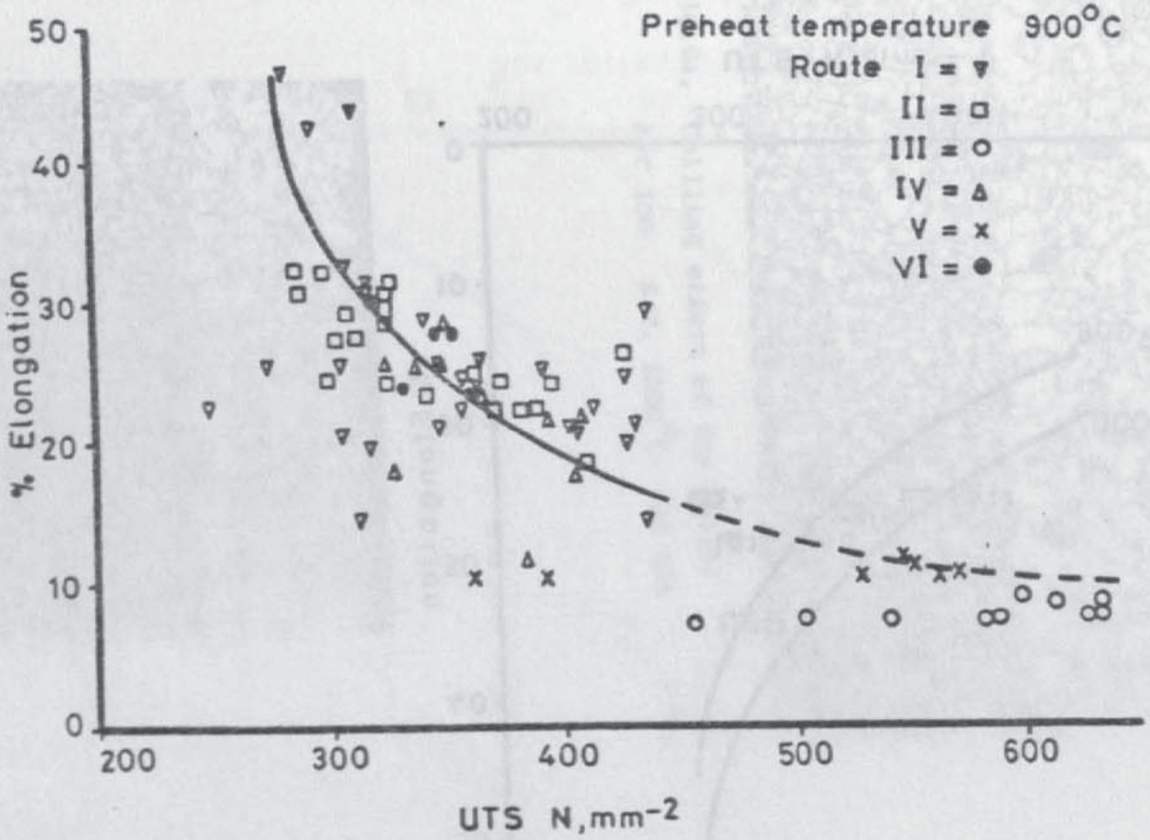


Fig 6 UTS vs Elongation

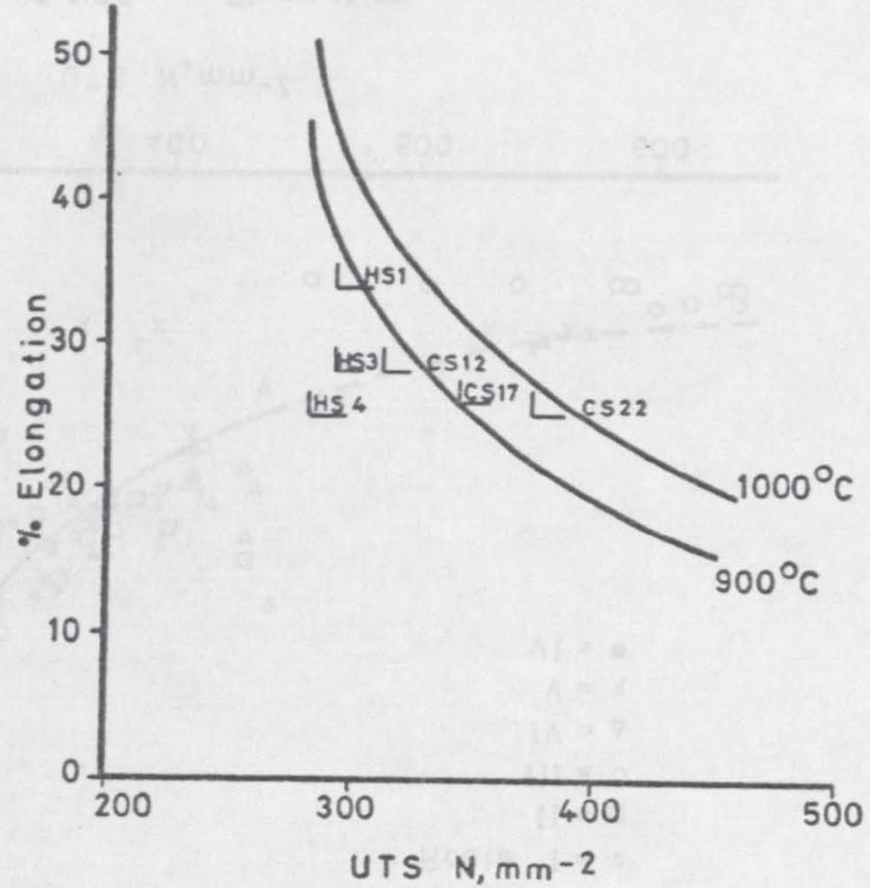


Fig 7 UTS vs Elongation

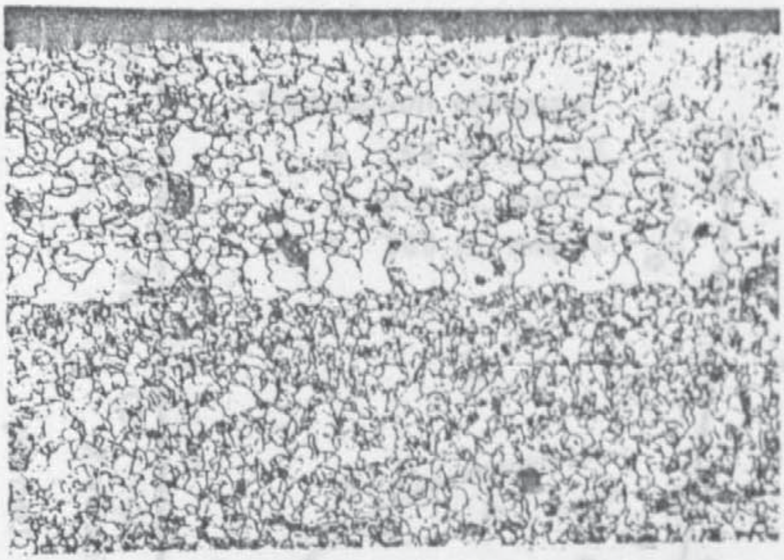


Fig.8a. Chilling effect of the rolls.
ASC 100 S.T. 1000°C HR 60% x 50

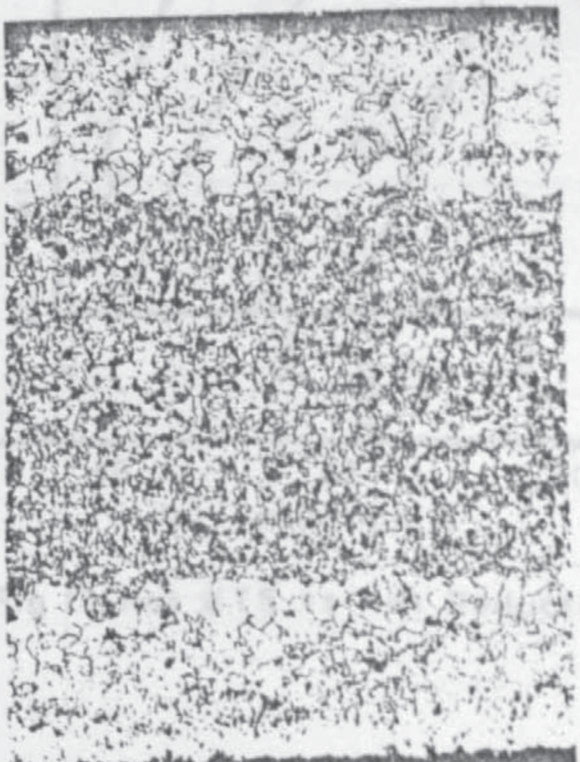


Fig.8b. Chilling effect of the rolls
ASC 100 S.T. 1000° C. HR 60% x 25

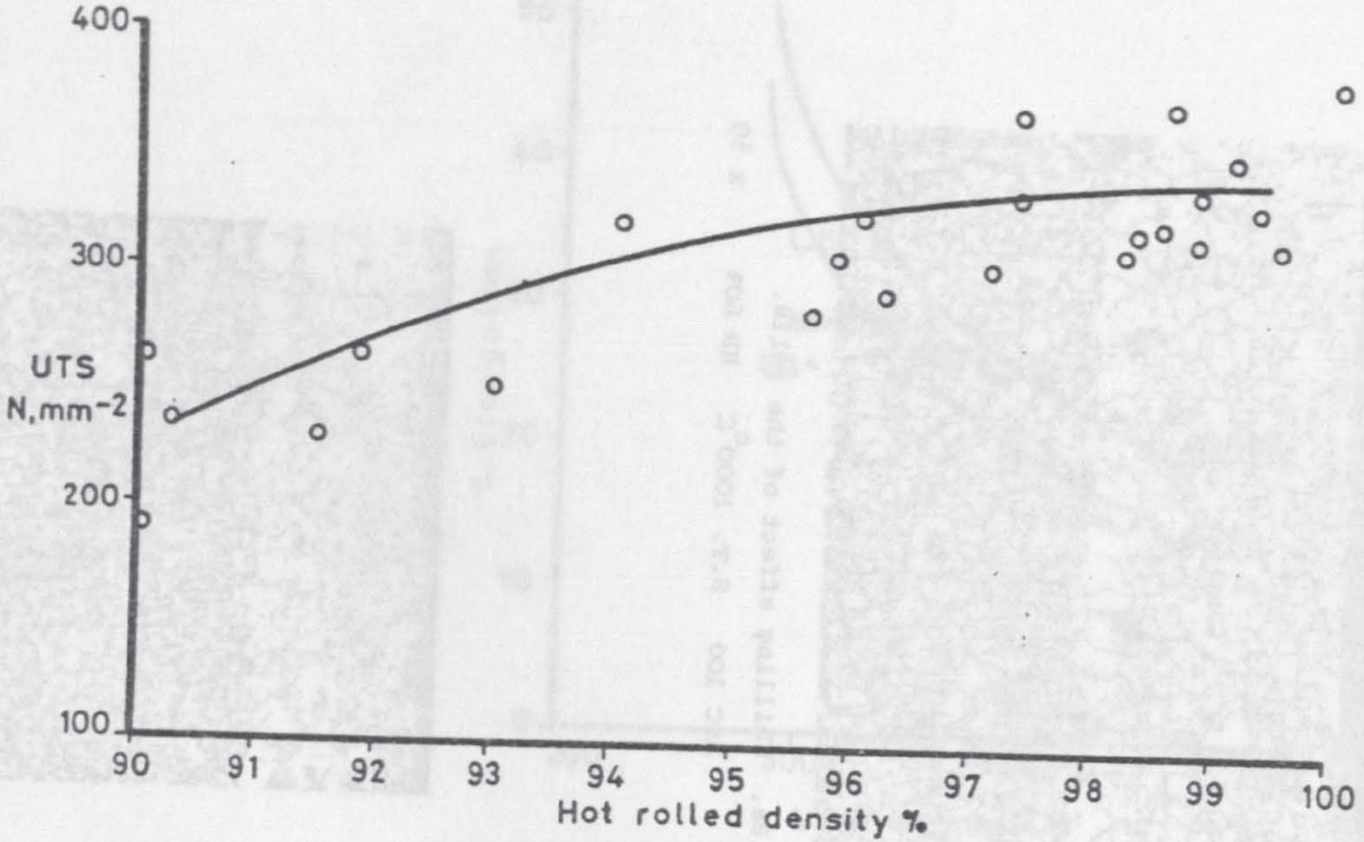


Fig 9 Hot UTS vs Hot Rolled Density

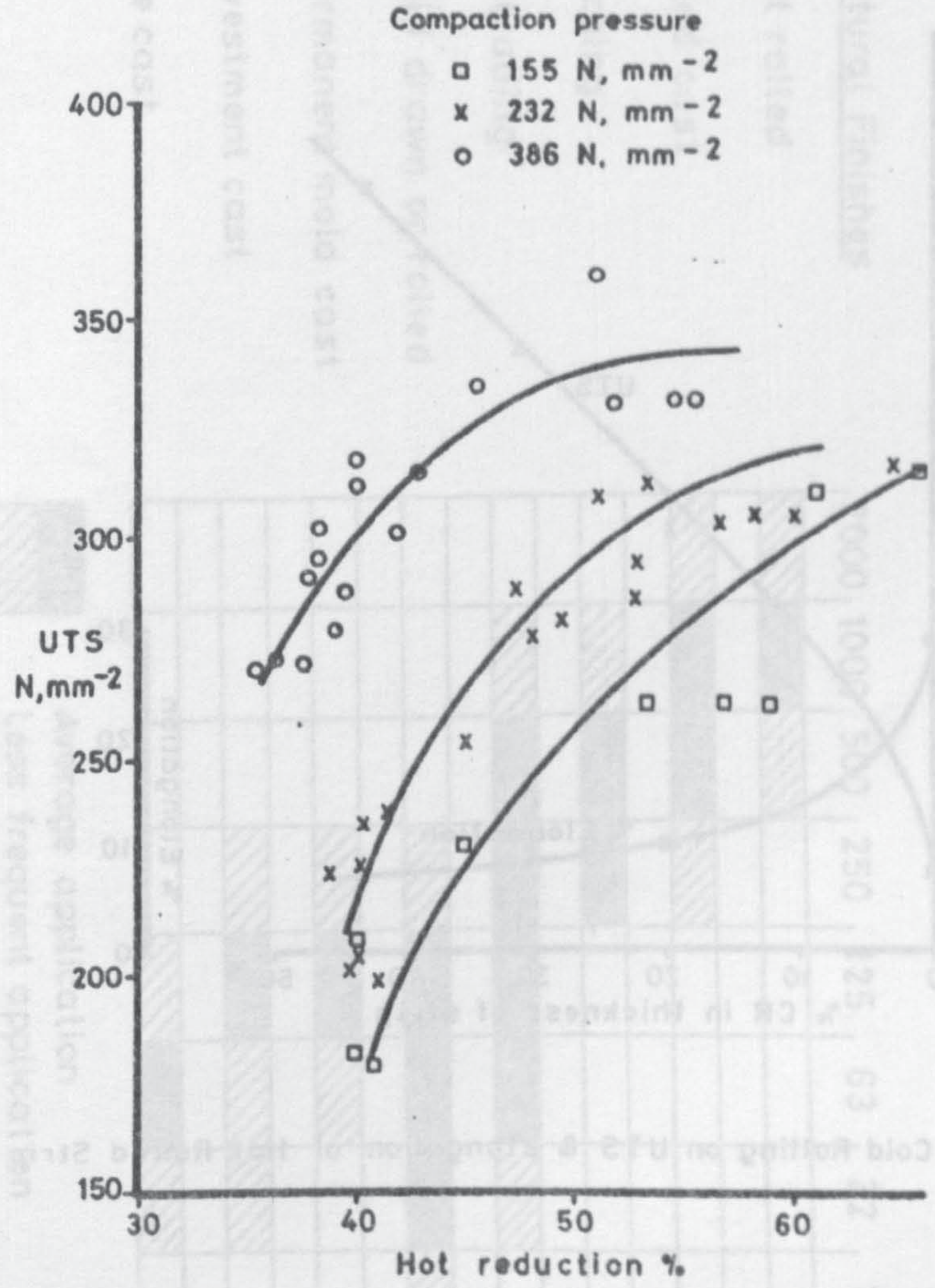


Fig 10 Hot UTS vs Hot Reduction

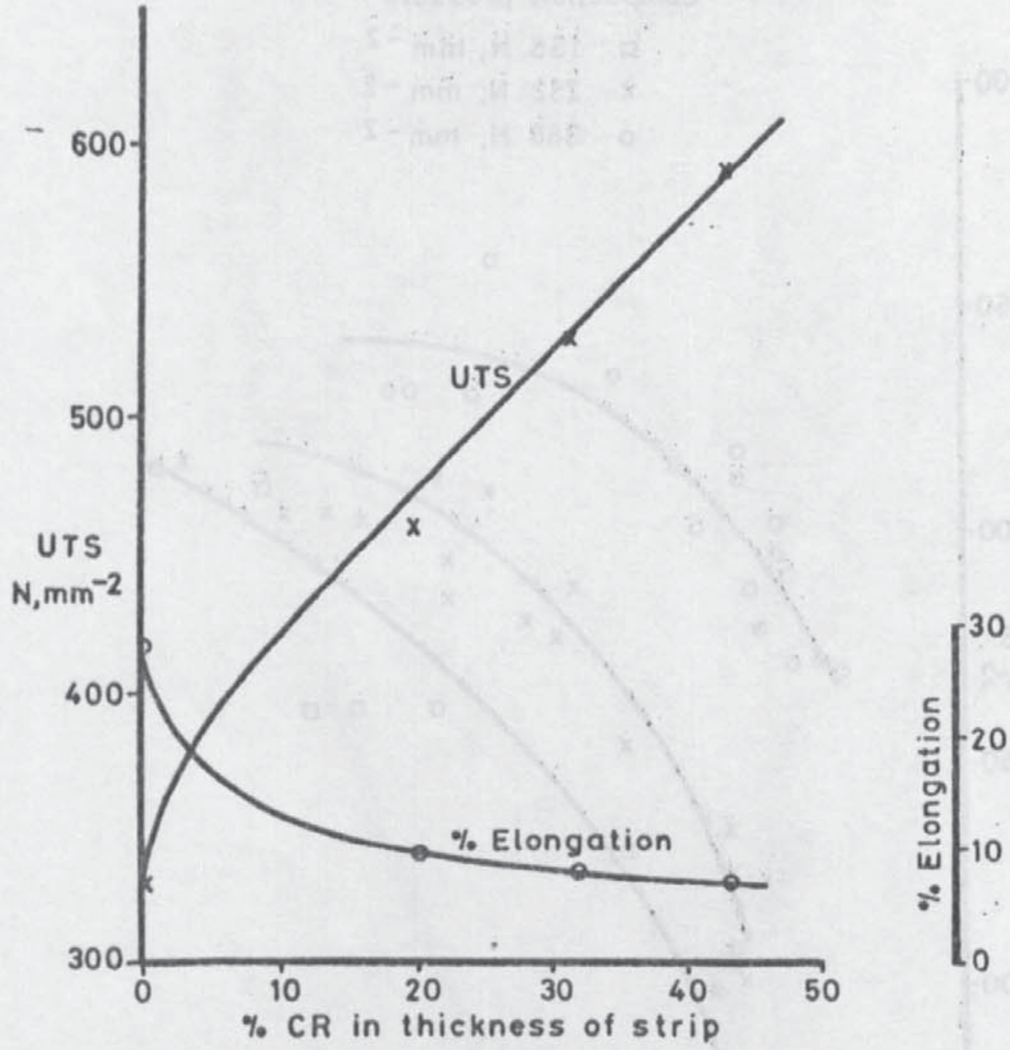


Fig 11 Effect of Cold Rolling on UTS & Elongation of Hot Rolled Strip

PROCESS	ROUGHNESS HEIGHT (MICROINCHES)							
Natural Finishes	2000	1000	500	250	125	63	32	16
Hot rolled	▨	■	▨					
Sand cast	▨	■	■	▨				
Forging		▨	■	■				
Extruding		▨	■	■	■	■	▨	
Cold drawn or rolled				▨	■	■	■	▨
Permanent mold cast				▨	■	▨		
Investment cast				▨	■	▨	▨	
Die cast					▨	■	▨	

■ Average application
▨ Less frequent application

FIG 12 SURFACE ROUGHNESS PRODUCED BY COMMON PRODUCTION METHODS