EFFECT OF PROCESS VARIABLES ON MICROSTRUCTURE AND PROPERTIES OF CENTRIFUGALLY CAST PRODUCTS

A Thesis

by

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Submitted to the Department of Metallurgical Engineering, Bangladesh University of Engineering & Technology, Dhaka, in partial fulfilment of the requirements for the Degree of Master of Science in Engineering (Metallurgical).

February 1988

Bangladesh University of Engineering & Technology, Dhaka

CERTIFICATE

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ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to Dr. Md. Mohafizul Haque, Associate Professor, Department of Metallurgical Engineering, BUET, Dhaka, for his supervision, guidence, constructive suggestions and comments during the course of this project.

The author is indebted to Dr. Md. Serajul Islam, Professor andHead, Department of Metallurgical Engineering and also Professor M. Ibrahim and Professor Ehsanul Haque, for their suggestions and encouragement during the experiment.

Sincere thanks are also extended to Messrs Fazlul Haque Bhuiyan, Lutfar Rahman, Binoy Hhusan Shaha and other technical staff of the Metallurgical Department for their support at various stages of this work.

Finally, a word of thanks to my wife for her patience and support towards completion of my work, sometimes at the expense of her own pleasure.

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ABSTRACT

The present investigation has been carried out to study the effects of speed of rotation of the mould and pouring temperature of the melt on the microstructures and properties of pure aluminium and brass. A comparative study has been made between the products of centrifugal casting and that of the sand (static) casting using the same materials in order to evaluate the differences. Properties like hardness, density, percentage porosity, tensile strength and percentage elongation have been investigated.

In case of centrifugal casting, all these properties exist in their best conditions when rotational speeds of the mould varies between 1400 - 1800 rpm and 1800 - 2200 rpm for brass and aluminium respectively. A superior quality of grain refinement was also obtained under such speed range. The effect of pouring temperature of the melt which is a process variable of dire importance, has shown a great effect on the structure and properties of the cast products as well. According to the observation, a too high pouring temperature means a greater time for solidification promoting coarser grains in the microstructure that in turn affects the physical properties of the product adversely. Optimum pouring temperatures, on the other hand, yields maximum grain refinement with better properties.

Effects of heat-treatment on the microstructures of the products have also been carried out in this study. Annealing

has shown a great influence on the microstructures of the centrifugally cast aluminium and brass.

Finally, attempts have been made to establish a correlation between structures and physical properties of the products so obtained with optimum rotational speed of the mould and pouring temperature of the melt.

1. INTRODUCTION

Now a days the importance of Centrifugal Casting process is getting priority because of it's economic viability as well as it's capability of delivering high strength and inclusion free products. Usual products of this process include cylindrical pipes, liners, pressure vessels, piston, rings, steam and gas reformer tubes, pyrolysis tubes, pulleys etc. The centrifugal casting method imparts some essential qualities in the products as high tensile strength, high density, consequently low porosity and necessary hardness. In order to obtain the optimum conditions for attaining these properties, a thorough study of centrifugally cast products under different conditions of speed of rotation, solidification time and pouring temperature is imperative. With this end in view, investigation has been carried out on microstructures and properties of centrifugally cast products. The materials under test were commercially pure aluminium and brass.

A comparative study has been made between the products of centrifugal casting and that of the sand casting using the same materials. Properties like hardness, density, percentage porosity, yield strength, tensile strength and percentage elongation have been investigated and compared with this method over that of sand casting.

During the present investigation, microstructures of the products were also examined under different magnification using optical microscope. Micro-examination of the specimen was carried out in the as-cast and annealed condition. Finally, attempts have been made to establish a correlation between structures and physical properties of the products so obtained with optimum speed of rotation of the mould and pouring temperature of the melt.

2. LITERATURE SURVEY

2.1 Introduction

Modern day material science has spread it's wings in various directions in order to cope with the increasing new demands of the ever expanding civilization on Earth. But it did not take place in a certain span of time. Rather it took years perhaps centuries for the people on earth to realise that its only further and deeper studies in this field can only help cutting new grounds towards meeting the challenge of the future years. One of the major part of the vast world of material science and it's different applied sectors is the production of different objects using the concept of Metallurgy. This again has got different criteria and subcriteria. The criteria include Casting, Forging, Welding, Electroforming, Powder metallurgy etc. Casting is the one method of producing different objects from molten metals and alloys, it has got a number of subcriteria as well and the one that is dealt with here is called "Centrifugal Casting". Perhaps the most modern break-through in the field of casting is this one. It has tremendous potentiality in the exploration and innovation of newer more dynamic type of products that remained far from being realised or too expensive to produce by other methods.

The principle of Centrifngal Casting is long establised, dating originally from a patent taken out by A.G. Eckhardt[1(a)] in 1809. Following early development during the nineteenth century, the process began after 1920 to be used for the manufacture of cast iron pipes on a large scale and has since been extended to a much wider range of shapes and alloys. Gradually the demand of ductile iron pipes started increasing. Large diameter ductile iron pipes found a boost in production in Japan[2] during the early 60's. In 1966 in particular, 300,000 tons of ductile iron pipe, from 3" to 94" dia were produced which was 70% of the total production of cast iron pipe in Japan for that year.

During these time, the process involved melting in a acid lined hot-blast cupola and shaking ladles were used for desulfurizing. Magnesium addition was done by means of a pressure ladle. Moulds consist of a light coating of resin sand in fabricated or Cast steel flasks. Centrifugal casting was done retractively-a long trough moved relative to the pipe mould. Inoculation with ferrosilicon is made during the pouring operation. After casting, the pipes were annealed in either horizontal or vertical furnaces to obtain adequate ductility.

In Soviet Union[3] about the same time ductile iron pipes were cast centrifugally in water-cooled high strength steel moulds. These moulds were previously sprayed with a thin refractory coat consisting of silica flour mixed with a small amount of bentonite and water. After the pipe was completely cast, the mould was kept rotating at its original speed until the pipe had cooled to 1500°F (815°C). The pipe was then taken from the machine and transferred to an annealing oven.

(More recent research report[4] shows that centrifugal atomizing can produce deposits, very similar to those produced by gas atomizing, in the form of a large-diameter tube, and from this tube, sheet is also made. The experimental conditions used were such that it was not possible to attain a sufficiently low oxygen level within the atomizing chamber to avoid the presence of some oxide films. Consequently, the porosity of the deposits was higher than expected, and the mechanical properties of the strips were lower than those of similar conventional materials. This report came out in 1976. Another research report[5] came out in 1983 which devoted to work carried out using the centrifugal spray process under carefully controlled conditions, in which oxygen access was scrupulously avoided. It also includes a note on the developments by Aurora Steels Ltd, Sheffield, who have applied the centrifugal spray process to the commercial production of tool steels.

Centrifugally cast stainless steel has become the material most used for steam reformer and pyrolysis tubes[6] during mid 80's. A cheaper alloy HK40 (0.40 - 25Cr - 20Ni), have a much higher creep rupture strength than low-carbon material having similar chromium and nickel contents, was used as a cast material for reformer applications. Extensive work has been done to optimize the structure and high-temperature mechanical properties of these materials.

At the same time, in tube production, tubular blanks are produced by the method of centrifugal casting which can be used, after slight modifications, successfully in the production of consumable electrodes[7]. Extensive tests have been carried out in the production conditions with the method of centrifugal casting of consumable electrodes for various remelting processes. The hollow billets produced by this method aro most suitable for remelting the consumable plasmatron (RCP) because the presence of the through cavity along the entire length of the billet in the case is the constant condition.

Latest report[8] that is dated 1986 has revealed a new process called Centrifugal Melt Spinning (C.M.S.) process. The C.M.S. process is a technique for the production of rapidly solidified ribbon. The report also indicates that a beneficial combination of high ejection pressures (up to 269 KPa) and high linear velocities (up to 10^3 ms^{-1}) yield good thermal contact between the melt puddle and the cooling substrate. As a result, cooling rates up to $\sim 10^8$ Ks^{-1} are achieved, higher than those generally reported for other melt spinning techniques.

The Centrifugal Casting Method (C.C.M.) has got a significant boost because of resulting rapid solidification which is imperative for the purpose. The purpose of rapid solidification is to achieve high solidification rates by means of small cross section and good thermal contact with a cooling substrate. It has been well established that high cooling rates during solidification can result in uniform, refined microstructures.

The C.C.M. used now a days generally entails the use of a fixed crucible. The molten alloy is poured into the mould and impinges on a substrate so that the well spread out over the entire length of the mould cavity. With further flow of metal from the crucible, pipe wall thickness builds up gradually and uniformly, over the entire length of the pipe. The use of high rotational speed of the mould results in improvement of the wetting pattern and hence in better thermal contact between the melt puddle and the rotating mould. High mould velocities also result in uniform pipe wall thickness.

2.2 Solidification of pure metal and alloy

(Pure metals melt and freeze at a single temperature, the melting point (or freezing point); above this temperature they are completely liquid, and below completely solid (under equilibrium conditions). If a thermocouple is placed in a crucible of pure molten metal and the metal allowed to solidify slowly, a cooling curve such as that of Figure 1(a) is obtained. It is observed that the metal cools quite quickly to its freezing point. At the freezing point the temperature remains constant briefly i.e. a hold occurs while the metal loses its heat of fusion. Only after the metal is completely solid can further cooling occur. This type of cooling curve is obtained only if solid foreign particles, described as heterogenous nuclei, are present in the liquid metal and the rate of cooling is relatively slow. When there is no suitable solid matter present, a liquid experiences difficulty in starting to crystallise and may cool 1-10 deg.[9] below its real freezing-point; i.e. nucleation under-cooling. Nuclei or 'seed' crystals then form , followed by their growth which is the second stage of freezing and the temperature mey rise to the true freezing point. The type of cooling curve in this case is shown by Figure 1(b).

When heat is abstracted rapidly, solidification (i.e. growth) occurs at a temperature intermediate between that of nucleation under-cooling and the equilibrium freezing point.) This gives rise to solidification under-cooling which is significant in centrifugal castings and in die castings. It leads to fine structure due to a decrease in diffusion rates. Most commercially 'pure' metals contain impurities which may have significant secondary effects on solidification.

During solidification, heat evolution raises the temperature at the solid-liquid interface, but protruding solid fingers may extend into a cooler, undercooled region and their growth is accelerated. Radial arms are formed which send out secondary arms at right angles to them. This is repeated until a fir-tree type of crystal is produced, known as a dendrite (Figure 2).

The dendrites grow out wards until contact is made with neighbouring growths; this contact surface becomes the boundary of the crystal or grain. The dendrite arms then become thickend until finally a solid crystal remains with no indication of the dendritic growth, except where shrinkage occurs, with the formation of interdendritic porosity.

Pure metals melt and freeze at a single temperature. Alloys, in most cases, do not. For a given alloy, there is a particular temperature (the liquidus temperature), above which it is all liquid. There is another, lower temperature (the solidus temperature), below which it is all solid. Between these two temperatures is a region where liquid and solid coexist. Such an alloy, in this temperature range, has some consistency because of the solid material existing, but little or no strength, because of the liquid interspersed with the solid. It has the consistency of "mush" and for this reason the portion of a solidifying casting whose temperature lies between the liquidus and solidus is often termed the "mushy zone"(10). A sketch of the liquidus and solidus temperatures of a typical alloy is shown in Figure 3(a).

When a molten alloy such as alloy'a'of Figure 3(a) is slowly cooled, freezing begins at T_L but is not complete until a lower temperature, T_S is reached. The cooling curve of an alloy of this type would be very different from that of a pure metal. If a crucible of the alloy were cooled slowly and temparature measured as a function of time, the rate of cooling would be rather rapid until the liquidus temperature, T_L was reached. At this temperature, as solidification began and continued over a range of temperatures, the cooling rate would be slowed down, but not arrested. Below the solidus the metal would be completely frozen, and more rapid cooling would again take place, shown in Figure 3(b).

2.21 Solidification of Commercially Pure Aluminium

Commercially pure Aluminium contains impurities like silicon which have a significant secondary effects on solidification. In practice, dissolved or insoluble impurities in aluminium are frequently expelled by the growing crystals to the grain boundaries and are also trapped in between the arms of the dendrites. The distribution of these impurities betrays the dendritic growth. Microstructure of commercially pure aluminium is shown in Figure 4. Here it is seen that impurities like Si are expelled by the α - aluminium dendrite to the grain boundaries.

It should be noted here that

1) Since each grain starts from a nucleus the final crystal size is dependent on the number of effective heterogeneous nuclei.

2) Orientation of the atomic pattern or crystal lattice is constant in a given crystal but varies from grain to grain.

2.22 Solification of Brass

Brass is essentially an alloy of copper and zinc, but for special purposes small proportions of other metals are sometimes added to obtain increased strength, hardness or resistance to corrosion. The industrially important alloys of the copper-zinc system contain zinc varying from 0 to 50% and are particularly important in view of their wide-range of mechanical properties, their ease of working, their colour and resistance to atmospheric and marine corrosion.

The equilibrium diagram of copper-zinc system is shown in Figure 5. It must be remembered that the changes of phases which is shown in aquilibrium diagram rarely reach completion during normal rates of cooling. The main features of the system are:

Compositions between F and G solidify as α-solid solution, usually cored. Compositions G to H commence by forming α and finally form some β solid solution of composition H due to peritectic reaction. On cooling to room temperature the amount of the β constituent decreases according to the solubility lines GM and HN. Compositions between H and J form α-crystals which, at 905°C, react with liquid of composition J to form β-crystals. On cooling, α-crystals are precipitated from the β when solubility line HN is passed. Compositions between J and K solidify as β; alloys containing less than 46.6% zinc precipitate some α-crystals; while alloys with more than 50% zinc precipitate γ-crystals on cooling to room temperature. The range of composition for the three phases is shown in Table-1.

It is interesting to note that the solubility of zinc in α-solid solution increases upto 39% as the temperature falls to 453°C which is contrary to general behaviour; then decreases down to room temperature.

Between 453°C and 470°C the β-phase transforms to a low temperature modification known as β'. This transformation is due to the zinc atoms changing from a random to an ordered arrangement on the lattice.

The properties of a brass will depend on the volumes of the phases present and Figure 6 serves to show the general connection between the phases present in the structure and the properties.

The tensile strength and the elongation increase in the α region, the ductility reaching a maximum at 30% zinc. The presence of β-phase causes a considerable drop in elongation, but rapidly increases the tensile strength up to a maximum, when the alloy contains all β. The strengths fall rapidly at the apperance of the weak and brittle γ constituent. The resistance to shock decreases while the hardness increases by the presence of β phase, and the alloy becomes hard and extremely brittle when γ-phase appears. Consequently the presence of the γ constituent is avoided. The only commercial alloy likely to contain γ is one containing 50% zinc and used as a brazing solder because of its low melting point. In brazing, however, some of the zinc is lost by volatilisation and some diffuses into the metals being united.

The β-phase is much harder than α-phase at room temperature and will withstand only a small amount of cold deformation. It begins to soften suddenly at 470°C (i.e. disordered change) and at 800°C is very much easier to work than α-phase. Thus it is advantageous to hot work β-phase.

Annealed α-brasses withstand a remarkable degree of deformation by cold work without the slightest sign of fracture. The impact resistance of α-brass at 350 to 650°C is extremely poor, but the resistance to creep at elevated temperature is superior to that of $\alpha-\beta$ -brasses. Consequently there is no appreciable advantage in hot working α-brass, except that when breaking down large ingots into strip, the handling costs are reduced and repeated annealing is unnecessary.

2.23 Nucleation and growth

(Nucleation is the appearence at points in the liquid of centers upon which further atoms can be deposited for the growth of solid crystals. Nucleation occurs in two ways - (1) Homogenous and (2) Heterogenous nucleation.

Homogenous nucleation is the occurrence of ordered groups of atoms forming small zones of higher than average density. These embryonic crystals are ephemeral and unstable, but some reach a critical size at which they become stable and grow. The smaller the critical size of the nucleus, the higher the probability of homogenous nucleation occurring. Under-cooling helps in diminishing the critical size of the nucleus.

In heterogenous nucleation the initial growth interface is provided by a foreign particle included or formed in the melt. The foreign particle must be capable of being wetted by the metal, forming a low contact angle, and must possess some structural affinity with the crystalline solid.

It is generally agreed that crystal growth starts in the molten alloy by means of heterogenous nucleation on some preferred site or substrate that lowers the surface energy which is essential for nucleation. Most commercial metals contain a sufficient number and variety of insoluble impurities for nucleation to occur at undercoolings of 1-10 deg[9]. If the number of effective nuclei is insufficient for a given purpose nucleating agents (nucleation catalysts) may be added to the melt.)

In the case of pure metals, once nucleation has occurred, crystal growth begins and the structures that develop can be related to the growth conditions, in particular to the undercooling. For growth to occur, more atoms must join the solid than leave it and for this to happen, the temperature of the interface must be slightly below the equilibrium freezing temperature. This means that some undercooling must exist if the growth is to advance.

2.24 Factors affecting the nucleation and growth processes

(Since solidification is a process of nucleation and growth, anything that influences the solidification process must influence the process of nucleation or the process of growth or both. The factors affecting the nucleation and growth processes are
(a) Variation of cooling rate and (b) Nucleating agents.

(a) Cooling rate: If the cooling rate is increased, the greater is the amount of under-cooling of a melt which increases the number of effective nuclei relative to the growth rate. The more the undercooling, the more extensive is the nucleation and the smaller the grain size in the final structure. Slow cooling, conversely, favours growth from few nuclei and produces coarse grain structures.

The cooling rate of a casting can be changed by varying the pouring temperature. High pouring temperature is conducive to slow cooling, which reduces the nucleation rate and minimises the concentration gradient in the liquid,) there is also an opportunity for the remelting of crystallites transported from the surface region. In practice, however, columnar structures are favoured by high pouring temperature.

(On the other hand, low pouring temperatures increase the cooling rate of the casting throughout the freezing range. With higher cooling rates, the degree of undercooling increases and more nuclei are available for growth which eventually contributes to the formation of fine equiaxed structures.)

(b) Nucleating agents: (A nucleating agent is a substance which can be intentionally added to make effective substrates that facilitate the nucleation in the melt. The nucleant must be capable of survival in superheated liquid and must be in a sufficiently fine state of division to remain as a widely dispersed suspension. The most direct effect of the nucleating agent is the formation of stable particles as nuclei in the melt, for which small additions are usually sufficient. A further important effect is that of growth restriction due to solute concentration gradients and constitutional undercooling in the liquid adjoining the crystal.

Effective grain refinement in copper alloys is obtained from small additions of iron, whilst for aluminium alloys, titanium, sodium (recently strontium) are effective agents. In certain cases the function of the inoculant is to modify the growth rather than the nucleation process. This is consistent with the fact that undercooling is associated with the modification.

2.25 Development of fine equiaxed structure

Two factors have been shown to be significant in affecting the nucleation and growth process, viz. variation of cooling rate and nucleating agents. The most common aim of affecting nucleation and growth process is to control the metallographic structure achieving refinement through one or both of the above factors.

The association of rapid cooling with fine grain size arises from the influence of undercooling on the comparative rates of nucleation and growth. Highly effective grain refinement can be accomplished by inoculation- the addition to the melt of small amount of substances designed to promote nucleation — although in certain cases the function may be to modify the growth rather than the nucleation process.)

Significant effects also arise from crystal multiplication and transport of crystallites by gravity or by mass movement of liquid. Such movement can result from turbulence originating during pouring, from mass feeding, from thermal convection, or from gravitational separation due to the difference in density between liquid and solid phases.

(Direct evidence of dendrite fragmentation as an important mechanism in the formation of the equiaxed zone in castings was obtained by Jackson and Hunt and their collaborators in studies of solidification in transparent organic compounds analogous to metals[11]. Dendrite arms in the columnar zone become detached by local recalescence due to thermal fluctuations and change in growth rate. These are carried by convective stirring and turbulence into the central region, where they grow independently in undercooled liquid[12].)

Fragmentation is not the only source of such centres for equi-axed growth. Contact with the cool mould surface on pouring initiates the nucleation of many crystallites, which become widely distributed by pouring turbulence. If castings are poured with little superheat, these continue to grow rapidly to form fine equiaxed structure.

2.26 Development of dendritic structure

In general, heat transfer from the casting to the cooler mould produces a positive gradient on a macroscopic scale, shown in Figure 7. But in many cases local evolution of latent heat is sufficient to reverse the temperature at the interface. The thermal conditions in this case are represented in Figure 8. Since the minimum temperature in the liquid is no longer adjacent to the interface, growth by the general advance of a smooth solidification front gives way to other modes of growth in which deposition can occur in regions of greater undercooling.

When undercooling occurs in the band of liquid adjoining the interface, any existing protuberance on the solid face tends to become stable and to act as a centre for preferential growth. Whilst general advance of the interface is retarded by the latent heat or solute barrier, such local growth centres can probe further into the zone of undercooling.

Therefore, the conditions for dendritic tree-like growth are (1) Undercooling due to evolution of sufficient latent heat and (2) Undercooling due to differential freezing or solute barrier.

This type of growth most commonly encountered in the freezing of commercial casting alloys forming solid solutions. The primary axis of the dendrite is the result of preferred growth at an edge or corner of an existing crystallite. The projection develops into a needle and subsequently a plate following the general direction of heat flow; this growth direction is usually associated with a particular crystallographic direction[13].

Lateral growth of the primary needle or plate is restricted by the same latent heat or solute accumulation as inhibited general growth at the original interface, but secondary and tertiary branches can develop by a similar mechanism to that which led to the growth of the primary stem, shown in Figure 9.

Dendrite growth in a pure metal can only be detected by interrupted freezing and decantation, but is evident in alloys through the persistence of compositional differences, revealed on etching as the characteristic cored structure. Coring results from differential freezing and it can be explained in the following way.

(In a solid-solution alloy, as the one shown in Figure 10 solidification begins with the formation of crystals having the composition S_1. During solidification the composition of the solid changes until at the end it has become S_2. This change in composition requires diffusion to take place in the solid. Atoms of metal A, which are mostly concentrated in the centre of the crystal; diffuse toward the outside and are replaced by atoms of B, until equilibrium is reached and every part of the crystal has the same composition. Diffusion in the solid state is slow. If the cooling rate is fast, diffusion cannot keep pace with solidification, equilibrium cannot be reached, and a cored crystal results. This crystal contains the amounts of the two metals corresponding to the alloy composition, but they are unevenly distributed; the centre contains a higher percentage of the higher-melting-point metal, and the outside is richer in lower-melting-point metal[14].

In severe nonequilibrium conditions, as produced by very rapid cooling, the compositions of the centre and the outside differ widely. With slow cooling, when longer time is available at elevated temperature for diffusion to take place, little or no difference results. Figure 11(a) and 11(b) shows the same alloy, rapidly and slowly cooled, and demonstrates the difference in coring produced by different rates of cooling. Coring is found not only in alloys of completely miscible metals but in all alloys in which a phase forms over a range of temperature.)

The coring effect can only be eliminated by high temperature diffusion in the solid state, time for which is not normally available during cooling from the casting temperature. Prolonged annealing or homogenisation can bring about complete diffusion of the solute, but even in this case visible evidence of the original coring may persist as a pattern of segregated impurities. The actual time for homogenisation is less when grain size and the spacings of the dendrite substructure are small, since the diffusion distances are then shorter[1(b)].

2.27 Solidification under centrifugal force

The effectiveness of centrifugal force in promoting a high standard of soundness and metallurgical quality depends above all on achieving a controlled pattern of solidification, this being governed by the process used and by the shape and dimensions of the casting. High feeding pressure is no substitute for directional freezing, which remains a primary aim of casting technique.

Considering firstly the casting of a plain cylinder, conditions can be seen to be highly favourable to directional solidification owing to the marked radial temperature gradient extending from the mould wall. Under these conditions the central mass of liquid metal, under high pressure, has ready access to the zone of crystallisation and fulfils the function of the feeder head used in static casting[1(c)].The steepest gradients and the best conditions of all occur in the outermost zone of the casting, especially when a metal mould is employed. Another important factor is the length to diameter ratio of the casting, a high ratio minimising heat losses from the bore through radiation and convection. Under these conditions, heat is dissipated almost entirely through the mould wall and freezing is virtually unidirectional until the casting is completely solid:the wall of the casting is then sound throughout. This ideal is closely approached when producing long, thin walled tubes in metal dies and an effective casting yield of 100% is sometimes attainable[1(d)].

As the wall thickness increases or as the ratio of length to diameter is reduced, however, radial temperature gradients become less pronounced. Heat loss from the bore surface eventually attains a level at which the temperature gradient is locally reversed, initiating some freezing from this surface. Under these conditions a zone of internal porosity is associated with the last liquid to freeze, being normally confined within a band of metal close to the bore. To achieve a wholly sound end product this porosity needs to be removed by machining, an operation analogous to feeder head removal in static casting. For this purpose an appropriate allowance must be made on the cast dimensions.

2.3 Centrifugal Casting

Centrifugal Casting is a special form of casting by which hollow cylindrical shapes in particular may be conveniently produced. The mould rotates and the molten metal is fed inside and distributed around the mould by the centrifugal action; rotation continues until solidification is complete. When the molten metal is poured into rotating moulds, during freezing each layer of metal is subjected to a pressure gradient across its radial thicknesses such that the pressure is maximum in the outermost layer and minimum in the innermost layer. Actually this pressure gradient assists the removal of gases and also makes the casting more dense and sound. The use of gates, feeders and cores etc. is eliminated in this casting process.

2.31 Principles of Centrifugal Casting

The centrifugal force produced by rotation is utilised in two ways:

1) During pouring the force can be used to distribute liquid metal over the inner surfaces of a mould forming hollow cylinders and other annular shapes.

2) The force is used in the development of high pressure in the casting during freezing. This assists feeding and accelerates the separation of non-metallic inclusions and precipitated gases.

The casting of a plain pipe or tube is accomplished by rotation of a mould about its own axis, the bore shape being produced by centrifugal force alone and the wall thickness determined by the volume of metal introduced.

In the centrifugal process a casting solidifies and cools in the centrifugal field of forces. The centrifugal casting cools both on the outside (the surface in contact with the mould walls) and on the inside (its inner surface) as a result of radiation and air convection. This gives rise to convection currents in the liquid metal, a cooler and, hence, denser metal moves from the inner surface to the mould walls, thereby effecting solidification of the casting in the direction from the mould walls to the inner surface.

But intensive cooling of the liquid metal due to convection and radiation from the inner surface leads to the growth of crystals which move towards the mould walls under the centrifugal forces. The crystale growing at the mould walls have an ample supply of the liquid metal, so that they grow in a direction more or less perpendicular to the melt motion. These features of solidification are favourable for the formation of a tight-grained outer surface of the casting. The light particles such as slag substances, non-metallic inclusions, and gases move to the inner surface of the casting; this procese also aids in producing a finer-grained structure and tends to give better mechanical properties.

2.32 Classification of Centrifugal Casting

Centrifugal Casting is divided into three categories:

1. True Centrifugal Casting
2. Semicentrifugal Casting
3. Centrifuging

(1) True Centrifugal Casting, in which the casting is spun about its own axis; no risers are required and no central core is needed since centrifugal force forms the inner diameter of castings such as pipe naturally.

(2) Semicentrifugal Casting

This process is also known as profiled centrifugal casting. In this process, the mould is rotated about its vertical axis shown in Fig. 12(a) and the centre of the casting is usually solid. The central cavity in such cases is formed by machining out the central solid or is formed by using a central core and pouring the metal around it. Semicentrifugal casting is usually preferred for castings which are symmetrical about a central axis, for example, gear blanks, wheels and discs. In practice, the mould is rotated at a speed which will give a linear speed of about 600 ft. per minute[15] at the outer edge of the casting. As a result of this low speed, the pressure developed is not high and, therefore, as compared to centrifugal casting, the impurities are not rejected towards the centre as effectively as in the true centrifugal casting.

(3) Centrifuging: The main difference between true centrifugal or semicentrifugal casting and centrifuging is that in the case of true centrifugal or semicentrifugal casting, the axis of mould coincides with the axis of rotation whereas in the case of centrifuging, the axis of rotation does not coincides with the axis of the mould but it coincides with the axis of the whole assembly. In centrifuging, several mould cavities are located around the central feeder which feeds these mould cavities through radial gates shown in Fig. 12(b). In this case also the stack moulding can be advantageously employed.

2.33 Method of calculation of the rotational speed

The following two methods are available in the literature for calculating the rotational speed of the mould.

(1) The choice of the rotational speed of moulds determines the strength, structure, and the distribution of slag inclusions, gas and shrinkage cavities, and segregates in castings. The rotational speed depends on the axis of rotation (horizontal or vertical), properties of the melt, and the diameter of the casting.

In determining the rotational speed of a mould, one should take into account not only the position of the axis of rotation, but also the casting's internal surface distortion contingent upon the axis position. Experiments show that the optimal speeds which give high-quality castings differ with the kinds of alloy and, in general, depend on the casting dimensions, pouring temperature, and the mould temperature.

According to Professor L.S. Konstantinov[16], the rotational speed (N) may be calculated with the formula

$$N\ (\text{rpm}) = \frac{5520}{\sqrt{\rho r_2}} \quad \ldots\ldots\ldots \quad (1)$$

where 5520 is the value of the coefficient, taken to be constant for all alloys, ρ is the density of a casting (gm/cc), and r_2 is the internal radius of the casting, cm.

Formula (1) disregards the effect of the castings wall thickness since it is of little significance for thin-walled castings.

For thick-walled castings, however, this effect should be taken into account because the centrifugal force that acts on the outer surface of a casting reaches a value high enough to rupture the surface of metal adjacent to the mould wall and thus to cause a tear in the casting. Consequently it is necessary to change the rotational speed of moulds when casting thick-walled parts. At the beginning of pouring, the rotational spaed of the mould is kept at a minimum, then, as the mould receives more metal and the layer of melt grows, the speed is raised to a maximum, at which, however, the surface layer should not be torn.

In casting shaped parts, one should choose such a rotational speed as to effect good filling of the mould and accurately reproduce the contours of the casting. The best results are posible to obtain when the rotational speed of a mould is so chosen that the peripheral speed of a casting point most distant from the axis of rotation and is found to be equal to 3-5 m/s[16].

The peripheral speed of any point of a rotating body may be calculated by the formula[16]:

$$v = \frac{\pi r N}{30}, \quad \text{or} \quad N = \frac{v \times 30}{\pi r} \quad \ldots \quad \ldots \quad (2)$$

where N is the rotational epeed, rpm, and r is the distance from the point to the axis of rotation, m.

(2) The centrifugal force acting upon a rotating body is proportional to the radius of rotation and to the square of the velocity:

$$F_c = \frac{mv^2}{r} = mrw^2 \quad \ldots \quad \ldots \quad \ldots \qquad (1)$$

where $v = wr$.

Here, F_c = Centrifugal force (N,pdl)

m = mass (kg, lb)

r = radius (m,ft)

w = angular velocity (rad/s)

v = peripheral speed (m/s, ft/s)

The gravitational force on the same mass would be given by

$$F_g = mg. \quad \ldots \quad \ldots \quad \ldots \qquad (2)$$

where g = acceleration due to gravity (m/s^2, ft/s^2)

Hence the factor by which the normal force of gravity is multiplied during rotation is given by –

$$\text{G factor} = \frac{Fc}{Fg} = \frac{rw^2}{g} \quad \ldots \quad \ldots \qquad (3)$$

Expressed in the more convenient speed units of revolutions per minute, N, the expression becomes:

$$\text{G factor} = \frac{rw^2}{g} = \frac{r(\cancel{m}) \times 4\pi^2 n^2/\cancel{sec}^2}{9.81\ \cancel{m}/\cancel{sec}^2}$$

$$= \frac{D \times 4\pi^2 n^2}{2 \times 9.81}$$

$$= 2Dn^2 \quad .. \quad .. \qquad (4)$$

Here,

$w = 2\pi n/sec$

$w^2 = 4\pi^2 n^2/sec^2$

n = revolutions/sec

$g = 9.81\ m/sec^2$

$$\text{or} \quad n^2 = \frac{\text{G factor}}{2\ D} = 0.5\,\frac{\text{G factor}}{D}$$

or $n = 0.7 \left(\frac{G \text{ factor}}{D} \right)^{1/2}$ ... ... (5)

$\therefore$ $N \text{ (rpm)} = 60 \times 0.7 \left(\frac{G \text{ factor}}{D} \right)^{1/2}$ where D=rotational diameter (m) ... ... (6)

Alternatively, $N = 265 \left(\frac{G \text{ factor}}{D} \right)^{1/2}$ where D = rotational diameter (in)

These relationships between rotational speed, diameter and centrifugal force are illustrated graphically in Fig. 13; this and similar charts or nomograms are normally used to select the speed in accordance with the magnitude of centrifugal force required.

There is no standard criterion for selection of the required force. In true or open bore casting, circumferential velocity is imparted from mould to metal by frictional forces at the mould surface and within the liquid. In horizontal axis casting, the metal entering the mould must rapidly acquire sufficient velocity to prevent instability and 'raining' as it passes over the upper half of its circular path: because of slip, the generation of the necessary minimum force of 1G in the metal requires a much greater peripheral mould velocity than would be the case if metal and mould were moving together. One investigation placed the minimum limit in the region 3-4.5 G[17] but much greater force is required in practice for full advantage to be taken of the process. Based on practical observations, Cumberland[18] reported a range of minimum speeds required to avoid ejection of metal. These are presented by the dotted line superimposed on Figure 13 and approximate more closely to a constant peripheral velocity of 0.5 m/s

($\simeq$ 100 ft/min) than to a fixed magnitude of centrifugal force: the required force dimineshes with increasing diameter. Although centrifugal forces exceeding 200G are attained in some cases, speeds generating forces of 60–80G are most commonly quoted for true centrifugal castings.

2.34 True Centrifugal Casting Technique

The widest application of centrifugal casting is for the production of components which are essentially cylindrical and therefore suitable for casting by the open bore or 'true' process. Such castings are utilized in either of two ways. Many tubes are used in the as-cast state. These can embody limited taper or simple external features, although the latter must, when casting in metal dies, permit extraction of the casting. True centrifugal casting is also used for the manufacture of plain cylindrical blanks or 'pots' for the production of rings, bushes and other annular components by machining.

The main characteristic of the true centrifugal casting is that the axis of rotation of the mould coincides with the axis of the casting and the formation of a central hole through the casting takes place by the centrifugal force without the use of a central core. The axis of rotation of the mould may be horizontal, vertical or at some other convenient angle between 0 to 90°. The axis of rotation mainly depends upon the

$\frac{\text{L (length of the job)}}{\text{D (bore of the job)}}$ ratio of the tube. The following

practice is usually adopted:

	Axis of rotation
for $\frac{L}{D} > 4$	Horizontal
$4 > \frac{L}{D} > 1$	At an angle between 0° to 90°
$\frac{L}{D} < 1$	Vertical

Horizontal axis of rotation:

Horizontal axis of rotation is more common in the production of castings having tubular shape, such as water pipe, gun barrel etc. In fact, when the liquid metal is introduced in a rotating horizontal mould, the metal is distributed over the inner surface of the mould. Due to the high speed of rotation, the friction that is set-up between the liquid metal and the mould material allows the liquid metal to be evenly distributed and the inner surface of the casting assumes a cylindrical shape.

There are two principal horizontal axis centrifugal casting processes available in the literature.

1) De Lavaud process, and
2) Moore sand spun process.

The two methods are principally the same, differing only in details of mould construction and the method of introducing the metal.

De Lavaud process: This is the most popular method for the production of socketed cast iron pipes[19] in metal moulds. In this process, illustrated in Figure 14, a long pouring spout, supplied from an automatic ladle, is initially inserted to the far extremity of the mould, a forged steel die enclosed in a water cooling jacket. As pouring proceeds, the rotating mould is withdrawn over the spout so that the metal is laid progressively along the length of the mould wall, control being achieved by synchronising the rates of pouring, mould travel and mould rotation. The casting is extracted as the mould returns to its original position and its accuracy is checked by weighing. High rates of output are achieved, each machine producing a casting every two minutes. The fastest output of all, however, is attained in the production of rainwater pipes using a simplified variation of the pipe casting process in which several moulds are circulated through a number of stations for coating, casting and extraction: rates of over 100 castings per hour are achieved[19].

Moore sand spun process

With the slower rates of cooling obtained in sand moulds, fluid alloys can be poured without the retractable spout system. The Moore[15] system employs a sand lined mould, driven by a variable speed motor: the process is especially suitable for large pipes required in small quantities. The metal is introduced into the mould by a pourer and a controlled tilting mechanism at the raised end. At the beginning of pouring, the mould is at its maximum tilt position and the speed of rotation is minimum. Thus low speed is maintained during pouring but the mould is steadily lowered into horizontal position. Once the horizontal position is reached, and the pouring has ceased, the speed of rotation is raised depending upon the thickness of casting and is maintained until the solidification is complete.

The horizontal axis machine is suitable both for tubes and for long pots production. Since heat loss from the bore is lower than in the case of short pots, a smaller machining allowance suffices to clean up to sound metal and a higher yield can be achieved.

2.35 Characteristics of Centrifugal Casting

The main quality characteristic of centrifugally cast material is the high standard of soundness arising from the conditions of feeding. This factor is predominant in the improvement of properties relative to those of statically cast material. To this advantage may be added a degree of structural refinement, affecting grain size and the distribution of microconstituents. The extent of this depends on the particular process. The most important contribution to refinement is rapid cooling in metal moulds, but other factors include physical disturbance in the liquid in pouring and rotation and the ability to achieve satisfactory metal flow using lower pouring temperatures than would be necessary in the absence of centrifugal pressure. Refinement is greatest in true centrifugal castings made in metal dies, whilst pressure castings show little structural difference from static castings of similar shape: the same may be said of the degree of freedom from non-metallic inclusions and random defects.

The macrostructure is subject to similar influences to those governing the structure of static castings, the important factors being alloy constitution, the temperature gradients and cooling rates induced by the thermal properties of metal and mould, and conditions for independent crystallisation as affected by the motion of the casting. Alloys undergoing dendritic crystallisation are characterised by regions of columnar and equiaxed growth. The factor in the case of centrifugal casting is the relative movement of liquid by slip during acceleration to the speed of the mould. This has been held in some cases to promote columnar growth by disturbance of the growth barrier of solute rich liquid at the interface. The overall effect of motion on structure is, however, complex, since vibration, diminution of thermal gradients in the liquid, and the possible fragmentation of dendrites can also induce the nucleation of equiaxed grains. A further effect of motion is a tendency for columnar grains to be inclined in the direction of rotation, evidently due to the movement of undercooled liquid towards the dendrite probes.

The structures encountered in a large number of individual alloys, particularly the zones of columnar and equiaxed grains occurring under a wide range of conditions were described and explained by Northcott[20]. In practice the most consistent influence is that of a low pouring temperature in producing grain refinement and equiaxed structures, whilst somewhat higher temperatures tend to promote columnar grains by suppressing nucleation and increasing the radial temperature gradient towards an optimum level.

With respect to properties, centrifugal castings have been frequently compared with forgings. Ductility is in general lower than in forgings, but there are many instances where a centrifugal casting has satisfactorily fulfilled the same function. At elevated temperatures the cast structure offers positive advantages with respect to creep strength[21].

Much direct evidence is available of improved properties compared with the normal run of static castings. A remarkable feature of the mechanical properties was the low degree of scatter compared with that usually obtained in sand castings: no weak zones were encountered and high elongation values testified to the degree of soundness achieved. Little difference was observed between circumferential and longitudinal properties in annular castings.

2.36 Advantages of Centrifugal Casting

Pouring into a spinning mould and solidification of the casting in the mould rotating under centrifugal forces are the factors which determine the basic advantages of this casting method. These advantages include:

1. It is a economical process for making hollow interiors in cylinders:

No core is needed to form the bore as in static casting since the rapidly turning mould causes the melt to move to the periphery under the force of rotation. Elimination of gates and risers is possible.

2. Casting is cleaner:

A function of centrifugal force is seen in the tendency for non-metallic inclusions to segregate towards the axis of rotation. Centrifugal force helps in forcing molten metal quickly into moulds to prevent premature freezing and also assists in proper directional solidification, so that a high standard of freedom from inclusions is achieved.

Owing to the pressure gradient within the casting, nucleation of dissolved gases to form bubbles will occur if at all in the bore region, where the gas can escape readily from the casting.

3. The process produces quality products:

Solidification of the metal in a rapidly rotating mould results in a fine-grained structure, free of gas and shrinkage cavities and porosity.

2.37 Application of Centrifugal Casting

Examples of components produced by true Centrifugal Casting are listed in Table 2. Amongst special products produced by centrifugal casting are bimetal tubes and composite products.

Bimetal tubes - Alloys of widely different properties can be combined in a single structure by successive pouring of the two alloys under closely controlled conditions[22], the time interval before the second pouring operation being critical. Alloy combinations are restricted by the relative melting temperatures and the danger of excessive remelting of the outer by the inner layer, but in a suitable case a metallurgical bond is achieved without this difficulty.

Composite products - Centrifugal casting can be used to line a structural outer shell with an alloy of special properties. A notable case is the production of white metal bearings by pouring the low melting point bearing alloy into tinned outer shells. A further example is the spinning of cast iron friction linings into steel castings for the production of aircraft brake drums.

2.4 The effects of process variables on Centrifugally cast products

The main variables controlling the casting quality are the speed of the rotation, the pouring temperature of the melt and the solidification time of the casting.

(a) Speed of rotation: The speed of rotation of the mould is the main governing factor influencing the fundamentals of the process. Rotational speed exerts an influence upon structure and properties of the casting, the most common effect of increased speed being to promote refinement, although this can also rise from turbulance induced by instability of the liquid mass at very low speeds. On balance, to secure maximum benefit from centrifugal casting, it is logical to use the highest speed consistent with the avoidance of tearing. The main factor also considered in true centrifugal casting is retention of the bore shape against gravity whilst avoiding longitudinal tearing through excessive hoop stress[1(e)].

(b) Pouring temperature: Pouring temperature exerts a major influence on the mode of solidification and needs to be determined in relations to the type of structure required. Low temperatures are associated with maximum grain refinement and with equiaxed structures, whilst higher temperatures promote columnar growth in many alloys. However, the pouring temperature must be sufficiently high to ensure satisfactory metal flow and freedom from cold laps whilst avoiding hot tearing due to excessive superheat.

(c) Solidification time: Longer solidification time is conducive to slow cooling, which reduces the nucleation rate and minimises the concentration gradient in the liquid. It also increases the radial temperature gradient towards an optimum level[21]. In practice, these effects usually predominate and columnar coarse structures are favoured.

Fine equiaxed structures, on the other hand, are encouraged by shorter solidification time, which not only increase the nucleation rate but also produces extreme undercooling favouring the formation of many nuclei. Columnar growth is thus restricted.

2.5 The effects of heat-treatment upon Brass and Aluminium:

Cast brass shows a dense dendrite structure and when it is fully annealed then these dendrite structures disappear and grain boundaries become prominent. Also uniformly distributed pores are visible across the entire matrix. If partial annealing is carried out then traces of coring are found in the structure. Now if the cast brass specimen is subjected to full deformation so that it becomes work hardened, and is partially annealed at 600°C and held for 5 minutes, then recrystallization with traces of coring takes place[23]. If the same deformed specimen of brass is annealed fully and held at a longer length of time (say 1 hour) at the annealing temperature of 800°C then twinned equiaxed grains are found in the structure[24]. Again if the same specimen is partially deformed and then annealed, bent twins and strain bands are visible in the micrograph[23].

Mention may be made here that if an aluminium specimen is annealed, either as cast or after deformation, twin crystals do not form in the structure but grain refinement may happen. Traces of coring is likely if partial annealing is done. It is found in the literature [25] that the more the stacking fault energy, the lesser the tendency for the formation of annealing twins. In aluminium, stacking fault energy is found to be 200 erg/cm^2 where as in copper it is only 40 erg/cm^2. Now the condition for obtaining annealing twins, stacking fault is to be wide which means low stacking fault energy. The lower the stacking fault energy, the greater will be the seperation between the partial dislocations i.e. the wider will be the stacking fault. Hence aluminium rarely shows annealing twins because of having high stacking fault energy i.e.narrow stacking fault. Again, X-ray work has shown [26] that the energy of stacking fault in brass decreases with zinc content, and this is in agreement with the fact that alpha brass forms a greater number of annealing twins then copper.

Stacking faults enter into the plastic deformation of metals in a number of ways. Metals with wide stacking faults strain-harden more rapidly, twin easily on annealing and show a different temperature dependence of flow stress from metals with narrow stacking faults. The important role of twinning in plastic deformation comes from the fact that orientation changes (resulting from twinning) may place new slip systems in a favourable orientation. Twinning is also important in the overall deformation of metals even with a low number of slip systems.

3. EXPERIMENTAL SET-UP

3.1 Introduction

The experimental set-up wasassembled after designing the individual components, considering the length, weight and thickness of the job. The description and operation of all these items are given in the following sub sections.

3.2 Description of the experimental set-up

The experimental setup mainly consisted of a permanent mould, a hollow mild steel shaft, a four wheel trolly with a ladle and ladle holder, a gauge ring and a motor. Details of the experimental set up are shown in Fig. 15(a).

The permanent barrel like mould was made of cast iron and was horizontally inclined with the three feet long mild steel shaft. The dimensions of the mould were; length-14", outer diameter-6", thickness-½". In order to ease the removal of the product, the pouring end of the mould was made slightly larger in diameter and a ring was fixed at the end to hold the casting within the mould while it is in motion. There were two slots on both ends of the shaft — one for key arrangement with the flange and another for locking with the pulley.

A ¾" bore was made throughout the entire length of the shaft and a mild steel rod (Fig. 15c) was inserted through it for holding the end plate within the metallic mould. The end plate was used for determining the axial length and ejecting the casting from the hot mould. There were two sets of pulleys in use in order to achieve four different speeds (ranging from 1000 to 2200 rpm.). The pulleys were made of aluminium alloy.

Trolly was an essential part of the experimental setup. Its main purpose was to make an arragement for uniform and regular pouring of metals and alloys into the rotating mould. It could move backward and forward on two rails. The dimensions of the trolly were about 15" long and 12" wide. About a two feet long hemispherical shaped spout lined with fire clay was attached with the trolly. The height of the long spout was such that at the instant of pouring some melt would have split out. In order to prevent this, the height of hemispherical spout was increased by 2" on both sides and subsequently fire clay lining was provided with a view to reduce the heat loss. It was moved on a slopy rail track and its entry into the mould could thus be regulated. The main function of the spout was to transfer the molten metal into the revolving mould uniformly from the ladle (Fig. 15d) which was placed above it. The ladle (capacity 30 ibs) was made of mild steel sheet over which fire clay lining was imparted to withstand massive thermal shock. It was an inverted conical type with a slopy bulge at the rim to facilitate pouring. One of the conditions to obtain a uniform thickness of the hollow casting to ensure a constant flow of the molten metal/alloy from the ladle. The ladle holder, made of cast iron pipe, had a bracket end and an extended handle to ease the pouring manually yet safely by simply rotating the handle. The length of the handle was extended to till the ladle between 0 to 90° by simply-rotating the other end of the handle from a far distance. The arrangement also avoids the risk of having any split of melt from the rotating mould.

The gauge ring is employed to determine and maintain the required thickness of the product, shown in Fig. 15(e).

A 7 H.P. electric motor was used for rotating the casting machine and its speed was about 2800 revolutions per minute. The required spinning speed of the mould was achieved by changing pulleys of different diameters which were connected with shaft of the machine utilising a V-belt.

4. EXPERIMENTAL PROCEDURE

4.1 Introduction

A series of experiments were carried out with Brass and Alunimium to determine the effects of pouring temperature and speeds of rotation of the mould on the microstructure and properties of the products. In order to achieve these objectives, a centrifugal casting machine, 7-HP electric motor; natural gas fired furance and a trolly with crucible holder were used.

4.2 Moulding Materials

For centrifugal casting, cast iron mould was chosen since the casting conditions are more constant and controllable with this type of mould. The casting cycle was kept constant in order to maintain dimensional consistency. The mould was dressed with graphite powder along the gauge length and preheated by gas torch before pouring the melt.

For sand casting , green sand was used as the moulding material to make sand moulds and cores. The properties of the moulding sand depend on its composition and the manner of its preparation (mulling or milling conditions). In the present work the moulding mixture consisted of natural silica, clay, coal dust to which 4 to 6% water was used. The A.F.S. fineness number of the sand was measured by Tylor's Sieve Shaker and was found to be about 69. The same sand was also used for making the core.

4.3 Charge Materials

The total weight of each casting was about 3.2 Kg and 10 Kg for alunimium and brass castings respectively. Commercially pure aluminium (99.5%) was used for aluminium casting and for brass casting, the chemical composition of the charge was 73.0% cu, 25.5% Zn, 1.5% Sn and 0.5% other elements (may be Pb, Sb, Fe etc.).

4.4 Melting and Casting

A number of preliminary melting were carried out in order to standardise the melting technique and same procedure was adopted for the main experiments. During melting, care was also taken to measure the superheating temperature as well as the pouring temperature of the melts.

4.41 Melting

Local brass scrap consisting of water taps was taken in a graphite crucible and melted in a natural gas fired pit furnace. The addition of heat continued beyond the melting range of the brass which is about 1010°C - 1030°C. After raising the temperature of the furnace well above the melting range of the brass for sufficient time, the crucible was removed from the furnace with the help of a clamp having a long pair of arms. The molten brass contained a huge quantity of slag and in order to remove these slags the addition of flux became imperative. Therefore $Na_2B_4O_7$, $10H_2O$ (Borax) or NH_4Cl (ammonium chloride) was added into the crucible and stirring continued for sometime. Then the melt was poured into the sand made ingot mould and the molten brass was allowed to solidify in the form of tapered ingot each weighing about 15 Kgs. After solidification the material was tested to determine it's content and also to evaluate how much more material is to be added to get a composition of 73% Cu, 25.5% Zn and 1.5% Sn.

After evaluating the required amount, the additional amount of copper was added to the prepared brass ingot and melted in the pit furnace in the same manner. After melting the crucible was removed and additional amount of Zinc was added to the melt and stirring continued.

Once again flux materials like borax or NH_4Cl was added and skimming from the top of the melt was necessary prior to pouring. The melt was then poured into the ladle fitted with the trolly. By revolving the long handle, the ladle was tilted and the melt was poured into the mould which was already rotating at a particular speed.

4.42 Temperature Measurement

After melting the charge the temperature of superheat and pouring temperature were measured with the help of a Digital Thermometer which gave a direct reading of $\pm 2^{\circ}C$ accuracy. Since one of the process variables was pouring temperature of the melt so before casting it was necessary to take note of the desired temperature in order to maintain a high degree of experimental accuracy.

4.43 Mould Preheating

The mould was heated to about 200 to 250°C before pouring the melt. The principal significance of the mould temperature lies in the degree of expansion of the mould with preheating, expansion diminishes the risk of tearing in true centrifugal castings. Mould preheating also decreases the temperature gradient between the mould and the cooling substrate which tends to promote grain refinement during solidification.

4.44 Casting

There were about 16 main castings carried out in the present investigation among which 14 using the centrifugal casting process and 2 using the sand casting process. Finally comparison was made between the products of centrifugal casting and those of sand casting in order to evaluate the advantages of centrifugal casting over the sand casting.

Each casting was individually marked for identification. shown in Fig. 16 and the metallographic specimens with a vibrotool to avoid deformation of the structure.

4.5 Process Variables

Among the various process variables which affect the quality of the casting, only two, the effect of pouring temperature and the effect of rotational speed of the mould were studied in the present investigation. These are briefly described below:

4.51 Pouring Temperature

In order to select an appropriate pouring temperature as well as to see it's effect on the cast products, commercially pure aluminium and brass were poured at three different temperatures. For aluminium, these temperature were 710°C, 730°C and 750°C and for brass they were 1080°C, 1100°C and 1120°C. However in each case, the melt was superheated to about 30°C above the pouring temperature in order to subside the loss of heat during the transfer of the melt from the furnace to the rotating mould.

4.52 Rotational Speed of the Mould

There were four speeds of rotation used in the present study, which were recorded with the help of a Digital Tachometer which gave the direct measurement of the speed. These were 1000 rpm, 1400 rpm, 1800 rpm and 2200 rpm. The speeds were varied with the help of pulleys of different diameters. A V-belt worked as a medium for transfer of power from motor to the shaft of centrifugal casting machine.

4.6 Heat Treatment

Although a number of heat treatment process can be applied on brass and aluminium but in the present work only the effect of annealing on the micro-structures was investigated. Annealing processes for aluminium and brass are decribed briefly in the following subsections:

4.61 Annealing of Aluminium

For this purpose the specimens were heated in the muffle furnace at 650°F (344°C) and cooled to room temperature. No appreciable holding time is required for Aluminium annealing. However, it is important to assure that the proper temperature is reached in all portions and therefore the specimens were soaked for 1 hr at 650°F (344°C).

4.62 Annealing of Brass

Annealing of brass was accomplished by heating it to 1000°F (538°C) in a muffle furnace and holding it at that temparature for 1 hour and then relatively slow cooling to room temperature in the furnace. Except for Alpha-beta alloys and certain precipitation hardening alloys, the rates of heating and cooling are relatively unimportant for brass annealing[27]. After cooling to room temperature, the specimens were removed from the furnace and were studied on the basis of their micro-structure.

4.7 Metallography

Metallographic specimens were prepared from the cast hollow cylinders made of brass and aluminium. These were polished in the usual manner. Final polishing was carried out with fine alumina powder (0.1 micron)by hand. This was necessary to remove the micro scratches from the specimens.

The brass specimens were etched in 20 ml NH_4OH and a few drops of fresh H_2O_2(3%) by swabbing the specimen for 1 minute.

Aluminium specimens were etched in 100 c.c. H_2O, 5 c.c HNO_3 and 2 c.c HF. The etching time for aluminium was not excatly fixed but repeated etching and polishing was necessary to reveal the structure. The micro structures of both specimens (Brass and Aluminium) were examined under optical microscope to see the structural difference at different magnifications. Wetzlar Universal microscope and Swift-master photographic microscope were used for the examination and photographically recording of the representative microstructures respectively.

4.8 Determination of Mechanical and Physical Properties

Properties like ultimate tensile strength (U.T.S.), yield strength, % elongation, hardness, density and % porosity were determined for aluminium and brass casting. The detail procedure is given in the following sub-sections:

4.81 Determination of Tensile Properties

Tensile testing on brass and aluminium was conducted using a 24 Kg Hydraulic tensile testing machine with a screw type operating cylinder using 15 KN scals. A schematic diagram of a gripping device for threaded-end specimens was shown in Figure - 17(a). The standard 0.25 in (6.25 mm) diameter round test specimen with dimensious shown in Figure - 17(b)was used for tensile testing of both aluminium and brass[28]. The U.T.S. in newtons per square mm and percentage of elongation were obtained. The yield strength in newtons per square mm was measured by the offset method using specified value of set (= 0.2%) from stress strain curve. The results were averaged from three determinations.

4.82 Hardness Measurement

Brinell Hardness testing was conducted using Avery Brinell hardness testing machine. To determine the Brinell Hardness of the Brass and Aluminium , 10 mm diameter indenter and applied load of 500 Kgf were used. The Brinell hardness number (BHN) was calculated from the following equation

$$\mathrm{BHN} = 2P/\left\{\pi D\left(D - \sqrt{D^2 - d^2}\right)\right\}$$

where P = applied load, kgf.

D = diameter of the ball, mm, and

d = mean diameter of the impression, mm.

4.83 Density Measurement

In order to determine the density of the cast product, the specimens were taken in such shapes that the volumes were calculated easily. Aluminium specimen was taken in the shape of a uniform cylinder, while the brass specimen was taken in the shape of a rectangular block. The volumes of aluminium and brass specimens were determined in the following manner:

For Aluminimum Cylinder:

Volume, $V = \frac{\pi D^2 H}{4}$

where D = Diameter of the cylinder

H = Height of the cylinder.

For Brass rectangular block

Volume, V = Length x Breadth x Height.

The weight of each specimen was measured in the laboratory balance (accuracy 0.1 mg) and the density was thus calculated using the formula

$$\text{Density} = \frac{\text{Weight}}{\text{Volume}}.$$

4.84 Percentage Porosity Measurement

It may be desirable to determine the percentage porosity of metals and alloys, especially when they are dense and the absorption of water is incomplete or when closed pores exist into which the liquid cannot penetrate. For materials not attacked by water, porosity determination can be made by using water. When necessary, kerosene may be used as the liquid. For the calculation of the percentage porosity.

of the casting, it is necessary to determine both the bulk and the true density. The former is determined by obtaining the weight of the dried piece, in air, and its exterior volume. The bulk density (d), obviously, is equivalent to the relation w/v, where w is the weight of the specimen and v its volume. The true density is found by grinding the material, passing it through the 100 mesh sieve, and determining the values sought by means of a pycnometer in the following manner:

Weight of the empty pycnometer = w_1 gm

Weight of the pycnometer and sample (powder) = w_2 gm

Weight of the pycnometer, sample (powder) and water = w_3 gm

Weight of the pycnometer and water = w_4 gm

Weight of the sample in air = $(w_2 - w_1)$ gm

Weight of the water displaced by the sample = $\{(w_4 - w_1) - (w_3 - w_2)\}$ gm

$\therefore$ Volume of the sample = $\{(w_4 - w_1) - (w_3 - w_2)\}$ c.c.

$\therefore$ True density of the sample

$$D = \frac{\text{Weight of the sample in air}}{\text{Volume of the sample}}$$

$$= \frac{w_2 - w_1}{(w_4 - w_1) - (w_3 - w_2)}$$

The percentage porosity (P) of the casting is then computed from the following relation

$$P = 100\left(1 - \frac{d}{D}\right),$$

where, d = bulk density

D = True density.

5. RESULTS

5.1 Introduction

The entire result was divided into two phases for the purpose of comprehensibility and convenience. The first phase appropriately referred to as Preliminary tests, involves the selection of pouring temperature. This section was done on the basis of resulting microstructure and mechanical properties following the castings poured at three different temperatures. The second phase which can he referred as main tests comprises the results obtained from the experiments carried out at different rotational speeds of the mould.

5.2 Effects of pouring temperature on structure and properties

Results of these set of experiments are summerised in the tabular form in Table 3 to 6 and represented graphically as well in Figs. 18 to 20. Figs. 18 and 19 show that with the increment of pouring temperature, tensile properties decrease both in case of aluminium and brass casting as well. Figs. 21 and 22 show the micrographs of aluminium and brass respectively. As evident from these figures, the higher the pouring temperature, the larger the size of the grains. The pouring temperatures of 710°C and 1080°C for aluminium and brass respectively yield the best result.

5.3 Effects of rotational speed of the mould on structure and properties.

Details results of this set of experiments are shown in Tables 7 to 11 and graphically presented in Figs. 23 to 27. Figs. 23 and 24 show that tensile properties are better when the speeds of the mould were 1800-2200 rpm for aluminium and 1400-1800 rpm for brass. Microstructures of aluminium are shown in Figs. 28 to 32 while Figs.33 to 37 show the microstructures of brass. Of the structures shown in Figs.28 to 32, Fig. 28 shows the microstructures of sand cast aluminium whereas Fig. 29 shows that of centrifugally cast aluminium when the speed was 1000 rpm. While comparing between Figs. 28 and 29, it can be inferred that in both cases impurities are found to have been divorced by α aluminium and are concentrated at the grain boundaries. Cellular dendrites however, are larger in size in case of sand cast specimen than those of the centrifugally cast specimen. Figs. 30, 31 and 32 show the microstructures of centrifugally cast aluminium at 1400, 1800 and 2200 rpm respectively, all containing equiaxed grains. But only in case of the specimen of 2200 rpm shows fine smaller grains whereas the other two specimens show larger and coarser grains.

Fig. 33 shows the microstructure of sand cast brass while Fig. 34 shows the microstructure of centrifugally cast brass at a speed of 1000rpm. Both the Figures give the picture of fir-tree like dendrites of α-brass. Only difference is that in the sand cast specimen, massive and dense dendritic structures are visible whereas in centrifugal cast specimen, thin dendrites with smaller arms are prevailing.

Figs. 35 to 37 represent the structures of centrifugally cast brass when the speeds of the mould were 1400, 1800 and 2200 rpm respectively. Comparison reveals that all contain equiaxed grains but when the speed was 1800 rpm, the grains are very fine compared to other two. However, each specimen contains uniform dispersion of cuprous oxide and other impurities (black dots).

5.4 Effects of heat-treatment on the structures of aluminium and brass.

Figs. 38 to 42 show the annealed structures of aluminium specimens. It can be seen that the traces of coring effect are prominent near the grain boundaries in sand cast specimen (Fig. 38) whereas this effect is less prominant in the 1000 rpm centrifugally cast specimen (Fig. 39). In the case of aluminium castings at 1400, 1800 and 2200 rpm, they all contain equiaxed grains (Figs. 40-42) and no coring effects are visible. However, the finer grains are obtained in the structure when the mould speed was 2200 rpm.

When annealing is carried out on sand cast brass specimen, traces of coring effects are prominently visible near the grain boundaries (Fig. 43). But when centrifugally cast brass (1000 rpm) is annealed, twin crystals come into being with less prominent strain bands (Fig. 44). When the castings (obtained at speeds of 1400, 1800 and 2200 rpm) are annealed, the microstructures show twin grains with more prominent strain bands (Figs. 45-47). However, in case of the specimen obtained at the speed of 1800 rpm, the microstructure shows finer and more equiaxed twinned regions compared to those obtained at other two speeds.

6 DISCUSSION

6.1 Introduction

The structure and properties of aluminium and brass vary appreciably due to the use of the process variables like pouring temperature and rotational speed of the mould etc. The theme of the present work was largely confined to study the structure and properties of aluminium and brass as affected by process variables during centrifugal casting.

To establish and evaluate their effects in centrifugal casting, a number of preliminary trails were performed to optimise the pouring temperature of the melt to be used in the main experiments. Finally the main experiments were carried out by changing the speed of rotation in the mould. All these aspects are discussed in the following sub-sections.

6.2 Solidification Mechanism during centrifugal casting

In centrifugal casting the mould is rotated at a desired speed so that the pipe is formed almost as a series of welded rings and analogous to winding, a rope into a helical coil. It is worth considering the mechanism by which the pipe wall thickness is built up. Two opposing views[23] are that the individual coils acquire their final thickness in a single mould rotation, or that the pipe wall solidified in layers requiring several mould revolution. The latter view appears to be valid for the present case.

As the head of the stream contacted the rotating mould, the melt spread out over the entire length of the mould cavity. With further flow of metal from the crucible pipe wall thickness builds up gradually and uniformly over the entire length of the pipe. The melt when poured into a rotating mould, would acquire the rotational movement because of the tangential forces. Immediately on pouring however, inertia would prevent the melt from taking up the speed of the mould instantly. Relative motion would exist between the adjacent liquid layers and also between the melt and the solidified layer. In the latter, the melt would flow across the front of the growing crystals. The fine equiaxed structures would develop because the shear stress fractured the growing dendrites, just after solidification begins.

6.3 Nucleation and growth hypothesis during centrifugal casting

Conventional casting consists of pouring (teeming) molten metal into a mould cavity which has the shape of the article required and then allowing it to solidify. Although there are many variations on this simple theme, but the basic concept is that the melt should initially be poured more rapidly than the rate of which the metal solidifies in the mould, so that a sump of liquid accumulates which ensures that, until the end of solidification, there is always an excess of molten metal available for feeding. The importance of this sump is demonstrated by the shrinkage during solidification, leading to internal unsoundness in the form of porosity or piping, which occurs in its absence.

The situation is illustrated in very simplified form in Figure -52 , the assumption is made that heat is being extracted only from the side wall of the mould. The Figure shows the excess metal above the solidification front, with dendrites growing in a direction opposite to the heat flow. The well known deficiency of this form of casting, either continuous or discontinuous, is that segregation occurs with most alloys because the solidification time is sufficiently long for major compositional differences to occur, yet not long enough for homogenization to take place. Other problems are caused by porosity and/or piping, and by a cast grain size that is usually much coarser than that of centrifugal casting of similar composition.

The Figure above shows a saturated feed of molten metal supplied by the large sump of liquid contained by the walls of the mould. The sump ensures that the shape of the mould cavity is eventually taken by the solidified metal, because movement of liquid can, and does, take place freely in a plane parallel to the solidification front. A further point to note is that any molten metal fed into the sump remains there for a considerable time usually with convective movement, before it eventually solidifies.

Let us compare this situation with that shown in Figure - 53 drawn on a much larger scale, illustrating a typical instance of incremental solidification during centrifugal casting using a high rotational speed of the mould. In this case, the sump of liquid is replaced by a very thin film covering most of the solidification front. Assuming the rate of heat extraction from the side wall is the same as in Figure 52, it is essential to preserve continuity that the rate at which molten metal is added, is matched to the rate of heat extraction in such a way that an unsaturated feed is retained. This, of course, cannot be achieved by pouring in the ordinary way, because pouring delivers molten metal at either one or several places only, and depends on liquid movement within the sump to bring about an even distribution across the freezing front. Such movement is impossible within a very thin film.

The critical difference in incremental solidification during Centrifugal Casting is that molten metal arriving at the mould surface or the prior solidified surface remains where it is delivered. This molten metal moves due to rotational movement because of tangential forces, inside the mould.

The contrast between the two concepts is very marked. In the situation illustrated in Figure-53, for example, a droplet 200 μm in diameter arriving at the solidifying surface forms a splat (consisting of few droplets) with a diameter of, say 500 μm, but with a thickness of only, say 20 μm. The speed of formation of the splat, that is the flow of liquid inwards until stopped by friction, surface tension, or freezing, depends on its size and surface tension, and the velocity of its arrival[29]. Freezing of the splat will depend on the temperature of the mould or the prior deposit, but it takes lesser time than splat formation. Careful observation of the micrographs (Figure-50) reveals that the outer surface of a splat deposited on the cool base or on the prior splat freezes very rapidly but that the inner surface cools at a slower rate.

If the rate of arrival of droplets is sufficiently high, i.e. the rotational speed of the mould is very high (2200 rpm for brass), the new droplets will land on prior splat which have not solidified totally as yet. Due to this incomplete solidified splat formation a thicker film of liquid is formed. But the thickness of the film of liquid metal on the surface of the splats is not much greater than the splat thickness or this film is not like that of a sump type which is normally found in conventional casting for saturated feeding. However there will be a liquid/liquid interface between the arriving droplet and the surface on which it is splatting. Consequently, there is very rapid liquid mixing, because of high impact velocity, which causes union of two liquids and obliterates any boundary effects[29].

Under an optimum speed of mould (1400-1800 rpm for brass and 1800-2200 rpm for aluminium), the rate of arrival of droplets can be optimised so that a thin film of molten metal will land over the entire length just after the solidification of the prior splat. Solidification will proceed normally from this situation, with the solidification front moving forward through the new molten splat until the next droplet arrives at the surface. In this way, liquid metal is supplied constantly as an unsaturated feed, each portion of which freezes immediately, causing an incremental change in the dimensions of the casting. Unsaturated feed is used here to indicate that there is no large sump of supernatant liquid metal into which solute can be rejected, and from which solidifying dendrites can be formed.

In this case, the structure of the product depends to a great extent on the conditions of splating. It might be thought that dendrite arms from the solidifying prior splat are broken off by the rapid flow of new liquid, thus forming a multitude of nuclei in the new arrival. Equiaxial grains then grow in the new splat until the next arrives, the process continuing infinitely. In such cases, the final structure is a fine-grained, equiaxial structure with low porosity. This property is unusual in conventional casting and, therefore, needs explanation. The observation that no porosity exists at the boundary when one splat is deposited directly on to an earlier solidified splat implies that one wets the other. A solidified splat always has angularities associated with its outer surface and, clearly, these have been infilled by the following liquid splat as it arrives on the surface. While some of the earlier splats may still be liquid at their top surface when the next splats arrive. As so little porosity is evident[30]. Segregation is also at a very low level in Centrifugal Casting and is confined within areas approaching towards the centre. Therefore the potential benefits from this situation are very considerable, including near-zero segregation and rapid solidification, the latter leading to enhanced mechanical properties[31]. It is assumed in all these arguments that the operation is carried out under controlled atmospheric conditions which minimize oxide formation.

6.4 Effects of pouring temperature on microstructure and properties

In order to obtain desirable and optimum property from the casting, the pouring temperature of the melts must be correct, selective and decisive. Of the three pouring temperature is shown in Figure- 18 , it is seen that the lowest temperature gave the best desired result. Mention may be made here that the low temperature does not mean lower or very near to melting point. This temperature was well above the melting point of the metal and it was fluid enough to flow within the mould. Now, the question is why best desired result obtained at a lower pouring temperature. Actually, at lower pouring temperature, the melt can solidify quickly that means more nucleation and lesser growth, resulting equiaxed grain. On the other hand higher pouring temperatures give more slow cooling of the casting throughout its freezing range. With lower cooling rates, the degree of under-cooling is less and fewer nuclei are available for growth which eventually leads to the formation of comperatively coarse crystals and hence inferior mechanical properties. Meier and Conture[32] found that employing high pouring temperatures for certain aluminium alloys results in an increase in grain size and a consequent decrease in tensile strength and elongation. Similar observations were also made by other investigators[33,34].

Not only the smaller grain size obtained in low temperature cast product but the tensile strength, yield strength, BHN etc. were also very satisfactory compared to the castings poured at higher temperatures. This type of increasing results was witnessed both in case of brass as well as in case of aluminium.

6.5 Effects of speed of rotation on microstructure and properties

The entire experimental operation was carried out having four different speeds which were 1000 rpm, 1400 rpm, 1800 rpm and 2200 rpm. Of all these experiments at different speeds, the microstructure and properties of the brass and aluminium when cast at 1800 and 2200 rpm respectively were found to be the best (Tables 7-8). The reason that may be attributed to this observation and the failure in attaining superior quality in those aforementioned parameters in other speeds will be explicated in the following paragraphs.

Because of the high rotational speed i.e. 1800 rpm for brass and 2200 rpm for aluminium, there is always a thin film of liquid metal distributed over the mould surface or over the prior solidified surface. This contributes to the rapid solidification of the melt and as a result there is no scope of forming the dendritic structure. Instead a equiaxed grain formation is evident. Even if there is any possibility of formation of dendrites, because of the high rotational speed these dendritic structures break up to give rise to equiaxed grains. Another reason of forming equiaxed grains may be that due to high speed of rotation there exists a mechanical turbulance inside the mould. Thus the crystalites formed over the inside surface of the cold mould are split out and wherever they land, undercooling takes place (because of sufficient latent heat of crystallisation). As a result fine equiaxed grains are obtained at every stage. Also due to high speed, all the impurities and inclusions get flushed out towards the centre of the mould resulting fine microstructure as shown in Fig. 36.

At a lower speed such as at 1000 rpm, comparatively a thick layer of liquid film is spread over the mould surface or over the prior solidified surface which needs more solidification time. This in turn favours the formation of dendritic structures. However, here solidification time is less than that of a sand casting. Therefore, the arm spacing of dendritic structures are less than that in sand cast products. The other reason which results in the nonformation of equiaxed structures while operating at 1000 rpm is that the force required for the fragmentation of dendritic structures is not enough in this speed. Besides, due to insufficient force the crystalites cannot get detached (as it does in case of higher speeds). So equiaxed grain formation fails to come into being. Therefore, at 1000 rpm the entire microstructure of the product is dendritic in nature as shown in Fig. 34.

When the speed has been increased to 1400 rpm in case of brass, the force to create fragmentation of the dendritic structures was enough resulting equiaxed structures. Under the microscope, it was observed that the equiaxed grains obtained at 1400 rpm were slightly larger in size than those obtained at a higher speed of 1800 rpm. Besides, micropores were visible in the structures of the product obtained at 1400 rpm whereas they were virtually nil when the mould rotates at 1800 rpm.

In case of aluminium, when the speed has been increased to 1800 rpm, the force for complete fragmentation of the dendrites was enough resulting equiaxed structures. But the equiaxed grains obtained at 1800 rpm, were slightly larger in size than those obtained at a higher speed of 2200 rpm.

When the speed of the mould is increased to 2200 rpm for brass, very interesting outcomes were obtained. For example, it was anticipated that there would be even more fragmentation of the dendritic structures and a more minute equiaxed structures would be available in the microstructures. Instead the grains are found to have become equiaxed yet larger in size, somewhat like those at 1400 rpm or perhaps little bigger. The reason for this outcome may be explained with the help of nucleation and growth hypothesis during a very high speed of rotation. What happens here is that due to high speed of revolution, a layer of liquid film is over lapping with another layer in very quick succession. As a result the former layer does not get enough time to solidify before encountering the second layer. Therefore instead of forming a thin film of liquid over a previously solidified layer as evident during the case at 1800 rpm, a thicker liquid film accumulates. Hence, during the course of solidification there would have been a possibility of formation of dendritic structures, but since another layer of liquid metal immediately strikes the previous one and breaks the tips. Thus instead of forming dendrites, equiaxed apparently similar to or perhaps little bit bigger in size than those at 1800 rpm would result. Now, because of the interaction of one layer over another here, there would have a boundary effect also. But as the centrifugal force is very high at the speed of 2200 rpm, mixing of the two liquid fronts becomes very quick. Therefore, the boundary formation could not happen and even under the microscope, no boundary effect was observed, (Figure- 37). However due to the solidification of the thick layer at this speed (2200 rpm), there appear some micropores in the microstructure. As a result, the tensile properties for these specimens are slightly inferior to those obtained at 1800 rpm specimensas shown in Figures 23 and 24.

As regards the microstructures, Fig. 51 shows the outer surface, middle zone and inner surface of the sand cast brass specimen. It can be seen that at the outer surface there is columnar growth of dendritic structure and the arm lengths are shorter. In the mid zone the dendritic structure, are medium sized and at the inner surface they are larger and quite prominent. Therefore throughout the entire structure the presence of dendrites of various sizes are predominating. Besides, there are innumerable and large pores throughout the structure. But in the centrifugally cast product (at 1800 rpm), the structure shows no dendrites. Instead fine and equiaxed structures of almost same size are seen in the entire structure (Fig. 50) and the pores are also negligible. In fact microporosity in sand casting is about 5.5% whereas it is 2.7% in case of centrifugally cast brass as already tabulated in Tables 12 and 6. As a result the ultimate tensile strength for brass in case of sand casting is 170 N/mm^2 (Table 12) but in centrifugal casting it is 235 N/mm^2 (Table 8). Similarly the UTS for aluminium is 70 N/mm^2 (Table 12) for sand casting but in centrifugal casting it is 125 N/mm^2 (Table 7).

Speed of the mould to obtain optimum quality of the product was calculated theoretically with the help of a mathematical formula derived by Professor L.S. Konstantinov[16] and it was observed that the resulting microstructure of the product did not contain fine equiaxed grains. Under the circumstances, products were cast using various speeds (1000 to 2200 rpm) and looked forward to investigate a particular speed which one would yield fine grain equiaxed structure. It was theoretically found that the optimum speed should be 1200 rpm using above formula but in the present study, best results were obtained when the speeds were 1400 - 1800 rpm for brass and 1800 - 2200 rpm for aluminium.

Cumberland[18] has shown in Fig. 13 that the rotational speed of the mould is independent of the density of the material used. But in the present investigation it has been found that density has got a tremendous effect on the selection of optimum speed to obtain the best quality product. In fact lower the density, the higher the rpm and vice versa. Suffice it to say that brass has higher density than aluminium. Again according to Professor L.S. Konstantinov[16] the constant used in the equation was 5520. But the present study differs from this value which is found to be about 5800 and 6500 for aluminium and brass respectively, this constant will differ for other metals depending on the density and give the accurate value for determining the optimum speed.

6.6 Structural modification during centrifugal casting and properties

Differences in grain refinement due to differences in solidification rates markedly affect the mechanical properties of metals and alloys. In the present investigation, it is observed that the mechanical properties slightly vary at different rpm of the mould but whatever may be the speed, the tensile strength and hardness are always better than those obtained in traditional sand casting[31]. For example in sand casting the tensile strength of brass and aluminium were found to be about 170 N/mm^2 and 70 N/mm^2 respectively (Table 12), whereas they were 210 N/mm^2 (Table 8) and 95 N/mm^2 (Table 7) respectively as the minimum in case of centrifugal casting. The Brinell hardness of the brass and aluminium under studies in case of sand casting was found to be 55 and 33 respectively whereas in centrifugal casting it was obtained 70 BHN at 1800 rpm for brass and 45 BHN at 2200 rpm fnr aluminium. Percentage porosity was maximum in sand casting and it was 6.3% whereas in centrifugal casting at 1800 rpm it was found about 2.7% for brass and at 2200 rpm it was 3% for aluminium.

The better results can be obtained in centrifugal casting compared to those obtained in sand casting even when the rpm is low. This is because during centrifugal casting rapid cooling takes place which includes higher degree of undercooling. Thus formation of nuclei increases that in turn restricts further growth of the crystal in a chunk and this leads to the formation of fine equiaxed structure.

6.7 The effects of heat treatment on structures

As mentioned before high speed centrifugal casting has given birth to equiaxed grains for brass as found in the micrographs. When these brass specimens were annealed, equiaxed twin crystals came into being along with hatched marks that is referred to as strain bands. As explicated in the literature survey, when sand cast brass specimen is annealed after partial deformation, bent twins with strain bands are visible throughout the structure[22]. These bent twins appear due to the annealing of the partially deformed specimen where the grains become elongated, where-as in centrifugal casting, equiaxed twins and strain bands are found. Now the question is that why these typee of phenomena are being happened in case of centrifugal casting.

It is envisaged that in case of centrifugal casting dendrite fragmentation results equiaxed grains and the phenomenon can be considered similar in effect as partial deformation in the sand casting. Furthermore, during high apeed of the mould, the growing crystals undergo some sort of deformation and favour to form equiaxed grains. But due to imposition of external forces applied on the centrifugal cast products undergoing partial deformation, give rise to elongated grains. So when the centrifugally cast product is annealed, twin equiaxed grains are visible, whereas when partially deformed sand cast products are annealed, show bent twins. However, in both cases the existence of etrain bands are also found.

7. CONCLUSIONS

The following conclusions, may be drawn from the results of the present investigation:

1) Through out the entire operation it has been proved beyond doubt that centrifugal casting is far more superior to sand casting, in every aspects as was evident from the study of the overall appearance of microstructures, physical and mechanical properties of the casting obtained in the present investigation. To be precise, centrifugally cast products are stronger, denser, cleaner and free from voids, poras and impurities.

2) For aluminium, a pouring temperature of about 710°C yields best results with respect to structure and properties. Similarly, for brass containing 73% Cu, a pouring temperature of about 1080°C produces better products. Higher pouring temperatures are conducive to slow cooling which in turn produces larger grains resulting poorer properties. Comparatively lower pouring temperature (must be well above the melting temperatures of the metal and alloy) relates to faster cooling, offering finer grains with excellent properties.

3) The true centrifugal casting process yields satisfactory results with respect to appearence, structure and properties of the product when the rotational speed of the mould veries between 1400 to 1800 rpm (9.0 to 11.5 m/s) and 1800 - 2200 rpm (11.5 to 14.0 m/s) for brass and aluminium respectively. This set of experiments also suggest that the density of the material has a great effect on the rotational speed of the mould.

4) Annealing has shown a great influence on the microstructure of the cast specimens. Sand cast aluminium and brass specimens show prominent coring effect near the grain boundaries, whereas the centrifugally cast specimens (after annealing) do not show such effect.

At the same time, after annealing the sand cast brass specimen does not show any hatched marks or strain bands but the centrifugally dast brass specimen when annealed shows equiaxed twins with strain bands.

Table - 1

The range of composition for the three phases of brass at room and solidus temperature.

Temperature	Zinc %		
	α	$\alpha + \beta$	β
At room	0 - 35	35 - 46.6	46.6 - 50.6
At solidus	0 - 32.5	32.5 - 36.8	36.8 - 56.5

Table 2 : Typical Applications of Centrifugal Castings

	Products	Material
a) As-cast	Pipes for water, gas and sewage	Cast iron
	Tubing for reformers Radiant tubes	Heat resisting steel
	Rainwater pipes	Cast iron
b) Machined from pots	Bearing bushes	Copper alloys
	Piston rings Cylinder liners	Cast iron
	Paper making rollers	Copper alloys
	Gas turbine rings	Heat resisting steel and nickel Base alloys
	Runout rollers	Carbon steel
c) After heat-treatment (annealing)	Large diameter Iron pipe	Cast iron or Ductile iron

Table-3 Tensile properties of aluminium casting (1800 rpm) poured at different temperatures.

Pouring temperature (^{o}C)	Yield strength		U.T.S.		Elongation (%)
	N/mm^2	p.s.i.	N/mm^2	p.s.i.	
710	62	8985	125	18150	17.5
730	60	8695	122	17700	17.0
750	55	7980	118	17100	17.0

Table-4 Tensile properties of brass casting (1800 rpm) at different temperatures.

Pouring temperature (^{o}C)	Yield strength		U.T.S.		Elongation (%)
	N/mm^2	p.s.i.	N/mm^2	p.s.i.	
1080	125	18150	235	34,060	17.0
1100	120	17400	222	32,175	16.5
1120	116	16800	215	31,160	16.0

Table-5 Hardness of aluminium and brass casting (1800 rpm) poured at different temperature.

Aluminium		Brass	
Pouring temperature (^{o}C)	Hardness (BHN)	Pouring temperature (^{o}C)	Hardness (BHN)
710	43	1080	70
730	42	1100	68
750	40	1120	65

Table-6 Density and % porosity of (a) aluminium and (b) brass casting (1800 rpm) poured at different temperatures.

(a) Aluminium

Pouring temperature (°C)	Density (gm/cc)	Porosity (%)
710	2.71	3.3
730	2.7	3.5
750	2.66	4.0

(b) Brass

Pouring temperature (°C)	Density (gm/cc)	Porosity (%)
1080	8.39	2.7
1100	8.35	3.2
1120	8.31	3.7

Table-7. Effects of rotational speed of the mould on tensile properties of aluminium casting poured at 710 °C.

Speed		Yield Strength		U.T.S.		Elongation %
Rotational (rpm)	Peripheral (m/sec)	N/mm^2	P.s.i.	N/mm^2	P.s.i.	
1000	6.5	48	6960	95	13770	13.0
1400	9.0	58	8400	120	17400	16.0
1800	11.5	62	8985	125	18150	17.5
2200	14.0	67	9700	129	18700	17.0

Table-8 Effects of rotational speed of the mould on tensile properties of Brass casting, poured at 1080°C.

Speed		Yield strength		U.T.S.		Elongation %
Rotational (rpm)	Peripheral (m/sec)	N/mm^2	p.s.i.	N/mm^2	p.s.i.	
1000	6.5	105	15,765	210	30,440	15.5
1400	9.0	118	16,800	230	33,335	17.5
1800	11.5	125	18,150	235	34,060	17.0
2200	14.0	115	16,600	225	32,610	17.5

Table-9 Effects of rotational speed of the mould on Hardness of aluminium and brass casting.

Speed		Aluminium	Brass
Rotational (rpm)	Peripheral (m/sec)	Hardness (BHN)	Hardness (BHN)
1000	6.5	36	63
1400	9.0	41	67
1800	11.5	43	70
2200	14.0	45	65

Table-10 Effects of rotational speed of the mould on Density and % Porosity of aluminium casting poured at 710°C.

Speed		Density (gm/c.c)	Porosity (%)
Rotational (rpm)	Peripheral (m/sec)		
1000	6.5	2.674	4.5
1400	9.0	2.705	3.6
1800	11.5	2.71	3.3
2200	14.0	2.715	3.03

Table-11 Effects of rotational speed of the mould on Density and % Porosity of brass casting, poured at 1080°C.

Speed		Density (gm/c.c)	Porosity (%)
Rotational (rpm)	Peripheral (m/sec)		
1000	6.5	8.293	3.8
1400	9.0	8.367	3.0
1800	11.5	8.39	2.7
2200	14.0	8.307	3.65

Table - 12

Mechanical and Physical properties of sand cast Aluminium and brass.

	Aluminium	Brass
Yield strength	40 N/mm^2 (5,800 psi)	86.5 N/mm^2 (12,550 psi)
U.T.S.	70 N/mm^2 (10,150 psi)	170 N/mm^2 (24,640 psi)
Elongation	10%	13%
Hardness	33 BHN	55 BHN
Density	2.62 gm/c.c.	8.15 gm/c.c.
% Porosity	6.3	5.5

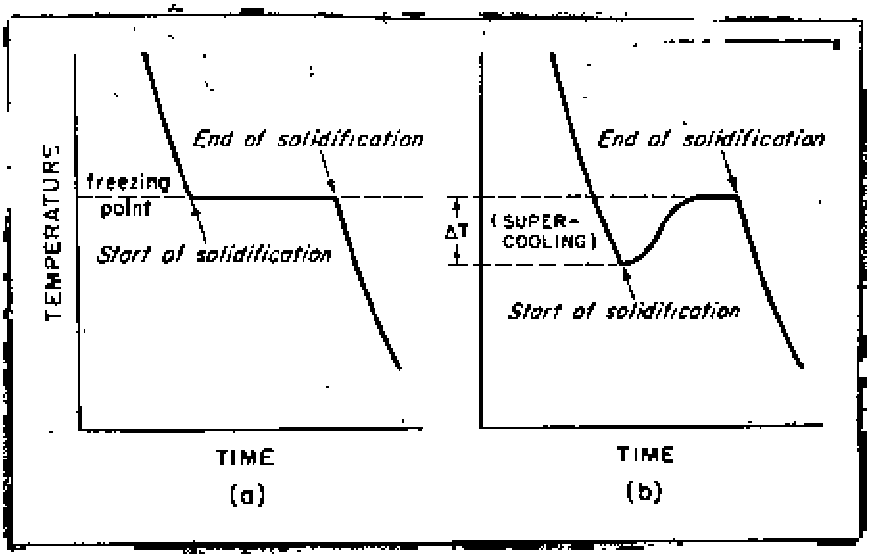


Figure-1: Cooling curves of a solidifying pure metal.

(a) Equilibrium cooling

(b) Cooling curve showing supercooling.

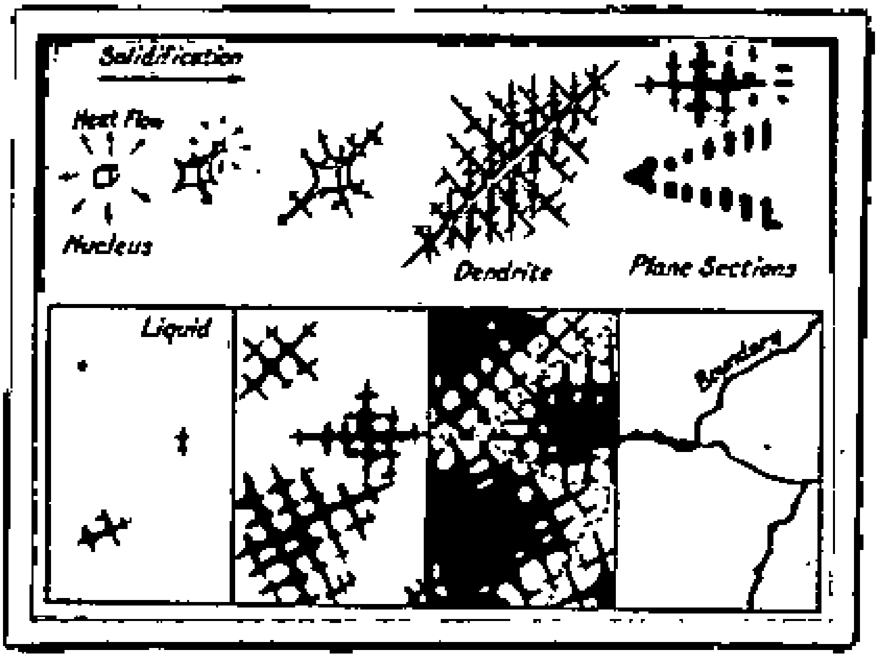


Figure-2: Solidification of a metal. For f.c.c. and b.c.c. metals dendrite arms extend in the cube face (100) directions.

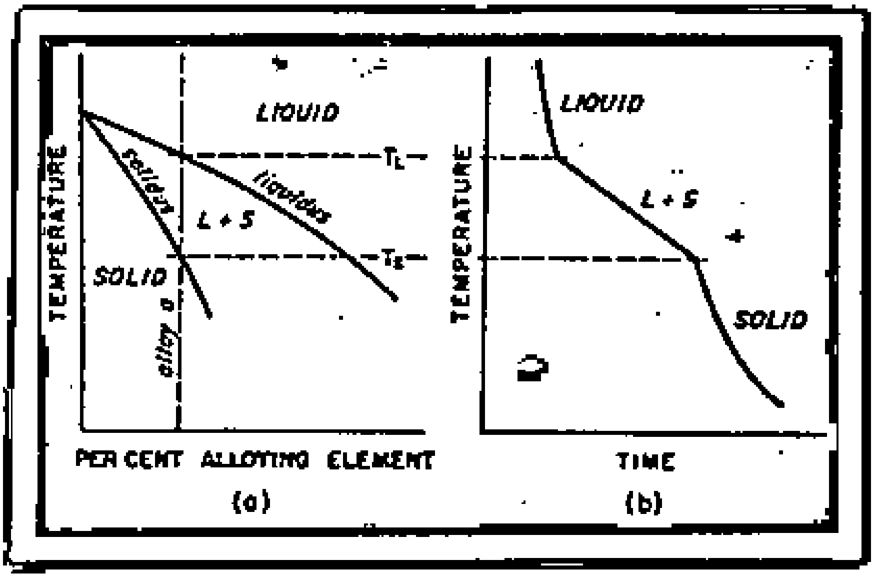


Figure-3: Effect of alloying on the solidification temperature of a metal.

(a) Plot of solidification temperature verse percent alloying element,

(b) Ideal cooling curve (equilibrium cooling) of alloy.

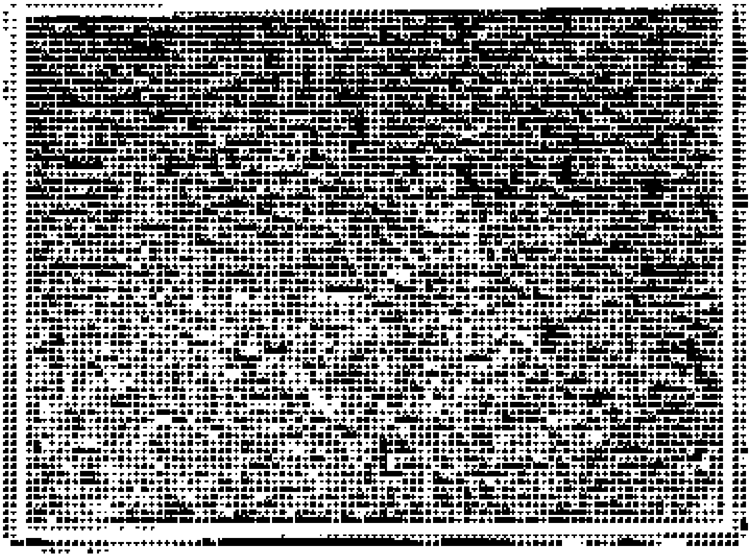


Figure-4 : Microstructure of commercially pure aluminium.

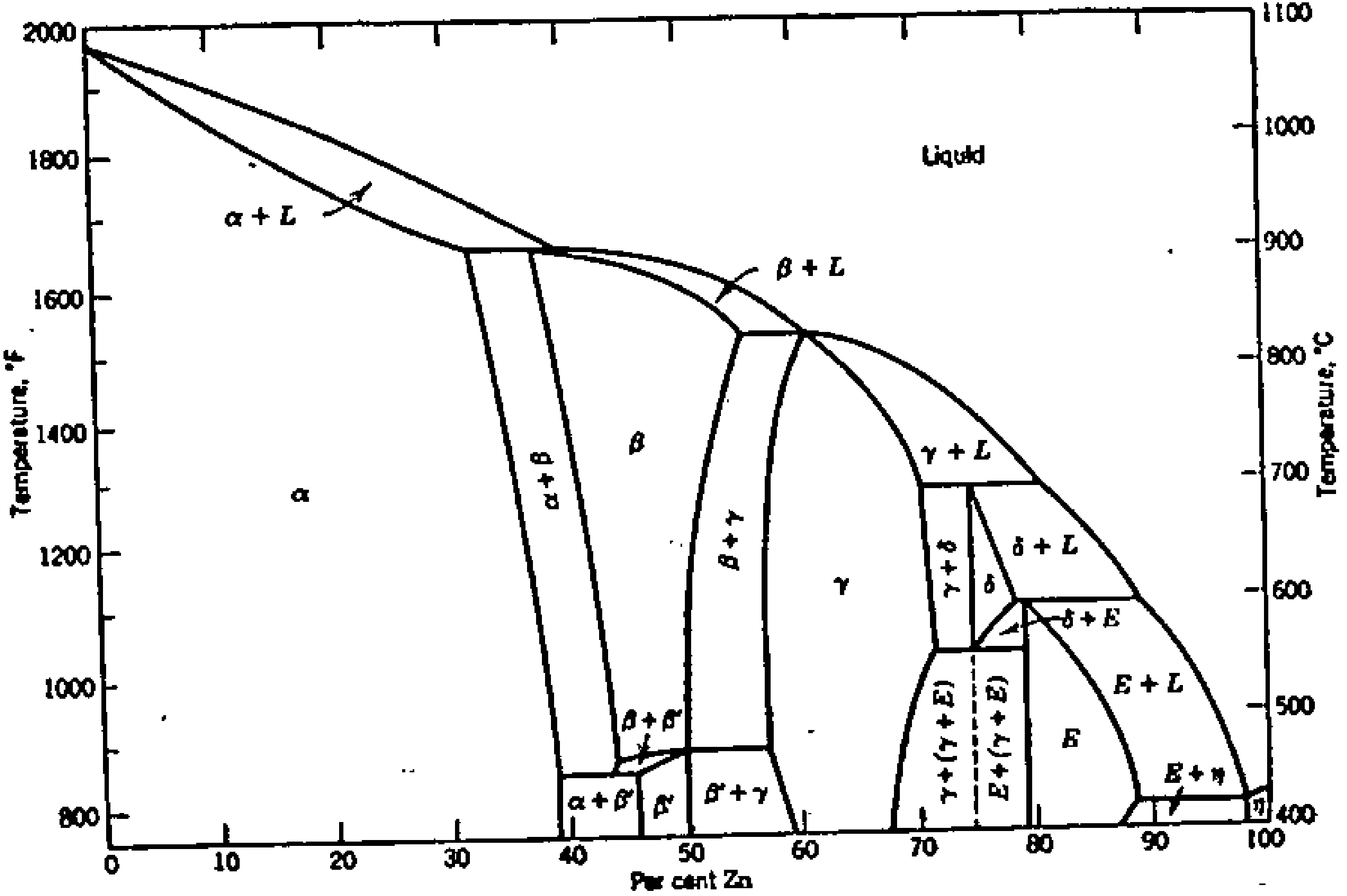


Figure-5: Equilibrium diagram of Copper-Zinc system.

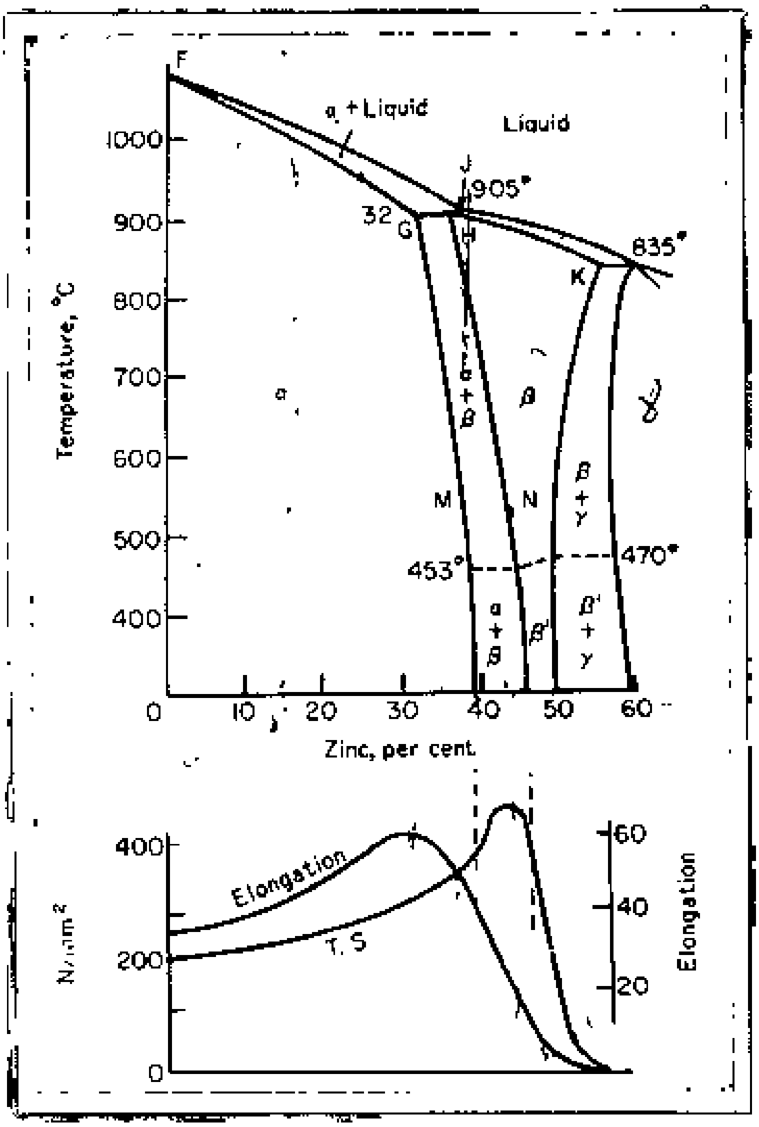


Figure-6: Equilibrium diagram and mechanical properties of brasses.

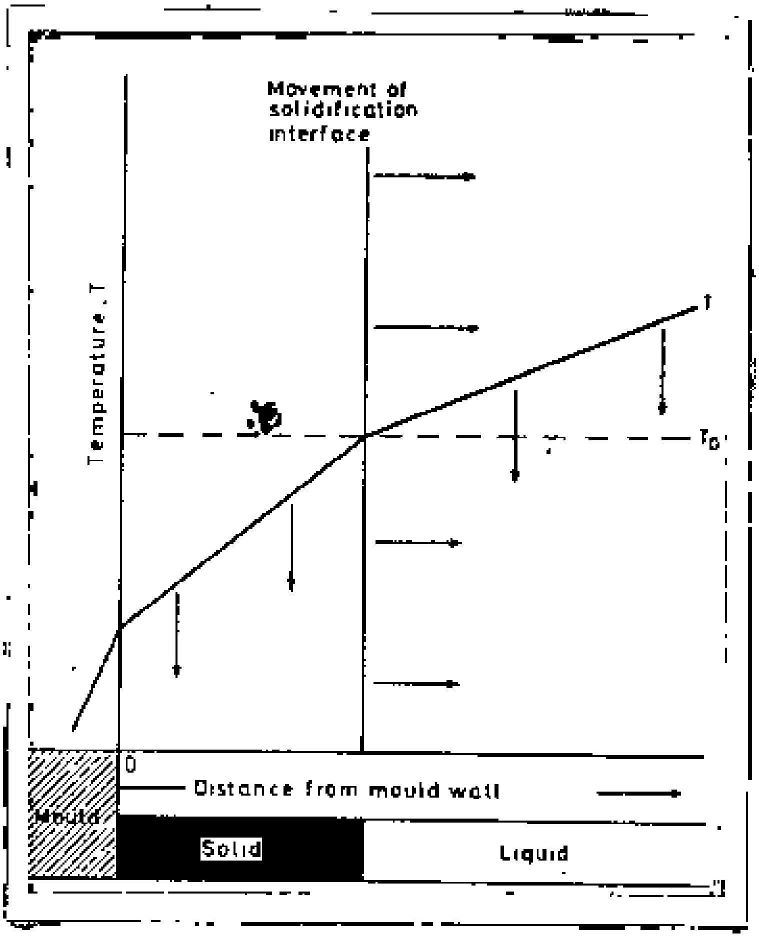


Figure-7: Schematic representation of temperature distribution in plane front solidification.

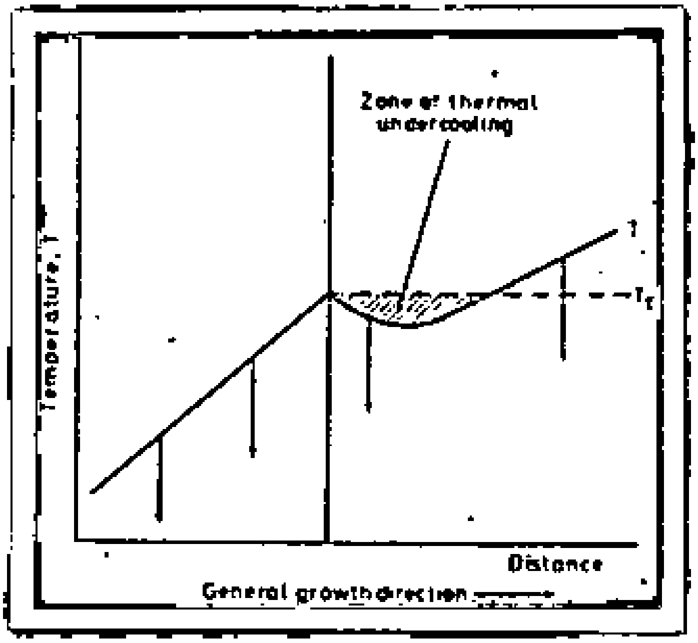


Figure-8: Thermal conditions with reversal of temperature gradient in liquid adjoining interface.

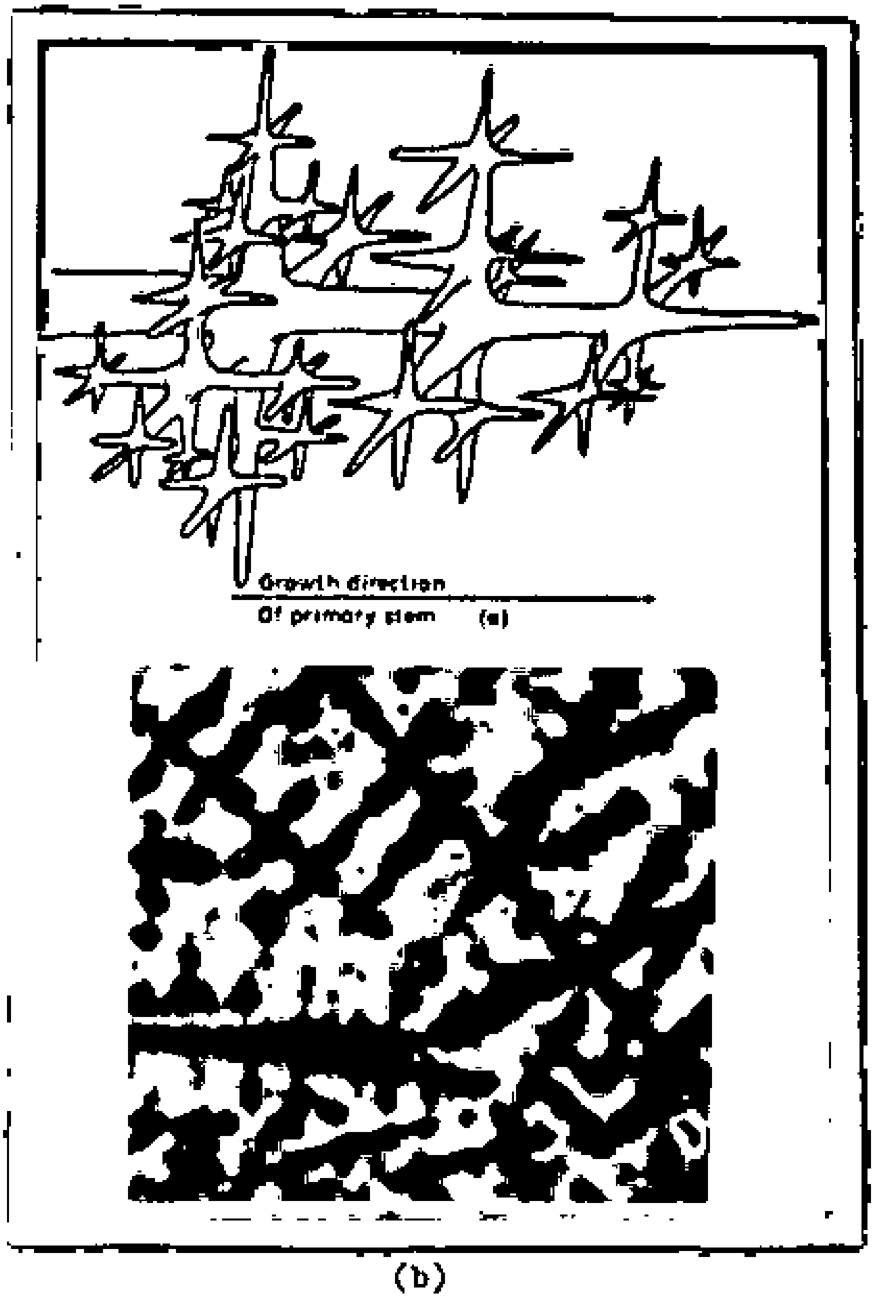


Figure-9: Dendritic growth (a) classical concept of a dendrite (b) dendrite microstructure in brass (Cu - Zn alloy), x 100

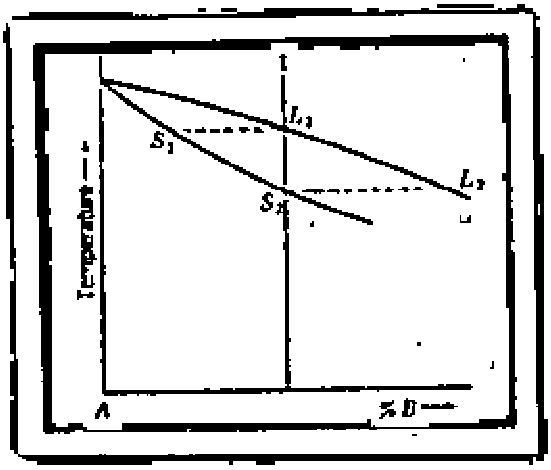


Figure-10: Solidification of a solid-solution alloy.

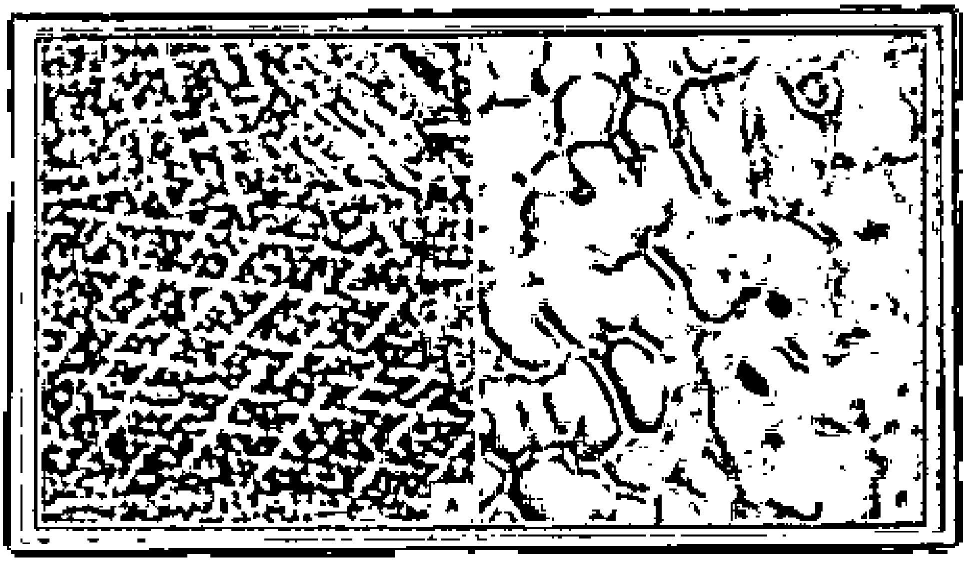


Figure-11: Coring A) Heavy coring in a fast cooled casting
B) Light coring in a slow cooled casting

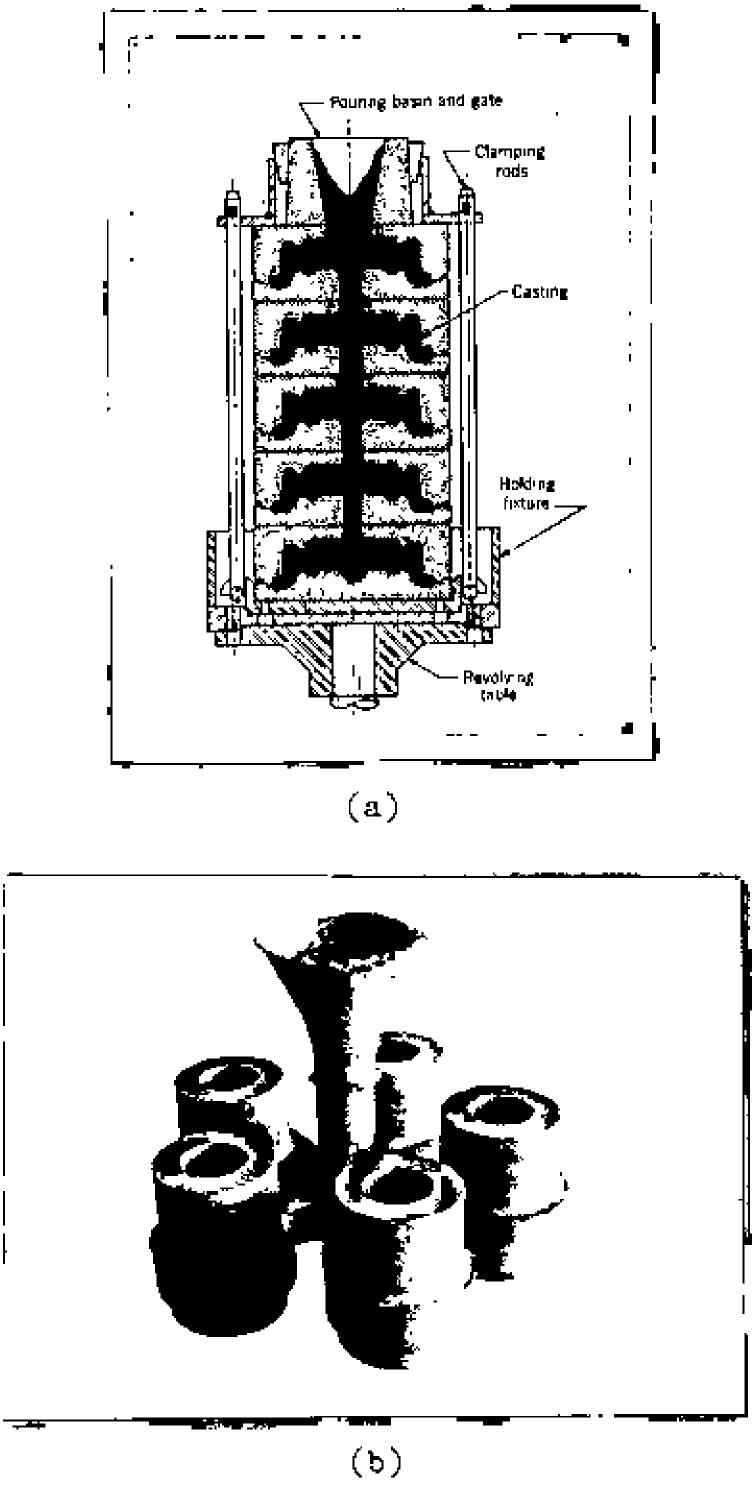


Figure-12: a) Semicentrifugal stack molding of track wheels.

b) Centrifuged castings with internal cavities of irregular shape.

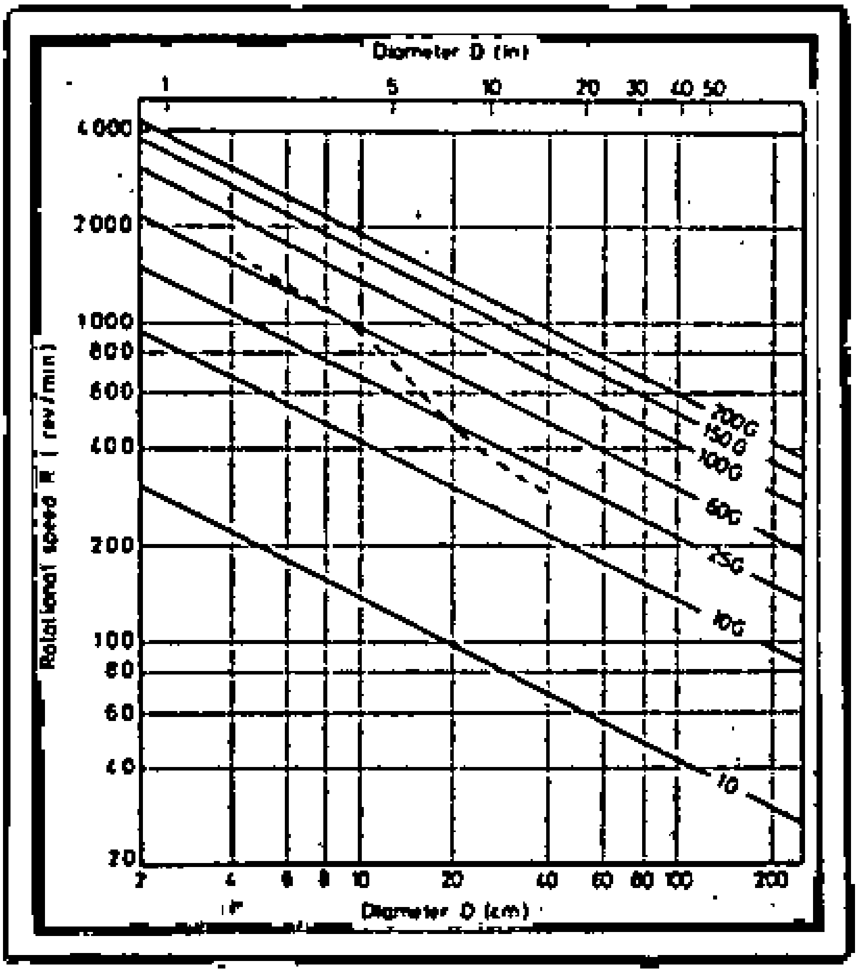


Figure-13: Relationship between rotational speed and diameter for various magnitudes of centrifugal force.

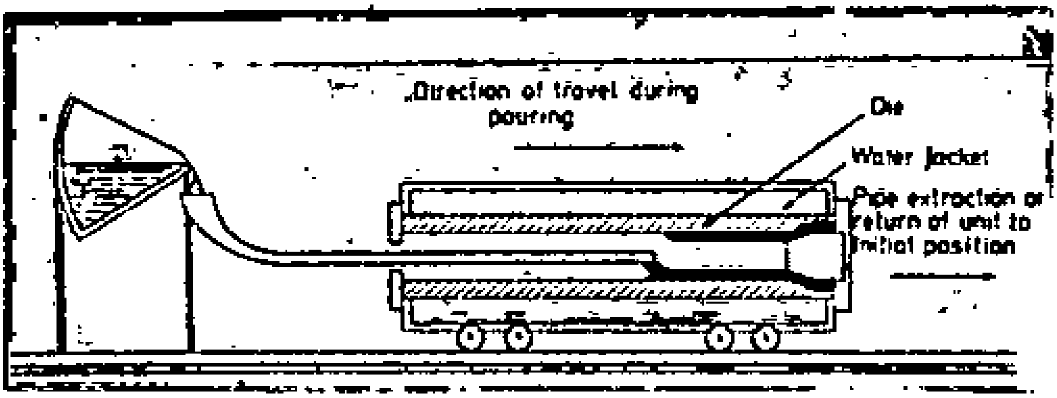


Figure-14: Essentials of de Lavaud pipe casting machine.

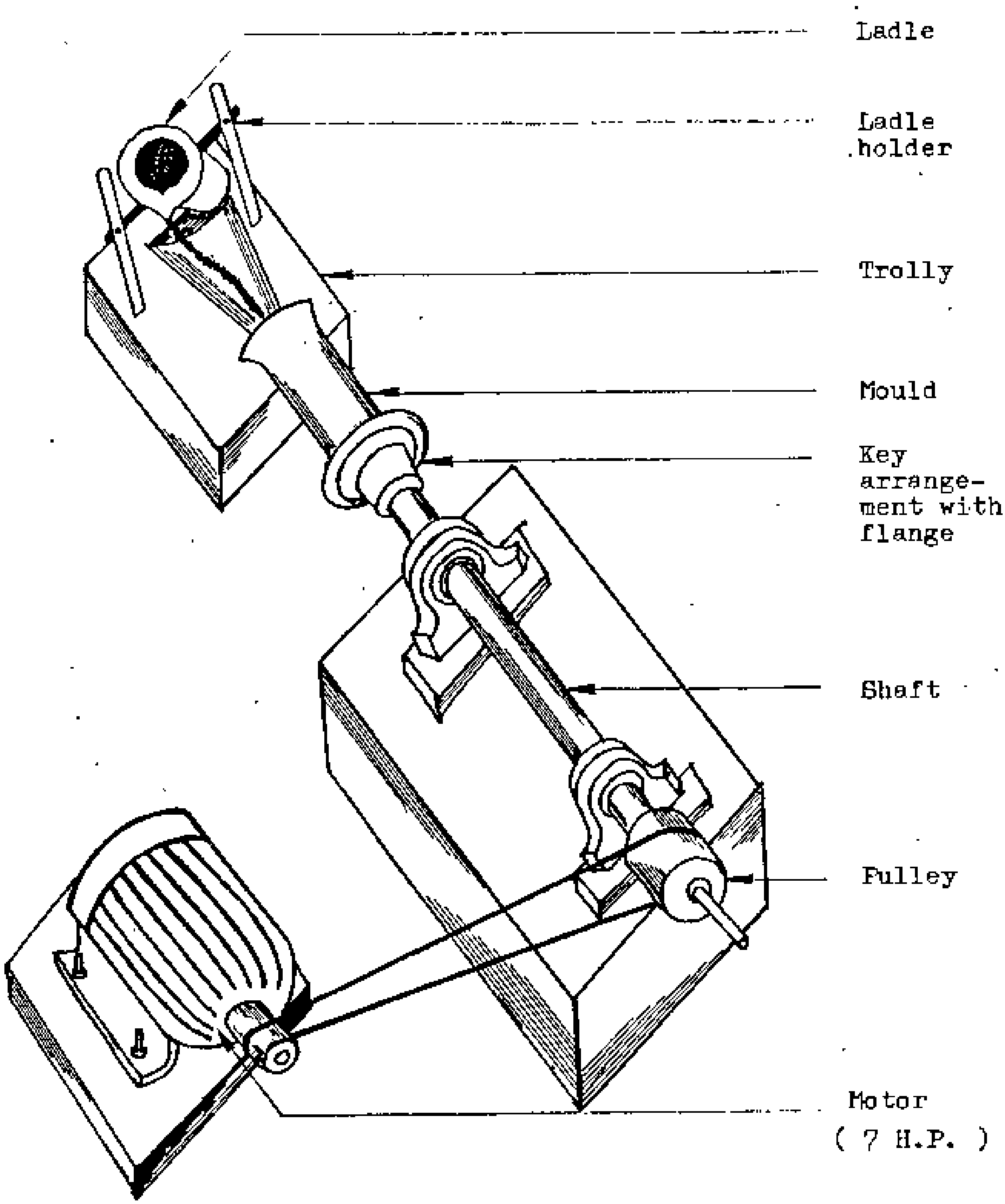


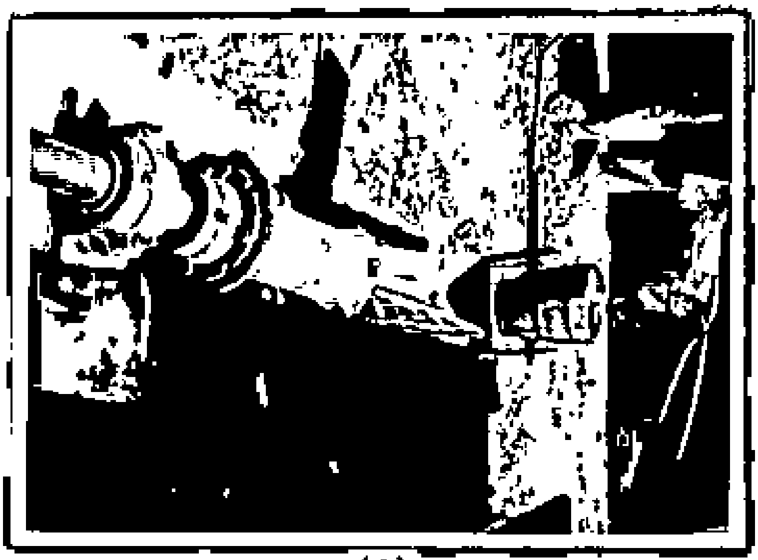
Figure-15(a): Schematic diagram of centrifugal casting machine.

(b)

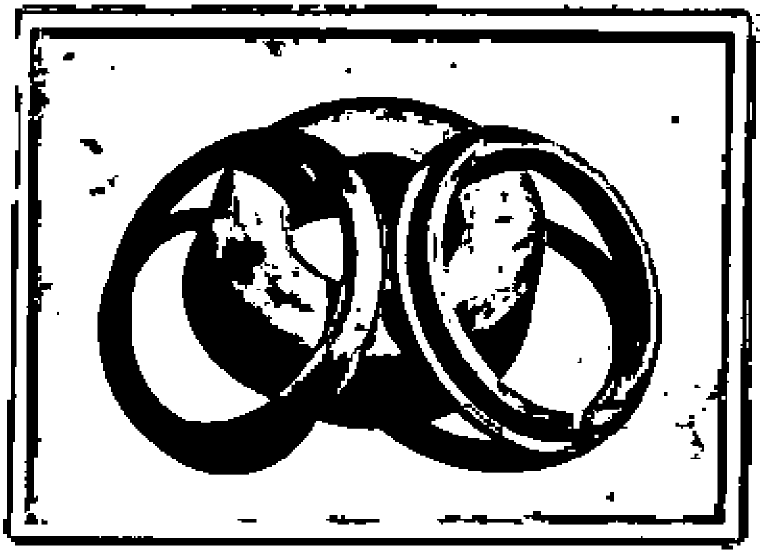
(c)

Figure-15(b) : Experimental set-up with all its accessaries.

Figure-15(c) : Mild steel rod attached with the gripping end plate.



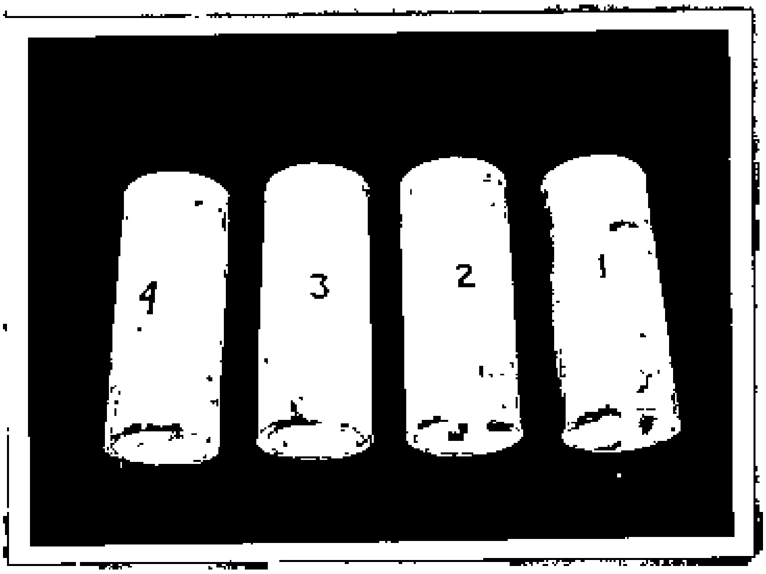
(d)



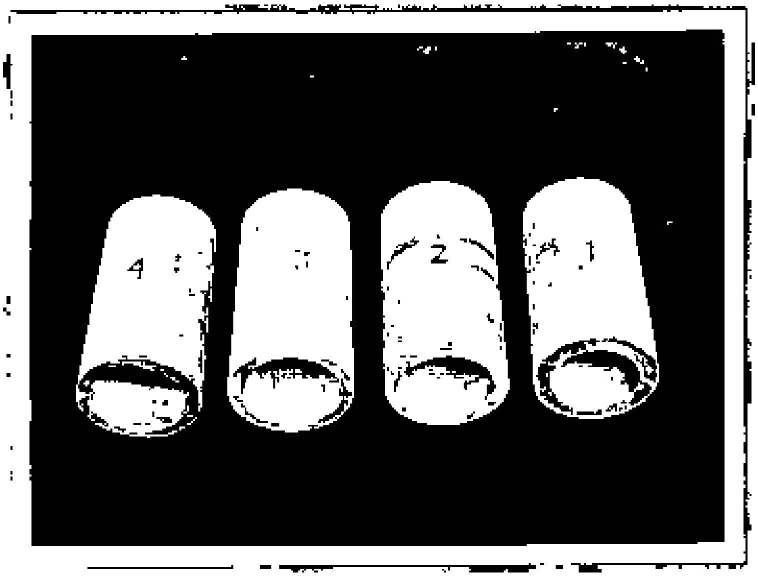
(e)

Figure-15 (d): Molten metal is being transfered from ladle to the rotating mould (via hemi sperical spout).

(e): Showing gauge rings and holder.



a)
1. - 1000 rpm
2. - 1400 rpm
3. - 1800 rpm
4. - 2200 rpm

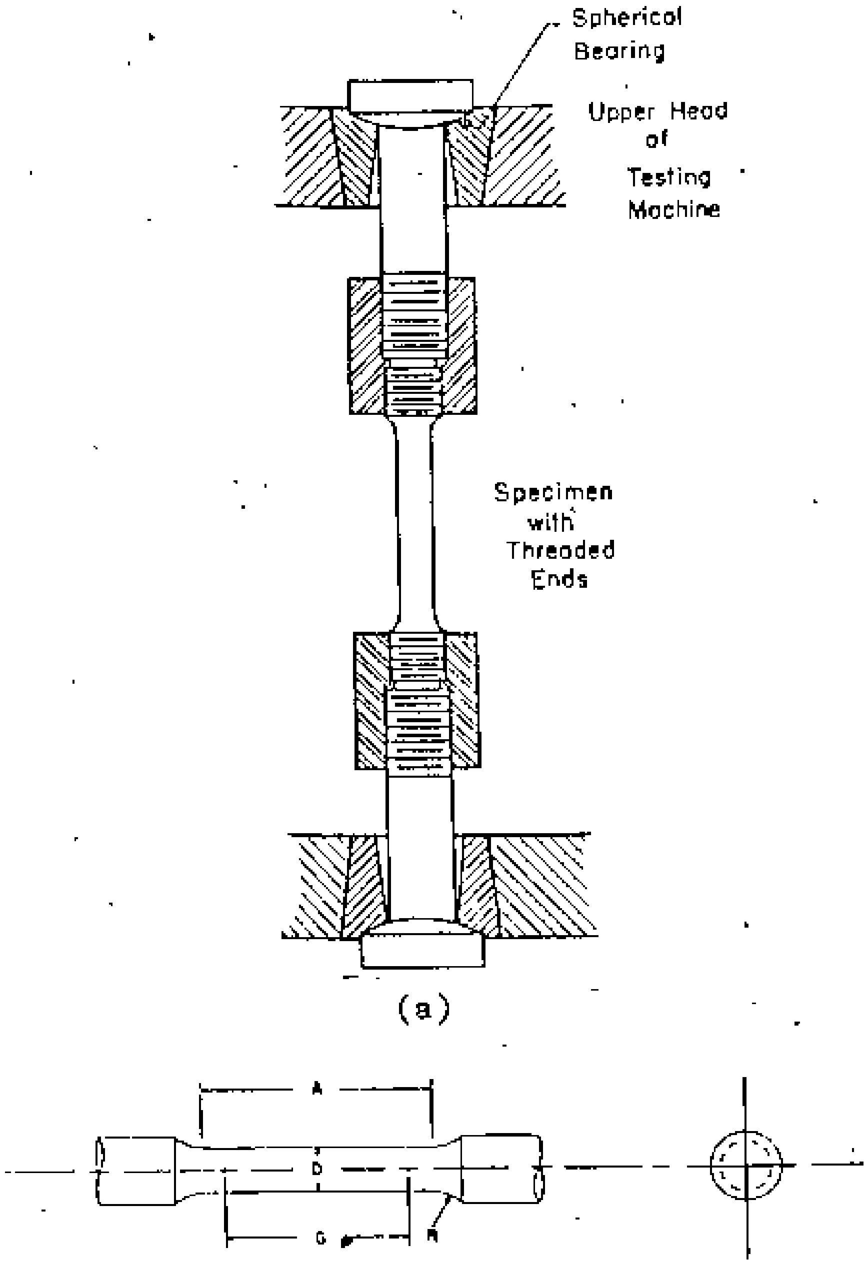


b)
1. - 1000 rpm
2. - 1400 rpm
3. - 1800 rpm
4. - 2200 rpm

Figure-16: Showing centrifugally cast products at different rotational speeds.

a) Aluminium

b) Brass



(b) Dimensions

	in	mm
G - Gage length	1	25
D - Nominal Diameter	0.25	6.25
R - Radius of fillet	3/16	5
A - Length of reduced section, (mm)	1¼	32

Figure-17 : a) Gripping device for Threaded-end specimen.
b) Round Tension Test specimen.

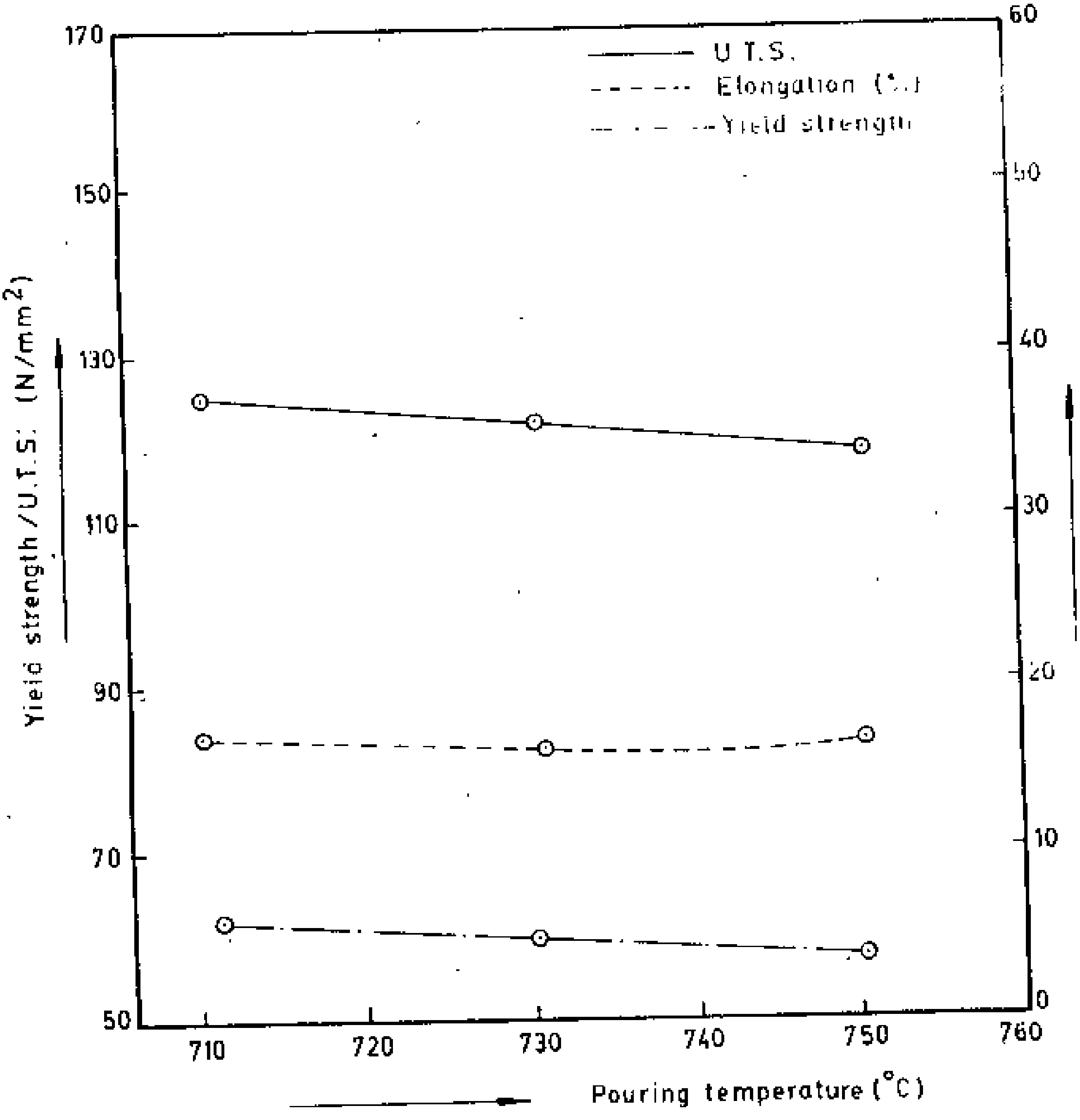


Figure-18: Effects of pouring temperatures on Tensile properties of aluminium casting (1800 rpm).

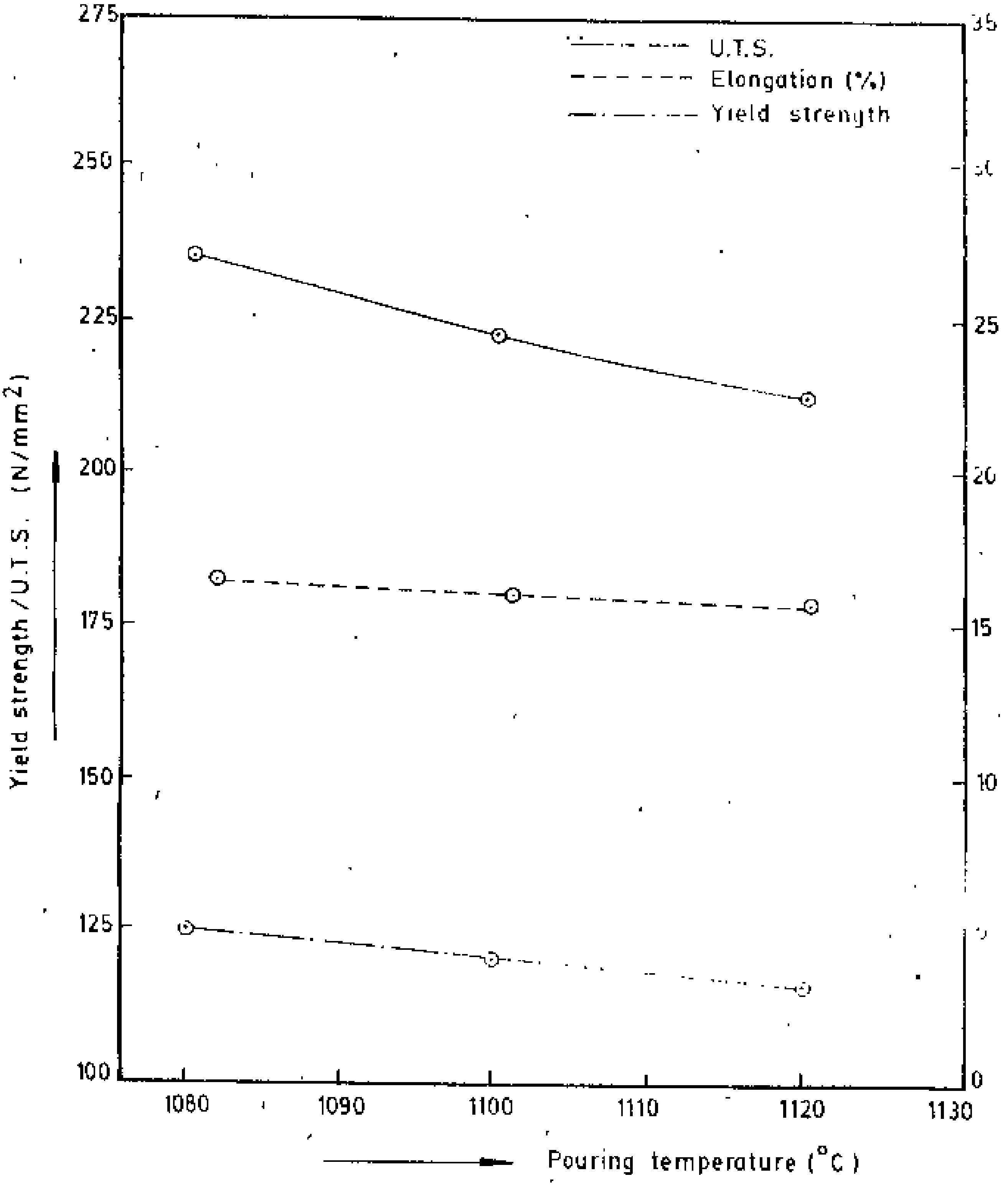


Figure-19: Effects of pouring temperature on Tensile properties of brass casting (1800 rpm).

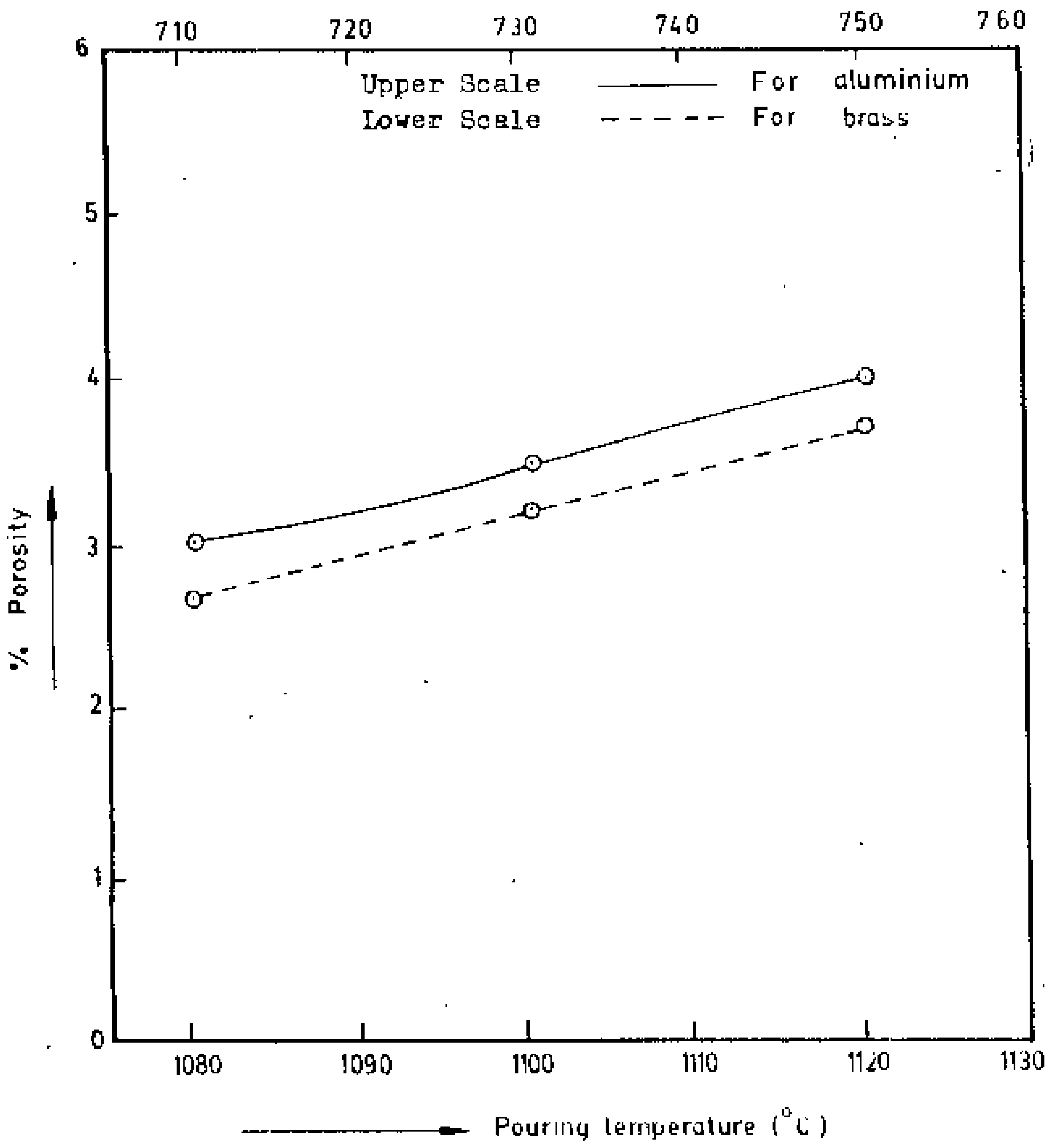


Figure-20: Effects of pouring temperature on % porosity of (a) aluminium and (b) brass casting (1800 rpm).

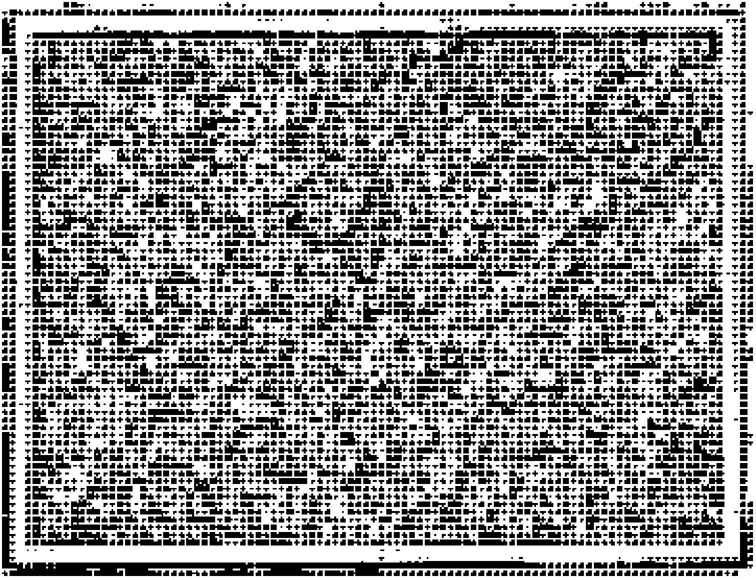


Figure-21(a): Showing microstructure of centrifugally cast aluminium poured at 710°C, rotational speed 1800 rpm, as cast condition, x 100

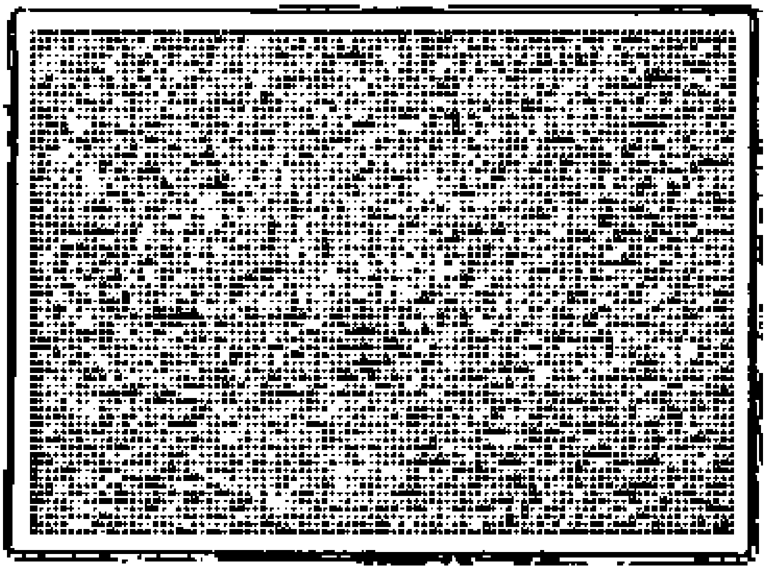


Figure-21(b): Showing microstructure of centrifugally cast aluminium poured at 730°C, rotational speed 1800 rpm, as cast condition, x 100

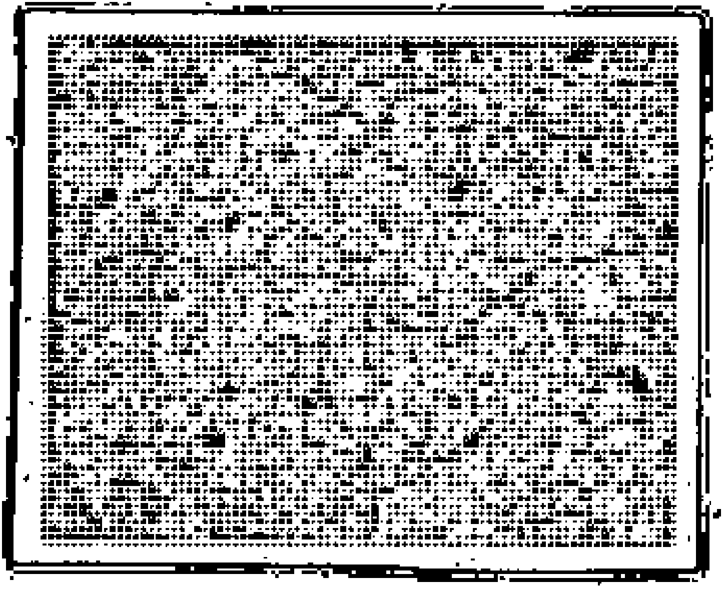


Figure-21(c): Showing microstructure of centrifugally cast aluminium poured at 750°C, rotational speed 1800 rpm, as cast condition, x 100

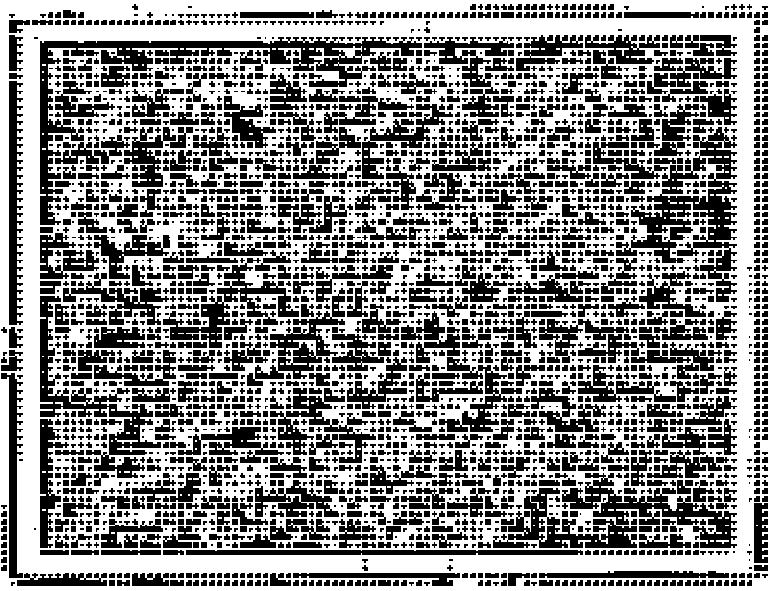


Figure-22(a): Showing microstructure of centrifugally cast brass poured at 1080°C, rotational speed 1800 rpm, as cast condition, x 100.

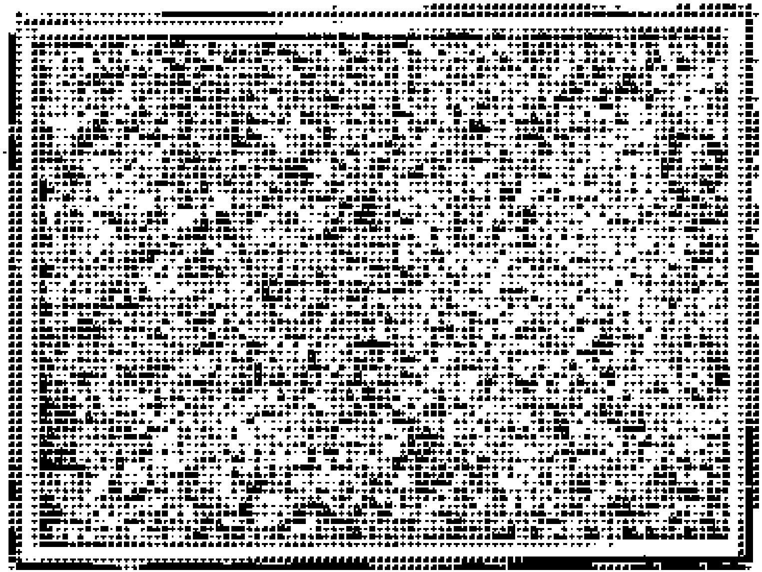


Figure-22(b): Showing microstructure of centrifugally cast brass poured at 1100°C, rotational speed 1800 rpm, as cast condition, x 100.

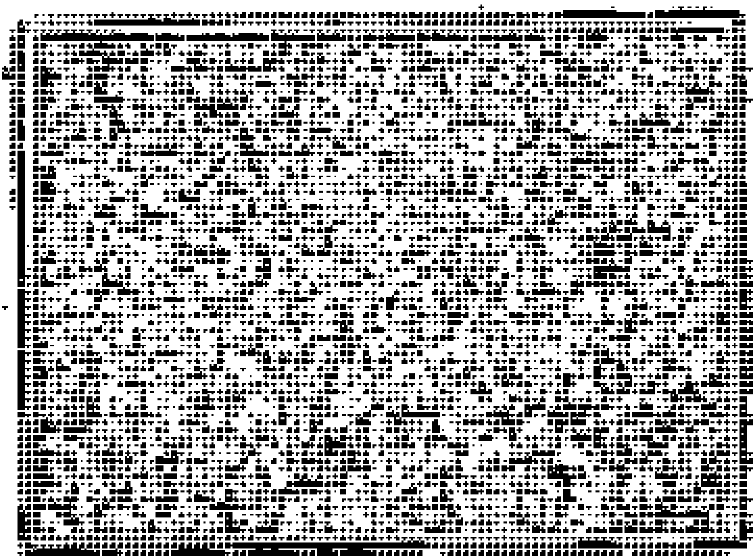


Figure-22(c): Showing microstructure of centrifugally cast brass poured at 1120°C, rotational speed 1800 rpm, as cast condition, x 100.

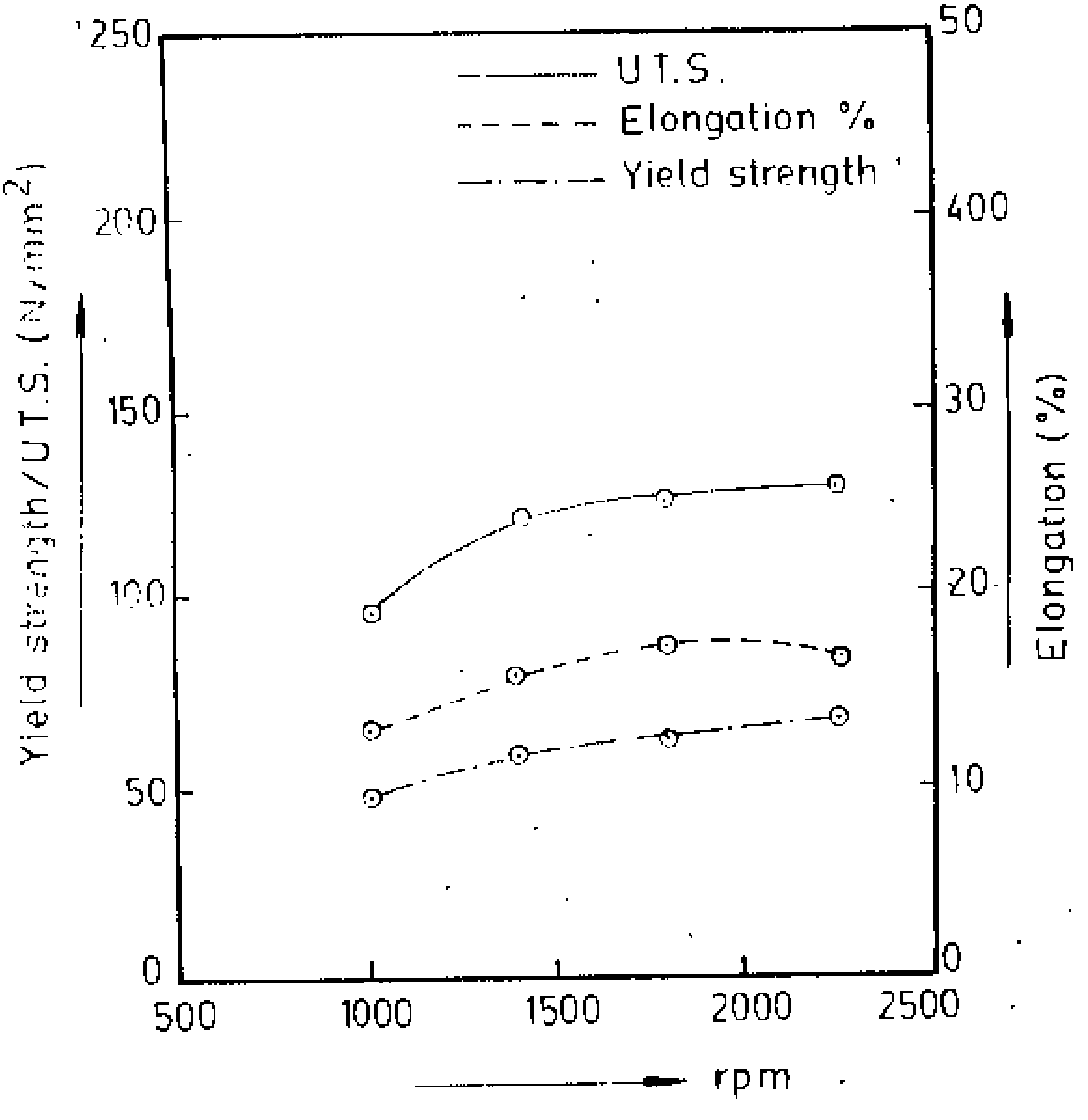


Figure-23: Effects of rotational speed of the mould on tensile properties of aluminium casting poured at 710°C.

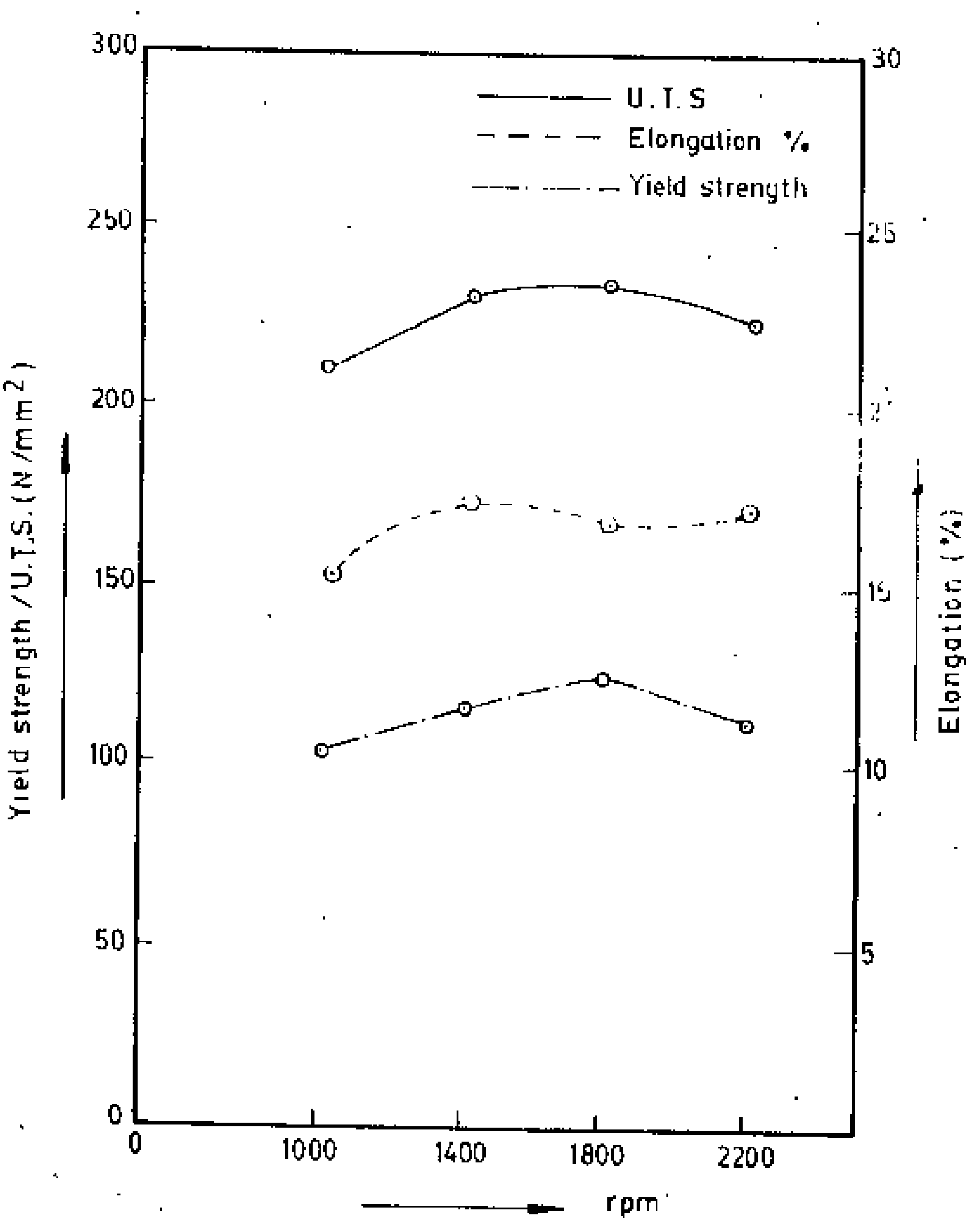


Figure-24: Effects of rotational speed of the mould on tensile properties of brass casting, poured at 1080°C.

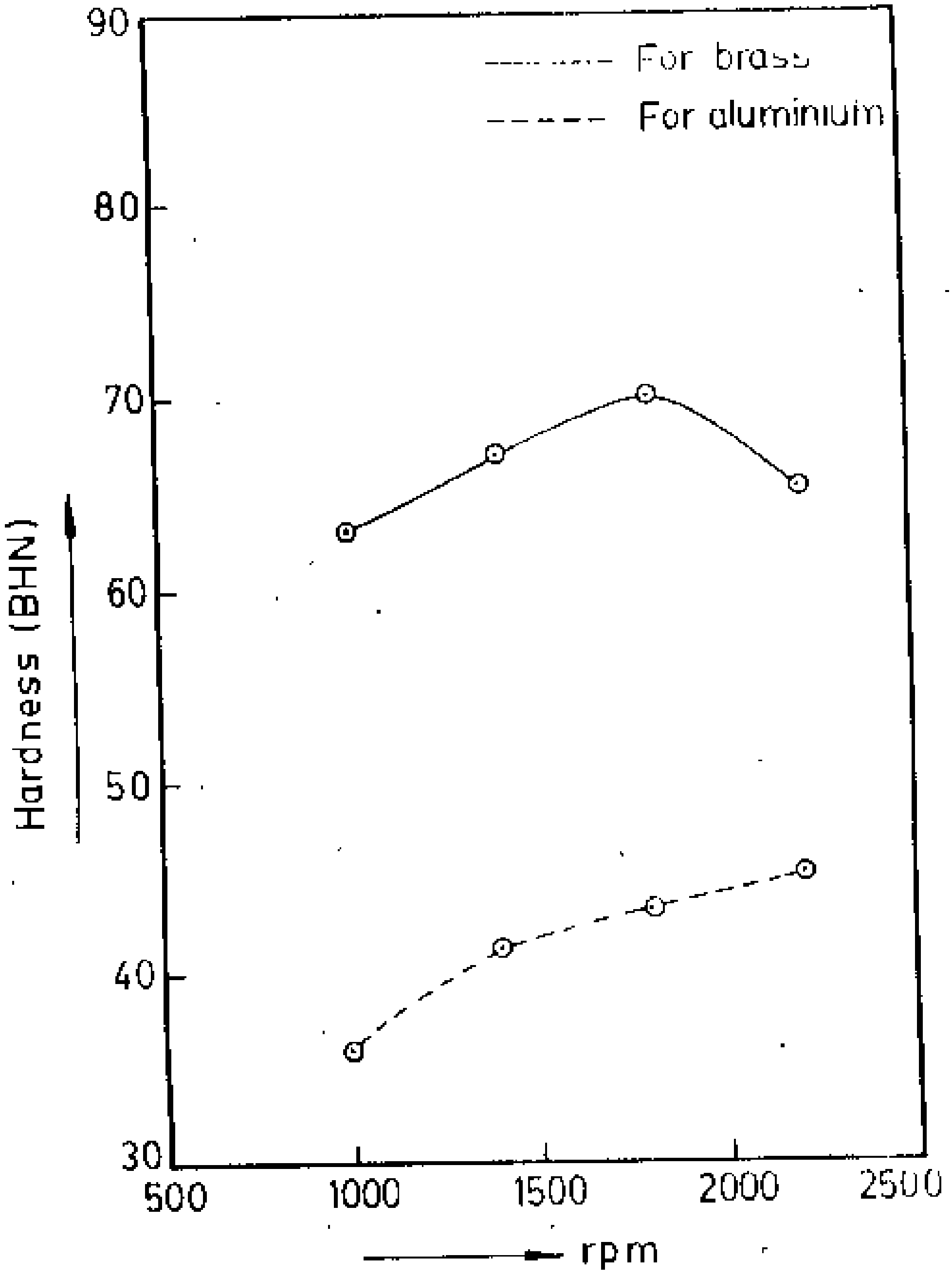


Figure-25: Effects of rotational speed of the mould on Hardness of aluminium and brass casting.

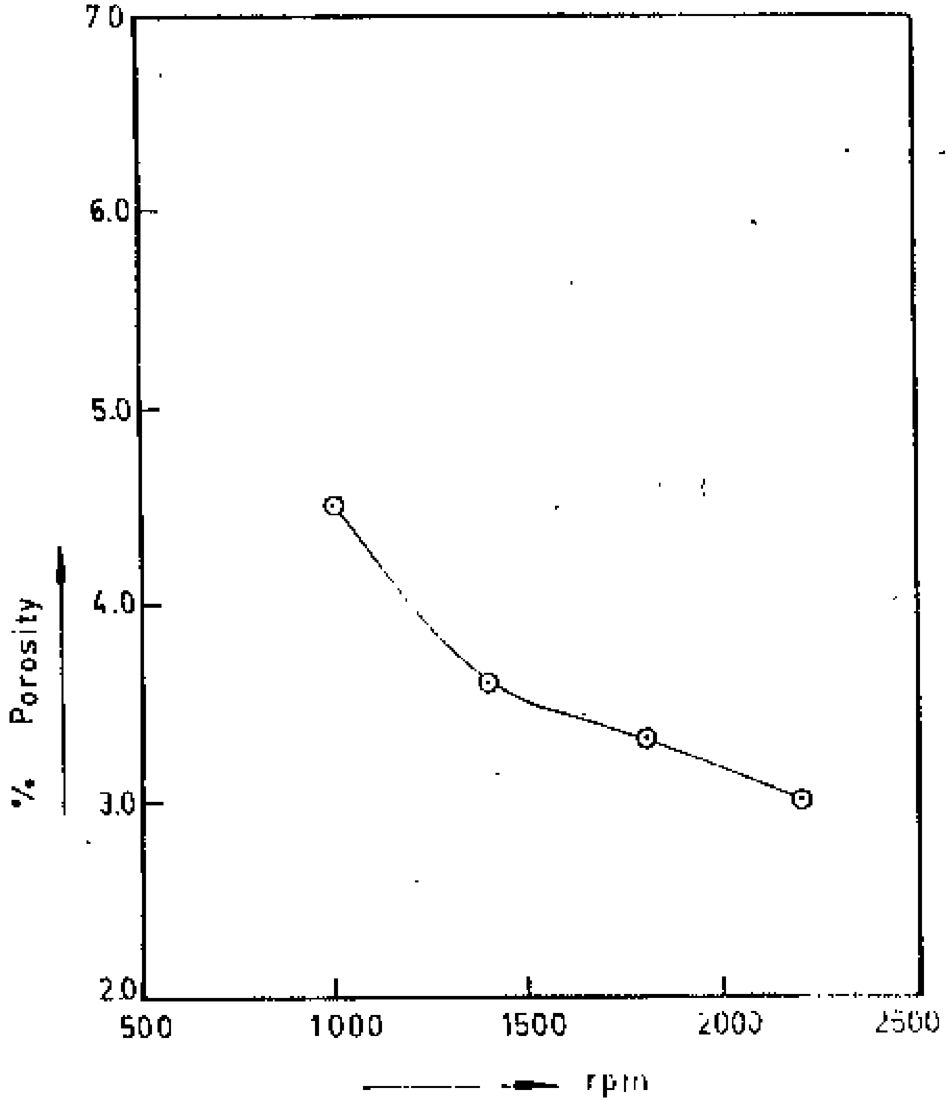


Figure-26: Effects of rotational speed of the mould on % Porosity of aluminium casting poured at 710°C.

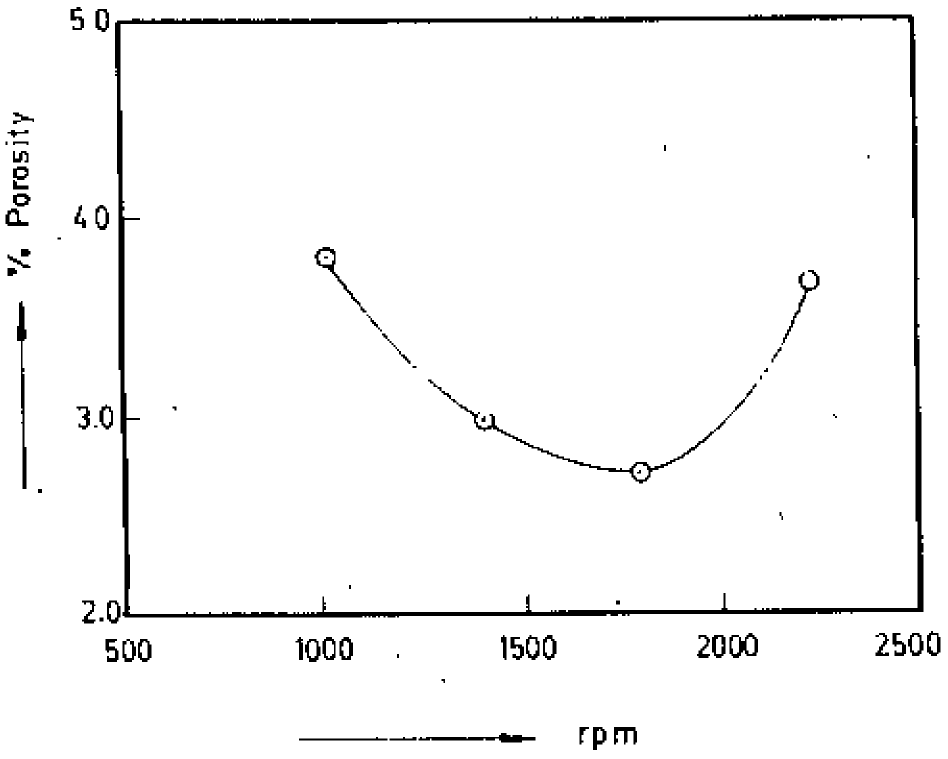


Figure-27: Effects of rotational speed of the mould on % Porosity of brass casting, poured at 1080°C.

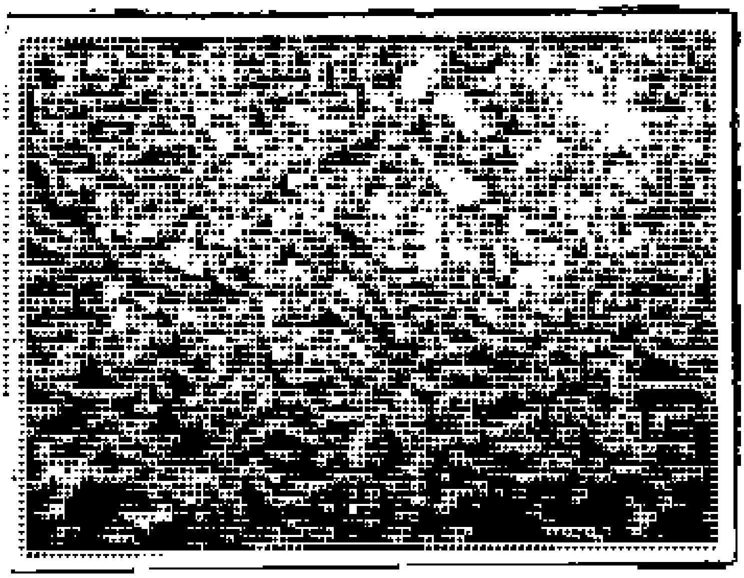


Figure-28 : Showing structure of sand cast aluminium, as cast condition, x 50

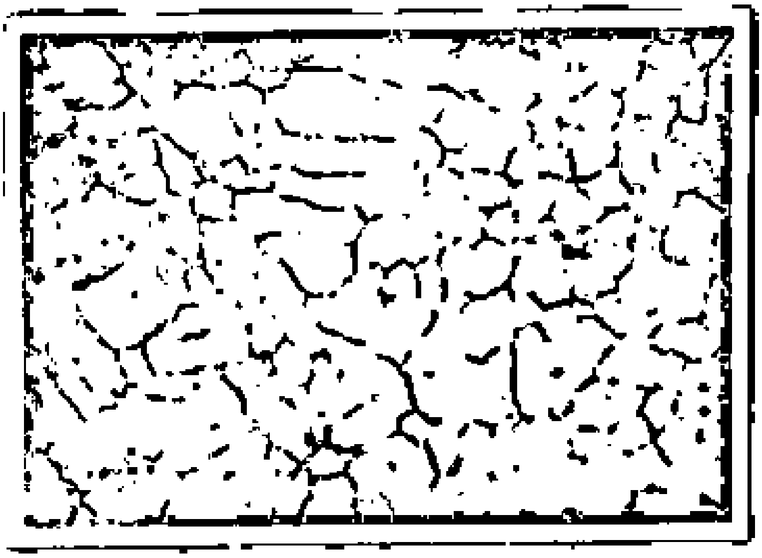


Figure-29 : Showing the structure of centrifugally cast aluminium, rotational speed 1000 rpm, as cast condition, x 100

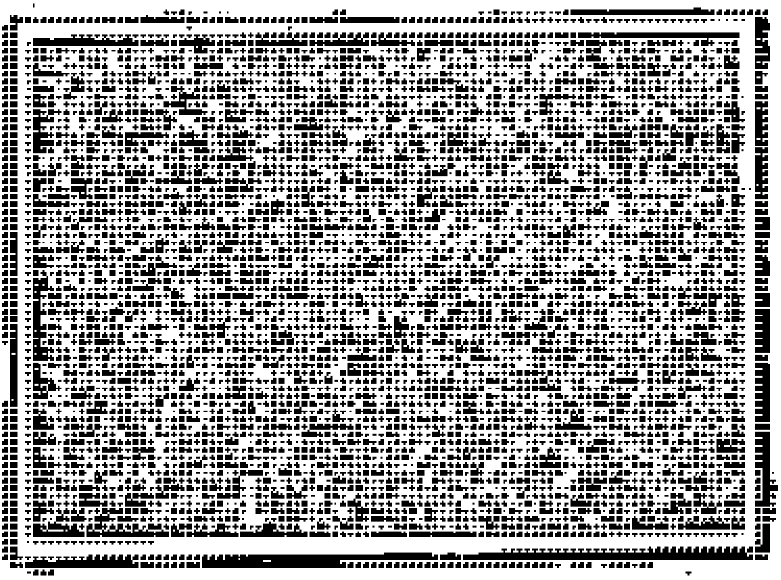


Figure- 30: Showing structure of centrifugally cast aluminium, rotational speed 1400 rpm, as cast condition, x 100

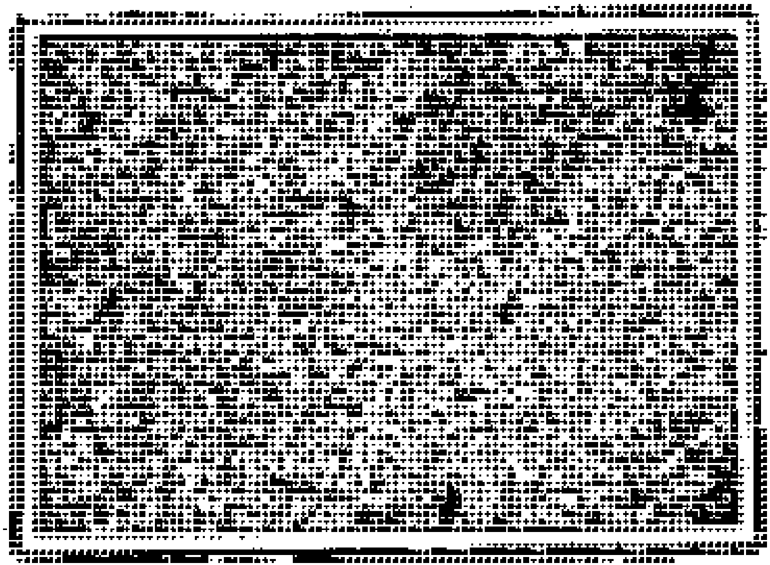


Figure- 31 : Showing microstructure of centrifugally cast aluminium, rotational speed 1800 rpm, as cast condition, x 100

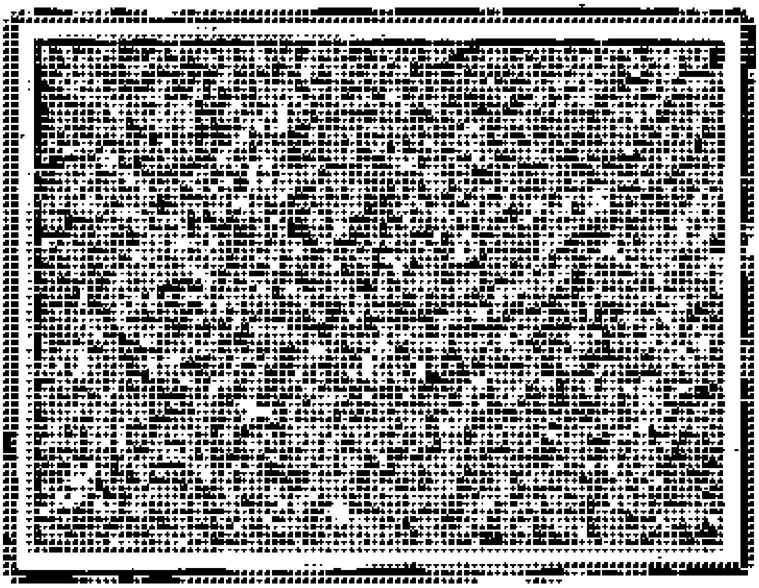


Figure- 32 : Showing microstructure of centrifugally cast aluminium, rotational speed 2200 rpm, as cast condition, x 100

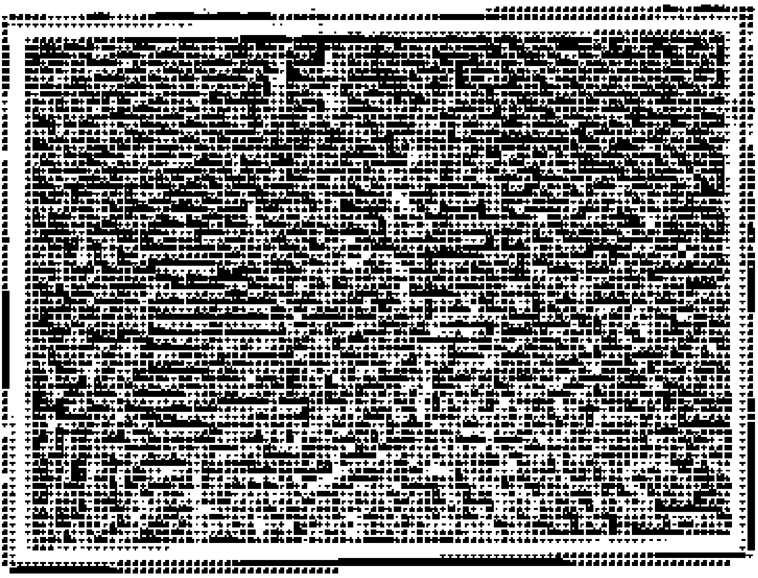


Figure-33 : Showing structure of sand cast brass, as cast condition, x 50

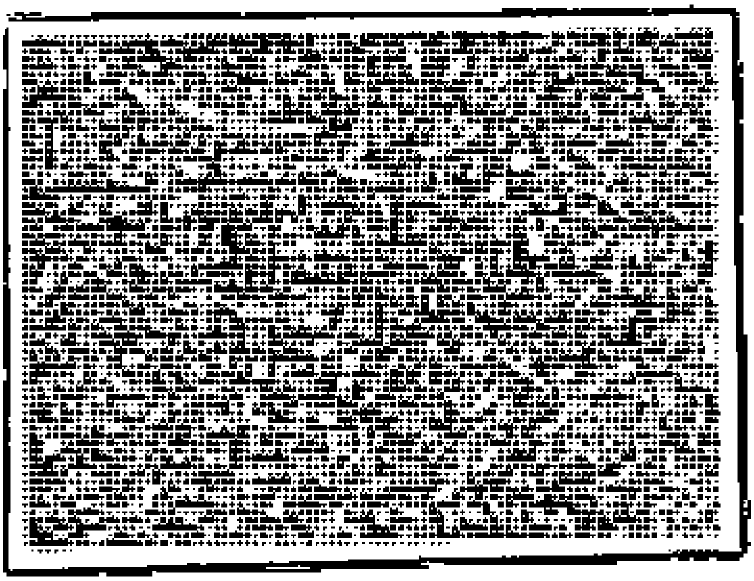


Figure-34: Showing structure of centrifugally cast brass, rotational speed 1000 rpm, as cast condition, x 100

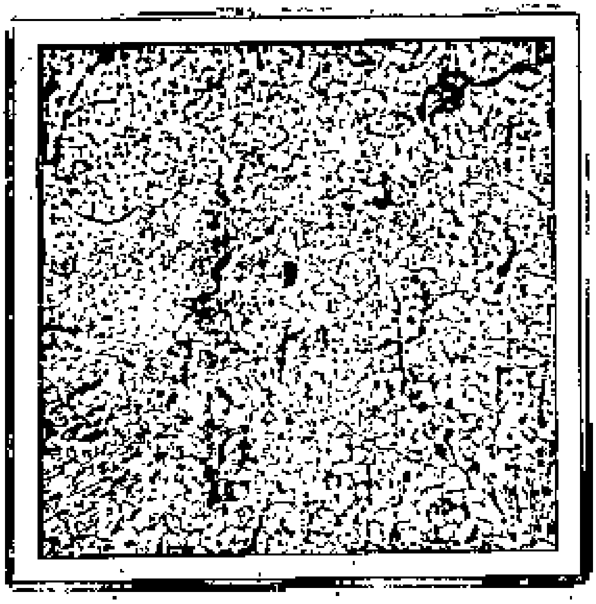


Figure-35 : Showing structure of centrifugally cast brass, rotational speed 1400 rpm, as cast condition, x 100

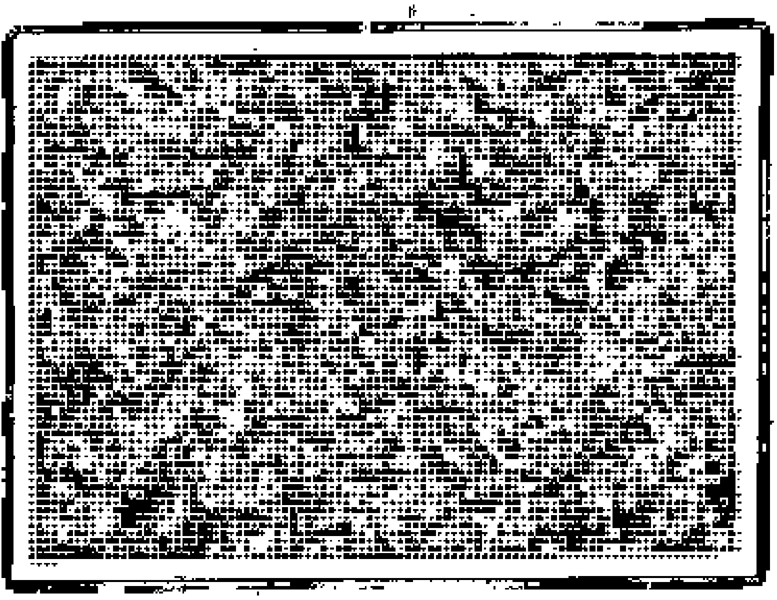


Figure-36 : Showing microstructure of centrifugally cast brass, rotational speed 1800 rpm, as cast condition, x 100

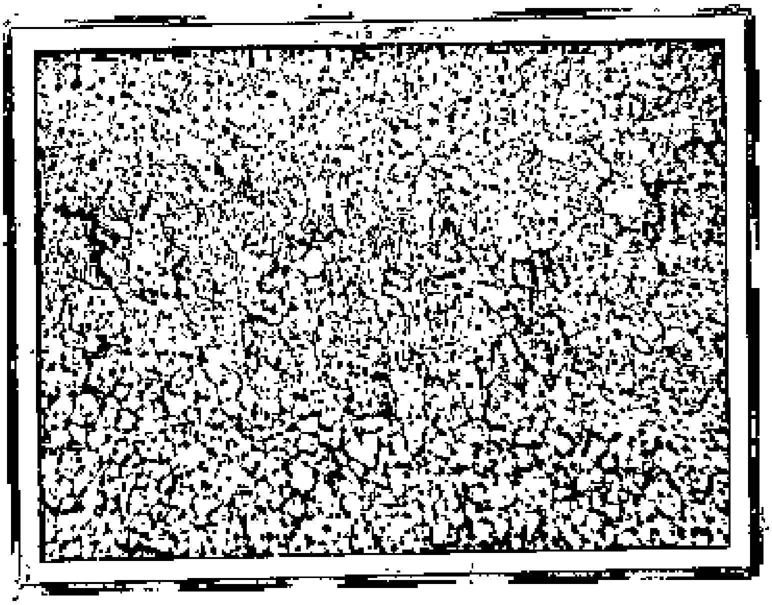


Figure-37 : Showing microstructure of centrifugally cast brass, rotational speed 2200 rpm, as cast condition, x 100

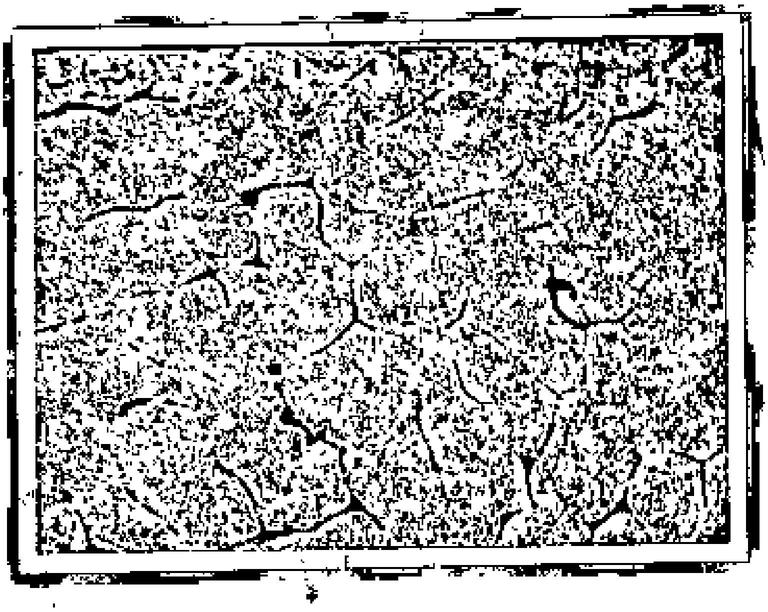


Figure- 38 : Showing microstructure of sand cast aluminium, annealed at 650°F (344°C) for 1 hour, x 100

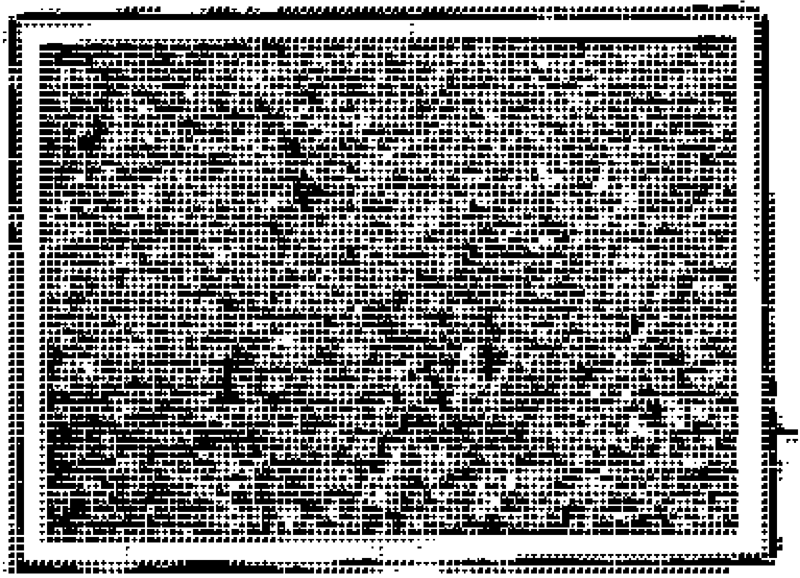


Figure- 39 : Showing microstructure of centrifugally cast aluminium, rotational speed 1000 rpm, annealed at 650°F (344°C) for 1 hour, x 100

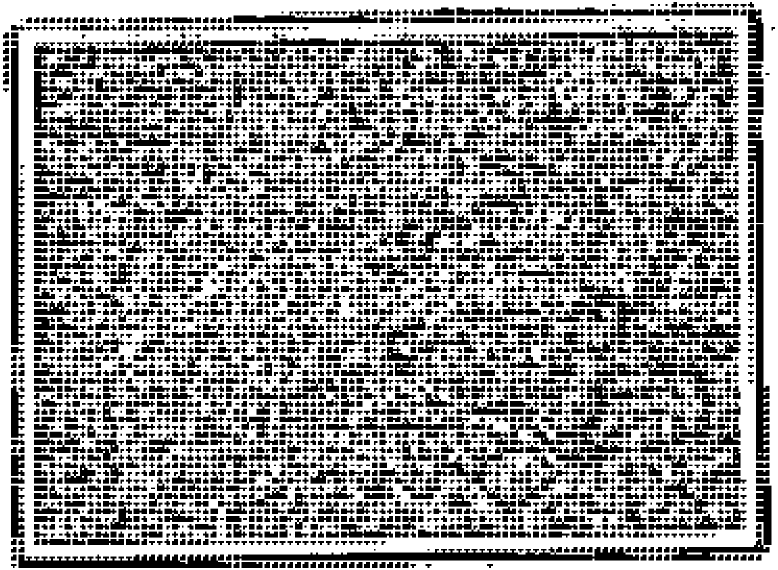


Figure- 40: Showing microstructure of centrifugally cast aluminium, rotational speed 1400 rpm, annealed at 650°F (344°C) for 1 hour, x 100

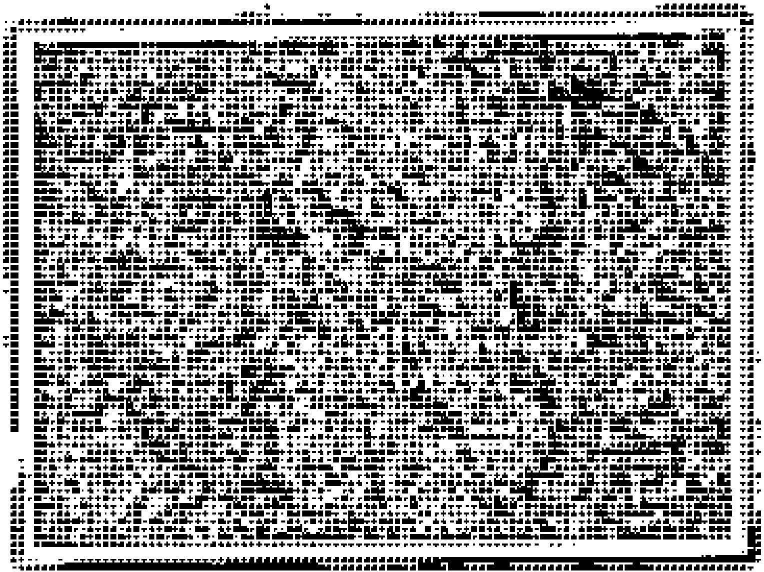


Figure- 41: Showing microstructure of centrifugally cast aluminium, rotational speed 1800 rpm, annealed at 650°F (344°C) for 1 hour, x 100

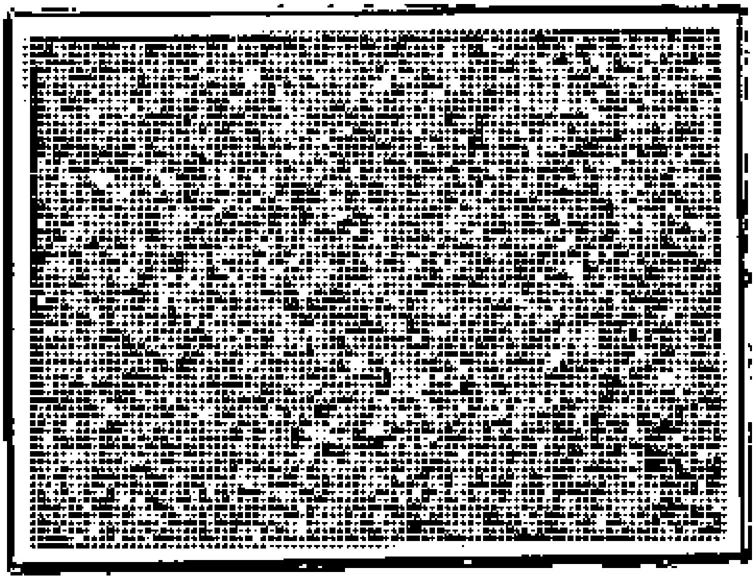


Figure- 42: Showing microstructure of centrifugally cast aluminium, rotational speed 2200 rpm, annealed at 650°F (344°C) for 1 hour, x 100

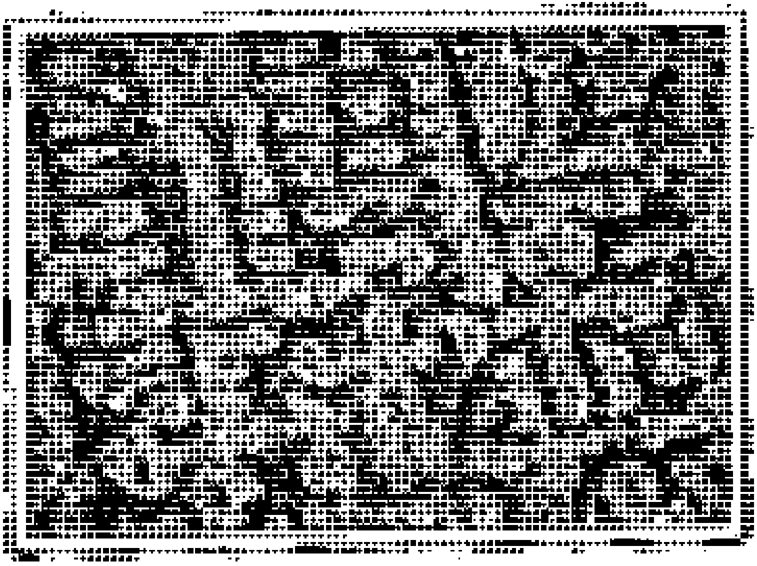


Figure- 43 : Showing microstructure of sand cast brass, annealed at 1000°F (538°C) for 1 hour, x 100

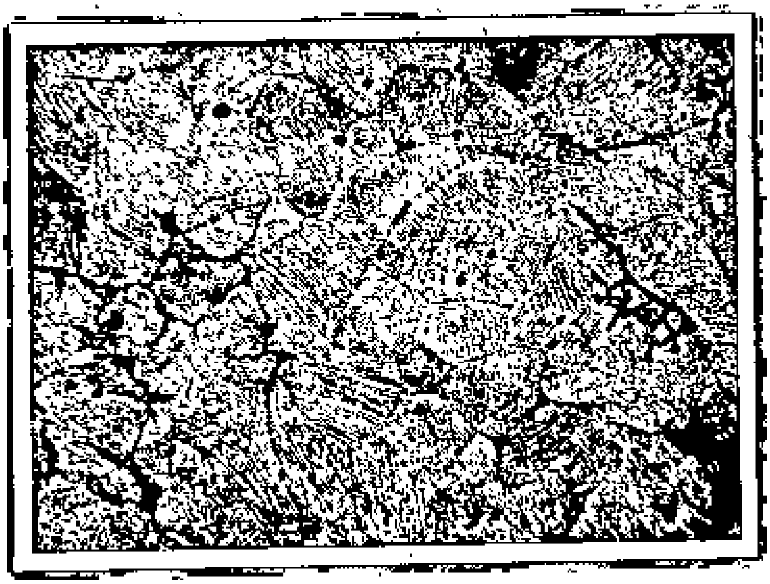


Figure- 44 : Showing microstructure of centrifugally cast brass, rotational speed 1000 rpm, annealed at 1000°F (538°C) for 1 hour, x 100

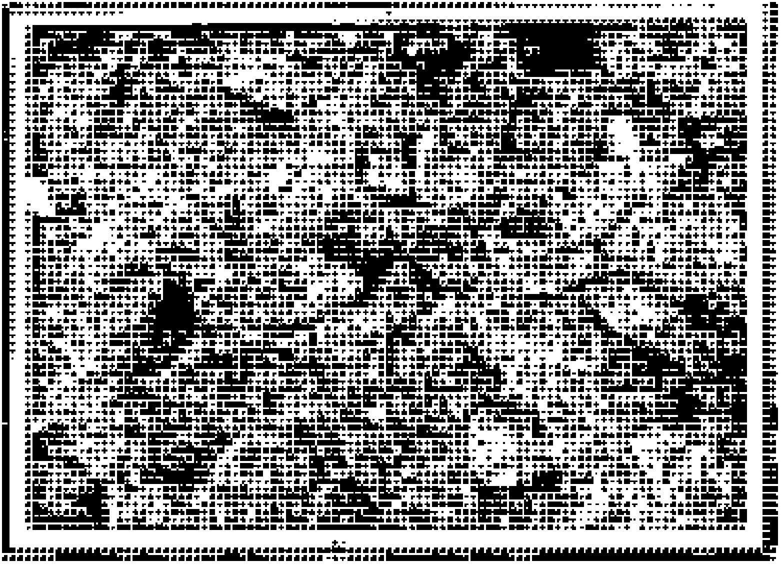


Figure- 45: Showing microstructure of centrifugally cast brass, rotational speed 1400 rpm, annealed at 1000°F (538°C) for 1 hr, x 100

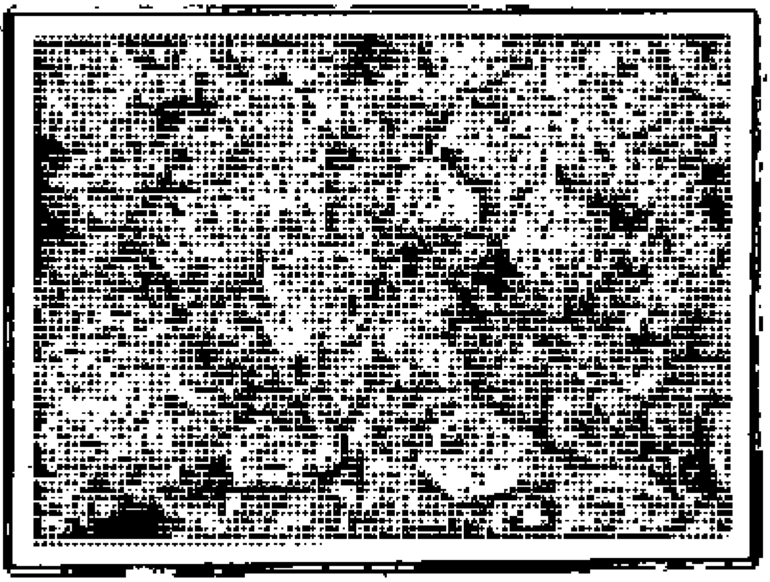


Figure- 46 : Showing microstructure of centrifugally cast brass, rotational speed 1800 rpm, annealed at 1000°F (538°C) for 1 hour, x 100

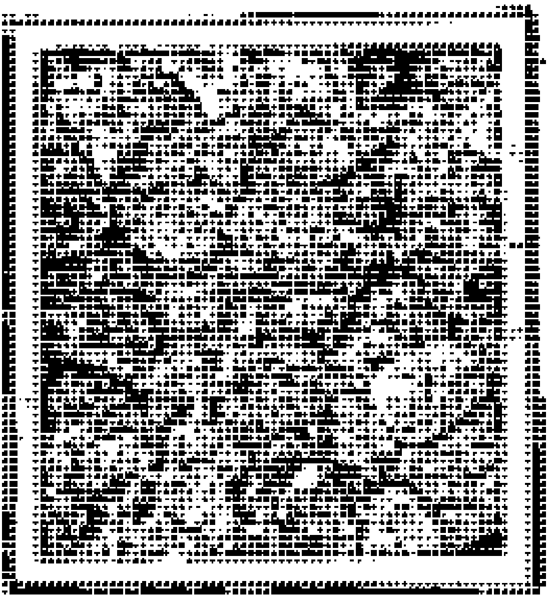


Figure- 47 : Showing microstructure of centrifugally cast brass, rotational speed 2200 rpm, annealed at 1000°F (538°C) for 1 hour, x 100

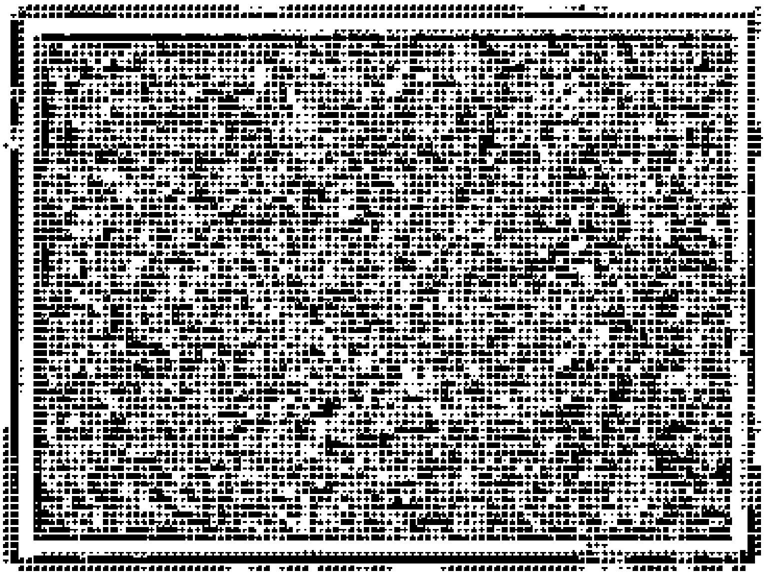


Figure- 48(a): Showing microstructure of centrifugally cast aluminium poured at 710°C, rotational speed 1800 rpm, annealed at 650°F (344°C) for 1 hour, x 100

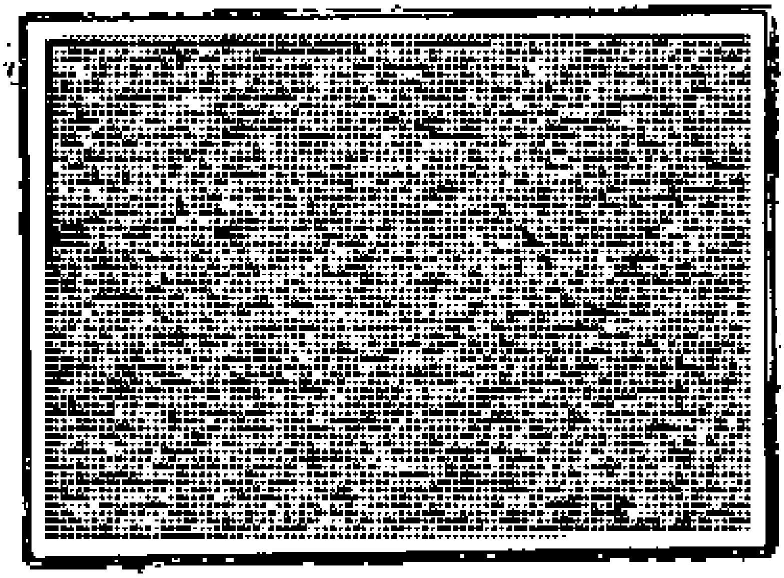


Figure- 48(b): Showing microstructure of centrifugally cast aluminium, poured at 730°C, rotational speed 1800 rpm, annealed at 650°F (344°C) for 1 hour, x 100

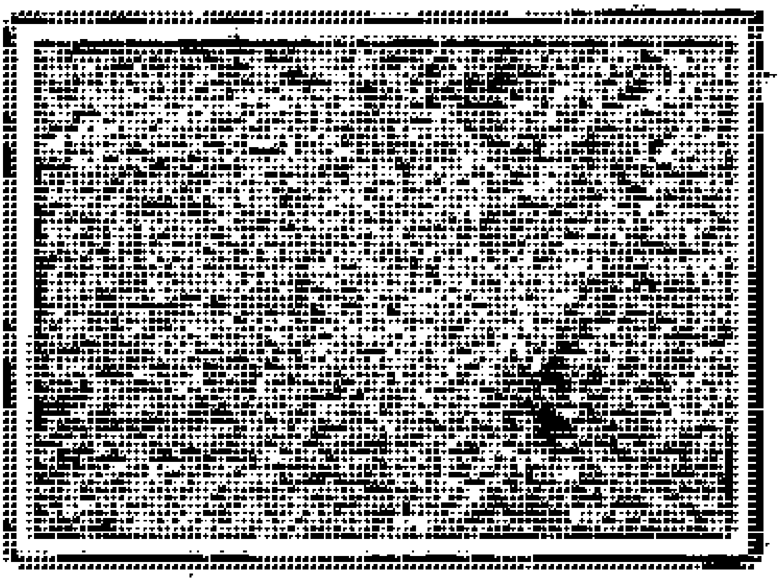


Figure- 48(c): Showing microstructure of centrifugally cast aluminium, poured at 750°C, rotational speed 1800 rpm, annealed at 650°F (344°C) for 1 hour, x 100

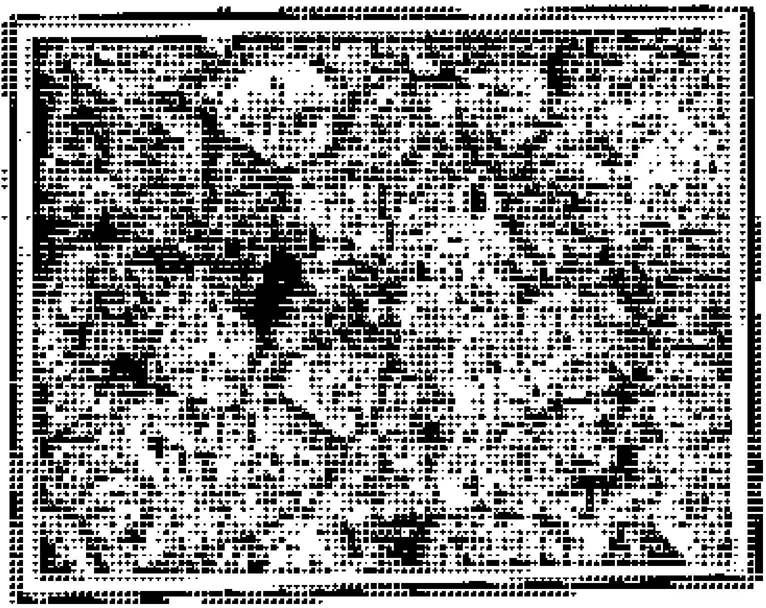


Figure-49(a): Showing microstructure of centrifugally cast brass poured at 1080°C, rotational speed 1800 rpm, annealed at 1000°F (538°C) for 1 hour, x 100

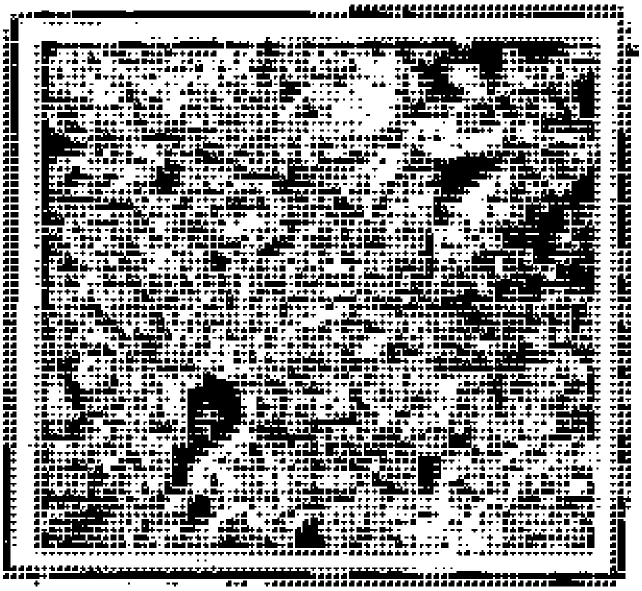
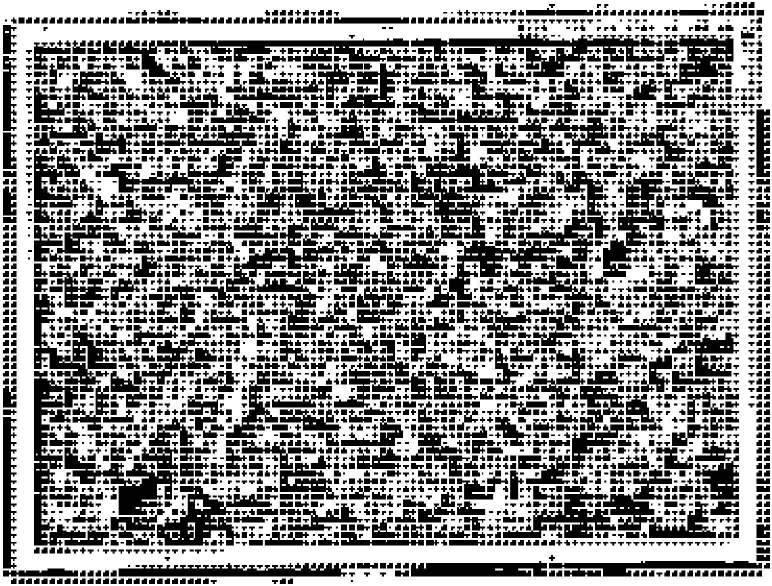
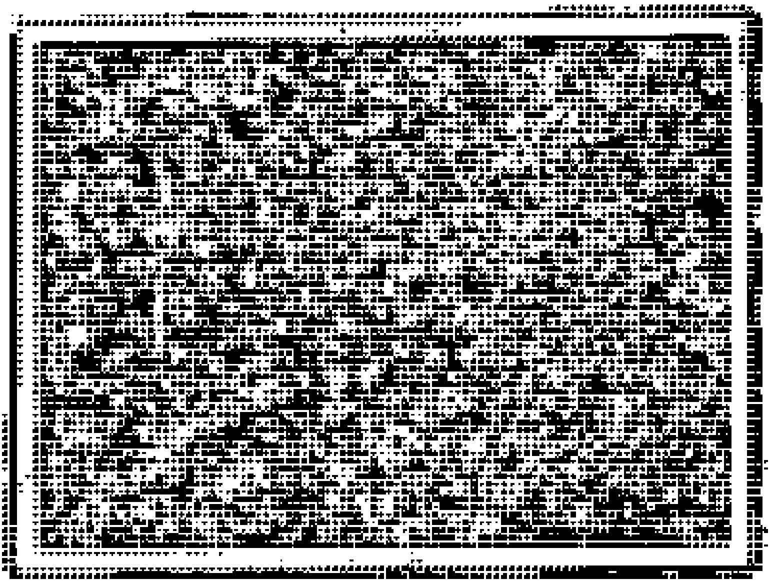


Figure-49(b): Showing microstructure of centrifugally cast brass poured at 1100°C, rotational speed 1800 rpm, annealed at 1000°F (538°C) for 1 hr, x 100

Figure-49(c): Showing microstructure of centrifugally cast brass poured at 1120°C, rotational speed 1800 rpm, annealed at 1000°F (538°C) for 1 hr, x 100



(a)

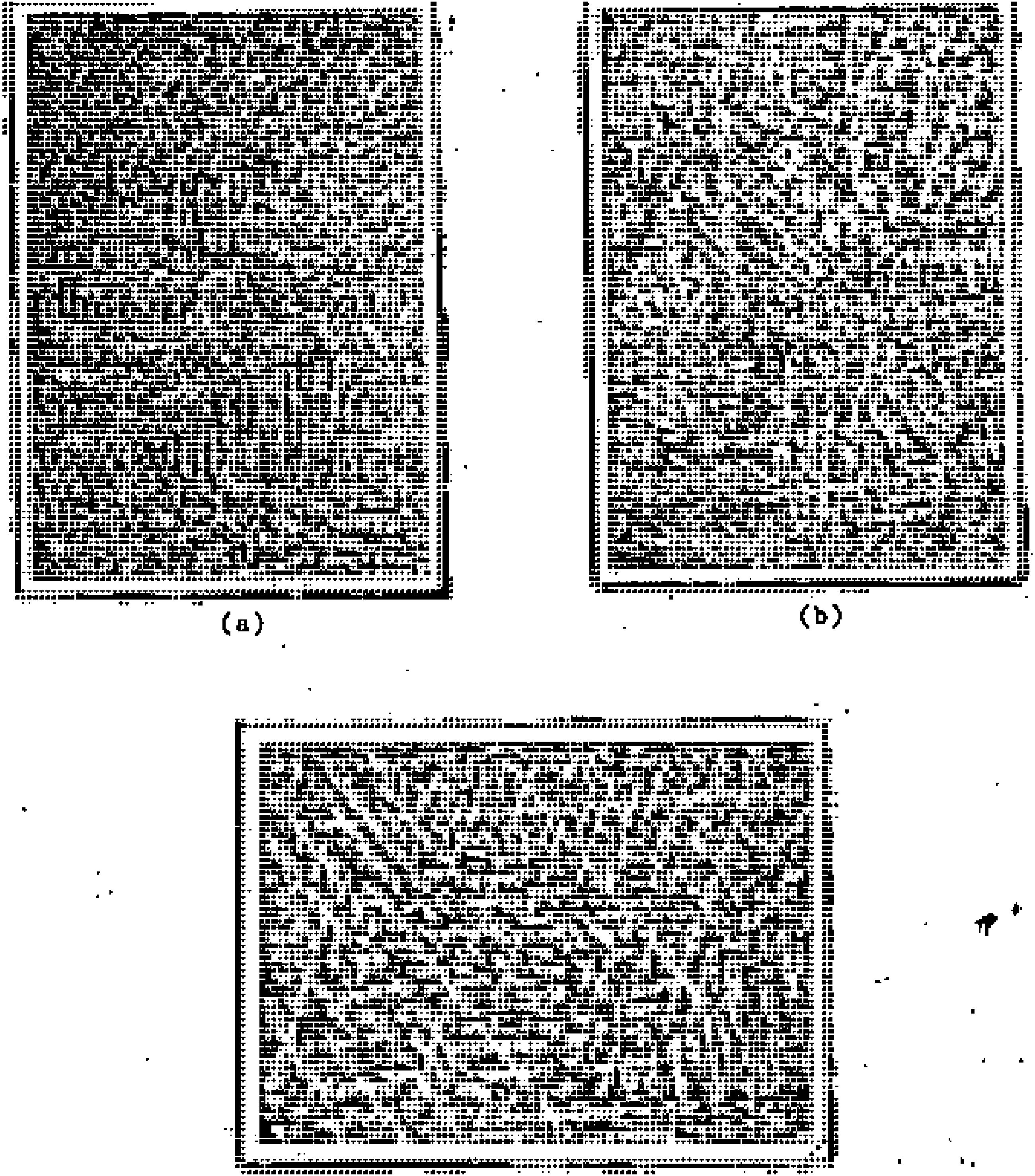


(b)

Figure 50 : Showing the microstructure of centrifugally cast brass, rotational speed 1800 rpm.

a) Outer surface

b) Inner surface, as cast condition, x 100



(a)

(b)

Figure 51 : Showing microstructure of sand cast brass

a) Outer surface
b) Middle zone
c) Inner surface, as cast condition, x 50

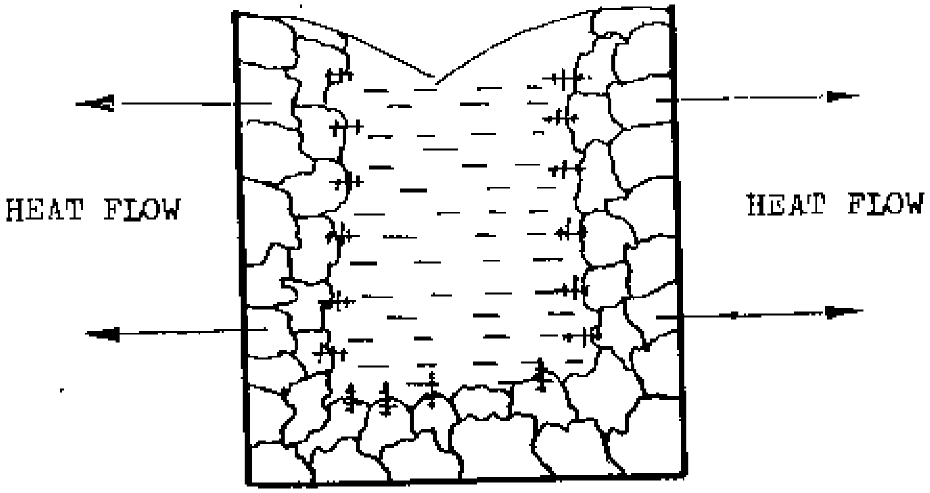


Figure-52: Schematic view of conventional casting solidification.

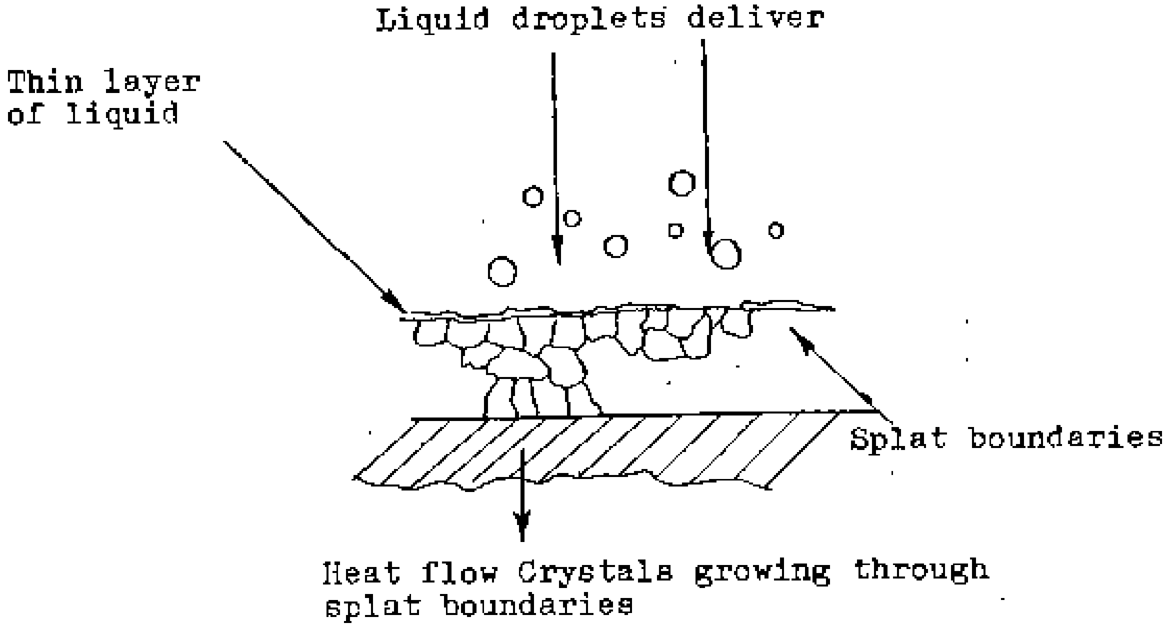


Figure-53: Schematic view of incremental solidification: x 100 compared to Figure-52.

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