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An Investigation into the Effect of the Application of Sub Sonic Vibrations during the Period of Solidification of Castings with particular reference to a Material for Gas Turbine Blades - 'H.R. Crown Max'

-by-

S. Hinchliff, D.C.Ae.,

and

Josiah W. Jones, M.Sc., F.I.M.

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SUMMARY

The report considers the theoretical relations between microstructures of castings and their mechanical properties and the possible effects and advantages of vibration during solidification; the design of a melting furnace and a mechanical vibrator to be used together, and the use of sillimanite bonded with Ethyl Silicate as a material for moulds to withstand vibration.

It is concluded that the process of vibration gives a smaller and more equi-axed crystal grain structure and that the expected improvement in mechanical properties is realised. These changes for castings of H.R. Crown Max poured at a temperature of 1,550°C and a frequency of 48 v.p.s. and an amplitude of 0.005in. are as follows:

	Non vibrated	Vibrated
Ultimate strength t.s.i.	37.2	43.2
Elastic Limit	16	21.5
Elongation per cent	33	41
Reduction in area per cent	27	36
Balanced Impact ft.lbs.	9.6	13
Grain Size (grains per sq.cm.)	3	15

Both amplitude and frequency are contributory factors, but the latter is more important.

MEP

CONTENTS

1. Advantages and Limitations of the Casting Process

With the exception of small and simple shapes which lend themselves to quantity production in automatic machines, there is no method of manufacture so attractive to the Production Engineer as Casting. Very intricate shapes can be made without joints and close dimensions often obtained which require little final machining. Particularly is this advantage true of die casting, lost wax or precision casting and only to a less extent true of shell moulding processes. Mechanical properties tend to be the same in all directions. Castings are produced in a range of sizes and weights from a shoe buckle of less than one ounce to large castings in steel of a hundred tons.

The demands of the aircraft industry for blades for compressors and turbines are likely to run into millions per annum and make an urgent economic demand for production of quantities. While it has become possible to use castings for stator blades, the combined stresses present in the rotor blade and the danger to the engine from failure of blade has necessitated the use of machined forgings, since castings do not at present possess the required properties, in particular fatigue strength.

Some materials, such as cast iron, alloys of magnesium and zinc alloys, have 'good casting properties', while others like steels and some alloys of aluminium do not have these properties to the same degree. These qualifications should include a low melting point, fluidity in the liquid state, a minimum change of volume during solidification and cooling, and a relative freedom from dissolved gases or inclusions. Castings, however, are traditionally low in mechanical properties compared with forgings, especially in impact and fatigue strength. These limitations are inherent in the microstructure produced by the mechanism of the solidification of the metal.

It will be helpful to explore the reasons for the greater strength of forgings and so point the way to technical processes which will confer similar superiority on castings.

2. The Microstructure of Castings

2.1. Comparison of structure and properties of castings and forgings

There is a long established tradition that forgings are stronger than castings and it is true in spite of the fact that, with the possible exception of wrought iron, all forgings are made from larger castings. The forging operation is said to break up (or break down) the cast structure and so produces a uniform matrix of small crystal grains in the finished forging. There are few industrial examples of the same alloy being specified both as a casting and forging but 'Y' alloy is such an example and the difference of properties is of interest. Both sand casting and forging are in the heat treated condition.

'Y' Alloy. Composition: Copper 3.5/4.5, Magnesium 1.2/1.7,
Silicon 0.6, Iron 0.6, Nickel 1.8/2.3.

	Tensile Strength tons per sq. in.	0.1% Proof Stress tons per sq. in.	Elongation % (2in.)
L.24 Casting Sand	14	13	1
L.25 Forging	24	14	15

This difference in mechanical properties is clearly a matter only of the arrangement of the microstructure since the chemical composition is the same in both cases. The microstructure of forgings in all alloys tends to approach that of the ideal structure which is associated with the highest mechanical properties for the material, the structure is uniform and has a matrix of small equi-axed crystal grains (Fig. 1). The lower mechanical properties are associated with a type of microstructure which is common to all castings, (Fig. 2).

Careful examination shows three types of crystal grains which vary considerably in size. Around the edge is a skin of very small crystals which have solidified quickly against the relatively cold wall of the mould. Next to these are long narrow and relatively large columnar type crystals and finally filling the centre are smaller equi-axed or spheroidal type of grains (Fig. 3).

Crystal grains grow rapidly when there is a critical gradient of temperature between the solid and liquid metal. In fact large single crystals are made by using this controlled technique. The casting, consisting of a relatively cold mould wall and a hot liquid metal, produces these conditions of gradient of temperature from outside to centre. As a general principle small crystals are produced by rapid cooling and large ones by slow cooling. Hence in most castings there are the conditions to produce the three zones of crystal size mentioned above.

2.2. Microstructure and Mechanical Properties

Under stress the resistance to deformation of the casting depends mostly on these large columnar crystals and the reasons for the strength or weakness of this structure justifies some detailed examination.

A large grained structure is always of much lower impact value than a small grained, and if the grain size is very large, tensile strength may be lowered at ordinary temperatures. When in a casting there is a sudden change in direction of section, the effect on the structure is to accentuate the weakness. This effect is shown in Fig. 4 as the typical corner structure of a cast ingot.

The strength of a metal is dependent not only on the crystal grain size but even more on the condition of the grain boundary between the grains. It has already been stated that increase of size of crystal grain will lower impact value but a factor controlling both tensile strength and impact is the condition at the grain boundaries. Impurities often have lower melting points and are mechanically pushed forward to the region of final solidification by the solidification process, or are precipitated from solution at the grain boundaries. Gas, causing blowholes, appears there for the same reasons and if the material has a relatively large specific change of volume with temperature, there will be a state of stress or actual discontinuity between the grains, so that grain boundaries in castings can be local areas of weakness (Fig. 5).

The effect of forging at high temperatures is to deform the grains and break up the grain boundary network so that adjacent grains diffuse into each other and impurities are distributed both inside the grains and in local agglomerates in the grain boundaries. The total effect of this change of structure is that grains tend to become smaller, equi-axed in shape and having a continuous metal phase across the section. This structure is similar to the ideal structure already shown in Fig. 1.

The cast structure may be compared with a loosely fitted mosaic of large pieces and the forged structure to a closely packed structure of small interlocking pieces. The reason for the higher strength of the forging is clearly demonstrated.

2.3. Modification of Cast Structures

The problem for the foundry man is to overcome the thermal conditions which promote the cast structure and approach the small uniform structure of the forging. The first condition is to reduce the time of solidification to a minimum by pouring at the lowest possible casting temperature to exclude as far as possible impurities and gases, and to arrange the mould materials to control rate and direction of solidification. Every artifice of the pattern maker to control and make uniform the rate of cooling and science of the metallurgist to control the temperature of pouring and the content of gas in the metal have failed to produce a casting with the properties of a forging of similar shape. Considerable progress has been made by these techniques but every new casting tends to be a triumph of hope over experience and the final result of many experiments. A casting technique which would promote a uniform microstructure would tend to remove these limitations.

When these thermal methods have been exhausted, some form of agitation of the solidifying metal has always proved helpful. Centrifugal casting, when the mould is rotated, is used for steel, cast irons, and bronzes and produces a small uniform structure with the expected improvement in mechanical properties. The mixing effect of the movement is considered to make the conditions of temperature more uniform and so decreases critical gradient of temperature and it is thought that the movement of the solidifying liquid breaks up the dendritic axes as they form, so decreasing the size of the crystal and removing the long narrow columnar crystals and substituting for them a uniform structure of small grains.

Peterson and Wahl[1] pointed out an interesting possible relation of fatigue and grain size. They postulated that in a small notched specimen of fine grained steel a crack, progressing from a surface stress raiser, would traverse several grain boundaries before it got beyond the area of high stress at the bottom of the notch. The crack would want to take up a direction perpendicular to the principal stress, and when it found a crystal suitably orientated, it would get such a start that it could cut across the crystal boundary; but if it were forced to zigzag more without finding suitably orientated cleavage planes, its progress would be hampered. Thus, the more crystals there are over a given distance, the better the chance there would be of finding one with a suitably orientated cleavage plane. Several papers have been written concerning grain size and fatigue strength, (refs. 2 and 3).

The creep behaviour of a material is influenced by both the inherent properties of the crystals and by the properties of the crystal boundaries, although in different ways. At high temperatures, i.e. high for a given material, the crystal boundaries are normally primarily responsible for creep, while at lower temperatures, the boundary is much stronger than the crystal. Consequently, in general, at elevated temperatures a coarse grained material will be more resistant to creep than a fine grained material. Experimental evidence with various metals has tended strongly to support this statement.

2.4. New Process of Vibrating the Casting During the period of Solidification

A few efforts have been made to vibrate large ingots but no established practice has developed. There is no record known to the authors of small castings being subjected to sub-sonic vibration during the solidification of the metal. It was felt that such vibration may be more uniform and promote more effectively the effects already associated with centrifugal casting. It is thought that the equipment and operation would be simpler and that the process could be extended to most products of the foundry. If the mould is vibrated during the pouring and solidification period, then the columnar crystals will either be broken up as they form or prevented, to a certain degree, from forming because of the agitation of the liquid metal. The dendrites themselves may move relative to the surrounding melt, because although the acceleration produced by the vibration is constant at any one time, the dendrite as it forms becomes heavier than the adjacent particles, and if this relative motion does occur, then the dendrite will experience difficulty in growing along a definite crystallographic plane, or even fracture. Also the critical temperature gradient from the mould face to the centre of the melt should be lessened and, therefore, a larger percentage of the molten metal will reach the liquidus temperature at the one time. Consequently, a larger number of smaller equi-axed crystals might be formed.

Any inclusions in the liquid metal should by the agitation be forced to the surface, but this may be a disadvantage if there are pockets in a complex casting where foreign matter collects and may be trapped. The majority of turbine blades are, however, cast vertically and undesirable particles should therefore be forced upwards into the runner.

Probably one of the biggest disadvantages of cast blading is porosity which is likely to be present in any casting. In this respect vibration may help by packing down the metal, and by the agitation keeping the liquid metal in a state of movement. Ultrasonic vibration has already demonstrated that gases may be removed from liquid metals by this mechanism. Gases not removed would be converted to smaller masses and distributed more uniformly, thus decreasing the tendency to reduce mechanical strength.

3. Choice of Test Casting and selection of test pieces to Examine the Mechanical Properties

The immediate interest of the research was the production by casting of a gas turbine blade with all the properties required by design, and equal at least to a forging of the same material. The choice of an actual turbine blade as a test casting was difficult in that from a large selection of actual blades there was such considerable variation in dimensions. Some examples are shown in Fig. 6. They have been macroetched to show the presence of the long columnar crystals already discussed. It was decided finally to simplify the shape and use a wedge type pattern with dimensions approaching an average for width and thickness of actual blades examined. The design is shown in Fig. 4 and a photograph of an actual dummy casting indicating the position from which test pieces were taken in Fig. 8. A 5/16in. diameter balanced impact test piece was taken $2\frac{1}{2}$in. from the round end of the runner and Houndsfield No. 11 test pieces adjacent to it.

4. Methods of Vibration

4.1. Nature of Vibration Required

(1) Frequency should be variable from zero to at least 100 v.p.s., the top limit being somewhat arbitrary, but dictated to some extent by the large powers which would be necessary to vibrate the weight of the mould, its contents and fixities, especially if any appreciable amplitude was to be attained.

(2) Control of amplitude should be possible, and although a large range was not thought to be necessary, at least a constant amplitude for a series of tests should be possible.

(3) The mode of vibration should be approximately sinusoidal and vertical.

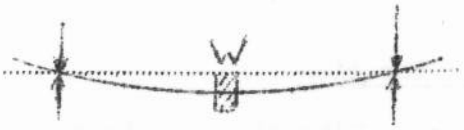
It was decided to try to vibrate at or near resonant frequency. This condition meant that the frequency range would have to be not only variable, but infinitely variable in order to pick up resonance.

Probably the easiest way of producing a resonant frequency is by exciting a beam, the loading and supporting conditions of which are known, and a simply supported beam with a central load was utilised, the central load being made up of the mould and some means of securing it, and of the vibrator itself.

A vibrator in the form of two contra-rotating gears half submerged in oil, each gear having identical off-balance weights was available. The off-balance weights were so placed that all except vertical forces were balanced. An ordinary A.C. motor with an infinitely variable arrangement of pulleys and belt was used. On turning the handle a worm gear opens out or brings closer together the two discs forming the larger pulley, thus causing the belt to ride up or down and so varying the speed of the driven pulley. At the same time the motor itself moves on the curved slide rails and so keeps the belt tight.

4.2. Calculation of Resonant Frequencies

The following method of calculation is simplified and some assumptions are made, but they are justified since the information obtained is indicative only of the size of beams required, and the frequencies quoted upon vibrating are figures actually measured.



Let y = deflection under load W at time t
and e = load acting at W which will produce unit deflection at W.

Then the restoring force when deflection is y, is $-ey$
Therefore the equation of motion becomes

$$-ey = \frac{W}{g} \cdot \frac{d^2y}{dt^2}$$

or

$$\frac{d^2y}{dt^2} + \frac{ge}{W} y = 0 \quad \text{which is Simple Harmonic Motion}$$

and the frequency N is $\frac{1}{2\pi}\sqrt{\frac{ge}{W}}$ v.p.s.

or $\frac{60}{2\pi}\sqrt{\frac{386}{\Delta}}$ v.p.m.

$= \frac{187.8}{\sqrt{\Delta}}$ v.p.m. where Δ is the static deflection in inches.

This calculation does not take into consideration the weight of the beam itself, but the effect of the mass of the beam is so small compared with the concentrated central mass that it can safely be ignored.

From the theory of bending, the deflection for a central mass is $Wl^3/48EI$ where l is the length of the beam.

Therefore, for this case

$$N = \frac{187.8}{\sqrt{\frac{Wl^3}{48EI}}} \text{ v.p.m.}$$

W, l and E are known, therefore the beam section can be calculated for a required frequency; alternatively, assuming a beam section, the natural frequency may be determined.

5. Foundry Practice

5.1. Type of Furnace

The furnace and pouring practice for gas turbine materials has reached a standard practice. An electric arc furnace is used to melt the alloy. The mould prepared from a mixture of Sillimanite and Ethyl Ester slurry is dried, fired and while at a temperature of about 1000°C fixed into the top of the furnace with top hole and runner in a suitable position. The furnace and mould are rotated to transfer the metal from the furnace to the hot mould. To use this technique and to vibrate the mould, it would be necessary to have available power to vibrate the whole structure of the furnace and the mould.

It was necessary to design a new arrangement with the vibrator and mould mounted at the side of the furnace. The trunnion tilting the furnace for pouring was moved to the outside adjacent to the mould so that as the furnace was rotated the pouring lip came into position immediately over the runner of the mould.

After many experiments, beginning with an open crucible in a furnace body of rammed Mag. chrome refractory, it was found that the high temperatures of 1600°C for pouring could only be attained and maintained by conserving all available heat: the type of crucible already extensively used, with closed in top and apertures only for feeding, pouring and inserting the two carbon arc rods was used. This crucible was mounted in a rammed body in such a way as to leave as much air gap as possible between crucible and furnace body. Experience had shown that Mag. Chrome refractory tended to decrepitate in use and the outside was built up with insultation brick and then filled with an aggregate of sillimanite cemented with

Sillimanite and sylester slurry. The aggregate was made from crushed mould material which is described later. The final general arrangement is shown in Fig. 9.

5.2. Material of Castings

H.R. Crown Max was chosen because of its almost universal use in the Gas Turbine field. It possesses very good strength at elevated temperatures and is used for such items as compressor and turbine blades, superheater supports, etc., and in fact anywhere where ability to withstand high stresses at prevailing high temperatures is of importance and a casting is required.

This material, which is non-magnetic, is a highly alloyed chromium nickel steel with an addition of tungsten. It has a good resistance to scaling and has good strength up to 1050°C.

A typical analysis is as follows:-

C	0.20,	Si	1.60,	Mn	0.40,
Cr	23.00,	Ni	11.50,	W	3.00.

It has an S.G. of 7.90 and in the heat treated condition has a yield stress of 30 tons/sq.in., with an elongation of about 30 per cent and a hardness of 220 Brinell.

The steel is normally produced in bar form and can be obtained to meet the specifications D.T.D. 282, and B.S. - En.55.

Both welding and casting properties are very good.

Before any investigation proper was made into the casting characteristics of Crown Max using semi-permanent moulds, it was thought that a preliminary investigation using existing foundry equipment would be useful. It was hoped to establish the solidification temperature by the normal cooling curve and to observe the casting properties of the metal under normal foundry conditions.

In both cases the metal was melted in a crucible in the coke fired furnace using forced draught. In order to arrest the cooling somewhat for the establishing of the solidification temperature, the small crucible containing the melt was placed in a pre-heated larger one. Temperature was read using a Platinum Rhodium thermocouple protected by a Silica sheath, and at the arrest point the indicator read 1400°C.

Two experimental wooden wedges were used as a pattern for the preliminary cast in green sand. They were cast horizontally and provided with a central runner. Prior to pouring, the sand moulds were heated by blow-lamp as much as possible.

Apart from gaining experience in the making of micro and macro specimens, little was gained from the casting itself, which solidified almost instantaneously upon entering the mould, thereby exhibiting pronounced cold shut, very little shrinkage and some porosity.

5.3. Materials for Moulds

Foundry sands dependent for their strength on wet clay would not, even in the dried state, be strong enough to resist vibration. It is more than doubtful if oil bonded core sands would resist the tendency to decrepitate, so a much stronger material must be found. The existing practice for precision casting would appear to provide the answer and allow all the advantages of the use of a heated mould so that the metal would run into thin sections. Basically the mould is simply a ceramic filler bonded with Amine Modified Ethyl Silicate.

Ethyl Silicate is a fairly recent innovation in the foundry world, and it is used as a binder for intricately and accurately shaped moulds of ceramic materials. It is used extensively in precision casting. At one time its use necessitated a close chemical control, but with the introduction of Amine Modified Ethyl Silicate, the usage has been considerably simplified, hydrolysis and subsequent gellation being brought about by the introduction of industrial methylated spirits. The liquid is an organic silicate with about 40 to 43 per cent silica content, and when it is fully hydrolysed a chemical reaction commences which results in the formation of an adhesive gel. When the hydrolysed liquid is mixed with a ceramic filler the result is a mould with sufficient green strength for handling. Heating reduces the gel to a finely divided amorphous silica which binds the particles of the filler together. Further heating to a high temperature permits inter-crystalline growth between the silica and filler and gives greater strength and thermal properties.

Hydrolysis is brought about by the addition of a solution with a water content of at least 2.5 per cent to cause gelation. Water is introduced through the medium of methylated spirits, a mutual solvent, and although the water content can be as high as 25 per cent, 15 per cent can be considered the top workable concentration for daily use. Emulsified Amine Modified Ethyl Silicate and water would gel (the two are not mutually soluble), but removal of the water afterwards would give rise to considerable difficulty. Alcohol is more easily disposed of, and during its expulsion it opens pores which also allow the escape of water in the form of steam.

Gel times can be accelerated or decelerated by varying any one of the following parameters:

1. Proportion of Silester A (Amine Modified Ethyl Silicate) to T.W.C.A. (I.M.S. and Water)
2. Temperature.
3. Percentage of T.W.C.A.
4. Ageing of Silester A.

The filler formulation used, except where specifically stated as otherwise, was -

P.B. Sillimanite	-30 + 80 grade	50	per cent by weight
	100 CML '	35	' ' ' '
	FF '	15	' ' ' '

and 1 lb. of filler to 75 ml. Silester A and 15 ml. 15 per cent T.W.C.A.

5.4. Type of Mould and Method of Production

Pattern preparation was found to be of the greatest importance to ensure a good mould with a good finish. Excellent moulds with an extremely good finish were made when sufficient attention was paid to the pattern preparation. In this case the patterns used were of light alloy, but there is no reason - apart from the extra time involved - why wax patterns should not be used. On occasions, machining marks on the patterns were faithfully reproduced.

A preparation of vaseline and paraffin mixed into a sloppy jelly was spread very thinly over the parting surfaces by hand, and then the pattern was warmed slightly so that the jelly ran and made its own surface. The mould boxes were then bolted down and the patterns placed onto a vibrating table ready to receive the slurry.

The following steps were found to give the best results and the method is recommended:

1. Weigh out the necessary amount of filler carefully in a large, clean container such as a zinc bucket.
2. Mix the filler thoroughly in the dry state to ensure even distribution of particle size.
3. Measure out the requisite amounts of Silester A and T.W.C.A. in separate flasks; when ready, mix together and pour into the filler a little at a time.

4. Hand or machine mix the liquid into the filler and make sure all the sand particles are wetted. Avoid a sloppy paste, the mix will begin to find its own level under the influence of vibration.

5. Put the mix into the mould boxes and vibrate immediately. Gelation should occur in about ten minutes; just before it does, however, switch off the vibrator and cover the top of the mould.

6. Let the mould stand for half an hour before the pattern is removed. Leave the mould in its green state overnight.

7. Heat treatment is to heat slowly up to 200°C over a period of four hours, and then to heat to 600°C in half an hour. There is no reason to hold the mould at 600°C, but if the furnace can be switched off and the mould left inside, the chances of distortion occurring are lessened.
Finally, the moulds should be fired at at least 1000°C, this can occur at any time after drying and normally the firing was done just prior to casting. The final heating can be much more rapid, and the length of soak should be sufficient to ensure that all the mould has attained a uniform temperature.

5.5. Development of Moulding Technique

Two types of mould were used during the experimental period when the preliminary ten casts were made; a two part mould for pouring a wedge horizontally, and a one part mould for pouring a wedge vertically.

At first a drying period of 200°C over four hours and firing at 1000°C+ was used as the heat treatment process, and moulds made in this manner were very good.

It was hoped that the silimanite mould would form a semi-permanent mould which could be used several times. When tried with an alloy of aluminium, this was the case but not with H.R. Crown Max. The mould itself was very sensitive to the conditions of manufacture. The details on p. 13 must be carefully followed but the mechanical operations must be found to be suitable and controlled. The proportions and sizes of graded silimanite are important especially to prevent large cracks and fractures on drying or fine hair cracks which reduce mechanical strength and could fracture on handling. The mixing must be very well done but the time for this operation is limited by the gelling time of the mixture. With the drying of the split mould, where each half of the mould weighed about 5lb., the drying period of 4 hours was found to be sufficient, but with the larger mass (10 lb.) of the one part mould the drying period had to be extended to 6 hours.

A certain amount of trouble was experienced with the formation of a white ash on the mould surfaces after firing which gave the resultant castings an appearance of surface porosity. This was found to be the incomplete hydrolysis of the Ethyl Silicate, and was overcome by carefully checking the water content of the 15 per cent T.W.C.A., (there should be an S.G. reading of 0.849 at 15.5°C) since 1 part of 15 per cent T.W.C.A. to 5 parts of Silester A introduces the absolute minimum water for complete hydrolysis. If there is any discrepancy, the error should be on the plus side for water. The white powder itself was extremely fine silica which had not been fixed in the filler.

Another way of dealing with this problem was found in the introduction of an intermediate stage in the heat treatment i.e. after drying, a further heating up to 650°C fairly slowly before firing. In the case of split moulds the white powder could be brushed or blown off with compressed air.

The main problem as far as the moulds were concerned was the tendency of the mould face (sillimanite) to slag with iron oxide, thus rendering the surface unsuitable for a further cast as far as accuracy and surface finish were concerned, although more than one cast could be made with one mould if the two factors mentioned were not of primary importance.

A solution to this problem was sought in the use of a facing to the Sillimanite mould. Mould washes in the form of Ethyl Silicate paint were experimented with and the use of colloidal graphite explored, and although each preparation lessened the amount of slagging, neither could be regarded as satisfactory. Finally, a facing of Zircon was used. Zircon in the form of a fine sand or an extremely fine flour contains Zirconium, Titanium, Iron and Aluminium Oxides and Silica, and has a melting point at about 2190°C. It is used in the lost wax process as a mould dressing. At first the use of Zircon showed great promise. A facing 1/4in. thick on a sillimanite mould showed little change after one cast, except for a honeycomb of minute hair cracks. Another cast was made, but this time, although the casting was satisfactory, the Zircon face broke away from the mould along the hair cracks which appeared after the first casting. The experiment was repeated several times and was also repeated using varying thicknesses of facings, including a Zircon spray. But at the best, only two completely satisfactory castings could be made, and this with the thicker facings.

A complete Zircon mould was also experimented with, but here the strength of the mould proved to be unsatisfactory, breaking even with the comparatively light pressure necessary to keep the two halves of the mould together to prevent a 'run out'.

Having reference to the photograph, Fig. 10,

(A) A vibrating table for packing down the slurry. Constructed largely of wood, the table top rests on four strong springs. Fastened underneath the table is a pneumatic hammer which knocks up against a metal plate fixed to the table top. The frequency of the blows is governed by a pressure reducing valve not shown in the photograph, but it was found that the best pressure to work on was the maximum available, i.e. 100 lb./sq.in.

(B) Both halves of the split pattern are in place and ready for the mould boxes to be bolted down. The patterns are made from Aluminium Alloy and have a fairly good surface finish. It was found that the first few moulds did not fit together correctly, due to spring-back of the patterns after machining, consequently, they were backed with heavy steel plates and bolted down flat.
Wedge size on the patterns was largely dictated by the necessity for at least one balanced impact specimen and two No.11 (Hounsfield) tensile specimens.
The patterns are dowelled to opposite hand for location purposes, and the slope on the runner is to facilitate casting removal.

(C) Mould boxes.

(D) The vertical one piece mould which was used to demonstrate that with an advantageous pattern design, excellent reproduction in shape was possible.

(E) Mould box for the vertical mould.

(F) A pair of horizontal moulds which have been dried and are ready for firing.

(G) Set of scales for weighing the filler.

(H) Measuring cylinders and supply of 15 per cent T.W.C.A. and Ethyl Silicate.

(I) Compressor capable of sustaining 100 lb./sq.in.

6. Melting and Pouring Techniques

6.1. Measuring and Controlling Temperatures of Metal and Mould

The temperature of the liquid metal, the rate of pouring and the temperature of the mould are all very critical and the minimum mould temperature (i.e. 1000°C) should be exceeded at the moment of pouring. The pouring spout was preheated with a blowlamp in order to avoid chilling the metal. A disappearing filament type pyrometer is very satisfactory if it has been carefully calibrated against a platinum platinum 3 per cent Rhodium in the exact conditions of the operation. If there is any loss of temperature in metal or mould the casting will form a cold shut in the thin section. Temperatures which are too high cause some fusion of the surface of the mould. Feeding of the casting tends to be poor since the top of the runner will chill and solidify and a deep pipe appear at the top of the casting. A blow pipe flame played on the top of the runner will help to retard the freezing of the runner.

6.2. Description of Apparatus (see Fig. 11)

A portable transformer (A) controls the power to the carbon arc furnace. Voltage is constant at 80, but the current can be varied in steps by adjusting the two handles. The arc is struck by manual manipulation of the carbon rods (B).

When heating the mould, the quickest method was found to be to allow the flame to play directly onto the faces for a time and then fit the mould together for a final 'soak'. With both furnace and mould initially cold, the time necessary to bring the mould to a temperature ready for casting is in the region of an hour.

On removal from the furnace the mould (D) is placed on the table (E) and clamped down, and then the various operations, (temperature readings, carbon removal etc.,) prior to pouring are carried out. Since these operations had to be carried out largely single-handed, it can be appreciated that heat loss in the mould gave rise to a certain amount of concern, but this was overcome by the use of a heat-loss-time graph (Fig. 12), which at the same time eliminated the reading of mould temperature.

Also shown in Fig. 11 are the two pyrometers in position, (K) a platinum-rhodium thermocouple attached to the sensitive potentiometer (H), and (M) achromel-alumel thermocouple attached to the ammeter (G).

(F), (I) and (J) respectively are the vibrator, the flexible drive and the table upon which is mounted the variable speed motor.

In order to vibrate the table holding the mould, it has previously been mentioned that the table is supported centrally on a beam. The apparatus and the method of suspension can clearly be seen in Fig. 13. The beam is clamped at each end between rollers so that line contact is maintained, and the ends of the beam can be regarded as being pin jointed. Measurement of Amplitude can be made by using a clock gauge rigidly fixed to an independent mounting. Frequency was checked with a stroposcope.

7. Programme of Work

Having developed the equipment to the point where castings could be made with reasonable facility and where temperature control of both mould and melt was adequate, it was decided to make a series of six casts at different temperatures in order to investigate the effect of pouring temperature on mechanical properties, and so obtain basic curves for purposes of comparison with curves from castings vibrated during solidification. No attempt was made to obtain perfect castings so long as minor defects did not interfere with the taking of the test pieces required. Castings after macroetching are shown in Fig. 14.

The test results are quoted in Appendix I, and their significance is discussed in Section 8.

7.1. Details of Castings Produced

With the results obtained from the castings which had not been vibrated, it was immediately apparent that temperature of pourings had a marked effect on the mechanical properties. In view of this, it was thought probable that the pouring temperature would still have an effect on the vibrated castings, and it might possibly be that such an effect would be different from that in the non-vibrated castings. Consequently, it was decided that the most comprehensive course to pursue would be to obtain a curve covering a range of casting temperatures for each alteration of frequency or amplitude. This, of course, meant that the number of castings required at each frequency and amplitude setting would be at least five times greater than if only one cast were made at each setting, after a choice of a fixed pouring temperature had been made. It was thought, however, that it would be much better to show a comprehensive trend, rather than to almost arbitrarily choose one particular set of conditions.

This point being decided upon, a set of castings were made using beams with a resonant frequency of about 25 and 50 cycles per second with two variations of amplitude for each frequency.

7.2. Examination of Macro and Microstructures

Each casting was etched so that the grain size could be measured. The etching reagent used was Aqua-Regia, a mixture of concentrated Hydrochloric and Nitric acids in a 3:1 ratio by volume.

An inflexible etching procedure cannot be quoted since the etching time varied considerably with the age of the reagent. With a new mix, an immersion lasting three minutes at a temperature of 35°C gave excellent results, whilst a reagent which had been used for about six macros and left standing for a few days etched satisfactorily only after an immersion of six minutes at 40 to 45°C.

Whilst etching, the fumes fiven off should be closely controlled since they are harmful to the more delicate membranes of the nose and throat.

The effect of casting temperature on size of crystal grain for both vibrated and static castings is shown in Fig. 16.

Whilst establishing a procedure for the etching of prepared micro specimens, several reagents were tried, and by far the most successful proved to be Acidic Ferric Chloride.

The best etching time proved to be quite short, only one minute, although successive tests indicated that over-etching did not take place for twenty-five minutes.

8. Discussion of Results

Generally speaking, the numerical results are very good and the amount of scatter is quite small, especially when it is appreciated that the tests are applied to a material in the 'as cast' condition.

With both the non vibrated and vibrated castings, no difficulty was experienced in obtaining test data, and from each casting one impact and two tensile (No. 11 Hounsfield) specimens were cut.

The effect of vibration on grain size is shown by the macro photographs in Fig. 15 and by the graph, Fig. 16, where grain size is plotted against pouring temperature. Reference to this graph will show that increasing frequency, rather than increasing amplitude, decreases the grain size. There is, however, a certain amount of scatter, and in practice the curves cross each other, whereas theoretically they should not.

From the graphs showing the influence of amplitude with constant frequency on mechanical properties, it can be seen that at the lower pouring temperatures the effect is not of much consequence, except, perhaps, on balanced impact, but at the higher pouring temperatures - and it is at these temperatures that blades are usually cast - the effect is quite marked. Why the balanced impact graph should apparently have an optimum value of 12.3 ft.lb. in this case is not quite clear, and it is thought that if, in the future, other casts can be made at a pouring temperature of 1520°C and with the frequency constant at 23 v.p.s., then the optimum value for the vibrated specimens might show an increase.

The graphs showing the influence of frequency are also very good and clearly indicate an increasing trend. Here again, at the lower temperatures, vibration does not appear to increase mechanical properties, with the exception of balanced impact. In fact, vibration appears to have an adverse effect on the ductility.

At the higher temperatures, however, and at the higher frequency, all the graphs show a marked improvement with vibration. Of special note is the big improvement of balanced impact at all pouring temperatures.

No significance can be attached to the different tensile specimens marked A and B, as far as the points plotted are concerned; each point is the average of the two specimens.

In the case of hardness, the results are scattered so widely that it is not possible to draw any curves whatsoever. The hardness numbers themselves varied widely over quite small areas, and for the results quoted, often as many as six readings had to be taken on one specimen in order to justify the recording of an average reading. Machine loads of both 10 and 30 kilos. were tried, but the results were the same.

For the sake of completeness, typical photo micro graphs of both vibrated and non vibrated specimens are included. It will be noticed that mould temperatures are not quoted in the results. This is because a range, rather than a specific temperature, was thought to be sufficient. All mould temperatures were between 1000 and 1030°C, and this was achieved by using the 'rate of heat loss' graph, Fig. 12.

9. Conclusions

The investigation into the effect of subsonic vibrations applied during the period of solidification of the Gas Turbine Material H.R. Crown Max, proved to be very successful, and it has been shown that by such an application the mechanical properties are generally improved.

It has further been shown that both the frequency and the amplitude of the vibrations are contributing factors, and that, of the two, frequency is the more important.

With the application of vibration, the grain size is considerably reduced.

A more detailed analysis of the results follows, and special reference is made to the pouring temperature of 1550°C, which is a temperature high enough to ensure the complete filling of complex moulds and thin cavities.

(1) Effect of Elongation

Elongation is improved at the higher pouring temperatures, and the highest value attained (41 per cent with a frequency of 48 v.p.s., an amplitude of 0.005 inches, and a pouring temperature of 1550°C) is an increase of 26 per cent of the value in the 'as cast' condition.

(2) Reduction of Area

The shape of the Reduction of Area curves are almost identical with those of Elongation, and the maximum improvement when vibrated is obtained under the same conditions. The increase is 33 per cent of the value in the 'as cast' condition.

(3) Balanced Impact

With the constant frequency of 23 v.p.s., increasing amplitude does not appear to affect the optimum value of Balanced Impact at a pouring temperature of 1520°C. At a pouring temperature of 1550°C, however, the Balanced Impact is improved by 10 per cent of the value in the 'as cast' condition.

Increasing frequency to 48 v.p.s. with constant amplitude increases the optimum value at 1520°C by 7 per cent, and at the pouring temperature of 1550°C the increase is 20 per cent of the value in the 'as cast' condition.

(4) Tangential Proof Stress

Both Frequency and Amplitude increase the proof stress, with frequency having the greater effect. When vibrating at 48 v.p.s. the increase in proof stress is 34 per cent of the value in the 'as cast' condition, at a pouring temperature of 1550°C.

(5) Ultimate Tensile Strength

Here again, the effect of vibration is more apparent at the higher pouring temperatures, and again the higher frequency of 48 v.p.s. gives larger increase in U.T.S., where at a pouring temperature of 1550°C the increase over the value in the 'as cast' condition in 16 per cent.

(6) Uniform Microstructure

These considerable improvements in mechanical properties are shown to be associated with the removal of typical columnar crystal structure and the substitution of a uniform equi-axed grain structure. Contributing to this relation of structure to strength there is doubtless a reduction in porosity and a more uniform distribution of the usual real segregation.

(7) Chemical Analysis

Except in the case of a single experiment when a piece of carbon rod fell into the melt and raised the carbon content to 1.53 per cent there was little change due to melting. The variations were

Carbon	0.19 - 0.24	per cent
Chromium	22.47 - 23.17	
Nickel	11.0 - 11.40	

(8) Advantages of the Process

The result was obtained without expensive alloying or very intricate and costly equipment. The type of equipment developed or other modifications of the out of balance vibrator are robust and can find a convenient place on a foundry floor.

It is important to note that the improved tensile strength is not attained by loss of ductility or impact value but all these properties are augmented.

(9) Limitations of Work

The effect of two frequencies only has been explored and the effect of pouring temperature is predominant. Further work to explore the effect of a range of frequencies at the best casting temperature is desirable.

While it is established that this type of vibration has improved the casting properties in this work, it is limited to one type of material and one pattern of fixed dimensions. Further work will need to be done to see if the principle is true for other materials and different sizes and shapes of castings.

10. Acknowledgements

The thanks of the authors are due to Professor J.V. Connolly, B.E.,F.R.Ae.S.,M.I.Prod.E., for suggesting the subject of the research and for his interest throughout the work, to Dr. T. Taylor, F.I.M. of N.G.T.E. for consultations and encouragement at the beginning of the work, and to Mr. B. Bagshawe of Firth Brown Ltd. for help with the chemical analysis of castings.

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APPENDIX I

DATA OF MECHANICAL TESTS, TABULATED AND PLOTTED.

NUMERICAL RESULTS

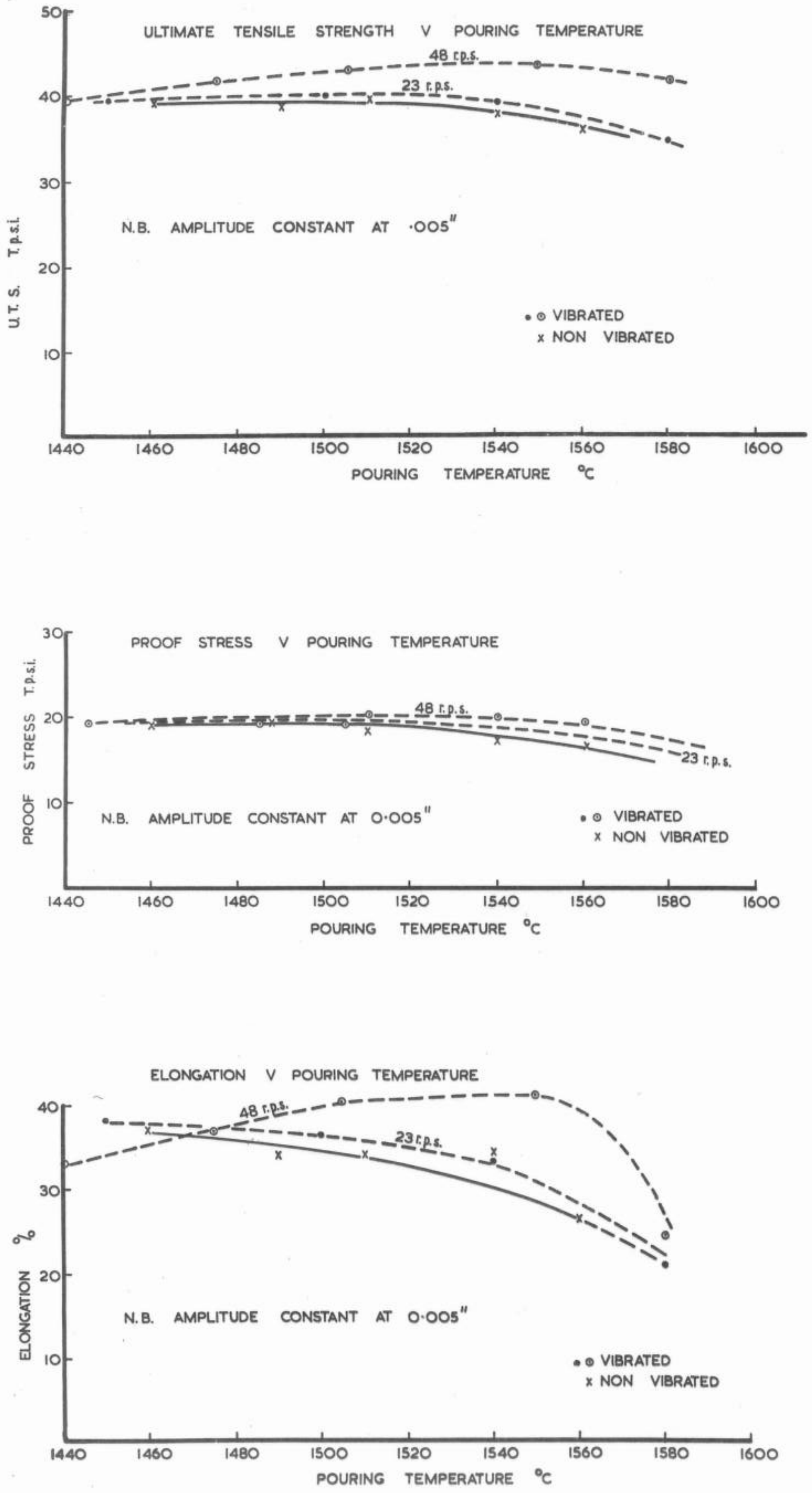
Specimen No.		Freq, Cy/Sec.	Amplitude in.	Pouring Temp. °C.	Grain Size No/ sq.cm.	U.T.S. T.p.s.i.	Elastic Limit	Elong'n %	Reduction of Area %	Balanced Impact ft.lb.	Hardness V.P.N.	REMARKS
1	A	Nil	Nil	1460	28	39.0	18.6	38	35	5.5	173	Normal Fractures
	B					39.0	19.3	36	35			
2	A	'	'	1540	30	38.0	16.8	34	30	11.6	161	' '
	B					37.2	17.5	34	33			
3	A	'	'	1560	2	35.3	16.0	28	20	10.0	165	' '
	B					35.8	16.5	25	20			
4	A	'	'	1490	8	39.2	19.5	35	40	8.0	179	' '
	B					38.5	19.6	32	37			
5	A	'	'	1510	6	39.7	18.0	35	30	12.0	202	' '
	B					39.5	18.2	32	35			
7	A	23	0.12	1550	4	29.2	21.0	14	14	4.7	237	Bad porosity and inclusions Tensile and Impact
	B					28.2	21.5	8	8			
8	A	'	'	1525	5.6	32.0	19.6	20	20	5.5	138	' '
	B					22.4	16.0	-	-			
9	A	'	'	1480	16	37.4	20.5	37	33	9.4	207	Bad porosity and inclusions Tensile specimen.
	B					35.3	17.8	25	32			

NUMERICAL RESULTS (Contd.)

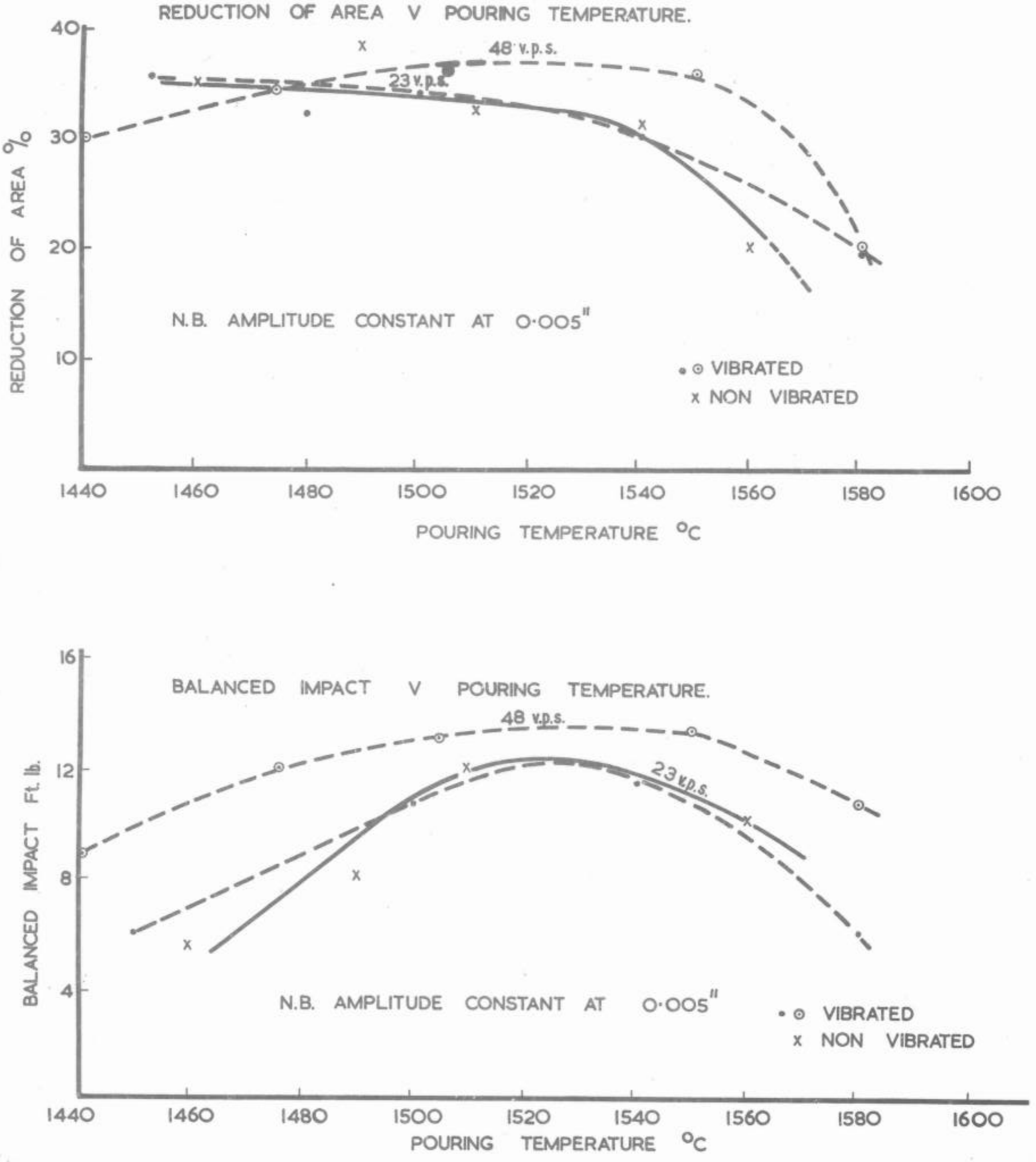
Specimen No.		Freq. Cy/Sec.	Amplitude in.	Pouring Temp. °C.	Grain Size No/ sq.cm.	U.T.S. T.p.s.i.	Elastic Limit	Elong'n °/o	Reduction of Area °/o	Balanced Impact ft.lb.	Hardness V.P.N.	REMARKS
10	A	23	0.12	1505	120	39.4	19.2	30	38	9.3	158	Bad porosity and inclusions impact specimen.
	B					39.5	19.2	27	30			
11	A	23	0.12	1445	90	39.0	17.8	40	38	6.5	182	Bad porosity and inclusions on impact specimen
	B					39.0	19.3	30	30			
12	A	'	'	1485	25	39.0	17.5	38	36	10.4	252	Normal Fracture (New crucible)
	B					40.0	19.3	37	36			
14	A	'	'	1510	27	40.5	19.5	33	35	12.0	245	' '
	B					41.5	20.0	40	35			
15	A	'	'	1540	16	40.3	19.8	35	30	12.0	297	' '
	B					40.3	19.0	35	28			
16	A	'	'	1560	13	39.5	18.7	36	30	10.5	264	' '
	B					40.0	19.0	35	30			
17	A	48	0.005	1440	80	39.0	18.5	32	30	9.0	250	Normal Fracture
	B					39.5	18.5	34	30			
18	A	'	'	1475	35	42.5	20.3	35	34	12.0	245	' '
	B					40.5	19.0	38	35			
19	A	'	'	1505	25	43.0	20.0	40	36	13.0	297	' '
	B					42.6	21.0	40	36			

NUMERICAL RESULTS (Contd.)

Specimen No.	Freq. Cy/Sec	Amplitude in.	Pouring Temp. °C.	Grain Size No/ sq.cm.	U.T.S. T.p.s.i.	Elastic Limit	Elong'n %	Reduction of Area %	Balanced Impact ft.lb.	Hardness V.P.N.	REMARKS
20 A	48	0.005	1550	12	43.0	21.0	40	35	13.5	230	Normal Fracture
B					43.4	21.5	42	37			
21 A	48	'	1580	10	41.5	19.0	24	20	10.5	264	Inclusion in one tensile specimen
B					20.0	20.0	0	0			
22 A	23	'	1580	12	35.0	15.0	25	20	6.0	230	Normal Fractures
B					34.0	17.0	17	19			
23 A	'	'	1500	20	40.0	19.5	35	34	10.5	290	' '
B					40.0	20.0	37	34			
24 A	'	'	1540	12	38.8	18.0	33	31	11.5	202	' '
B					39.3	19.0	33	30			
25 A	'	'	1480	30	29.0	25.0	31	33	6.0	189	Evidence of porosity
B					25.0	25.0	27	31			
26 A	'	'	1450	75	39.0	19.5	39	35	6.0	255	Normal Fractures
B					40.0	19.5	37	36			



INFLUENCE OF CASTING TEMPERATURE ON MECHANICAL PROPERTIES OF CASTINGS VIBRATED AT FIXED AMPLITUDE AND VARYING FREQUENCY OR NON VIBRATED



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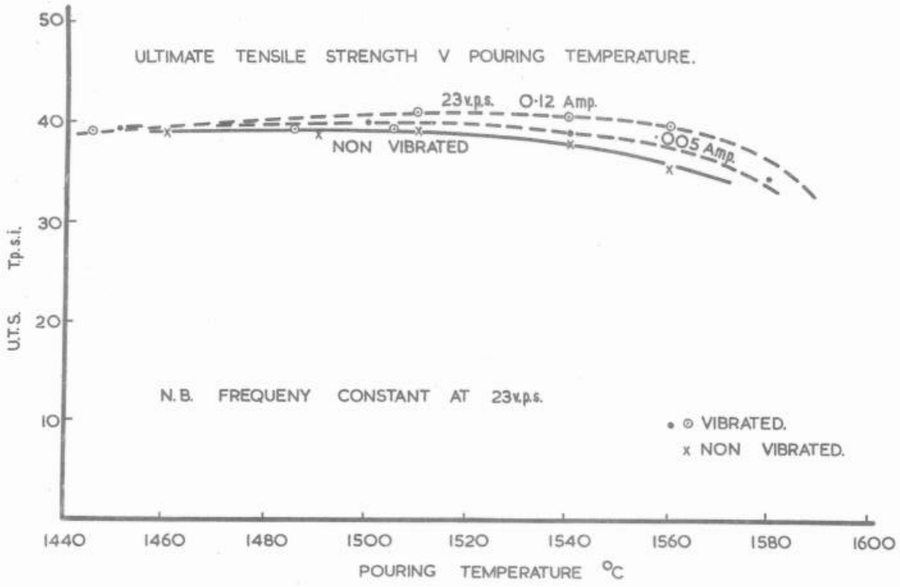

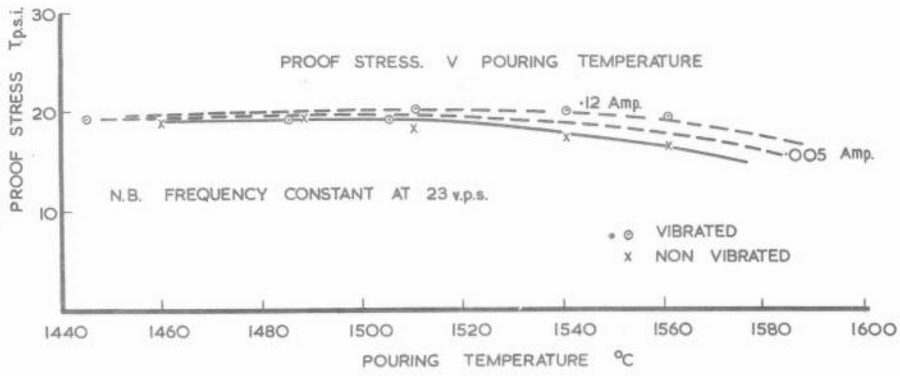

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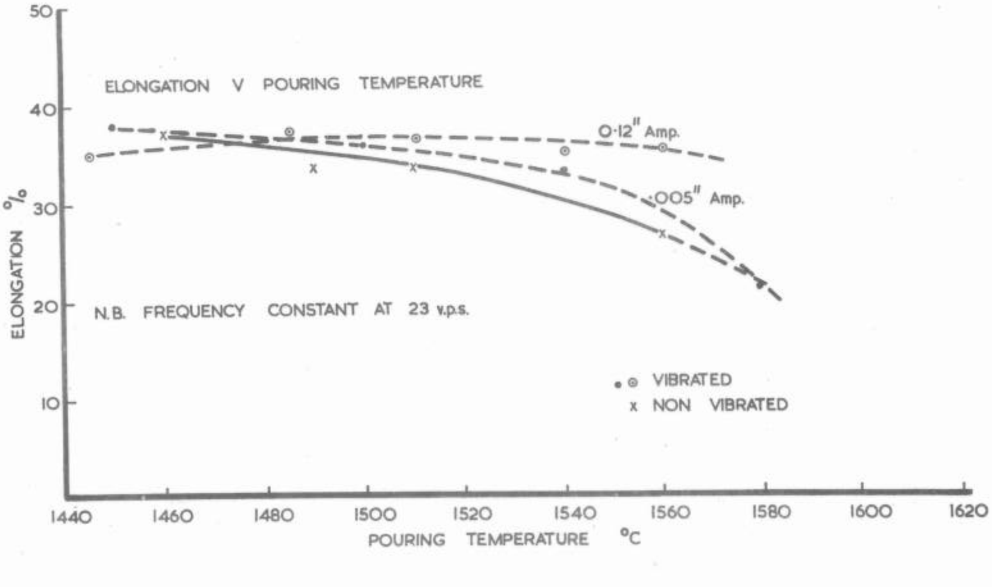
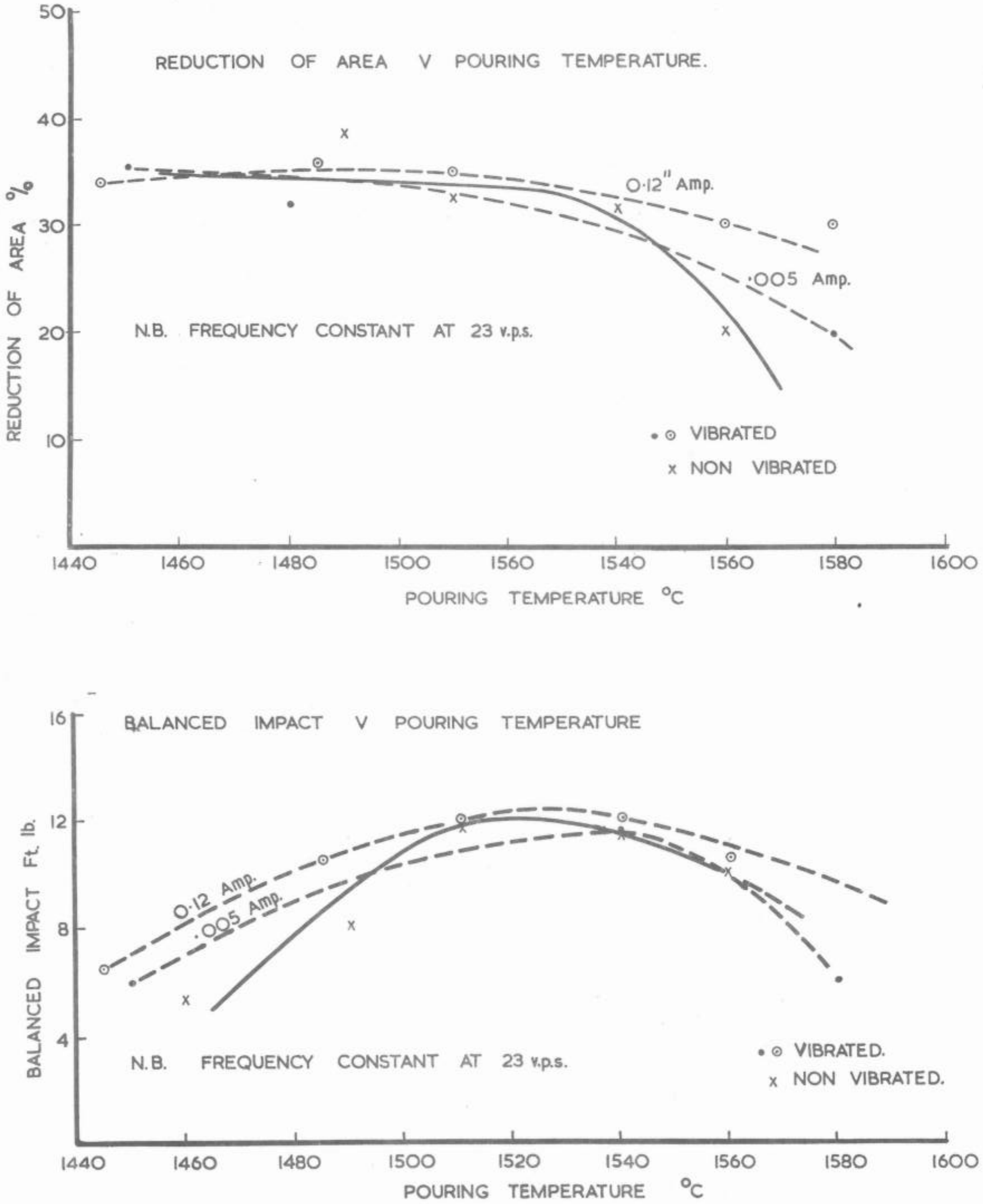




INFLUENCE OF CASTING TEMPERATURE ON MECHANICAL PROPERTIES OF CASTINGS VIBRATED AT FIXED FREQUENCY AND VARYING AMPLITUDE OR NON VIBRATED

APPENDIX II

COMPARISON OF MICROSTRUCTURE

It will be noted that the effect on the microstructure of vibration is that

1. There is a change in the type of microstituent. There is a much larger quantity of the half-tone duplex constituent. (V.T.1 and V.T.2).

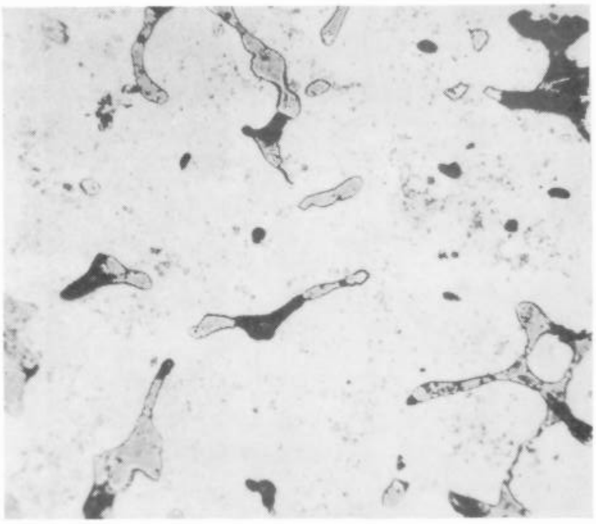
2. The dendritic arrangement gives place to a more uniform distribution.

3. At the higher temperatures where the maximum mechanical advantage is obtained there is an increased refinement of the structure.

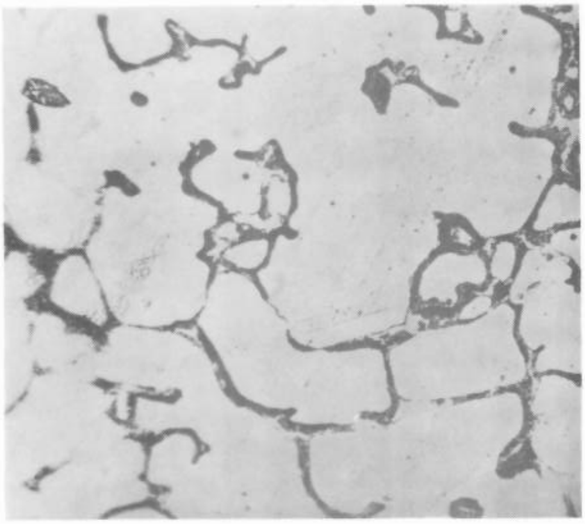
All these changes in structure confirm that the effect of vibration is to produce a more intimate admixture of the solidifying liquid and promote diffusion, so obtaining a step nearer equilibrium. This state could not be complete and deeper etching shows that the cored structure still remains though it is reduced in proportion. It is of interest that these changes in structure are associated with an increase on both tensile and plastic properties and also impact value, a property usually so deficient in the cast structure. It is doubtful if any form of heat treatment would achieve this combination of properties. There would appear to be good reasons why the theoretical suggestions made in Section 2 have become operative, i.e. that the strength of the grain boundary structure has been increased by the effects of the vibration.

Key to Photographs

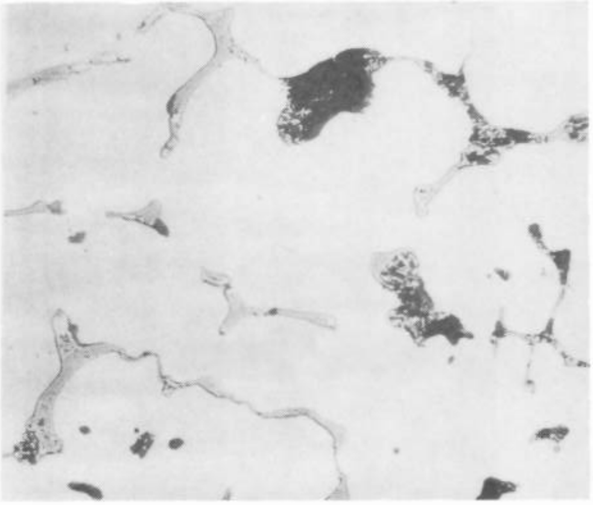
No.	Frequency	Amplitude	Pouring Temperature °C
VT1	23 v.p.s.	0.12in.	1550
VT2	23v.p.s.	0.12in.	1525
VT3	23 v.p.s.	0.12in.	1505
VT4	23 v.p.s.	0.12in.	1485
VT5	23 v.p.s.	0.12in.	1445
T1	Nil	Nil	1560
T2	Nil	Nil	1540
T3	Nil	Nil	1510
T4	Nil	Nil	1490
T5	Nil	Nil	1460



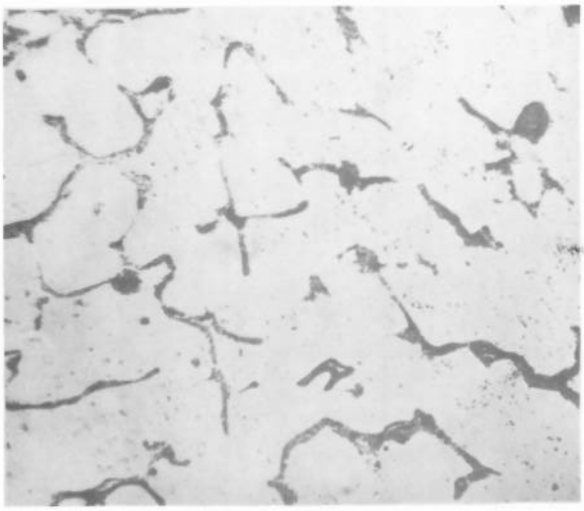
V.T. 1.



T. 1.



V.T. 2.



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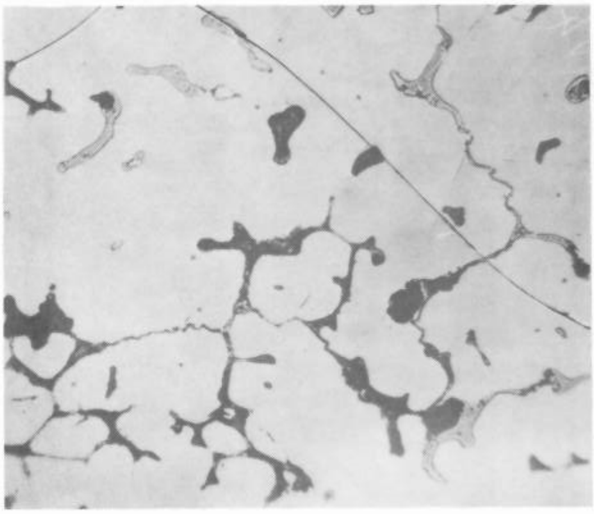
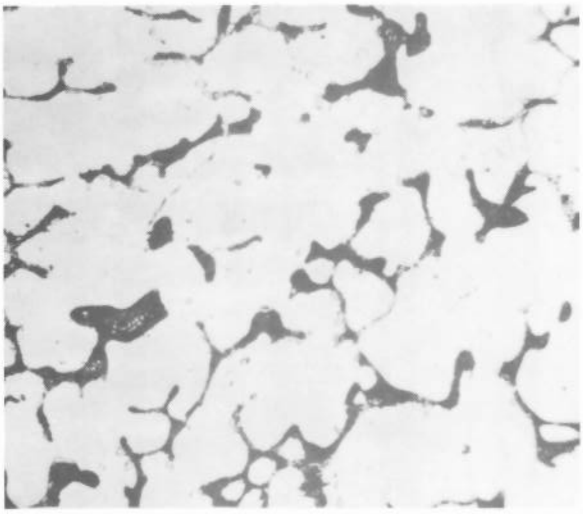


V. T. 3.



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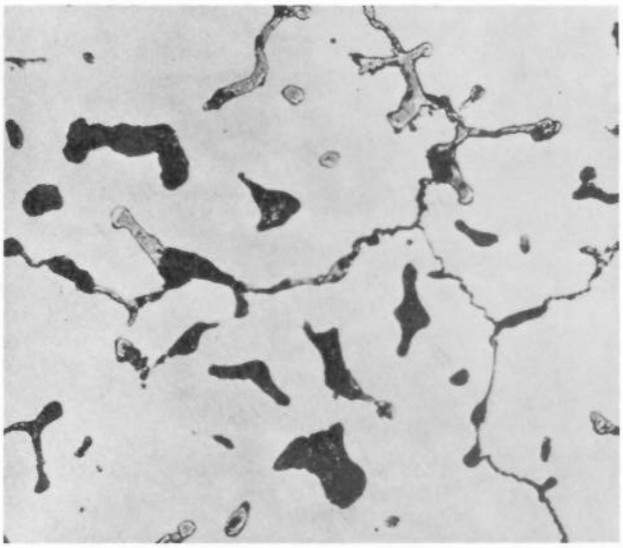

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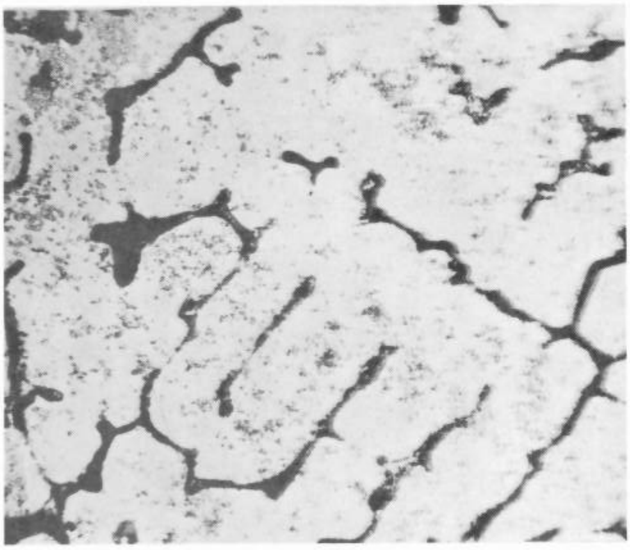

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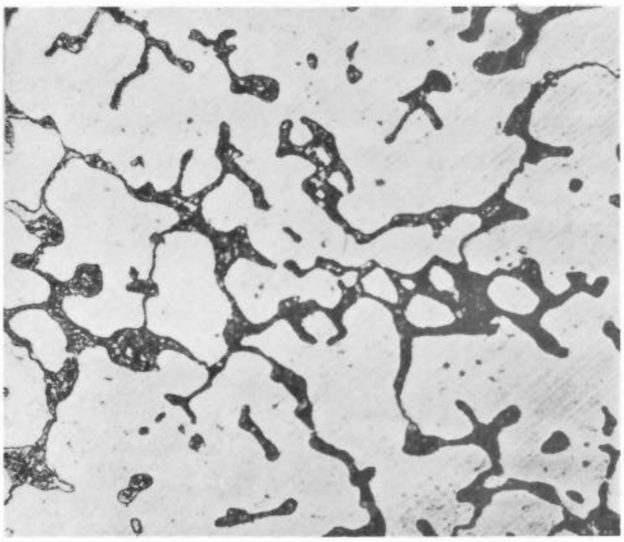
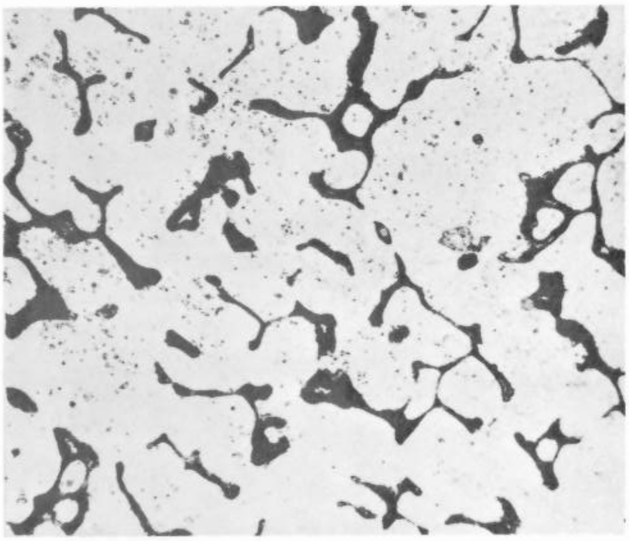


V. T. 5.



T. 5.

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FIGURE 1.

IDEAL MICROSTRUCTURE ASSOCIATED WITH HIGH MECHANICAL PROPERTIES.

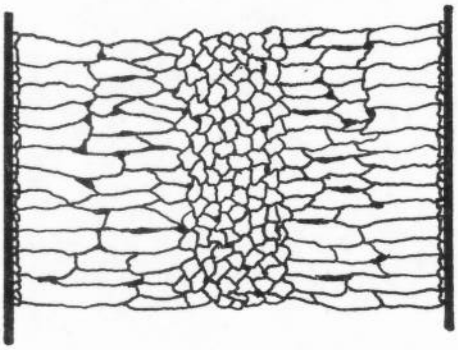


FIGURE 2.

DIAGRAM OF TYPICAL MICROSTRUCTURE OF A CASTING.

FIGURE 3.

MACROSTRUCTURE OF CHILL CAST ALLOY OF ALUMINIUM.

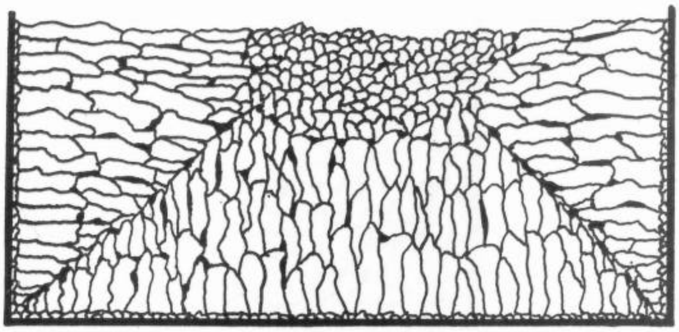


FIGURE 4.

TYPICAL CORNER EFFECT OF INGOT STRUCTURE.

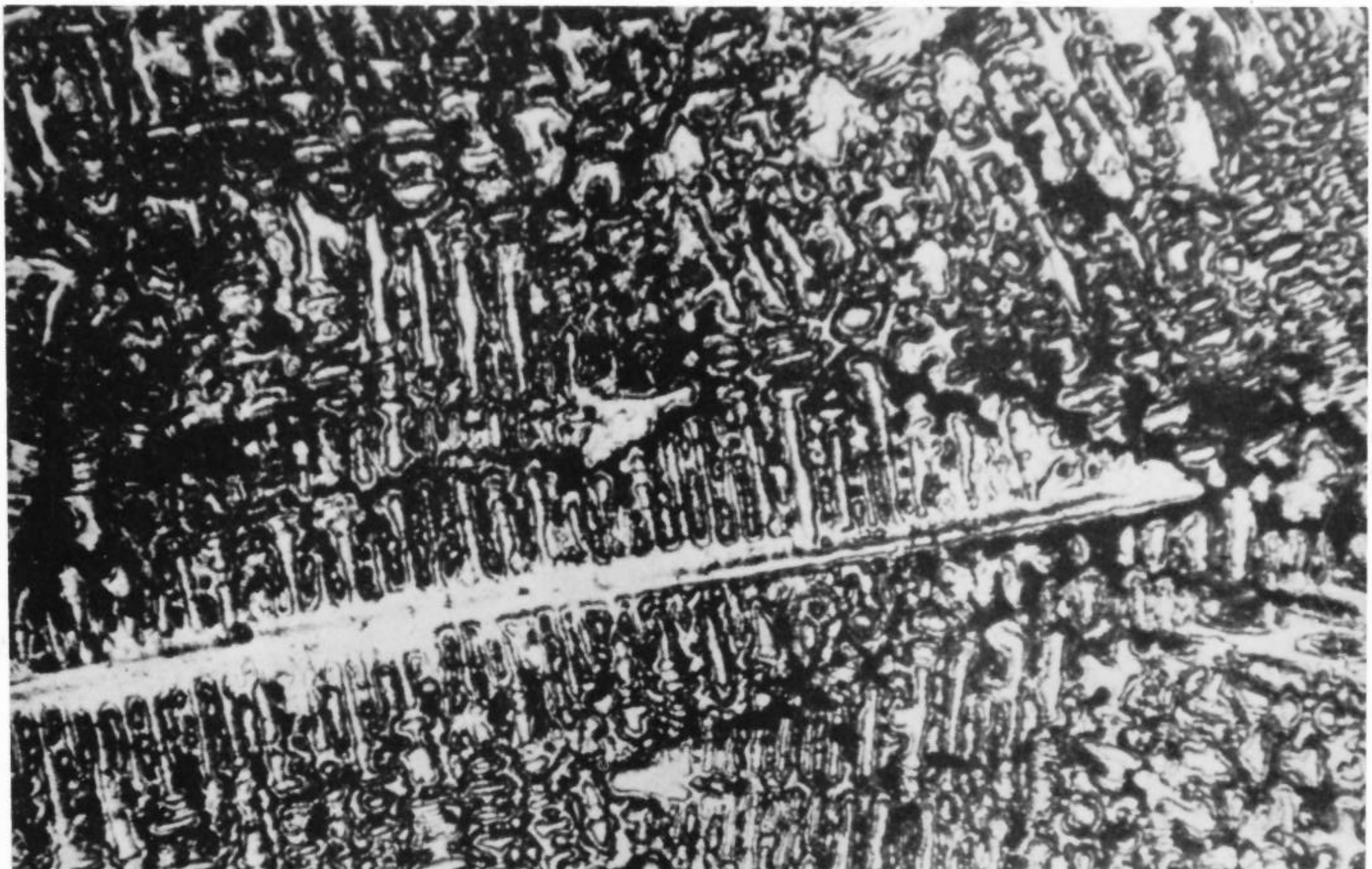


FIGURE 5.

MICROSTRUCTURE OF CAST TIN BRONZE SHOWING DENDRITIC STRUCTURE AND POROSITY AT GRAIN BOUNDARIES.

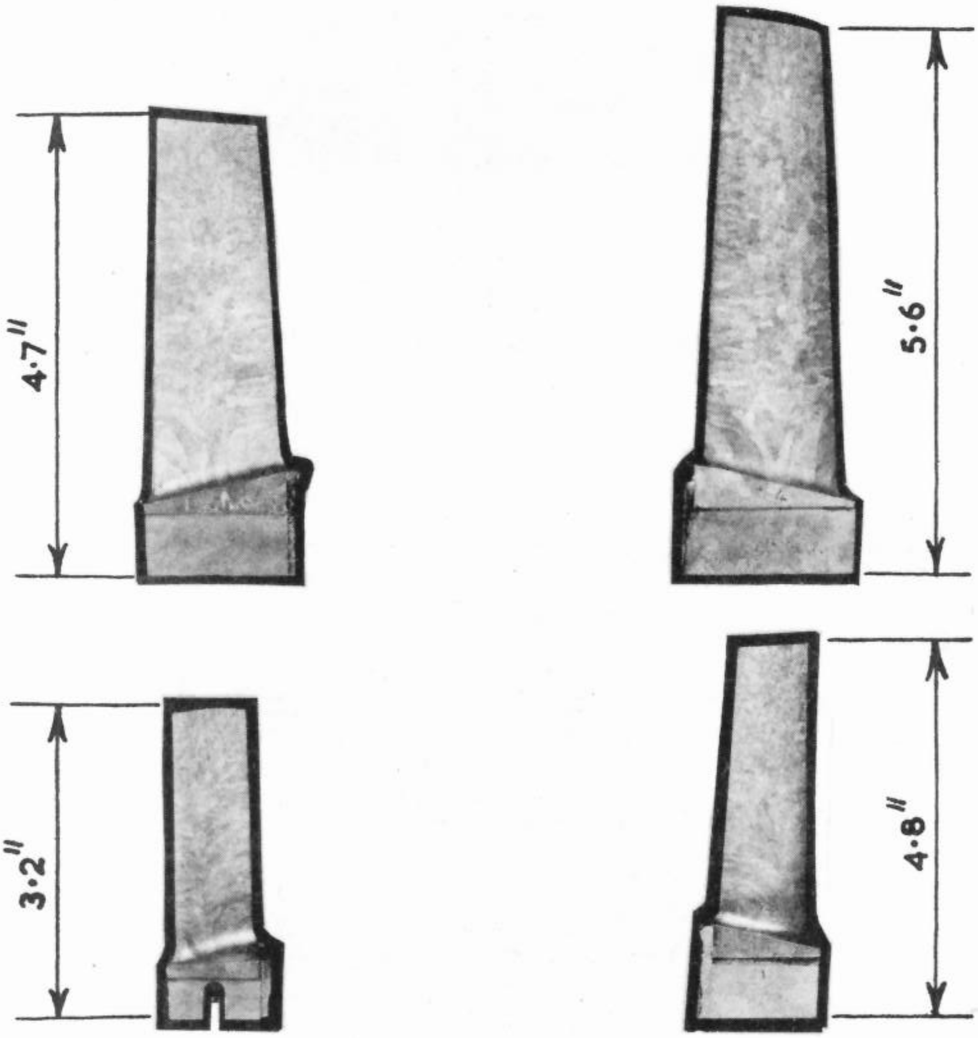


FIGURE 6.

MACRO ETCHED TURBINE BLADES.

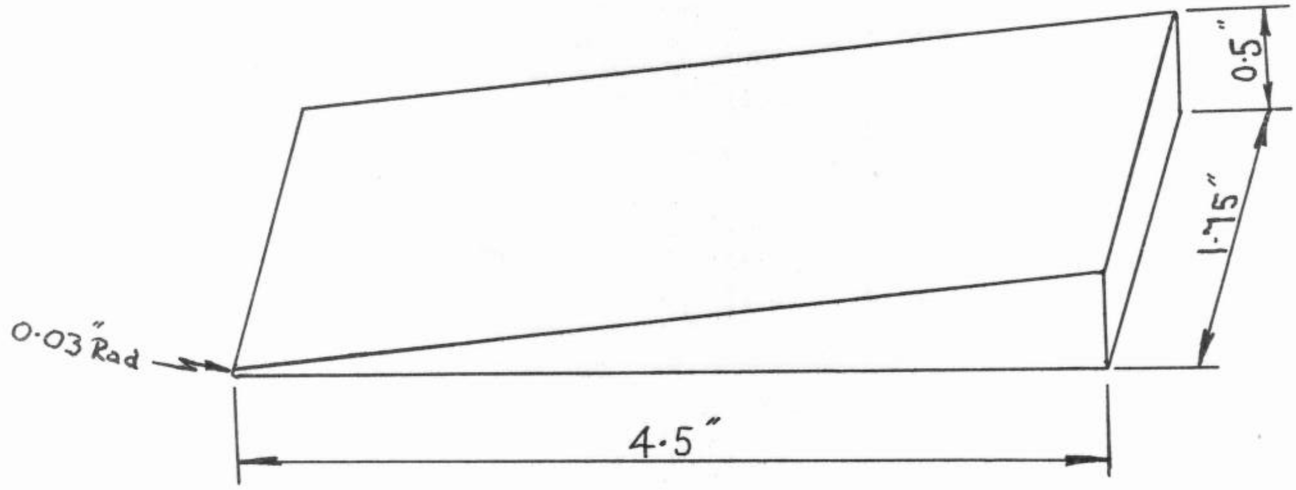


FIGURE 7.

DIMENSIONS OF TEST CASTING.

FIGURE 8.

PHOTOGRAPH OF DUMMY TEST CASTING SHOWING POSITION OF TEST PIECES.

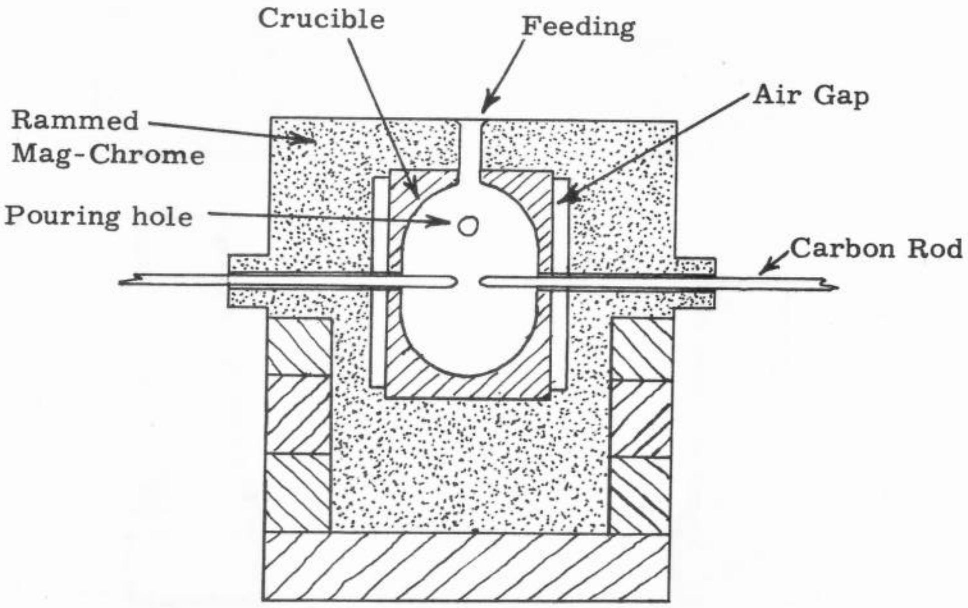


FIGURE 9 A.

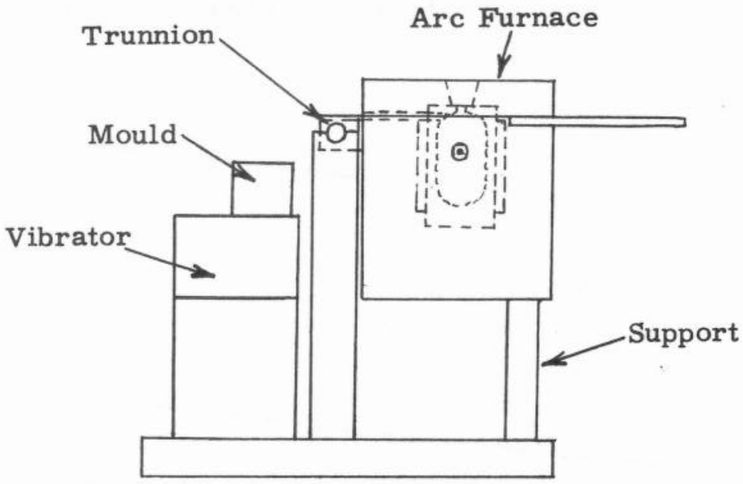


FIGURE 9 B.

FIGURE 9.

ARRANGEMENT OF FURNACE AND REFRACTORIES.

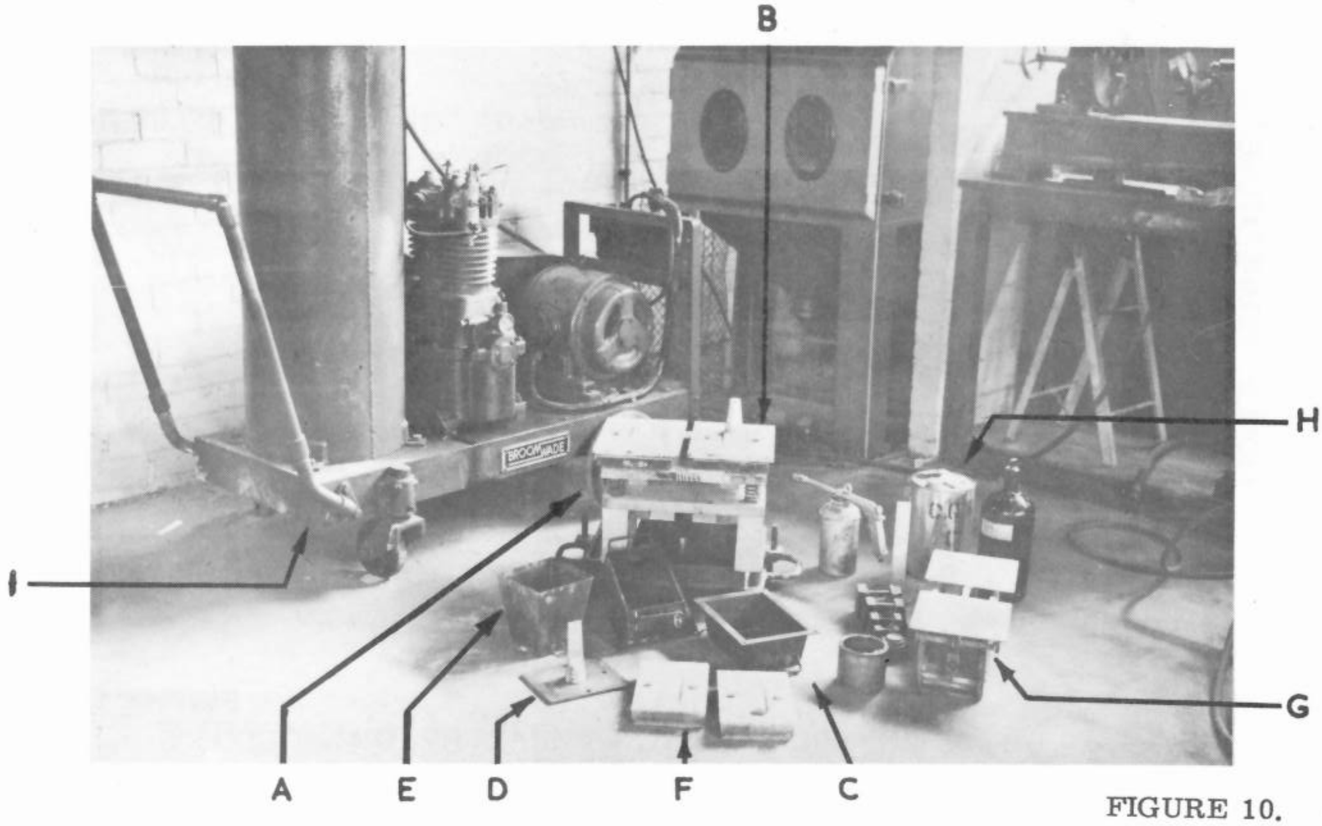


FIGURE 10.

APPARATUS FOR MAKING MOULDS.

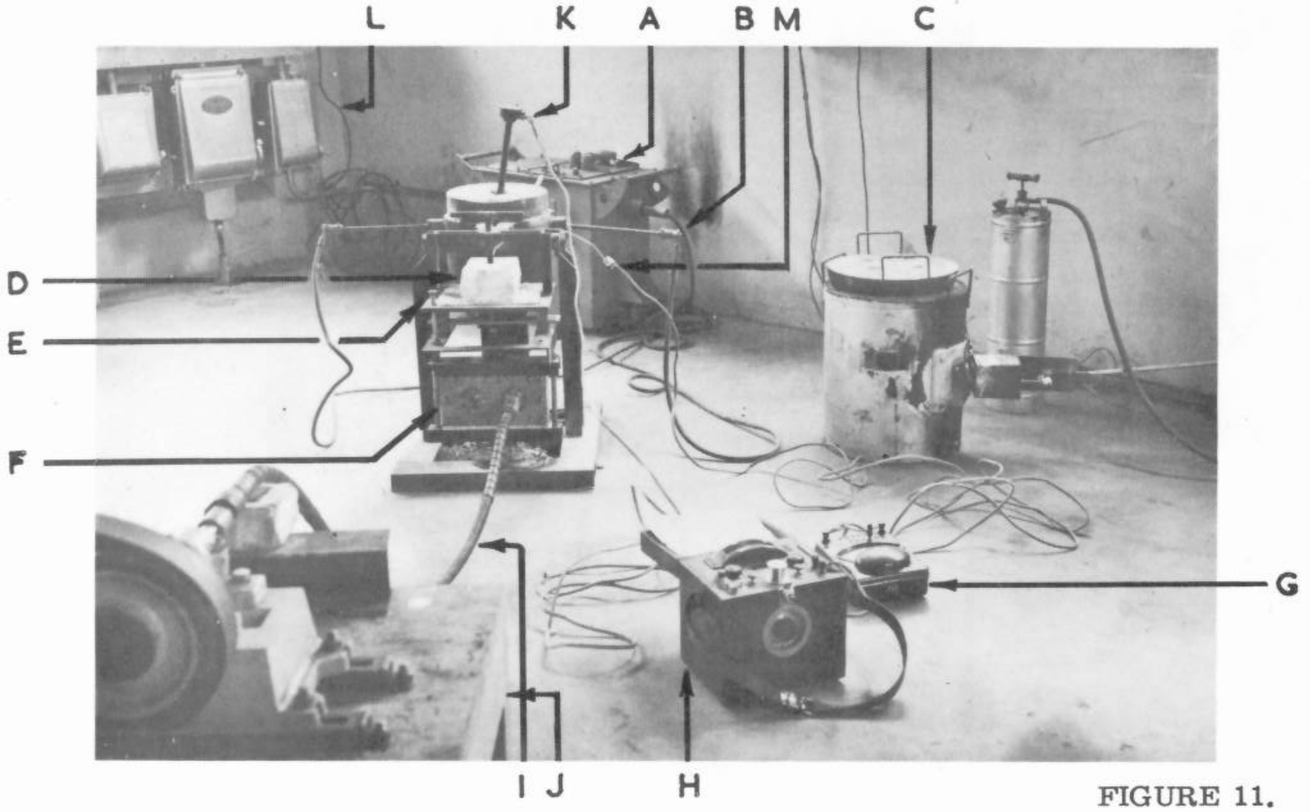


FIGURE 11.

LAYOUT OF EQUIPMENT IN FOUNDRY.

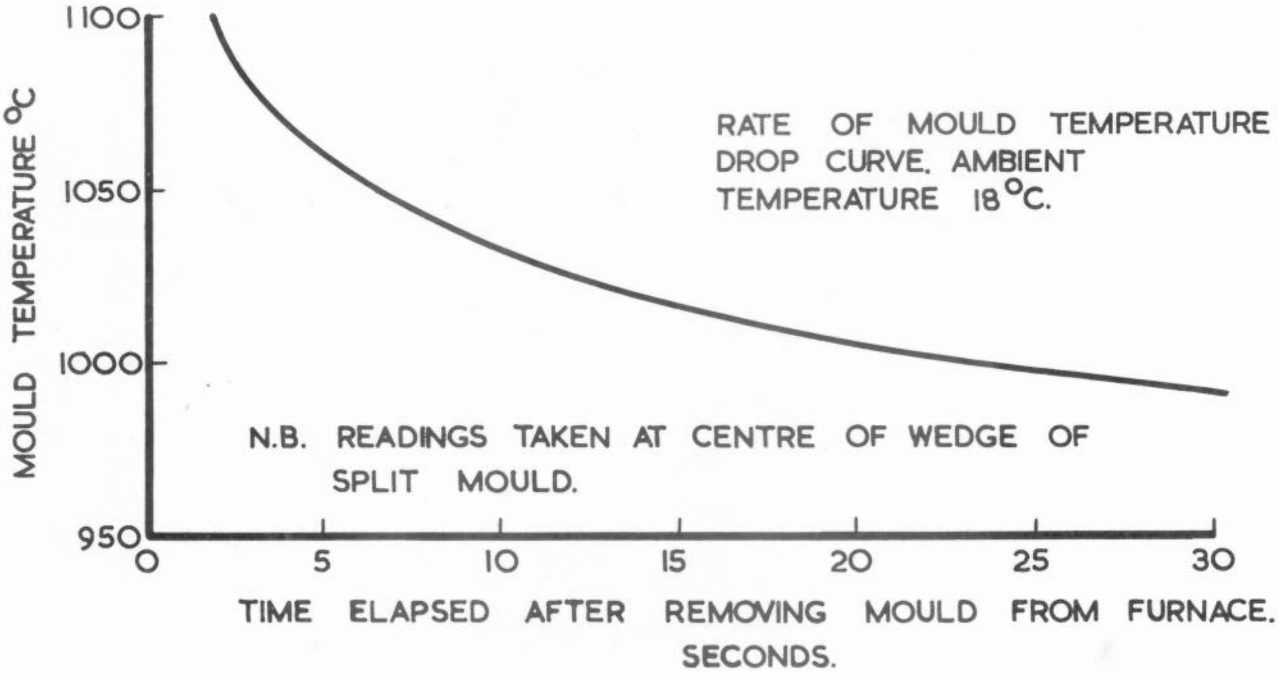


FIGURE 12.

RATE OF FALL OF TEMPERATURE OF MOULD AFTER WITHDRAWING FROM FURNACE.

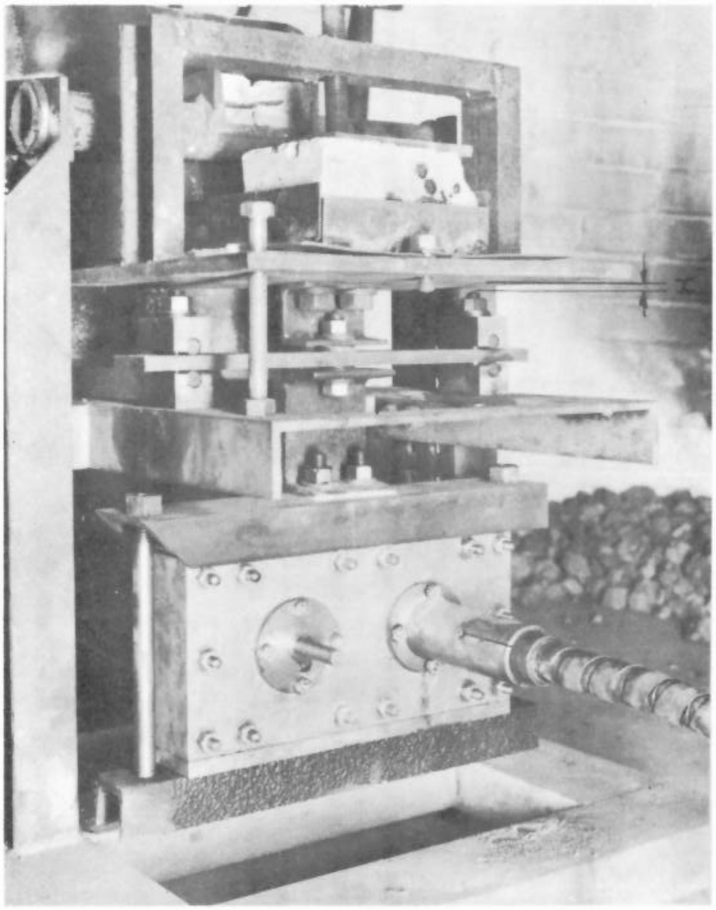


FIGURE 13.

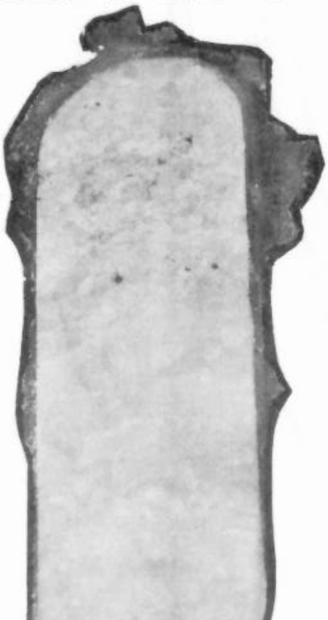
VIBRATOR AND MOULD.

FIGURE 14.

PHOTOGRAPHS OF SIX CASTINGS AFTER ETCHING THE MACROSTRUCTURE.

NON VIBRATED
CAST AT 1560° C

NON VIBRATED
CAST AT 1510° C



VIBRATED
CAST AT 1550° C

VIBRATED
CAST AT 1505° C

FIGURE 15.

PHOTOGRAPHS OF MACROSTRUCTURES OF TEST CASTINGS.

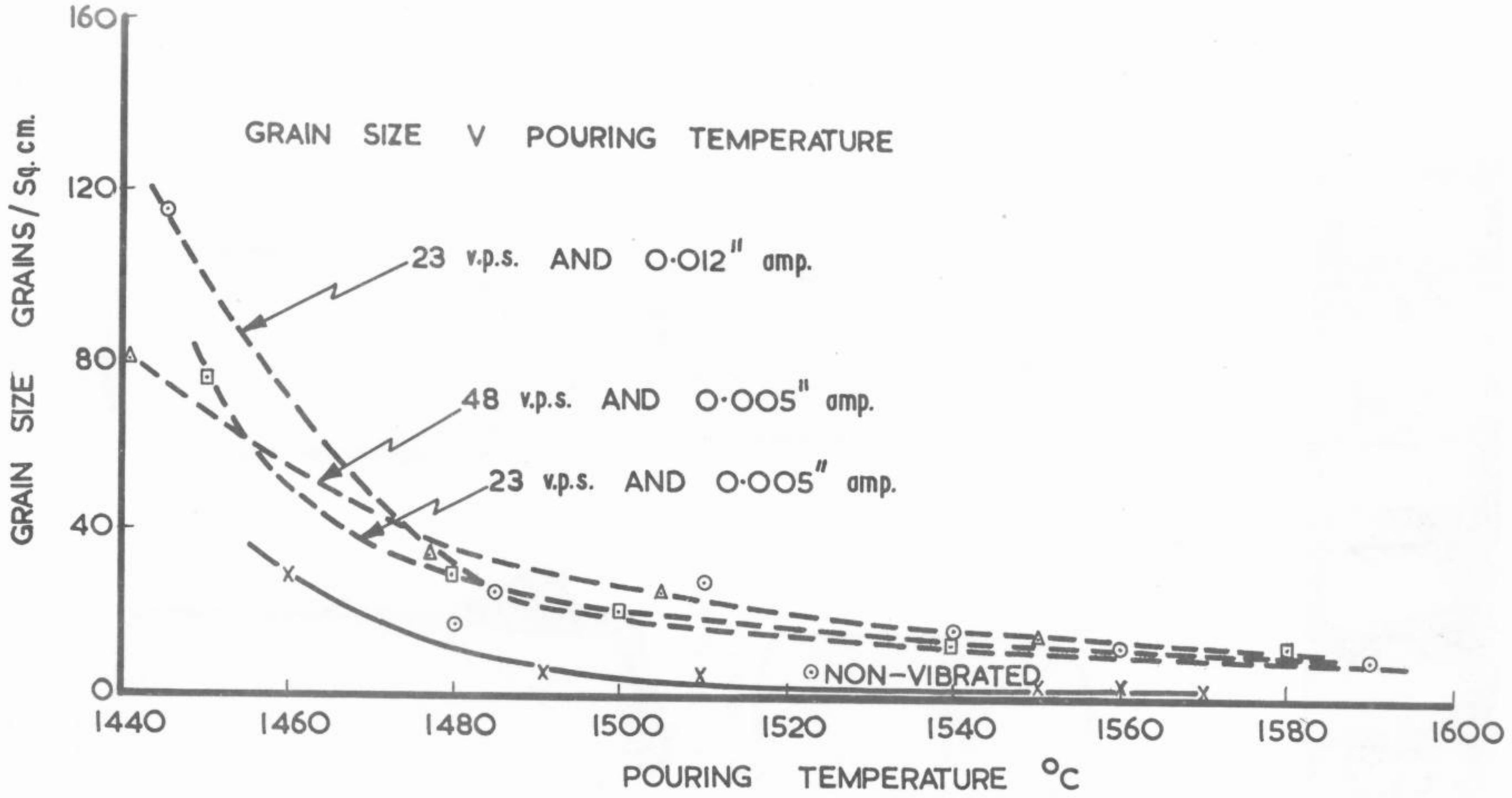


FIGURE 16.

INFLUENCE OF POURING TEMPERATURE ON

GRAIN SIZE OF CASTINGS.