EFFECTS OF FREEZING TIME ON THE SOLIDIFICATION CHARACTERISTICS OF CENTRIFUGALLY CAST α-BRASS.

A Thesis

by

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CERTIFICATE

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CONTENTS

ABSTRACT

The investigation carried out in this text was to find out the effect of freezing time on the solidification characteristics of centrifugally-cast α-brass. The variation of freezing time of the casting was achieved by delaying the solidification process with the application of heat using gas flame around the rotating mould in some instances and by spraying cooling water through special cooling device around the rotating mould which promoted faster solidification in the others.

A comparative study of different physical and mechanical properties was carried out upon sand mould castings and centrifugal castings obtained by using metal mould. De-oxidation of the molten metal was done to obtain the improved properties. Properties like hardness, percentage elongation, tensile strength etc, were found to improve with faster cooling rates keeping all other process variables such as mould speed, pouring temperature, metal composition constant. It was observed that the sand mould casting at room temperature shows a coarser-grained dendritic structure having less strength, percentage elongation and hardness, whereas the centrifugally cast α-brass with very fast cooling showed an improvement of about 160% in elongation and a slight improvement in strength and hardness values.

It was also observed that the longer the solidification time, the coarser was the grain size in the as-cast specimens which influenced adversely the physical and mechanical properties of the casting.

Heat treatment of both the sand cast and centrifugally cast α-brass showed improved properties. The casting obtained with the fastest cooling rate showed the greatest improvement in its properties as compared to the sand and slowly cooled centrifugally cast α-brass products. The experiments furnished a positive indication regarding the achievement of better physical and mechanical properties in the centrifugally cast α-brass products with decreasing freezing times.

1. Introduction

Modern casting industries employ centrifugal casting process because of its economic viability as well as its capability of delivering dense, strong and inclusion free products. Usually products of this process include cylindrical pipes, piston liners, pressure vessels, bush-bearings, steam and gas reformer tubes, pulleys etc. when compared to sand casting process, the centrifugal casting method offers some essential qualities in the products as high tensile strength, high density, consequently low porosity and necessary hardness. It is normal to anticipate that the properties and the solidification behaviour of centrifugally cast products will be quite different from those of the static castings.

However, the success of centrifugal casting process depends on a number of factors viz. mould spinning speed, heat transfer characteristics, mould material, mould coat, pouring temperature, pouring rate, mould pre-heat temperature, the alloy cast, and the dimensions and geometry of the casting[1]. The details on the influence of some of the above factors on ferrous metals are available in the literature[2,3], but not much on the non-ferrous metals. Recently a thorough study of the effects of speed of rotation of the mould and the pouring temperature of the melt on structure and properties of centrifugally cast non-ferrous metals, has been carried out[4]. But the effects of freezing time on solidification characteristics of centrifugally cast products have not yet much been investigated upto today. Therefore, the present project has been undertaken to study the various aspects of solidification, since the overall freezing time adversely affects the structure and properties of the casting, especially for centrifugal casting as it rotates during solidification promoting faster cooling rate. Since the solidification characteristics of the as-cast structure under dynamic conditions are different from those of static castings having similar cooling rate[5], the correlation of structure and properties in centrifugally cast products would be worthwhile. The material used in the present study was α-brass, since this alloy is widely used in the industry for fabricating various objects.

For comparison purposes, static castings were carried out in green saud mould with the same composition of the melt. Properties like hardness, tensile strength and percentage elongation have been investigated and compared with the centrifugal castings obtained at various cooling rate over that of the sand casting. During the present investigation, microstructures for both the products were also examined under different magnifications using optical microscope. Micro-examinations of the specimens were conducted in the as-cast and annealed condition.

2. LITERATURE REVIEW

2.1 Introduction :

The principle of Centrifugal Casting has long been established, dating originally from a patent made by Eckhardt (quoted from Ref. 6a) 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 and for other alloys. Gradually the demand of ductile iron pipes started increasing. large diameter ductile iron pipes found a boost in production in Japan[2] during 1960 to 1970.

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[7] shows that centrifugal atomizing can produce deposits, very similar to thoee produced by gas atomizing, in the form of a large-diameter tube, and form 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[8] 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 spary process to the commercial production of tool steels.

Centrifugally cast[9] stainless steel has become the material most used for steam reformer and pyrolysis tubes during mid 80's. A cheaper alloy HK40 (0.4c - 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[10]. 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 are 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[11] 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.

However, the Centrifugal Casting Method 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 solifification rates by means of small cross section and good thermal contact with a cooling substrate. The Centrifugal Casting Method 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 Solifification of pure metal and alloy under normal condition

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 and further cooling occurs. 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 need some degrees of under-cooling below its real freezing-point which is known as nucleation under-cooling. Nuclei or 'seed' crystals then form, followed by their growth which is the second stage of freezing and the temperature may 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 starts 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 certain 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 has little or no stength. 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"[12]. 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 temperature 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 as shown in Figure 3(b).

However, the influence of temperature gradient upon the mechanism of freezing and the extent of mushy zone of an alloy is illustrated in Fig. 4. This diagram indicates how steepening of the gradient narrows the zone of crystallization and so minimises the distance over which inter crystalline feeding is required The downward movement of the temperature line produces corresponding travel of successive start and end waves of freezing towards the centre of the casting.

2.21 Solidification rate:

The freezing rate has an important role to eliminate solidification shrinkage in a casting, and on such metallurgical factors as segregation and grain size. In a sand mould, the rate at which a casting freezes, is determined primarily by the ability of the mould to accept heat from the casting. If molten metal is poured against a flat mould wall heated only to room temperature, heat will flow into the mould, and a solid layer of metal will be deposited at the mould-metal inter-face. As heat continues to flow, the thickness of this layer will increase with time. The temperature distributions in the mould and metal after a given time are shown schematically in Figure 5.

Heat flows from the hot portions to the colder portions of the system according to the following relation[13]:

$$q/A = -C\,(\partial T/\partial x)$$

where, q/A = rate of heat flow per unit area in Btu/(hr.ft^2),

C = thermal conductivity in Btu/(hr.ft^{o}F); and

$\partial T/\partial x$ = thermal gradient in units of temperature (T) and distance (x).

The temperature of the boundary between liquid and solid metal is the freezing point of the metal and heat of solidification is being liberated at this boundary. The rate at which the boundary moves is determined by how rapidly heat of fusion is being removed.

If metal is freezing against a large flat mould wall and heat flow is normal to the mould surface, the thickness (x) of solid metal deposited will be proportional to the square root of time (t), i.e.

$$x \propto \sqrt{t}$$

Thus, thickness, x (in inch) = $K \times \sqrt{t}$

where, K, is a constant whose value depends on the mould material and its thermal conductivity; and 't' is time in minutes. This parabolic relation ship is shown graphically in Figure 6. The above equation[13] indicates that freezing begins at time t= o, and the initial freezing rate is very large since $\frac{dx}{dt} = \frac{K_1}{2\sqrt{t}}$

However, in actual castings, the rate of solid skin formation is affected by the shape of the casting. Figure 7 sketches the appearance of some castings which were bled at times shown after pouring. A bled casting is one in which the mould is filled with metal and allowed to partially solidify; then the mould is inverted and the liquid remaining is poured out leaving a shell.

It can be seen in Figure 7 that the solid skin builds up on flat surfaces ronghly as the square root of time, but that solidification is more rapid at external angles. This is because the heat is more easily dissipated at these points. Conversely, at internal angles the solidification is slower. It can also be noted that the shape of the casting results in directional solidification from the thinnest section toward the heavier sections. The cooling is controlled by designing the mould and by utilizing the intrinsic design of the casting, so that freezing begins in those parts of the mould furthest from the feeder heads and continues through the casting towards the feeder heads. The practical approach to directional solidification is based on a variety of measures designed to steepen those temperature gradients which lie in favourable directions. These measures include the following:

(i) The control of pouring rate and temperature,

(ii) The differential cooling by chilling and

(iii) The differential heating with the aid of exothermic materials.

2.22 Solidification time:

The influence of casting geometry is the main factor in determining the overall solidification time of a metal or alloy during freezing. Once the geometry of the casting is known, feeder heads can be designed to maintain the supply of metal throughout freezing. The ideal is to be able to predict the solidification time irrespective of the shape of the casting.

A notable step in this direction was taken with the discovery of the Chworinov Rule, which postulates that the total freezing time of any casting is a direct function of the ratio of its volume to its surface area[14] , i.e. the freezing or solidification time,

$t = K(\frac{V}{A})^2$ where,

V = Volume of casting (cm^3)

A = Surface area of casting (cm^2)

K = Constant = 2.1 min/cm^2

or $t = KM^2$, where $M = \frac{V}{A}$ = Modulus (cm)

Therefore, freezing time, t(in min.) = 2.1 M^2

This expression was developed theoretically and was found to correspond well with experimental determinations made on a wide variety of cast shapes ranging from plates to spheres. The overall solidification time for a given volume of metal is thus found to be greatest when the ratio V/A is a maximum, i.e. in the case of a sphere, becoming progressively less for cylinders, bars and plates. That is why, the shape of a riser should be designed in such a way that it would lose minimum heat and keep the metal in a molten state as long as possible. This condition can only be met by a riser which is spherical in shape. But in practice, a spherical riser is difficult to mould and therefore, a cylindrical shaped riser is most frequently used.

2.23 Solidification of Brass

Brass is essentially an alloy of copper and zinc, but for some special purposes, small proportions of other metals are added to obtain increased strength, hardness and resistance to corrosion. The industrially important alloys of the copper-zinc system contain zinc upto 50% and are particularly important in view of their wide-range properties such as:

(i) Mechanical properties,

(ii) Ease of working,

(iii) Attractive colour, and

(iv) Resistance to atmospheric and marine corrsion

The equilibrium diagram of copper-zinc system is shown in Figure 8. It must be remembered that the changes of phases which is shown in equilibrium 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^{o}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 preciptate 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^{o}C which is contrary to general behaviour; then decreases down to room temperature.

Between 453^{o}C and 470^{o}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 9 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 volatilisati 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 deformatio 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 α - β -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.

2.24 Nucleation and growth of solidification under normal condition:

Nucleation is the appearence of some points in the liquid upon which further atoms can be deposited for the growth of solid crystals. Nucleation occurs in the following 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 certain degrees of undercooling. 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.

2.25 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, large size 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. 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.

2.26 Solidification under centrifugal force

The effectivenees 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[6(

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[6(c)].

As the wall thickness increases or as the ratio of length to diameter is reduced, however, radial temperature gradients become less pronounced. Heat loes 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 machinig, 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:

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.

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 crystals 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 process 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.10(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 semincentrifugal 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.10(b). In this case also the stack moulding can be advantageously employed.

2.33 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^{o}. The axis of rotation mainly depends upon the

$\frac{L \text{ (length of the job)}}{D \text{ (bore of the job)}}$ 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^{o} to 90^{o}
	$\frac{L}{D} < 1$ ————	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 epeed 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[16] in metal moulds. In this process, illustrated in Figure 11, 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.

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.

2.34 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 predominent 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 micro-constituents. 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 temperatrues 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[17]. 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 stength[18].

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.

2.35 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:

a) <u>It is a economical process for making hollow interiors in cylinders:</u>

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.

b) <u>Casting is cleaner</u>:

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.

c) <u>The process produces quality products</u>:

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

2.36 <u>Application of Centrifugal Casting</u>

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[19] 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 Centrifugal Casting

The main variables controlling the casting quality are the speed of the rotation of the mould, the pouring temperature of the melt and the solidification time of the casting. These are described below:

2.41 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 [6(b)].

However, it has been found[4] 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 required for best result and vice versa.

2.42 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. Youdelis and others[20] found that employing high pouring temperatures for certain alloys result in an increase in grain size and a consequent decrease in tensile strength and elongation. Similar observations were also made by other investigators[21].

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.

2.43 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. In practice, these effects usually predominate and columnar coarse structure's 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 on Brass:

Cast brass shows a dense dendritic structure and when it is fully annealed then these dendrites disappear and grain boundaries become prominent. Also unfiformly 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[22]. If thesame 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[23]. Again, if the same specimen is partially deformed and then annealed bent twins and strain bands are visible in the micrograph.

3. EXPERIMENTAL SET-UP

3.1 Introduction

The experimental set-up was reconstructed ofter modifying some of the components of previous unit[4]. The detail description and operation of the present set-up are given in the following sub-section.

3.2 Description and operation of the experimental set-up

The experimental set-up mainly consisted of a permanent mould, a hollow mild steel shaft, a four wheel trolly with a ladle and a ladle holder, a hemispherical spout a gauge ring and a motor. Details of the experimental set-up are shown in Figure 12.

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 tho 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 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

Trolly was an essential part of the experimental set-up. 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 regualted. The main function of the spout was to transfer the molten metal into the revolving mould uniformly from the ladle Fig. 13(a) which was placed above it. The ladle (capacity 30 lbs) 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.

The ladle holder, made of cast iron pipe had a bracket end & an extended handle to ease the pouring manually yet safely by simply rotating the handle. The length of the handle was extended to tilt the ladle between 0 to 90^{0} 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 Figure 13(b).

A 7 H.P. electric motor was used for rotating the casting machine and its speed was about 2800 revolutions per minute. However, the required spinning speed of the mould was achieved by changing the pulley's diameter connected with the shaft of the machine utilising a V-belt. This speed was again compared and recorded with the help of a Digital Tachometer which gave the direct measurement of the speed. The V-belt worked as a medium for transfer of power form motor to the shaft of the casting machine. However, for the present investigation the mould speed was used as 1800 rpm, because this speed gave best results for brass casting[4].

3.3 <u>Cooling device</u>:

Cooling water for quenching of the rotating mould was supplied from a mild steel container with a rectangular cross-section in the form of a bottom less trough at the top (Fig. 14). The lower part of the container was made in the form of a truncated inverted pyramid welded to this trough. This inverted pyramid had also a perforated base having a rectangular cross-section through which cooling water could be sprayed to the rotating mould placed at the bottom.

The supply of water could be stopped by putting a flat stopper over the perforated base whenever necessary. The arrangement was such that when the container was full of water, the stopper could be turned on to make the water fall on the rotating mould as necessary through the small pores. The flow-rate was controlled by regulating the water tap which continuously supplied water from the pipe line into the container. Thus, a constant level of water could be maintained in the container. In order to facilitate the removal of the stopper easily, quickly and safely from the base of the container, a handle made of mild steel was attached to it. The container with about two gallons of water rested on four legs (made of m.s. angle) which were placed safely on the ground at a distance of about ½" from the rotating mould.

4. EXPERIMENTAL DETAILS

4.1 Introduction

A series of experiments were carried out with Brass in order to determine the effects of freezing time on the microstructure and properties of the centrifugally cast products. In order to achieve these objectives, a centrifugal casting machine with permanent mould, special cooling device, a natural gas fired pit furance, a trolly with crucible holder and a hemispherical spout etc were used.

4.2 Moulding Materials

Cast iron mould was chosen for the centrifugal casting machine because the casting conditions are more constant and controllable with this material. 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.

Green sand was used as moulding material for making sand moulds. 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 56. The same sand was also used for making the core.

4.3 Melting and Casting:

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 hugo quantity of slag and in order to remove these slags the addition of flux became imperative. Therefore, Foseco deoxidizing tube (DS-2)- one tube 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 10 Kg. After solidification, the material was tested to determine it's content. The material was analysed in the laboratory and obtained a composition of about 73% Cu, 25.5% Zn and 1.5% Sn.

This brass ingot was melted in the pit furnace in the same manner as before. After melting, the crucible was removed 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 at about 1080°C, while the mould was rotating at a speed of about 1800 rpm[4]

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 ± 2°C accuracy. In order to maintain a high degree of experimental accuracy for all experiments, it was necessary to take note of the desired pouring temperature.

Several castings were carried out in the present investigation using the centrifugal casting process solidified at various cooling rate and also using the conventional sand casting process.

Each casting was individually marked for identification as shown in Figure 15 and the metallographic specimens were identified with a vibrotool to avoid their deformation.

4.4 Process Variables

Among the various process variables which affect the quality of the casting, only the effect of freezing time on the structure and properties was studied in the present investigation. This is briefly described in the following sub-sections:

4.41 Variation of freezing time:

After bringing the centrifugal casting machine in operative condition, the variation of freezing time on the casting was achieved using the following procedures -

(i) by delaying the solidification process with the applicatio of heat using gas flame around the rotating mould.

(ii) by spraying cooling water through special cooling device around the rotating mould which promoted faster cooling.

In the first stage, two experiments were carried out. Firstly, the mould was preheated to about 100°C and the melt was poured into the rotating mould. When the casting solidified, it was taken out. The second experiment was carried out when the rotating mould temperature was about 400°C.

In the second stage, the third experiment was conducted at about 20°C. This was achieved by applying ice cooled water around the rotating mould. The solid ice was put into the funnel and water was poured on it, as a result the water temperature came down to about 20°C. The water spraying was continued until the casting became solid.

Another experiment was also carried out (fourth one) with same material in the conventional sand mould (static). This was done only to compare the results with those obtained in the centrifugal castings solidified either at longer or shorter freezing time.

4.42 Calculation of freezing time:

The freezing time was calculated using Chworinov formula in the following way:

Volume of the hollow cylindrical casting, $V = \pi r_1^2 h - r_2^2 h$
$= \pi h (r_1^2 - r_2^2)$

Surface area of the casting, A = Outer surface area + Inner surface area + Area of two end faces

$$= 2\pi(r_1 - r_2)\,h + 2\pi r_2 h + 2\pi(r_1^2 - r_2^2)$$

$$= 2\pi(r_1 h - r_2 h + r_2 h + r_1^2 - r_2^2)$$

$$= 2\pi(r_1 h + r_1^2 - r_2^2)$$

Modulus, $M = \frac{V}{A} = \frac{\pi h\,(r_1^2 - r_2^2)}{2\pi(r_1 h + r_1^2 - r_2^2)}$

$$= \frac{h\,(r_1^2 - r_2^2)}{2\,(r_1 h + r_1^2 - r_2^2)}$$

Height of the cylinder = 27 cm $\qquad h = 27$ cm

Outer diameter of the cylinder = 12 cm $\qquad r_1 = \frac{12}{2} = 6$ cm

Inner diameter of the cylinder = 9 cm $\qquad r_2 = \frac{9}{2} = 4.5$ cm

$$M = \frac{27\,(6^2 - 4.5^2)}{2\,(6 \times 27 + 6^2 - 4.5^2)}$$

$$= \frac{425.25}{355.5} = 1.1962 \text{ cm}$$

Solidification time, t (in Min.) $= 2.1 \times M^2$

$$= 2.1 \times 1.4309$$

$$t = 3.00 \text{ mins.}$$

The freezing time for the casting of present investigation was found to be about 3.00 minutes. Since the Chworinov rule holds good for sand casting, therefore the solidification time for the casting in rotating metal mould must be less and should be further less when cooling water was sprayed over the rotating mould. Thus, the solidification time should be less than 3.00 minutes for either cases. When the mould was heated upto 400°C, in this case it is very difficult to envisaga about the deviation of solidification time but the structure and properties of the casting would respond it better.

4.5 Heat Treatment

Although a number of heat treatment process can be applied on brass but in the present work only the effect of annealing on the macro-structures and properties was investigated. Annealing process for brass is described below:

Annealing of brass was accomplished by heating the specimen to 1000°F (538°C) in an electric autometic control muffle furnace and holding it at that temperature 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[26]. After cooling to room temperature, the specimens were removed from the furnace and were studied on the basis of their micro-structure and properties.

4.6 Metallography

Metallographic specimens were prepared from the cast hollow cylinders made of brass and solidified at different cooling rates.

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 a solution of 20 ml NH_4OH and a few drops of freshly made H_2O_2 (3%) by swabbing the specimen for 1 minute.

The micro structures of various specimens were examined under optical microscope to see the structural difference at different magnifications. Wetzlar Universal microscope and Swiftmaster photographic microscope were used for the examination and photographically recording of the representative microstructures, respectively.

4.7 Determination of Mechanical and Physical Properties

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

4.71 Determination of Tensile Properties

Tensile testing was conducted using a 24 Kg Hydraulic tensile testing machine with a screw type operating cylinder using 15 N scale. A schematic diagram of a gripping device for threaded-end specimens was shown in Figure-16. The standard 0.25 in (6.25 mm) diameter round test specimen with dimensions shown in Figure-16, was used for tensile testing[27] of various brass specimens. The U.T.S. in newtons per square mm and percentage of elongation were obtained. The results were averaged from three determinations.

4.72 Hardness Measurement

Brinell Hardness testing was conducted using Avery Brinell hardness testing machine. To determine the Brinell Hardness of the Brass casting, 10 mm diameter indenter and applied load of 1000 Kgf were used. The Brinell hardness number (BHN) was calculated from the following equation

$$BHN = \frac{P}{\frac{\pi D}{2}\left[D - (D^2 - d^2)^{1/2}\right]}$$

where,

P = applied load, kgf

D = diameter of the ball, mm, and

d = mean diameter of the impression, mm.

5. RESULTS OF THE EXPERIMENTS

5.1 Introduction:

The entire result was divided into two phases for the purpose of comprehensibility and convenience. The first phase comprises the results of the effect of freezing time on the microcopic observation of the cast specimens and the second phase comprises the results obtained from various properties of the cast specimens for both the as-cast and annealed condition. These results are explained through different figures, tables and micrographs:

5.2 Microscopic observations:

Metallographic studies of the specimens for both as-cast and annealed conditions are furnished below:

5.21 As-cast condition:

Microstructure of the centrifugally cast brass solidfied at mould temperature of 20°C, shows fine equiaxed grains, whereas the castings solidified at 150°C and 400°C show larger equiaxed grains (Figs. 17 to 19). It can also be seen that there is no existance of any dendritic structures in the micrographs. The average grain size of the castings solidified at 20°C, 150°C and 400°C are measured to be 3, 4 and 7 microns, respectively.

On the other hand, the microstructure of the conventional sand cast specimen shows fir-tree like massive and dense dendrites (Fig. 20).

5.22 Annealed condition:

Microstructure of the centrifugally cast brass solidified mould temperatures of 20°C, 150°C and 400°C are shows is Figs. 21,22 and 23 respectively. It can be seen that the grains of all the specimens are quite large and almost similar in size. Strain bands are also visible in the specimens. In sand cast specimen traces of coring are prominently visible near the grain boundaries (Fig. 24).

The comparature results of the grain size measurements for as-cast and annealed specimens are shows below:

Mould Temperature (°C)	Average Grain size (micron)	
	As-cast	Annealed
20	3	20
150	4	22
400	7	22

5.3 Tensile tests:

Tensile test results of the specimens for both as-cast and annealed conditions are graphically shown in Figs. 25 and 26 , and are summerised in Table-3. Descriibtion of the results are furnished below:

5.31 As-cast Condition:

It is noticeable from figure 26 . that the tensile strength of the specimen solidified at mould temperature 20°C is higher than those of the specimens solidified at 150°C and 400°C. It is also noticeable from figure 26 that the percentage elongation is higher in case of the rapidly solidified specimen compared to the other two specimens solidified at higher mould temperatures.

5.32 Annealed Condition:

It can be seen from figure 25 that the after annealing the strength of all the specimens increased almost in similar proportions.

From figure 26 it can be seen that the percentage elongation of all the specimens increased due to annealing but the rate of increamen is more promounced in case of the rapidly cooled specimen compared to others.

Comparative results of tensile properties of the as-cast and annealed specimens are shown below:

Mould Temperature (°C)	UTS (N/mm^2		Elongation (%)	
	As-cast	Annealed	As-cast	Annealed
20	312.0	331.6	21.0	54.0
150	300.5	320.5	18.9	35.0
400	240.0	262.0	15.0	20.0

5.4 Hardness:

Hardness test results of the specimens for as-cast and annealed condition are graphically shown in Fig. 27. and are summerised in Table-3. Description of the results are furnished below:

5.41 As-cast condition:

Hardness value of the specimen cast at lower mould temperature shows higher value than those cast at higher mould temperatures (Fig. 27).

5.42 Annealed condition:

It can be seen from the figure 27 that hardness value of all the specimens are increased after annealing.

Comparative results of the hardness test of the as-cast and annealed specimens are given below:

Mould Temperature (°C)	Hardness (BHN)	
	As-cast	Annealed
20	70	78
150	65	73
400	55	63

6. DISCUSSION OF THE RESULTS

6.1 Introduction:

Structure and properties of centrifugally cast α-brass as obtained from the experiments have been shown in the previous chapter. Now the results are to be discussed here with a view to suggest some recommendations.

6.2 Microstructure of the castings:

Microscopic observations of the specimens in the as-cast and annealed condition are discussed below.

6.21 As-cast condition:

In centrifugal casting, the mould is rotated at a pre-determined speed of 1800 rpm. which gave good result[4] and the pipe is formed almost as a series of welded rings and anologous to winding a rope into a helical coil. As soon as the molten stream contacts the rotating mould, the melt spreads over the entire length of the mould cavity. With further flow of the metal from the spout, the wall thickness of the pipe builds up gradually and uniformly over the entire length. Immediately after pouring, inertia prevents the melt from taking up the speed of the mould instantly. Thus relative motion exists between the adjacent liquid layers and also between the melt and the previously solidified layer. In the solidified layer, the melt flows across the front of the growing crystals and the shear stress fractures the growing dendrites.

It is considered that the arms of the dendrites from the solidifying front are broken off by the rapid flow of new liquid, thus forming a multitude of nuclei in the new arrival. Equiaxial grains then start to grow in the new wave until the next one arrives and the process continues. As a result, the structure consists of fine equiaxed grains (Fig.17); whereas in the sand casting, dendritic structures are visible, because no fragmentation or breaking of the structures occurs.

Average grain size of the castings has been measured by counting the number of grains in the length-wise interceptions. It can be seen from table-3 that the average grain size for the castings solidified at 20°C, 150°C and 400°C are 3 micron 4 microns and 7 microns respectively. Actually in water cooled mould, the melt solidifis quickly that means extreme under-cooling occurs for favouring more nucleation and lesser growth, resulting fine equiaxed grain. On the other hand, longer solidification time is conducive to slow cooling which reduces the degree of undercooling and the nucleation rate. Thus, fewer nuclei are available for growth which eventually leads to the formation of comparatively coarse crystals (Fig. 19) and hence the average size has increased. Therefore, the rate of extraction of heat from the mould wall has a tremendous effect on the structure of the solidified castings and as such it can be inferred that shorter the solidification time, smaller is the grain size.

6.22 Annealed Condition:

The centrifugally cast brass containing fine equiaxed grains, when annealed, gave rise to twin crystals along with strain bands. (Figs 21-24). When sand cast brass specimen is annealed after partial deformation, bent twins with strain bands are visible throughout the structure[19]. These bent twins appear due to the annealing of the partially deformed specimen where the grains become elongated. Now the question is why these types of phenomena occur in case of centrifugal casting.

It is envisaged that in case of centrifugal casting, dendrite fragmentation occurs, favouring equiaxed grains and the phenomena can be considered similar in effect as partial deformation in the sand casting. Actually, in centrifugal casting, the growing tender crystals undergo some sort of deformation due to high speed of the mould. Therefore, when the centrifugally-cast product is annealed, twin equiaxed grains with the existance of several strain bands are visible.

Due to annealing the average grain size of the structure has increased from 3 micron to 20 micron, 4 micron to 22 micron and 7 micron to 22 micron for the specimens solidified at mould temperatures of 20°C, 150°C and 400°C, respectively. This relationship is graphically shown in Fig. 28. It can be seen that the effect of annealing has become more pronounced in case of the specimen solidified at mould temperature of 20°C. This is because due to faster cooling more neucleation occured and higher numbers of small grains were available in this specimen than slowly cooled specimens. During annealing, smaller grains have more opportunity to diffuse and to be come bigger than those of others which were originally larger grains. Another reason may be that the grains of this specimen in the as-cast condition.

were in fully stressed condition. As a result, when this specimen is annealed, the stressed grains have been relieved fully i.e, the grains have got full recovery from the stressed condition. On the other hand, the specimens of the castings solidified at higher mould temperatures the grains were somewhat less stressed condition since they were cooled comparatively slowly. Therefore, the effect of annealing on the change of grain size responded more pronouncedly in the casting solidified at mould temperature of 20°C compared to other two types.

6.3 Features of as-cast and annealed Brass:

The properties, according to the results obtained from the as-cast and annealed Brass are shown graphically in figures 25 to 27. The salient features of the above curves are discussed below.

6.31 Tensile Strength:

It can be seen from Fig.25 that the strength is higher in the casting solidified at mould temperature of 20°C compared to the castings solidified at mould temperature 150°C and 400°C. It is considered that the faster cooling rate has given birth to smaller grains and dense structure with low segregation, resulting enhanced strength.

When these specimens are annealed, strength of all the castings improved to some extent. This is probably due to the uniform distribution of the particles concentrated at grain boundaries during annealire.

6.32 Hardness:

It can be seen from Fig. 27 that the hardness of fastly cooled cas-ting is higher than those obtained at comperatively slowly cooled casting for both as cast and annealed condition. The reason may be that before annealing the grains of fastly cooled specimen were in stressed condition compared to others. During annealing due to precipition hardening of the secondary phases, hardness of all the specimens have improved slightly.

6.33 Elongation:

It can be seen from Fig. 26 that the % elongation of the casting solidified at faster rate exlibits slightly higher elongation than those of the casting solidified at higher mould temperatures. The reason behind this may be that faster cooled specimen contained smaller grains compared to others (Table -3). When the castings are annealed at 538°C for 1(one) hour it is surprising to see that the castings solidified at lower mould temperature (20°C) shows 160% increase in elongation. On the other hand, the castings solidified at 150°C and 400°C mould temperatures show 84% and 33% increase in elongation. Facts believed these remarkable differential increase in elongation may be due to the removal of internal stresses and elimination of micro-segregation from the structure, since all cast alloys are subject to microsegregation[24]. The segregation may be only a concentration gradient within the dendritic arms or it may be a second phase precipitation at the grain boundaries. Again, the centrifugal seperation of suspended crystals or insoluble phases[25] can occur within the liquid, creating a tendency for the less dense constituents to be transported towards the centre. At a more advanced stage of freezing, low melting point liquid can flow outwards through passages between the rigid network of interlocking grains. The annealing treatment minimises or eliminates this concentration differences and homogenises the entire structure. As a result, the ductility of the casting improves.

Now the question may arisethat why this has happened sharply in water cooled casting. The probable answer may be that in the water cooled casting, the solidification was too rapid for appreciable diffusion yet to occur and thus concentration difference might not eliminate completely in the as-cast condition. On the other hand, castings solidified at other mould temperatures (specially at 400°C), had enough time to minimise the concentration differences in the structure. Therefore, the homogenization (annealing) treatment could not improve the strength and ductility of these castings as much as compared to water cooled casting.

During annealing, the concentration difference and the precipitations are absorbed by the matrix giving better results (Fig. 21). This indicates that the annealing treatment responded more effectively in the water cooled casting than the castings solidified at various mould temperatures.

7. CONCLUSIONS

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

(1) In general, the centrifugally cast α-brass specimens have superior physical and mechanical properties than the sand cast brass.

(2) The true centrifugal casting process yields satisfactory results with respect to physical appearance, microstructure and properties specially when ice-cooled water sprayed over the rotating mould. This set of experiments suggest that shorter the solidification time, finer the equiaxed grains and higher the mechanical properties.

(3) Annealing treatment responds more effectively in the casting solidified at water cooled mould than the castings solidified at various mould temperatures. Annealing has also shown a great effect on the grain size of the rapidly cooled centrifugally cast α -brass specimens.

(4) Sand cast brass specimen shows prominent coring effect near the grain boundaries, whereas the centrifugally cast specimen do not show such effect. At the same time, after annealing the sand cast brass specimen does not show any strain bands but the centrifugally cast brass specimen shows equiaxed grains with strain bands.

(5) The results of the tensile and hardness tests are completely in accordance with the metallographic structures obtained in the present investigation.

8. SUGGESTIONS FOR FURTHER WORKS

In Bangladesh a considerable quantity of Brass castings are being carried out to make products of various kinds for use in different industrial and commercial sectors. Conventional sand mould products are not quite good specially for pressure tight fittings and cylinders. If these are made by using centrifugal castings process, the quality would considerably improve. But true centrifugal casting method is not yet much familiarise in the local foundries of Bangladesh. The experiment carried out in this text may introduce a new chapter if implemented in the industry.

However, the following further works in this field needs to be carried out to give a conclusive suggestion regarding the improvement in use of Cu-Zn alloys in the industry:

(1) Study may be carried out using Bronze (85% Cu, 5% Sn, 5% Pb, 5% Zn) and gun metal (80% Cu, 10% Sn, 2% Zn), which are also very widely used in domestic and industrial appliances.

(2) Centrifugal casting machines are a bit costly and are used for only restricted shape, therefore study may be carried out how to make other products of intricate size and shape using this machine so that practical applications are more facilitated.

(3) Further study can be carried out by changing other parameters of the process such as pouring temperature of the melt, mould material, annealing temperature and time etc, to search out the best possible results.

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 : Properties of castings solidified at various mould temperatures, as-cast condition and annealed condition.

Casting Type	Mould Temp. (°C)	UTS (N/mm^2)		Elongation (%)		Hardness (BHN)		Grain size (Micron)	
		As-cast	Annealed	As-cast	Annealed	As-cast	Annealed	As-cast	Annealed
Centrifugal Casting	20	312.0	331.6	21.0	54.0	70	78	3	20
	150	300.5	320.5	18.9	35.0	65	73	4	22
	400	176.5	262.0	15.0	20.0	55	63	7	22
Sand Casting (static)	room Temp.	176.5	189.1	14.6	18.0	43	45		

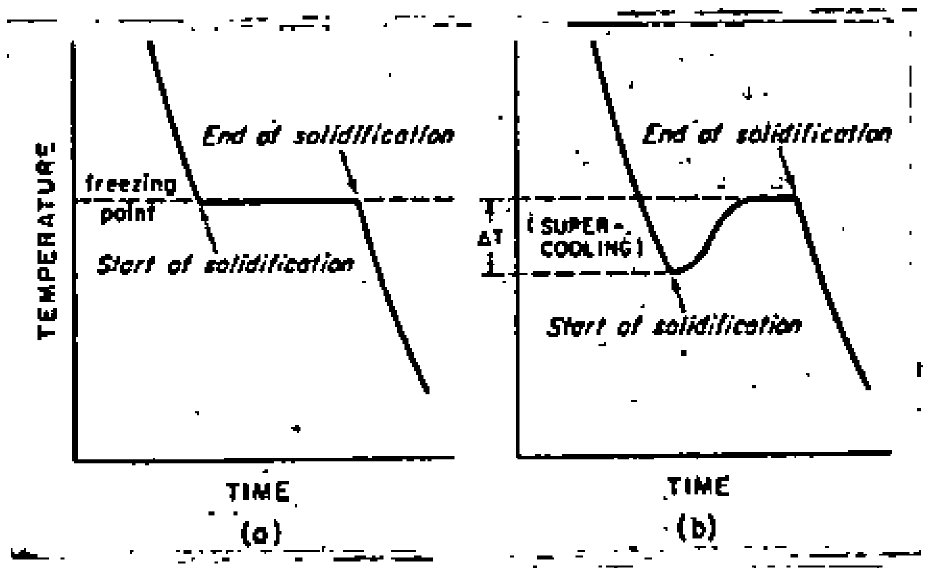


Figure 1 - Colling curves of a solidifying pure metal.

a) Equilibrium cooling

b) Cooling curve showing super cooliog.

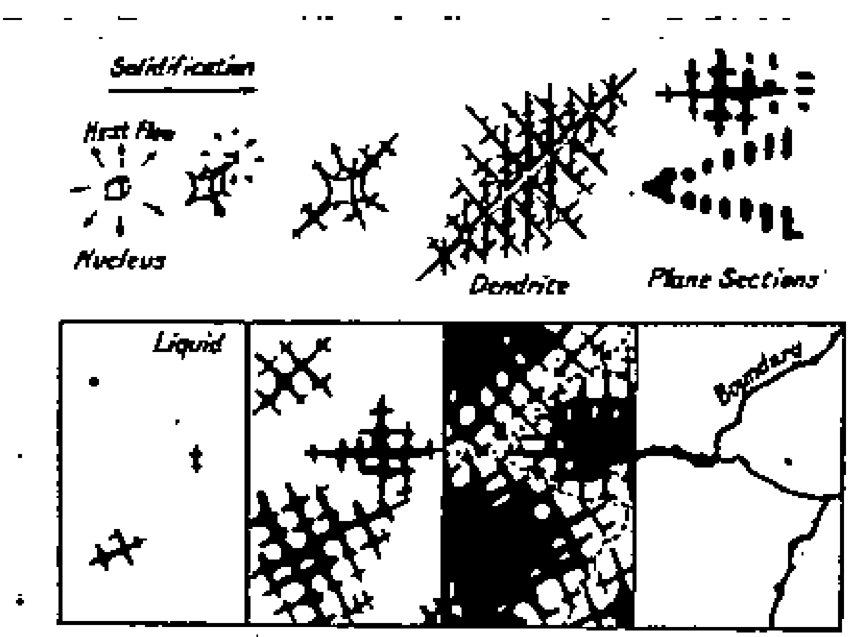


Figure 2 - Solidification of a metal. For f.c.c. and b.c.c. metals dendrite arms extend in the cube face (100) directions.

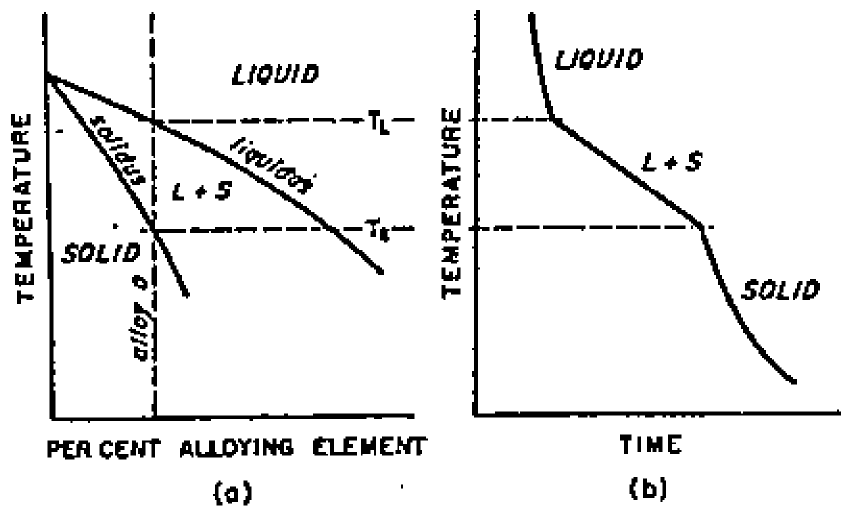


Figure 3 - Effect of alloying on the solidification temperature of a metal.

a) plot of solidification temperature verse percent alloying element,

b) ideal cooling curve (equilibrium cooling) of alloy

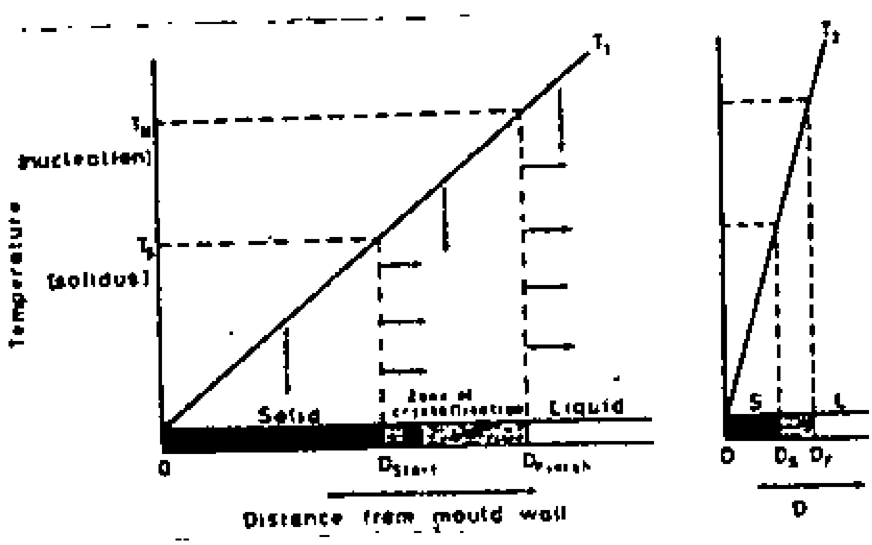


Figure 4 - Schematic represetation of temperature distribution in plane front solidification.

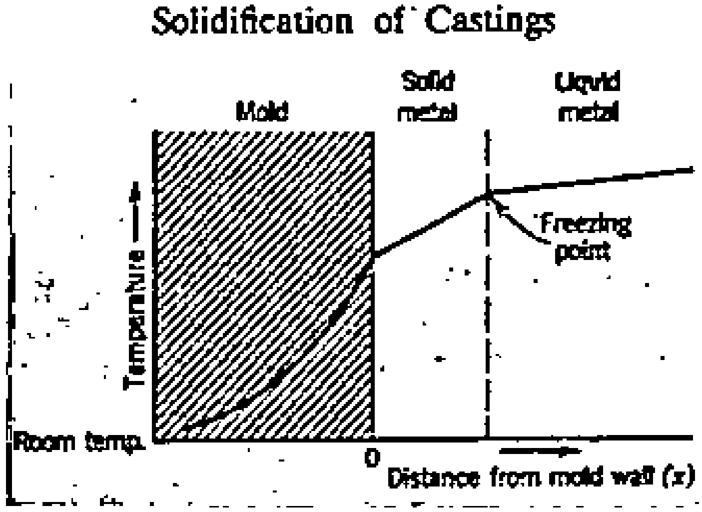
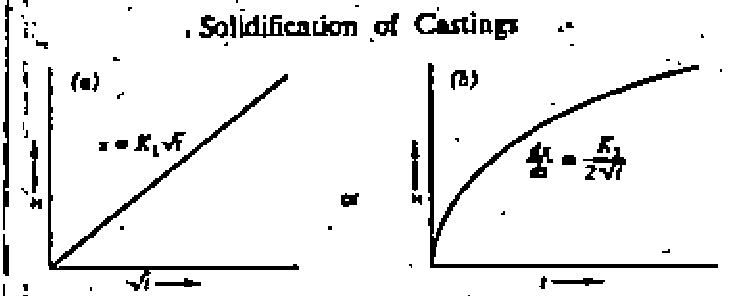
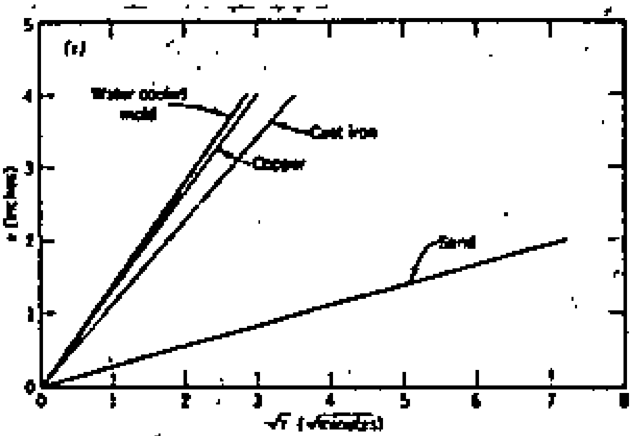


Figure 5 - Temperature distribution showing heat flow during unindirectional solidification from a flat mold wall.



Rate of solidification from a flat mold wall. Thickness of solid metal (x) plotted as function of time (t).

Fig. 6



Solidification of steel from mold walls of different mold materials.

Fig. 6b

Figure 7 - Steel castings "bled" at the times shown; solidified skin remaining.

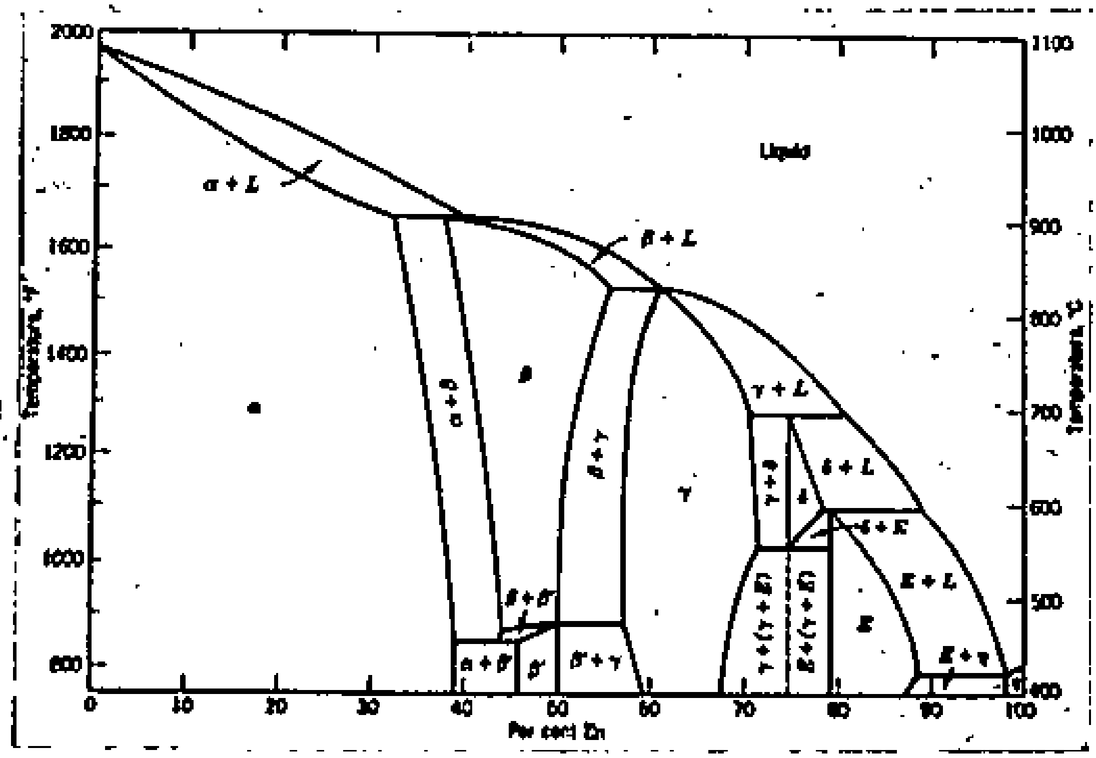


Figure 8 - Equibrium diagram of Copper-Zine system.

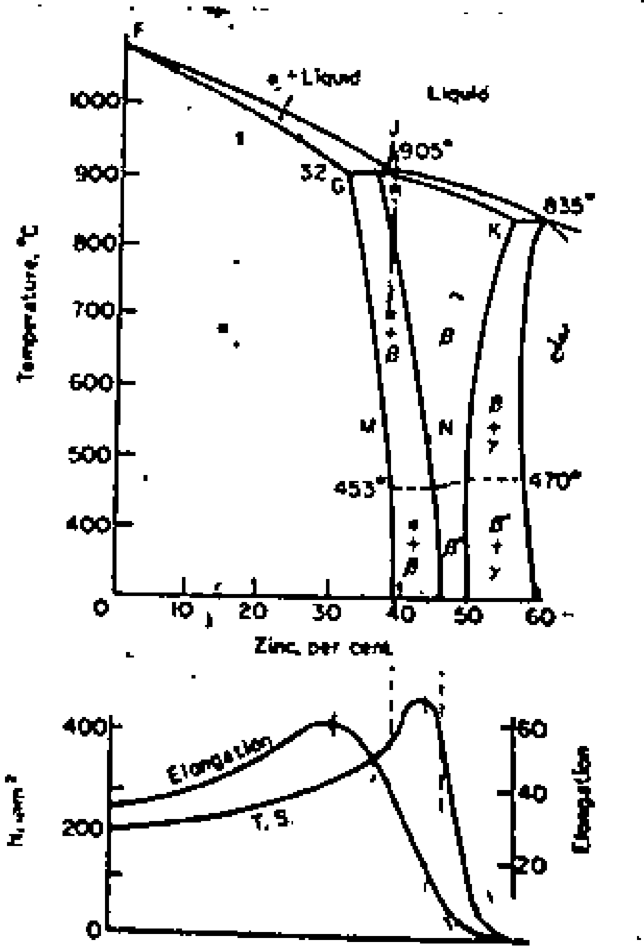


Fig. 9 Equilibrium diagram and mechanical properties of brasses.

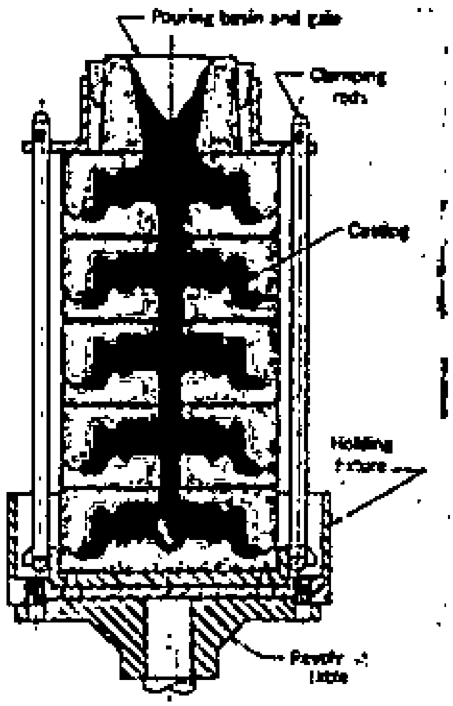


Figure 10. – a) Semicentrifugal stack molding of track wheels.

b) Centrifugal castings with internal cavities of irregular shape.

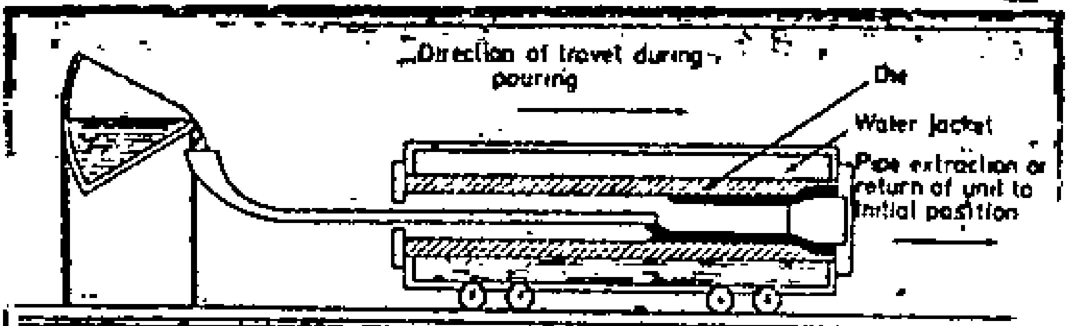
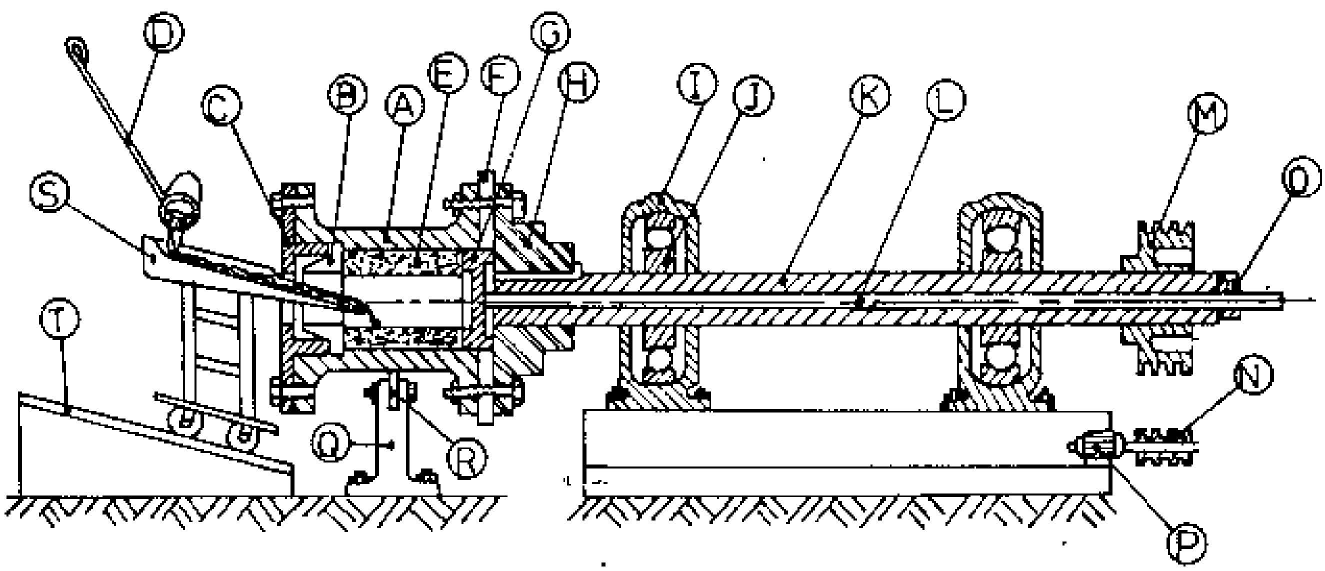


Figure 11.3 Essentials of de Lavaud pipe casting machine



A) C.I.Mould	K) Cylinder Shaft
B) Mould Guide(Front)	L) Ejecting Rod (Ejector)
C) Mould Guide Flange	M) Machine Pulley
D) Ladle Holder	N) Motor Pulley
E) Casting Piece	O) Adjusting Collar
F) Asbastos Washer	P) 7 H.P.Electric Motor
G) Mould Guide (Back)	Q) Mould Guide Stand
H) Mould Adjusting Flnage	R) Mould Runner
I) Bearing Housing	S) Hemispherical Spout
J) Ball Bearing	T) Slopy Rail Track

FIG 12(a) CENTRIFUGAL CASTING MACHINE

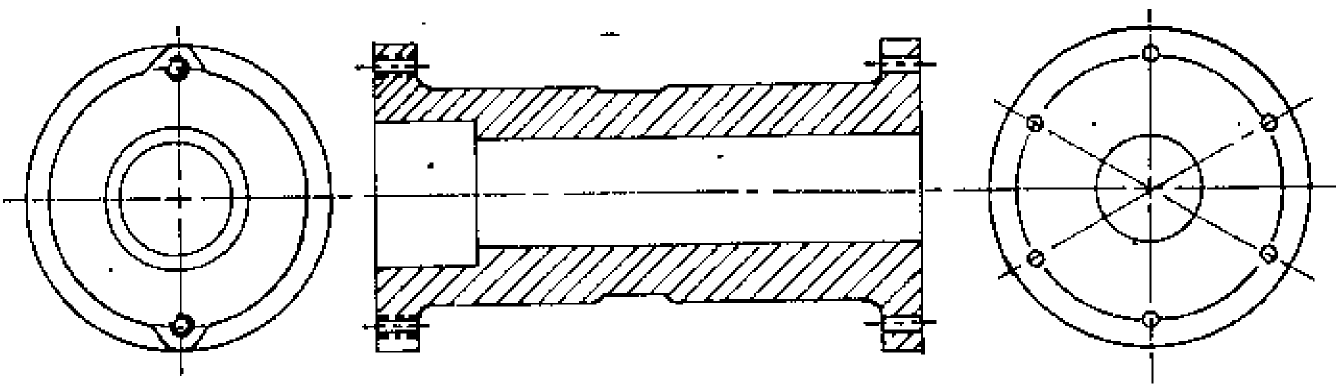
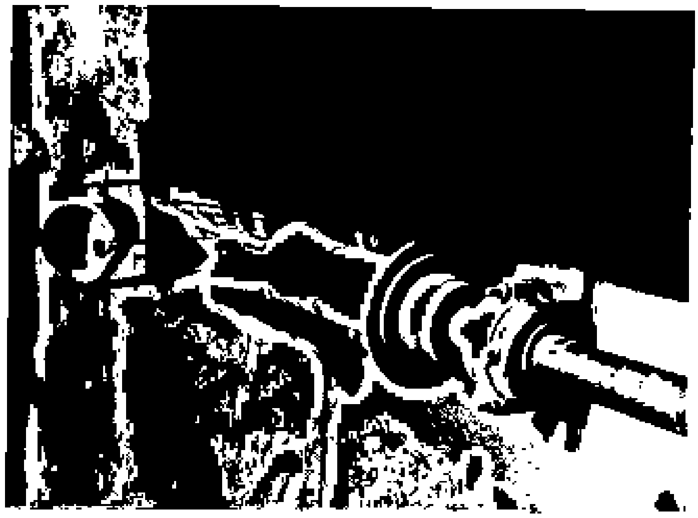


FIG-12(b) CENTRIFUGAL CASTING MOULD



(a)

(b)

Figure 13 - a) Molten metal is being transfered from ladle to the rotating mould (Via. hemisperical spout).

b) Showing gauge rings and holder.

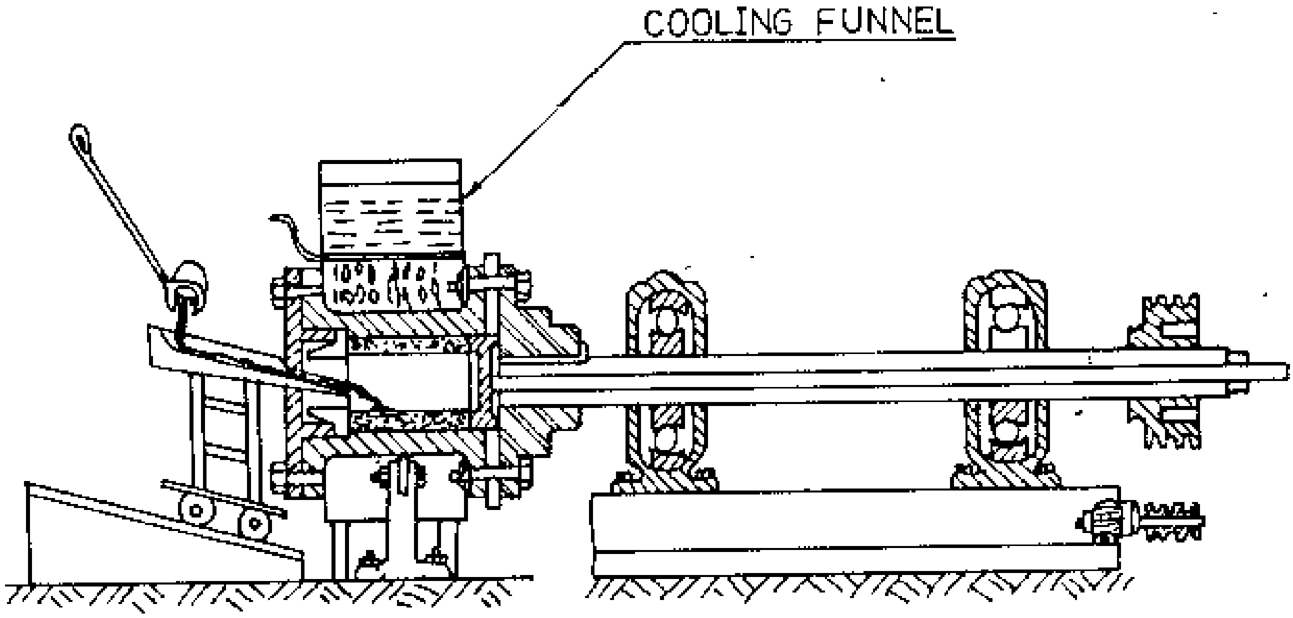
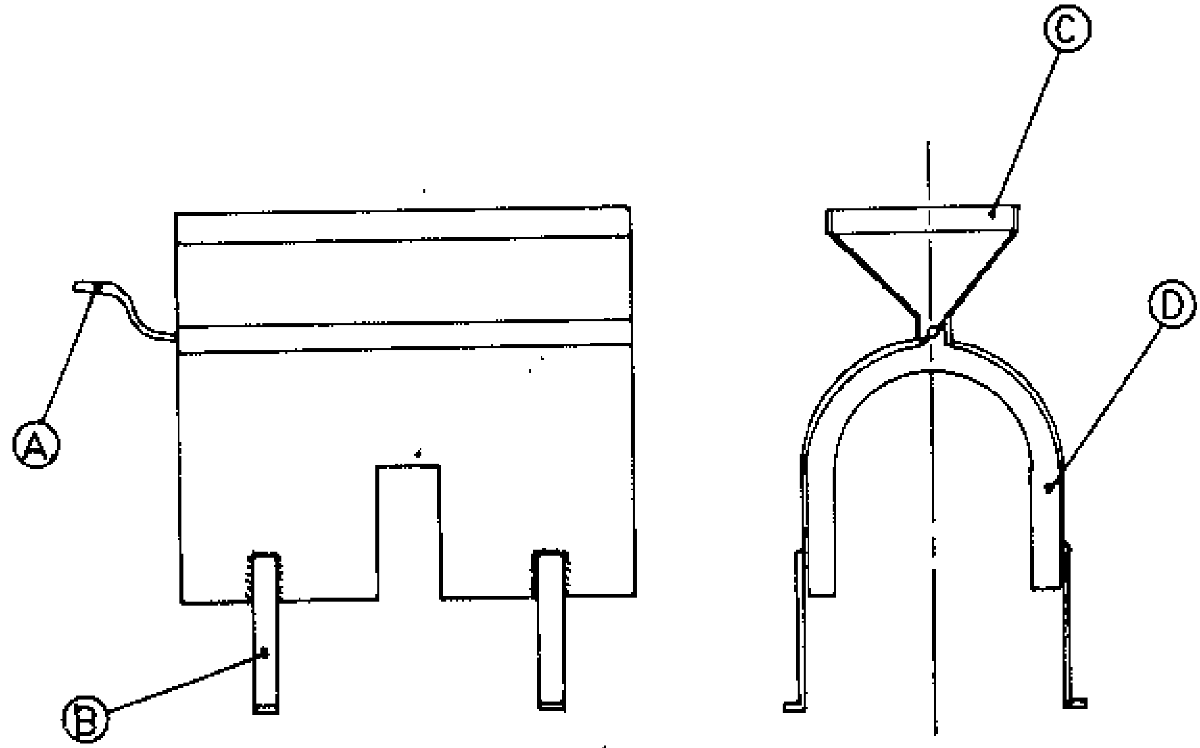


FIG 14(a) CENTRIFUGAL CASTING MACHINE WITH COOLING SYSTEM



A) Stopper Handle
B) Leg
C) Funnel
D) Cover

FIG: 14(b) DETAILS OF COOLING FUNNEL

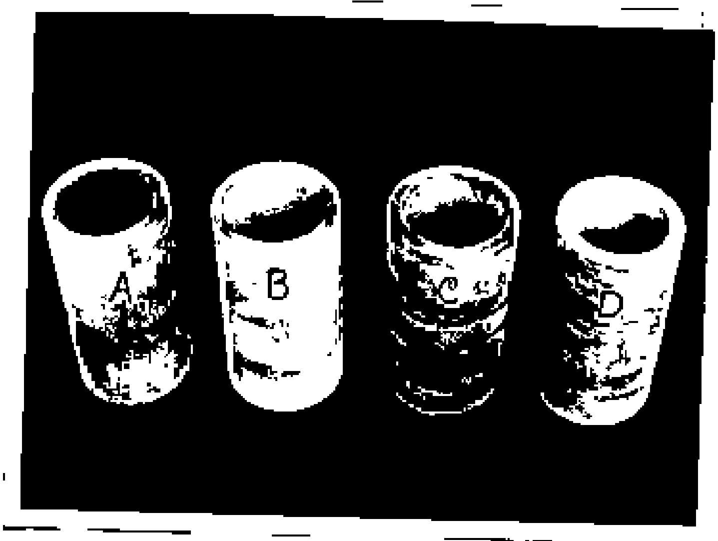
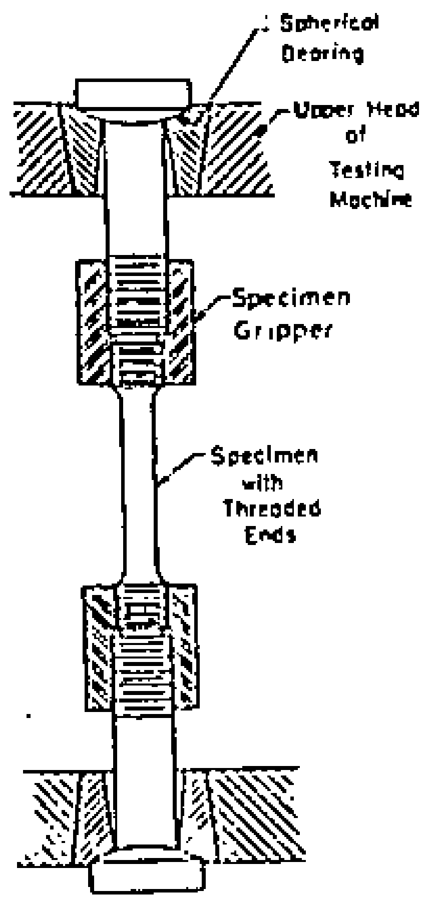
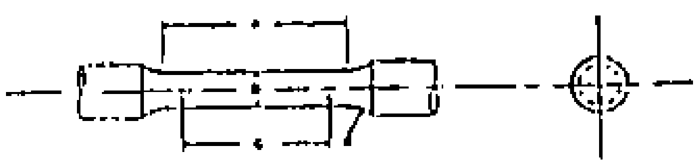


Fig. 15 Centrifugally cast and sand cast α-brass cylinders solidified at various mould temperatures.

A - Mould Temp. 150°C
B - Mould Temp. 20°C
C - Mould Temp. 400°C
D - Sand Cast.



(a)



	Dimensions in	Dimensions 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	1¼	32

(b)

Fig. 16 a) Gripping device for Threaded-end specimen.
b) Round Tension Test specimen.

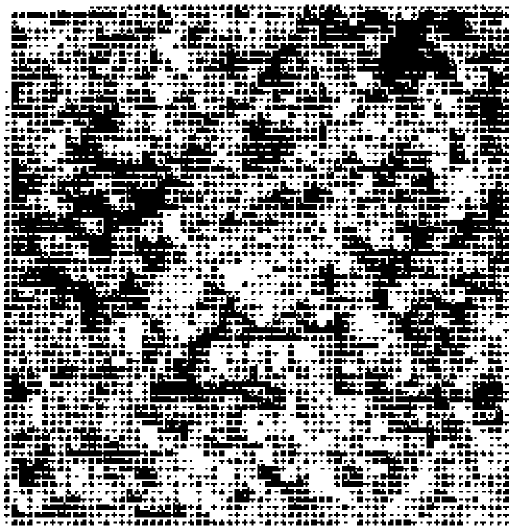


Fig. 17 Microstructure of centrifugally cast α-brass solidified at mould temp. 20oC, x1000

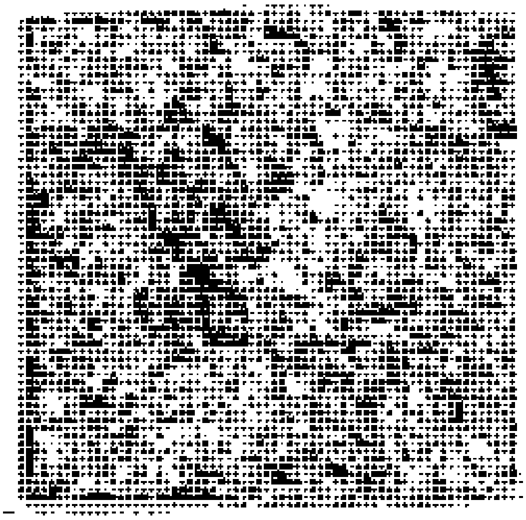


Fig. 18 Microstructure of centrifugally cast α-brass solidified at mould temp. 150oC, x1000

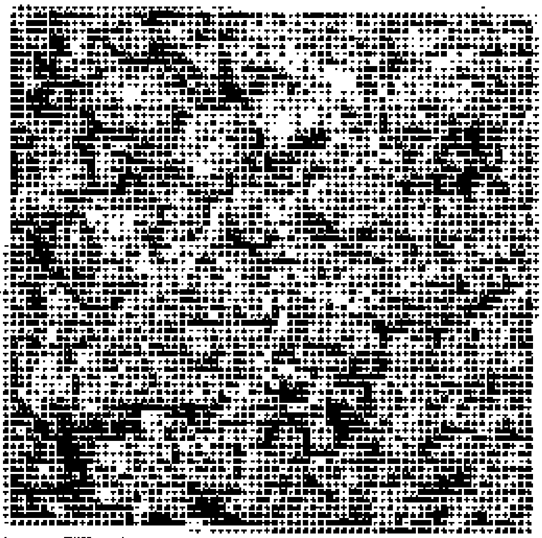


Fig. 19 Microstructure of centrifugally cast α-brass solidified at mould temp. 400oC. x 1000

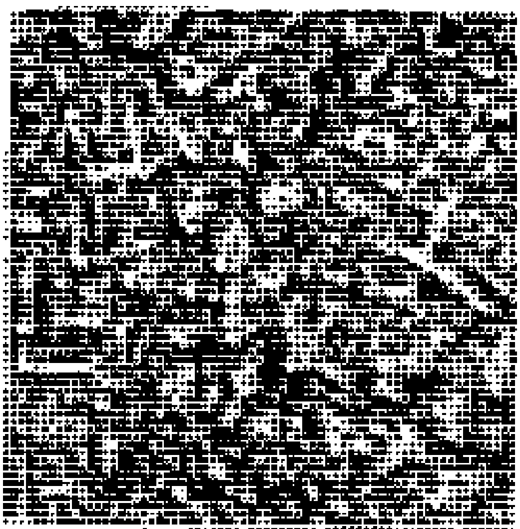


Fig. 20 Microstructure of sand cast α-brass x 1000

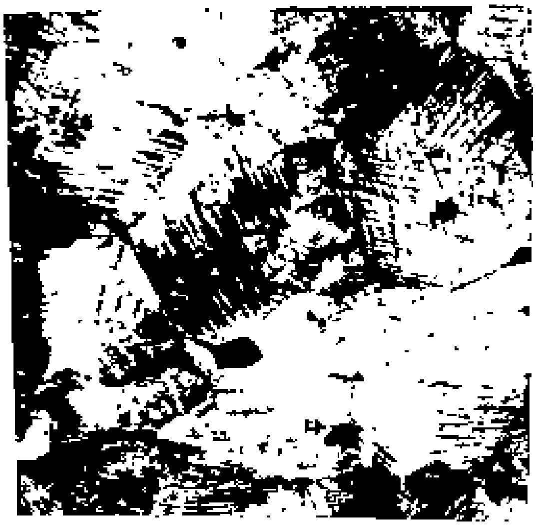


Fig.21 Microstructure of centrifugally cast α-brass solidified at mould temp. 20oC, annealed condition x 1000

Fig.22 Microstructure of centrifugally cast α-brass solidified at mould temp. 150oC, annealed condition x1000

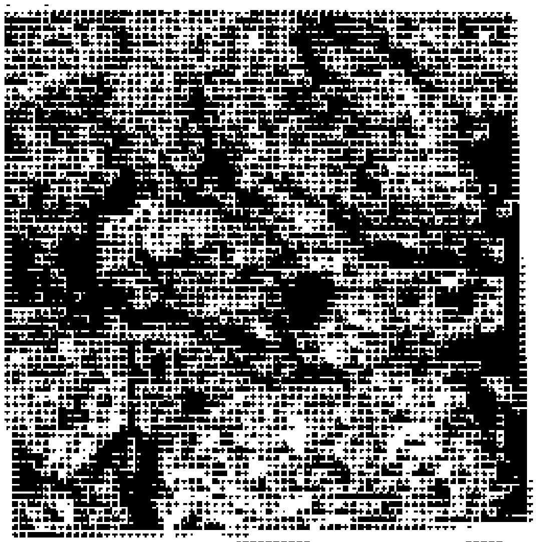


Fig. 23 Microstructure of centrifugally cast α-brass solidified at mould temp. 400°C, annealed condition x 1000

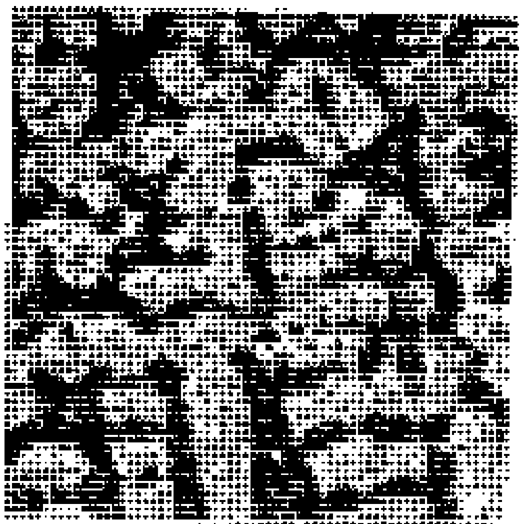


Fig. 24 Microstructure of sand cast α-brass, annealed condition x 1000

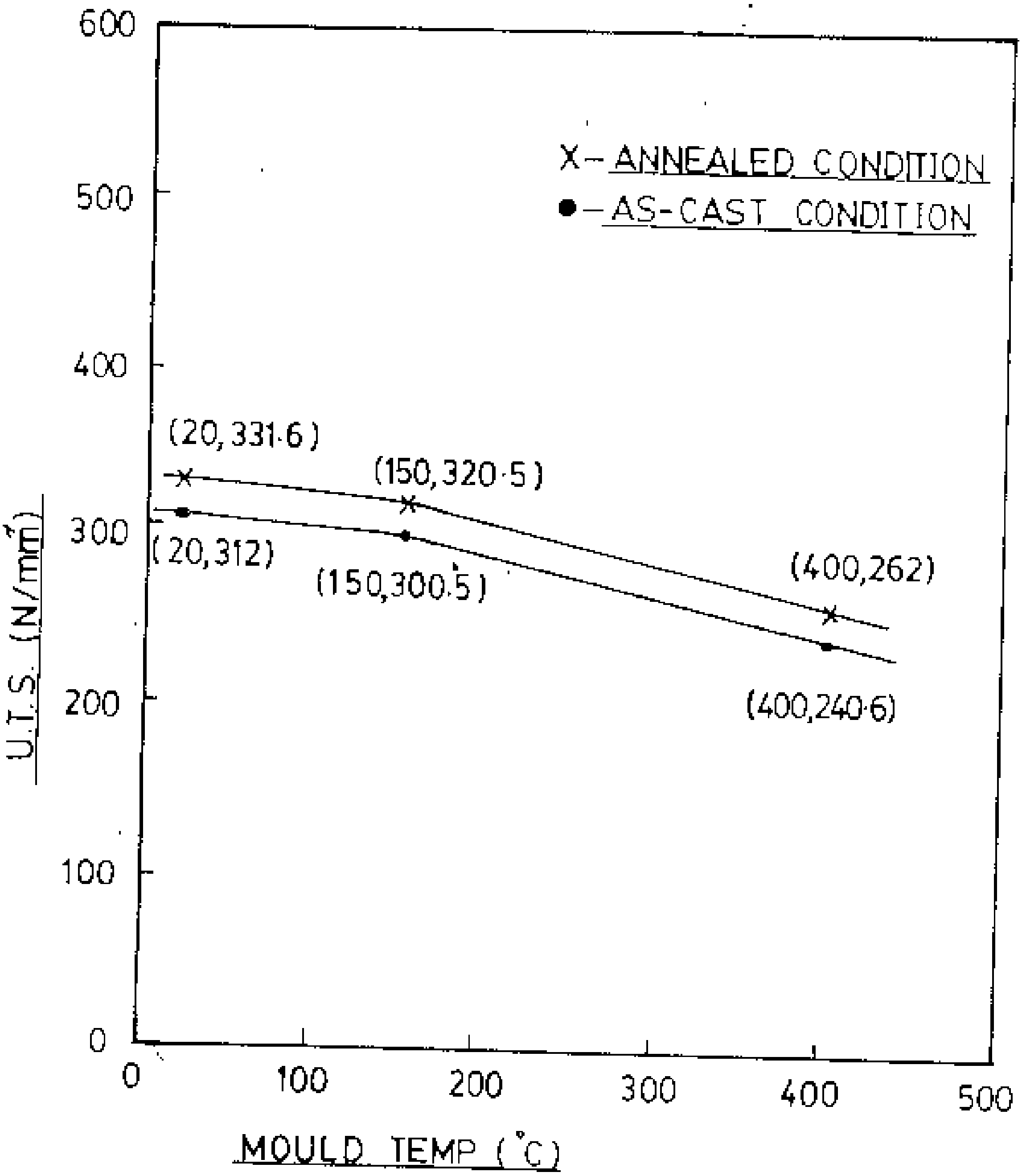


FIG. 25 : COMPARATIVE U.T.S. STUDY OF α-BRASS BETWEEN AS-CAST CONDITION AND ANNEALED CONDITION

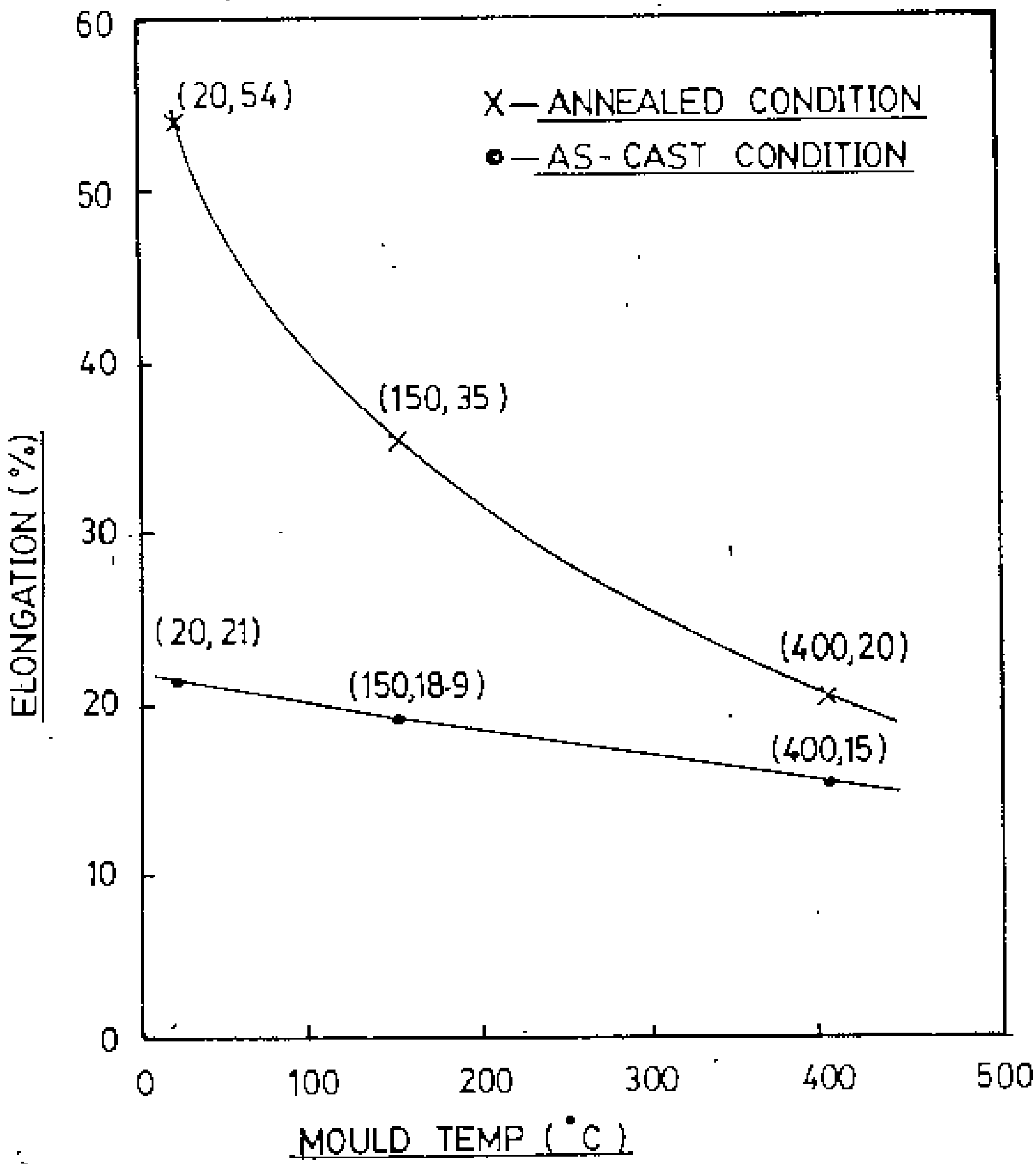


FIG. 26: COMPARATIVE ELONGATION (%) STUDY OF α-BRASS BETWEEN AS-CAST CONDITION AND ANNEALED CONDITION

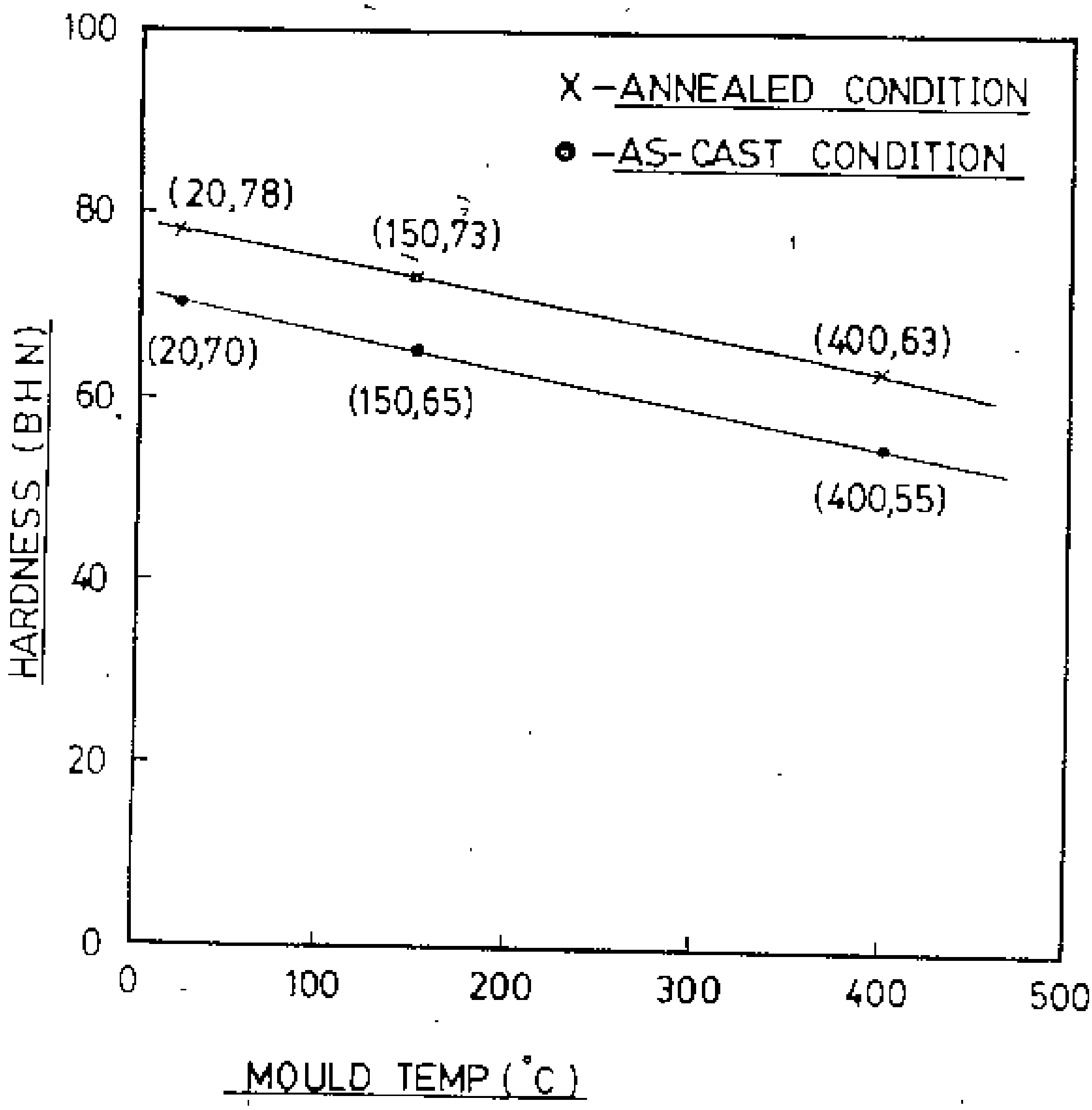


FIG. 27 : COMPARATIVE HARDNESS STUDY OF α-BRASS BETWEEN AS-CAST CONDITION AND ANNEALED CONDITION

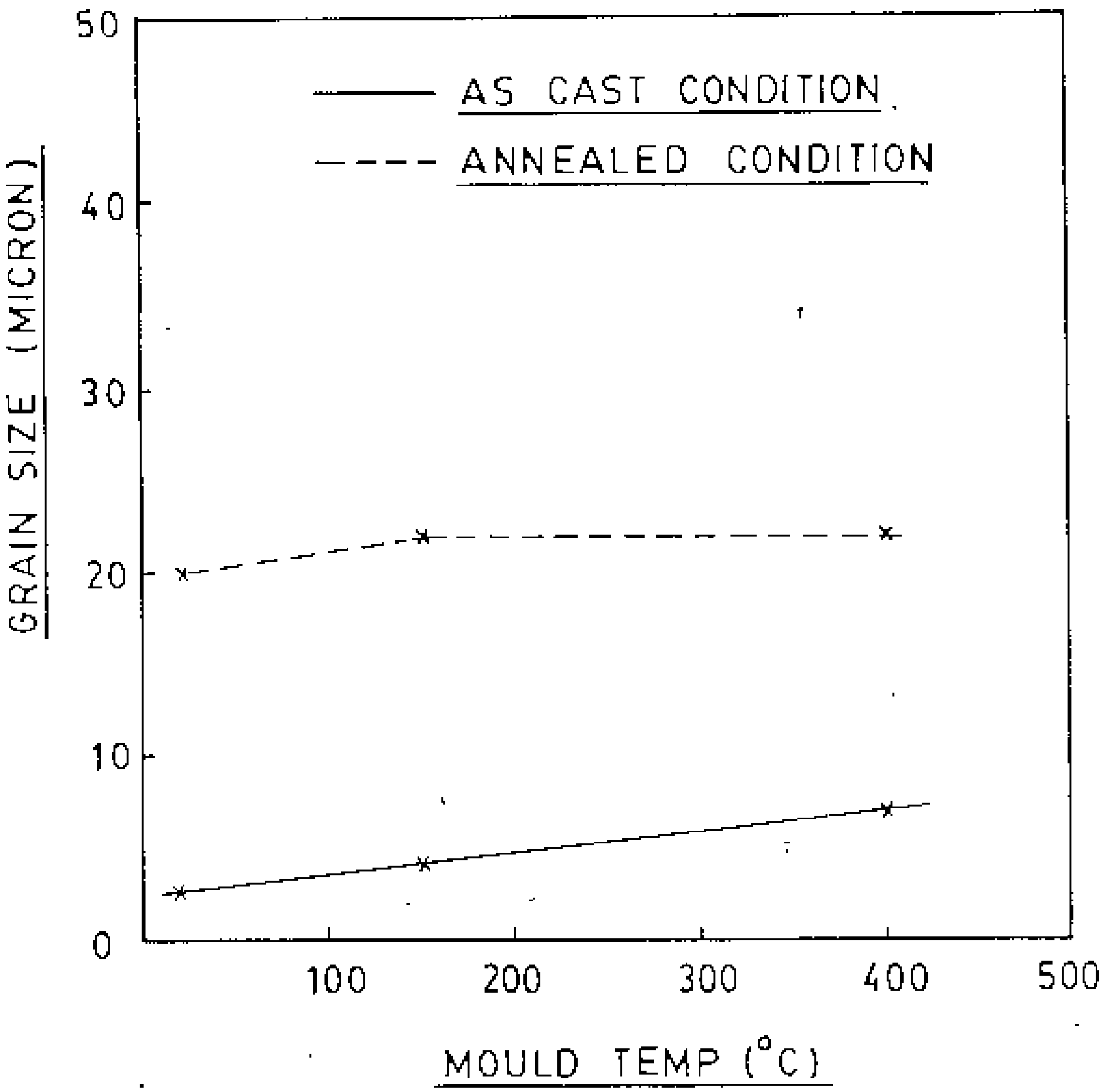


FIG. 28: RELATION BETWEEN GRAIN SIZE AND MOULD TEMPERATURE

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