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The Effect of Vibrations (Sonic and Subsonic Frequencies)
during the Period of Solidification on the Mechanical
Properties of Castings of Gas Turbine Materials with
Special Reference to H. R. Crown Max and Nimonic C. 75

by

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SUMMARY

Test castings were designed to produce data which would help in the production of gas turbine blades as castings. For castings in H. R. Crown Max the investigation is limited to the effect of sub-sonic frequencies and range of amplitudes; but in the experiments conducted on Nimonic C. 75, both sub-sonic and sonic ranges of frequency were investigated.

It can be concluded that certain frequencies notably improve the quality and properties of castings. This effect is attributed to the formation of more uniform and smaller crystals during this process, and to an increase in density.

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INTRODUCTION

The production of turbine blades for modern aircraft is a lengthy and complicated process. The rotor blades, for example, are forged and then machined to the required contours, both being expensive operations.

The object of the investigation outlined in this report was to develop a new method for producing the turbine blades which would save time, reduce the cost and give improved mechanical properties.

The proposed method was to cast suitable test castings, and overcome the non-uniformity of the cast structure by vibrating the casting during the solidification period. It was anticipated that the choice of a suitable casting technique would reduce the machining to a minimum, and that the method of vibrating would give the blades the desired strength.

Hinchliff and Jones (1) carried out some work on test wedge type castings of H. R. Crown Max, vibrating them, while solidification was taking place, at sub-sonic frequencies of 23 and 48 v. p. s. They showed that while mechanical properties were dependent on casting temperatures in the non-vibrated condition, there was some improvement as a result of the vibration at all frequencies. There were critical conditions of frequency and amplitude for the maximum effect but frequency was by far the more important factor. They reported an absence of literature on the phenomena but a later survey is now concluded. From the work on H. R. Crown Max, with new equipment which made possible greater control of conditions, the conclusions of Hinchliff and Jones are confirmed. The work is extended to include Nimonic C 75 at sub-sonic and sonic frequencies.

H. R. CROWN MAX

Composition - %

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

Properties

This steel possesses good strength at elevated temperatures, has specific gravity of 8.0, and in the heat-treated condition a yield stress of 30 tons per sq. in. It is usually produced in bar form. Both welding and casting properties are good, and the best casting temperature is about 1550°C.

NIMONIC C. 75Composition - %

Carbon	0.08 - 0.15	Iron	2.00 maxm.	Cr.	19-21
Si.	0.30 - 0.80	Sulph.	0.015 "	Al.	0.40 maxm.
Mag.	1.00 maxm.	Cu.	0.50 "	Ti.	0.25
				<u>Ni.</u>	<u>Balance</u>

Properties

Tensile strength 46 tons per sq. in. Rolled or cast condition
 0.1 Proof stress 30 tons per sq. in.
 20-30% elongation
 20-30% reduction of area

Nimonic C. 75 tends to lose titanium due to oxidation during melting and the operation requires experienced control.

PART I. EFFECT OF SUB-SONIC VIBRATIONS DURING SOLIDIFICATION ON THE MECHANICAL PROPERTIES OF H. R. CROWN MAX

1. FOUNDRY EQUIPMENT AND TECHNIQUE

Since it was desired to develop a technique which would be available in normal foundry practice, such methods were used as far as possible, but the actual equipment was improvised. It was necessary to design and construct an electric arc furnace of the required small capacity and the vibrating table had to be strong and dimensionally suitable for a framework already built. The other main requirements were large range of frequencies and amplitudes, together with considerable load carrying capacity. The ease, simplicity and speed of operation had to be considered. Such requirements were partly satisfied by the choice of a mechanical vibrator operated by an out of balance cam.

1. 1. Vibrating table

The vibrating table (Fig. 1) of German design was installed. The Vibrator operated directly from the mains, and worked on the principle of an offset weight rotating on a shaft driven by a small electric motor. The table was capable of vibrating up to 10 lbs. weight at 8, 000 vibrations per minute and amplitude 0.4 mm. The frequency was varied by means of a variable resistor for fine adjustment and by altering the position of the leaves supporting the vibrating table for coarse adjustment.

The apparatus was calibrated by the makers, but for the purpose of this investigation, frequency was measured for each casting, at first using a stroboscope and later a tachometer. The amplitude was measured using a microscope fitted with a mirror at 45° and a scale calibrated in $1/10$ mm. The microscope was located with a mirror facing a 1 in. x $\frac{1}{2}$ in. dark plate with a white thin line and mounted on a side of the vibrating table. During the test runs, the source of light was projected on a plate, and a white line appeared in a microscope as a measurable band.

1. 2. Melting furnace

A carbon arc furnace (Fig. 2) was used for the melting of H. R. Crown Max. The current of 120-140 amps. and 80 volts was supplied by a transformer and passed through $\frac{1}{2}$ in. diameter carbon rods. The capacity of the furnace was 3 lbs. and the time of heating to the required melting temperature varied between three and four hours.

Besides the slow rate of heating, a disadvantage of this furnace was an open spout, which, in spite of all the efforts of preheating it by blow-lamps, never reached a temperature higher than 300 to 400°C . Thus, on pouring, the spout was chilling the metal and this was a reason why the quality of some castings was not satisfactory.

1. 3. Measurement of temperature

It had been established by previous experiments that H. R. Crown Max has a wide range of temperatures where the properties of castings are not affected by pouring temperature (Fig. 3). For this purpose a Platinum and Pt/13%Rh. Thermocouple was used to keep the casting temperature within this range. Later, the cooling rate of the furnace was also found. (Fig. 12).

During the casting process, the temperature of the furnace was raised to 1650°C , the arc then switched off, the temperature checked and when it reached 1600°C the carbons were withdrawn and the melt poured into an already vibrating shell. This operation, from the withdrawal of the carbons to pouring, took five to six seconds. Therefore, the temperature in the furnace, on pouring, must always have been within the permissible range. (Fig. 12).

1. 4. Shell moulding technique

There are a few available types of moulds that could be used for this work, but the latest shell moulding technique seemed to be most suitable. For example, Sillimanite base moulds were used in previous work, but

because of their heaviness, expense and the difficult method of production, they were not considered to be ideal for the purpose of this investigation. The smoothness of castings and the precision of shell moulding indicates that the method may be considered for casting of turbine blades. Tolerances on castings can be reduced to as little as 0.002 in. to 0.005 in. The method is also suitable for mechanisation.

Briefly, shell moulding is the production of foundry moulds from resin-bounded sands, instead of the traditional clay bond. Already considerable information and experience exists of this method. The moulding material consists of a dry blend of silica sand and five to eight per cent of resin. This resin, known as 'thermo-setting' resin, may be of the phenolic, cresylic or urea type, which is produced by condensing phenol, cresol or urea respectively with aqueous formaldehyde in the presence of a catalyst. The resulting product is dehydrated, cooled and ground to a fine powder. It is important that the sand is quite dry and that the sand and resin are thoroughly mixed.

The method of application of shell moulding technique for the production of shell moulds is extremely simple and fast. It incorporates the use of a metal pattern, preheated to the required temperature, which is allowed to be in contact with the mix for the time required to melt the resin to conform to the contours of the pattern. Thickness of the semi-molten layer depends upon the time of contact and the temperature of the pattern. Next, the pattern and the crust adhering are transferred to an oven to complete the baking of a shell. This reaction takes place partly by heat transfer from the plate and partly from the heat of the oven.

A brief summary of the procedure for producing shell mouldings is as follows:

- * (a) Thorough mixing of sand and resin in the following proportions
 - 80 parts of sand H (Redhill)
 - 20 parts of sand F (Redhill)
 - .05 parts of Bakelite wetting reagent (Z. 11502)
 - 7 parts of Bakelite Resin (RO222)
- (b) Heating of pattern at 250°C. for two minutes and application of Bakelite Parting Agent (Z11501)
- (c) Pattern allowed to remain in contact with mix for about 100 seconds, in order to form about $\frac{3}{8}$ in. thick semi-molten layer (Fig.13)

* Pre-mixed sand and resin can now be purchased.

- (d) Curing of pattern and adhering crust in an oven at 350°C for about three minutes. At this stage, it is best to judge visually the quality of the shell, a brownish colour indicating the completion of this process. Overbaking or burning results in a weak pattern.
- (e) Ejection by gentle tapping.

1. 5. Choice of pattern

The object of this investigation was to cast an average shape of turbine blade in present-day use, and a mild steel pattern was made to comply with the specification used by Hinchliff and Jones (Ref. 1), i. e. a simple wedge type shape without curvature.

1. 6. Fixtures and clamps for vibrating the mould

In order to hold the mould in position while vibrating, it was necessary to design special fixtures and clamps. The clamps had to be easy to operate and able to withstand 'burning' by split metal. To test the rigidity of the clamps, the vibrations of the table were compared with a number of vibrations of shell mould and casting by means of a Stroboscope. It was found that there were no differences in vibrations per minute; the clamps were therefore considered satisfactory.

2. FOUNDRY PRACTICE

2. 1. Casting of H. R. Crown Max

One of the most important facts established from previous work is that the frequency, not the amplitude, has the greater effect on the mechanical properties of castings. The investigators believed that there may be some critical values of frequencies and amplitudes resulting in maximum improvement in mechanical properties of castings. Therefore, it was first necessary to find the range of frequencies and amplitudes showing maximum improvement in mechanical properties.

For this, ten preliminary castings were made, with frequency and amplitude being varied simultaneously. By cutting specimens from these castings, and testing them for properties, the effect of frequency and amplitude was determined. The results of mechanical tests are found in Tables 1 and 2 and plotted in Graphs 1 to 5. Hence, by this procedure, it was possible to fix the amplitude at the point of maximum improvement and vary the frequency independently and vice-versa.

2. 2. Method of testing the castings for properties

2. 2. 1. Vickers Pyramid Hardness Test

The ten preliminary castings were tested for hardness by using a Vickers Pyramid Hardness Machine at 30 kg. load. Readings were taken every half-inch along the length of the section of casting (Fig. 5). Table 2 shows the data obtained. From this the average Vickers Pyramid Hardness number was found for each casting. It is evident that although there is no marked increase of hardness in the case of vibrated castings, yet the values are more uniform throughout the whole section of blades, thus indicating a more uniform arrangement of crystals.

2. 2. 2. Macrostructures

The castings were polished and macro-etched, the etching reagent being Aqua Regia. It was found that the reagent was most efficient at about 30° to 35°C. Macroetchings of the castings showed the change from the columnar structure to the small and uniform equi-axed structure of the vibrated castings. The change was quite clear to visual examination but owing to the surface of the casting photographs were not very satisfactory. Examples are shown in Fig. 6.

2. 2. 3. Selection of test pieces from casting

The 'sampling' of the test pieces from the representative castings was considered carefully, and the best positions specified. (Fig. 7). It was decided to cut two No. 11 tensile test pieces, one 'vertical' and the other 'horizontal', together with one 'horizontal' impact test piece.

2. 2. 4. Mechanical tests

The tensile test pieces were tested on Hounsfield Testing Machines. The impact specimens were notched and tested using Hounsfield Impact Testing Machines. The values obtained are shown in Table 1.

It should be pointed out that the fractures of the tensile and impact test pieces were examined for inclusions and porosity before accepting any data as satisfactory. There were no false fractures due to the machining of the test pieces.

2. 3. Conclusions from tests of ten trial castings

The data obtained from the first ten preliminary castings revealed the general effect of vibrations on mechanical properties of castings

and the following conclusions can be drawn from Graphs 1 and 2 -

- (a) the sub-sonic vibrations cause an improvement in mechanical properties of castings
- (b) the most beneficial frequency is about 2,500 v. p. m. and amplitude of about 2 mm.

3. EFFECT OF FREQUENCY ON CAST H. R. CROWN MAX, AMPLITUDE BEING FIXED AT 2 MM.

3. 1. Method of casting

It was now decided to fix an amplitude at 2 mm. i. e. the point of maximum improvement in mechanical properties, and vary the frequency throughout the available range. As it was not possible to vary the frequency without altering the amplitude on the existing vibrator, a special cantilever was designed by means of which it was possible to load the table mechanically, suppressing the amplitude without altering the number of vibrations of the table. (Damping control lever Fig. 2)

The casting technique during this stage was exactly the same as in the case of the ten preliminary castings described in Part II. To cover the whole range of frequencies, fifteen castings were made.

3. 2. Testing specific gravity of castings to explore changes in porosity

In order to explore the effect of vibrations on castings as the means of improving the mechanical properties, it was decided to test the castings for density. For this purpose, special equipment was used, and the data is shown in Table 3 and plotted in Graph 11. The apparatus consisted of a precision balance and a vacuum flask. The specimens were degreased, dried and weighed in air. The Archimedes principle was used in the determination of values of densities, and it was therefore necessary to weight the test pieces again in water at 4°C. This low temperature was maintained by adding small particles of ice to the contents of the flask.

3. 3. Presentation of results

The results obtained in Part I are presented in Table 3 and Graphs 6 - 11, and Table 4 and Graphs 12 - 17, and summarised in the following table.

Effect on mechanical properties of variation of frequency from 2,000 to 6,000 v. p. m.

	Non vibrated	5,000 v.p.m.	4,000 v.p.m.
Tensile strength tons sq. in.	40	45.5	45.4
0.1% Proof stress tons sq. in.	22	23	24
Elongation % on 2 in.	30	36	38
Balanced impact ft. lbs.	9	13.3	-

The impact test was not available from the castings at 4,000 v. p. m. but there would appear to be little difference between the effect of these frequencies. It should be noted that strength, elongation and impact share in the improvement.

4. EFFECT OF VARYING AMPLITUDE WITH FIXED FREQUENCIES OF 4,000 V. P. M.

To find the influence of variation of amplitude on the mechanical properties of castings, it was necessary to fix the frequency at 4,000 v. p. m. and vary the amplitude. The cantilever described previously (Fig. 2) was used to control the right amplitudes. Ten castings were made covering the whole range of amplitudes. The castings were cut and tested in the usual manner. The data is given in Table 4, and shown in Graphs 12 - 16. There is a maximum value of amplitude to given the best improvement for both elastic and plastic properties. From the graphs it could be deduced as -

<u>Property</u>	<u>Maximum value of amplitude</u>
Tensile strength	1 to 1.5 mm.
Proof stress	0.75 to 1.25
Elongation per cent	0.5 to 1.0
Reduction in Area	0.5 to 1.0
Impact	0.75 to 1.25

A common value would be about 1.0 mm. but it suggests that the plastic properties respond more quickly to the effect of the vibration.

4.1. Examination of microstructures

The microstructure confirms the mechanical testing as the characteristic large dendrite in the static casting (Fig. 8) has completely disappeared under the influence of vibrating at 4,500 v. p. m.

It is difficult to decide if this refining effect continues at 6,000 v. p. m. at this magnification but at x 600 (Fig. 10) the increased resolution suggests that the areas of primary deposits and the coring effect is less as a result of vibration. The effect is similar to a slight annealing of cast structure and it may be that the vibration and mixing effect promote diffusion and so bring the structure nearer to equilibrium. It is difficult to say that the grain size of the matrix is smaller but the larger number of primary deposits suggest this effect and in fact would promote it.

The examination of the 'as polished' condition suggests that vibration distributes inclusions finely and more uniformly, and the determination of density has suggested that porosity is reduced.

Present theories of the influence of microstructure on mechanical properties would confirm that the changes in microstructure between the static and vibrated casting would be associated with the improvements in elastic and plastic properties which have been found.

5. CONCLUSIONS

The experimental data is presented in Graphs 6 - 16 from which it is concluded: -

- (a) That for H. R. Crown Max there is a simultaneous increase in the value of all tensile properties in the vibrated compared with the non vibrated castings.

	<u>Non vibrated</u>	<u>4,000 v.p. m.</u>
Tensile strength tons. sq. in.	39.6	45
0.1% proof stress tons. sq. in.	22.5	25.0
Elongation % on 2in.	29	39
Reduction in area	28.5	34.5
Impact ft. lbs. Hounsfield	7.4	10.0

The improvement in elastic and plastic properties suggest homogenisation of the structure and an approach to its maximum possible properties.

- (b) Microscopic and macroscopic examination reveal a refining of the structure, and a substitution of the traditional structure

of elongated crystal grains for a uniform equiaxed structure which confirm the improved mechanical properties recorded above.

- (c) The improved impact value meets a major need for castings.
- (d) The results are further confirmed by the increase in density which is quite definite as the effect of increased frequency reaches a maximum, but further work to measure density at higher frequencies would be of theoretical value.

PART II EFFECT OF VIBRATIONS, SUBSONIC AND SONIC, DURING SOLIDIFICATION ON THE MECHANICAL PROPERTIES OF NIMONIC C. 75

INTRODUCTION

It has been proved from the experiments conducted on H. R. Crown Max that the effect of frequency on the mechanical properties of castings is beneficial up to 67 - 83 v. p. s. , and that beyond this point the effect gradually diminishes. It was, therefore, of great interest to find the effect of frequency higher than 116 v. p. s.

Due to the type of vibrator used, it was not possible to increase the frequency above this value during the investigations on H. R. Crown Max so effort was directed to developing suitable apparatus that would enable this experiment to be performed. The expectations from such experiments were also increased by the report written by Russian workers investigating a similar problem (Ref. 2). Their approach was somewhat different, as they were introducing the changes in structure of steels by using high-frequency currents. One of their most relevant conclusions was that the properties of steels during these experiments were rising to a certain maximum, falling to normal again and rising infinitely afterwards. Impressed by this evidence, it was decided to investigate the effect of higher frequencies on mechanical properties of Nimonic C. 75 and this part of the report describes the development of suitable apparatus, the method of casting and the results obtained. The range of frequencies was between 0 and 10,000 v. p. s. (Note change of units to vibrations per second for Nimonic C. 75 only).

1. DESCRIPTION OF APPARATUS

1. 1. Electromagnetic vibrator (Fig. 14)

An electric vibrator built at the College was used. The apparatus consists of a power unit, an amplifier and an exciter. The associated units will vibrate mechanical structures linearly within the frequency range 0-10,000 v. p. s., and maximum thrust of 2 lbs. and maximum amplitude of 1 in, with a power requirement of 120 watts.

The frequencies at which the castings were made were read from the oscillator dial. The dial was carefully calibrated during the building period of the vibrator against a cathode tube.

The amplitudes were measured by using a travelling microscope calibrated in 1/100th,mm, and focussed on perspex mounted to the exciter rod. The perspex was coated with tinfoil except for a very thin horizontal line cut with a razor blade to permit the light to pass from behind. This process of measuring the amplitudes was rather complicated, requiring great accuracy and concentration. The method was still further complicated when it was found, during the test runs, that the wave pattern of the vibrating system was non-linear.

In spite of all the efforts to eliminate a superimposed frequency by means of cushioning the vibrator, the ideal conditions were never reached, as these oscillations are contributed by the vibrations of the building foundations.

It was necessary to make about twenty castings to cover the whole range of available frequencies. It was thought advisable to specify these and carry out the experiments in accordance with this schedule.

Realising the difficulties met while measuring the amplitudes, it was decided to obtain them at the specified frequencies prior to the casting process.

It was necessary to simulate the conditions met during the test runs. For this purpose, a static casting was made, placed back in a shell mould and fixed in a position 'ready for pouring'. At the selected frequencies, the amplitudes were measured and tabulated (Table 5).

1. 2. Development of new furnace

For this set of experiments, a new furnace had to be designed and built. Although similar in shape to that used in the first part of the report it had many modifications and improvements.

- (a) Suitable air gaps were introduced between crucible and furnace wall
- (b) The top of the furnace was reinforced with mild steel bars
- (c) An electrically preheated spout was introduced as a means of improving the quality of castings. It consisted of an electric element wrapped round a heat resisting tube. The current of 4.5 amps. was passed from the mains through a variac and transformer. The spout temperature just before the pouring was about 800-900°C.
- (d) The material used for the building of the furnace lining was crushed sillimanite and sillimanite silester mixture.

The capacity of the melting pot, as before, was about 3 lbs. The time required to raise the furnace to the desired temperature varied from 1 to 1½ hours.

1. 3. Measurement of temperature

The best casting temperature of Nimonic C. 75 is about 1530°C. During the casting process, the temperature of melt was raised to about 1620°C., arc switched off, temperature measured and the metal poured into the already vibrating shell. Fig. 16 gives the rate of cooling of the furnace and the operating sequence. It can easily be assessed that the casting temperature was always within the permissible range.

1. 4. Choice of pattern for casting

It was decided to cast a rod ½ in. diameter and about 6 in. long. Fig. 17 gives a detailed sketch, and the position of the test pieces. Two preliminary castings were made to see whether, due to excessive length of rod, the casting would not be porous at the bottom. It was found that the castings were perfectly sound and it was decided to use this pattern, except for the very local pipe at top of feeder head.

1. 5. Elastic suspensions and fixtures for shell mould

An exciter was capable of vibrating safely two pounds through the required range of frequencies. The weight of shell and casting was nearly this amount. It was considered necessary then to suspend a shell in a 'neutral position' so that the load on the exciter would be reduced practically to nothing. For this purpose, a special clamp was designed to which a shell could be easily fastened and a special frame built to facilitate this suspension. (Fig. 15). As described before, the

exciter rod was tapped 5BA, and in order to fasten the shell permanently to the rod, the shell was made with a screw at the bottom (Fig. 18).

2. FOUNDRY PRACTICE

2.1. Method of casting

It was decided to make about twenty castings covering the whole range of frequencies and amplitudes.

The method of casting, although similar in procedure to that described when dealing with H. R. Crown Max, involved the addition of two per cent Ni. Ti. or Fe. Ti. since at high temperatures Titanium tends to oxidise. The compositions of those are as follows -

Fe. Ti.	30 per cent Ti.	10 per cent Al. Balance Fe.
Ni. Ti.	20 per cent Ti.	10 per cent Al. Balance Ni.

In the case of the casts described in this section, Fe. Ti. was added on the completion of the melting process. Obviously, this meant that the bars ready for melting had to be weighed very carefully. Also, just before pouring into the shell, a deoxidising reagent, Magnesium, was added in the following proportion and composition -

0.05 per cent Magnesium - as 5 per cent Mg.- Ni. alloy

The sequence of operations when casting, can be summarised as follows:-

- (a) Furnace raised to the required temperature
- (b) Bar weighed and fed into furnace
- (c) When at the required temperature, checked by optical pyrometer, additions of Fe. Ti., and about half-a-minute later Mg. were made
- (d) Vibrator for mould switched on and set at the required frequency
- (e) Arc switched off and temperature checked by means of Platinum + 13 per cent Rhodium Thermocouple
- (f) When at about 1600°C. carbons withdrawn and melt poured into the already vibrating shell.

This last process took from 5 to 6 seconds, therefore it can be concluded that the pouring temperature must always have been at about 1530°C.

2. 2. Conditions of vibration

Owing to the limitations of power there is a tendency for amplitude to vary and decrease with increase of frequency. Above 100 v. p. s. however, the variation was only between 0.2 and 0.1 mm. and so frequency was considered the only variant above 100 v. p. s.

The major improvement in properties for this material was however found in the frequency range below 100 v. p. s. and there was a large variation in amplitude. Experience with H. R. Crown Max showed that the effect of amplitude was a minor one but it will be necessary to explore this effect for this alloy with other apparatus when available.

Also unlike H. R. Crown Max, which showed a maximum improvement and a critical frequency, the improved mechanical properties increased due to vibration to a maximum at 80 v. p. s., decreased to a low value at 1000 v. p. s. and then gradually increased to a new maximum from 5000 to 10,000 v. p. s. which was the limiting conditions of the work. These effects are summarised in Table 5.

2. 3. Method of testing

The test pieces were cut as specified in Fig. 17 and tested for mechanical properties using a Hounsfield Tensometer test specimen No. 11 and a Hounsfield Balanced Impact Test. The test data is tabulated in Table 5 and Graphs 17 - 21.

3. EFFECT OF CASTING TECHNIQUE ON MICROSTRUCTURE

It was found that the best etching reagent consisted of 16 parts of saturated ferric chloride, 1 part of sulphuric acid, 3 parts of hydrochloric acid, 16 parts of water and the best etching time was about 30 seconds.

Similar effects were found in the microstructure as with H. R. Crown Max and examples are shown in Figs. 20 and 21. The typical cored dendrites of the cast structure are changed to the equivalent of an annealed condition with suggestions of a small grain size and uniform distribution of fine constituents.

The surface in the 'as polished' condition shows the reduction in porosity which is confirmed by the determination of specific gravity. The fact that the maximum mechanical properties coincide with maximum density is of considerable theoretical interest and justifies further experiment.

4. CONCLUSIONS FROM EXPERIMENTS WITH NIMONIC C.75

The material showed improved mechanical properties as a result of the vibration. Unlike the H. R. Crown Max it not only showed a critical effect at subsonic frequency 80 v. p. s. but after falling to a low value similar to the non vibrated condition at 800 v. p. s. continued to rise again to the limiting conditions of the vibrator 10,000 v. p. s.

The following values are extracted from the full data in Table 5.

	<u>Non vibrated</u>	<u>80 v. p. s.</u>	<u>10,000 v. p. s.</u>
Tensile strength tons. sq. in.	45	50	48
0.1% proof stress tons sq. in.	30	34	32
Elongation % on 2 in.	24	31	27
Balanced impact ft. lbs.	16	25	19

This alloy confirms a most attractive feature of this method, in that not only are the ultimate and proof strength improved but so also are the elongation and impact values.

The valve operated electromagnetic vibrator is an expensive piece of equipment both in cost and maintenance, especially if provided with enough power to overcome the limitations experienced in this work and control both frequency and amplitude for a casting of practical size. Further it is not of a suitable robust character for use on a foundry floor. The improvements associated with the lower subsonic frequency, as available from an electromechanical device, will justify the practical use of the method.

PART III. GENERAL SUMMARY

1. THEORETICAL DISCUSSION

The theoretical possibilities and mechanism of vibration on the cast structure are discussed by Hinchliff and Jones (Ref. 1). It is suggested that high mechanical properties of a material, in particular a combination of strength, elongation and impact value, are associated with the microstructure found in forgings but the reverse of these conditions is always found with the structure formed by the ordinary mechanism of cooling associated with castings.

The vibration, by introducing mixing effects, should reduce the gradient of temperature which produces the long narrow dendrite of the cast structure and by promoting more uniform conditions of temperature and chemical composition produce a more uniform equiaxed crystal grain structure analogous to that found in a forging.

It is also suggested that these conditions would remove, by more uniform distribution, the weakening defects always found in the condition of the grain boundary of cast structures.

It is of considerable support to these theoretical suggestions that two quite different alloys respond in the same fundamental way to changes in microstructure and the associated improvements in all mechanical properties. It is anticipated that similar improvement will take place in fatigue strength.

2. GENERAL CONCLUSIONS

From the experiments conducted on H. R. Crown Max and Nimonic C. 75 the following conclusions can be drawn -

(1) There is a marked improvement in mechanical properties of castings due to effect of vibrations in sub-sonic range. The maximum improvements occur at about 4,000 to 5,000 v. p. m. for H. R. Crown Max and about 75 to 85 v. p. s. for Nimonic C. 75. These are tabulated below. ^{4500-5100 v.p.m.}

	<u>% Improvement in H. R. Crown Max</u>	<u>% Improvement in Nimonic C. 75</u>
Ultimate tensile strength	14	11
Impact	62	61
% Elongation	30	25
% Reduction of area	40	28
.1% proof stress	10	13

(2) The improvements in mechanical properties were confirmed by the changes in microstructure which were common to both materials. Large cored dendrites disappeared and in place of them there was a finer structure approaching an annealed condition. There was an increase in density associated with the highest test results.

(3) It is to be expected that general casting properties would improve in the vibrating mould and it is of interest to note there was no cold shut with the H. R. Crown Max even in the thin end of the mould representing the trailing edge of a blade, in spite of the fact that the shell mould was cold. It is probable that castings which are 'just failures'

under present practice may be possible by this method.

(4) The electro mechanical vibrator is not an expensive piece of equipment and is robust enough for use on a foundry floor.

(5) Further work will be necessary to investigate whether parts of a casting of varying thickness would share equally in the refining effect but with the H. R. Crown Max the casting decreased from $\frac{1}{2}$ in. thickness to a very thin section while the Nimonic alloy was of uniform section.

(6) Both alloys show the attractive effect that both strength and plastic properties are improved as also is the impact value which is often the particular limiting factor in the use of castings. From these effects there is good hope that even fatigue properties may be increased.

ACKNOWLEDGEMENTS

The authors are grateful to Professor J. V. Connolly, B. S., F. R. Ae. S. for originally suggesting the work and continued interest. The Appendix was written by Mr. J. Jagaciak while a student at Massachusetts Institute of Technology.

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APPENDIXSURVEY OF LITERATURE

The first known attempts to improve the properties of cast metals by means of vibrations were to irradiate ultra-sonic waves into molten metal. First Boyle and Taylor (1) found that ultrasonic vibrations could efficiently degas light metals. Patents along similar lines were issued to Kruger and Kosman (2) and to Herth (3) in 1934.

Yahu and Reisinger (4) patented a process for treating molten metal with high frequency mechanical vibrations of 100, 000 to 200, 000 v. p. s. produced by a piezo-electric source at a low energy level and coupled into the melt by means of vibrating metal probe or through an oil bath. It was claimed that gas inclusions, dross and slag were brought to the surface by the process, producing uniform, fine grained castings, and increasing the toughness, ultimate tensile strength and yield strength of metal.

In the same year (1935) Sokolof (5) studied the effect of supersonic vibrations on the solidification of zinc. Frequencies in the range 600-500 kcs/sec. were used. Sokolof reported that the vibrated metals had a different grain structure from those solidified without vibration. The grain structure showed a pronounced dendritic formation giving the appearance of coarser grain size, although close examination revealed that the actual grain size was finer.

Schmid and Ehret (6) used a magnetostrictive vibrator fixed to the crucible holding the melt. They found that, in general, the vibrated metals solidified to a finer grain size than those untreated but that the grain size was often refined non-uniformly throughout the ingot cross section. Antimony, cadmium and duralumin were used in these experiments. Antimony and cadmium exhibited marked grain refinement when vibrated. Duralumin behaved peculiarly, the dispersed phase was no longer present as a grain boundary network. Coring was absent after vibration and the hardness increased from 78 to 96 VPHN.

Schmid and Roll (7) attempted to isolate the effects of frequency and intensity of vibration on grain refining. Using frequencies of 50, 9, 000 and 200, 000 v. p. s. respectively and intensities of 2 - 39 watts/cm², they conducted experiments on several low melting Wood's metal alloys containing various combinations of bismuth, cadmium, lead, tin and zinc. All of these alloys showed a needle-like structure when solidified without vibration. Specimens solidified under vibration showed a disintegration of the needle structure, the effect becoming more marked as the intensity was increased, but frequency appeared to

have greatest effect.

These investigations developed a theory that grain refinement is caused by frictional effects between the metallic melt and the solidifying crystals. From approximate calculations they produced evidence that fragmentation was possible under the imposed experimental conditions of vibration. Hiedemann (8) endeavoured to refine the grain size of steel castings by high frequency vibrations but was unsuccessful.

Vibration has been used to disperse lead in aluminium (9) and cadmium in silumin (6).

Of special interest is the work done recently by Armour Research Foundation, whose results confirm the conclusions in this Report.

The investigation continued from 1951 to 1954. It was found that the most beneficial frequencies were from 50 - 100 v. p. s., and the conclusions drawn from their experiments are quoted -

(1) The impact vibration utilised in this work (about 60 v. p. s.) produced a refinement of the as-cast grain size.

The degree of refinement is subject to the following conditions:-

- (a) In any one alloy system, grain refinement is most effective at low alloy contents. That is the normal grain refining increasing alloy content to reduce differential effects.
- (b) Refinement is most effective when the rate of solidification is slow. Again, since rapid cooling is itself a recognised method of grain refining, the simultaneous use of vibrations can only be expected to exert comparatively little extra benefit.
- (c) The ability of vibration to induce grain refinement is not strongly impaired as the cross sectional area of the solidifying melt is reduced.
- (d) The relationship between vibrational intensity and grain refinement may be regarded as approximately parabolic in form, that is, above a certain intensity level little added grain refinement seems possible.

(2) The application of vibration during solidification resulted in a pronounced reduction in the depth of columnar grain growth.

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TABLE 1

Data obtained from the first ten preliminary castings.

Casting Ref. No.	Frequency v. p. m.	Amplitude - mm.	U. T. S. tons/sq. in.	0.1% proof stress tons/sq. in.	Hounsfield Impact Value ft. lbs.	% Elongation	% Reduction of area	V. P. Hardness No. at 30KG load
1	0	0	40	22	9.0	30	25	216
2	2,500	1.0	44	23	9.5	30	35	214
3	3,000	3.0	44.8	23.3	-	-	-	215
4	4,000	3.5	-	-	-	-	35	213
5	4,500	2.0	45.4	24	-	38	-	-
6	5,000	1.0	45	23.4	13.3	36	35	211
7	5,500	0.9	-	23.3	13.7	34	35	214
8	6,000	0.6	44	23	10.5	31	30	218
9	6,500	0.3	42	-	8.0	30	30	214
10	7,000	0.15	42	22.5	9.5	30	32	216

TABLE 2.

Table giving V. P. hardness numbers for the first ten preliminary castings.

Testing Position	1	2	3	4	5	6	7	8	9	10
Casting No. and Frequency	0	2500	3000	4000	4500	5000	5500	6000	6500	7000
1	235	225	223	-	-	236	231	233	224	227
2	222	221	220	-	-	206	219	220	219	214
3	220	212	-	-	-	207	207	220	216	213
4	211	205	210	-	-	210	207	210	208	213
5	209	211	213	-	-	201	207	215	211	208
6	201	213	210	-	-	204	-	214	200	-
7	-	-	-	-	-	-	-	-	208	-
Average values	216	214	215	-	-	211	214	218	214	216

NOTE that values given in this Table are already average values obtained from three readings across the section of the casting. To get all the 'averages' 210 V. P. Hardness numbers were taken.

TABLE 3

Data obtained when investigating the effect of frequency, amplitude being constant at 2 mm.

Casting Ref. No.	Frequency v. p. m.	U. T. S. tons/sq. in.	Hounsfield impact value ft. lbs.	% Elongation	% Reduction of area	0. 1% Proof stress	Density
1	0	39. 5	7. 4	29	24. 5	22. 5	8. 062
2	2, 000	43. 0	-	36	26. 0	23. 3	-
3	3, 000	44. 0	10. 0	36	33. 0	24	8. 170
4	3, 500	-	10. 0	-	-	-	-
5	4, 000	45. 0	-	39	34. 5	25	-
6	4, 500	44. 6	12. 0	38	33. 5	24. 3	8. 207
7	5, 000	45. 0	-	-	-	24. 7	8. 183
8	6, 000	44. 8	11. 2	31	30. 0	24	8. 130

TABLE 4

Data obtained when investigating the effect of amplitude. - frequency being constant at 4, 000 v. p. m.

Casting Ref. No.	Amplitude - mm.	U. T. S. tons/sq. in.	0. 1% Proof stress tons/sq. in.	Hounsfield Impact value . ft. lbs.	% Elongation	% Reduction of area
1	0	39. 7	22. 2	8. 5	30	25
2	0. 70	45. 5	25	13. 2	40	36
3	1. 0	46. 0	25	12. 5	36	35
4	1. 5	45. 0	24. 8	-	37. 5	31
5	2. 0	45. 0	24	12. 7	35	32
6	2. 5	44. 4	23. 3	11. 5	35	-
7	3. 0	43. 5	22. 8	9. 5	-	31
8	4. 0	-	-	-	-	-

TABLE 5

Data obtained when casting Nimonic C. 75

Casting Ref. No.	Frequency v. p. s.	Amplitude - mm.	U. T. S. tons/sq. in.	Hounsfield Impact Values - ft. lbs.	% Elongation	% Reduction of area	0.1% Proof stress tons/sq. in.	Density
1	0	0	45	16	24	27	30	8.301
2	50	.765	46	16.5	27	32	32	-
3	70 & 80	.36	50	25	31	35	34	8.354
4	100	.22	50	28	29	31	34	-
5	150	.16	47	26.5	26	28	31	8.318
6	200	.10	-	-	-	-	-	-
7	500	.11	45	16.5	26	28	30.5	-
8	800	.12	46	15.0	26	26.5	29	-
9	1000	.11	-	-	-	-	-	-
10	2000	.13	-	16.0	24	-	-	8.305
11	3000	.12	45.5	16.5	24	27	31	-
12	4000	.10	47.5	14.0	25	28.5	31	8.295
13	5000	.11	-	-	-	-	-	-
14	6000	.15	46.5	16.5	25	28.5	30	-
15	8000	.10	46.6	17.5	26	29.5	30.5	8.31
16	10,000	.09	48	19.0	27	30.3	32	-

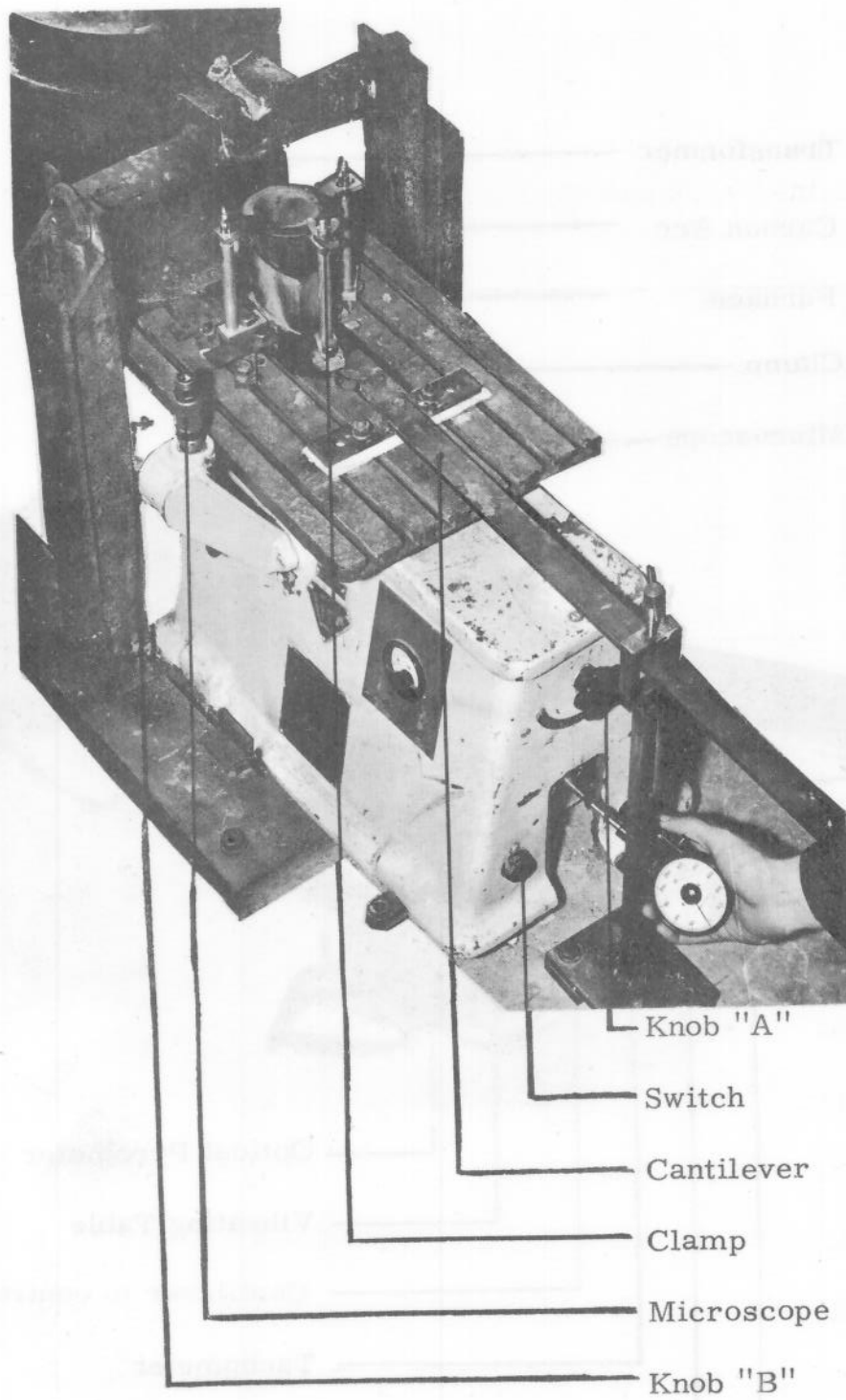


FIG. 1 - VIBRATING TABLE

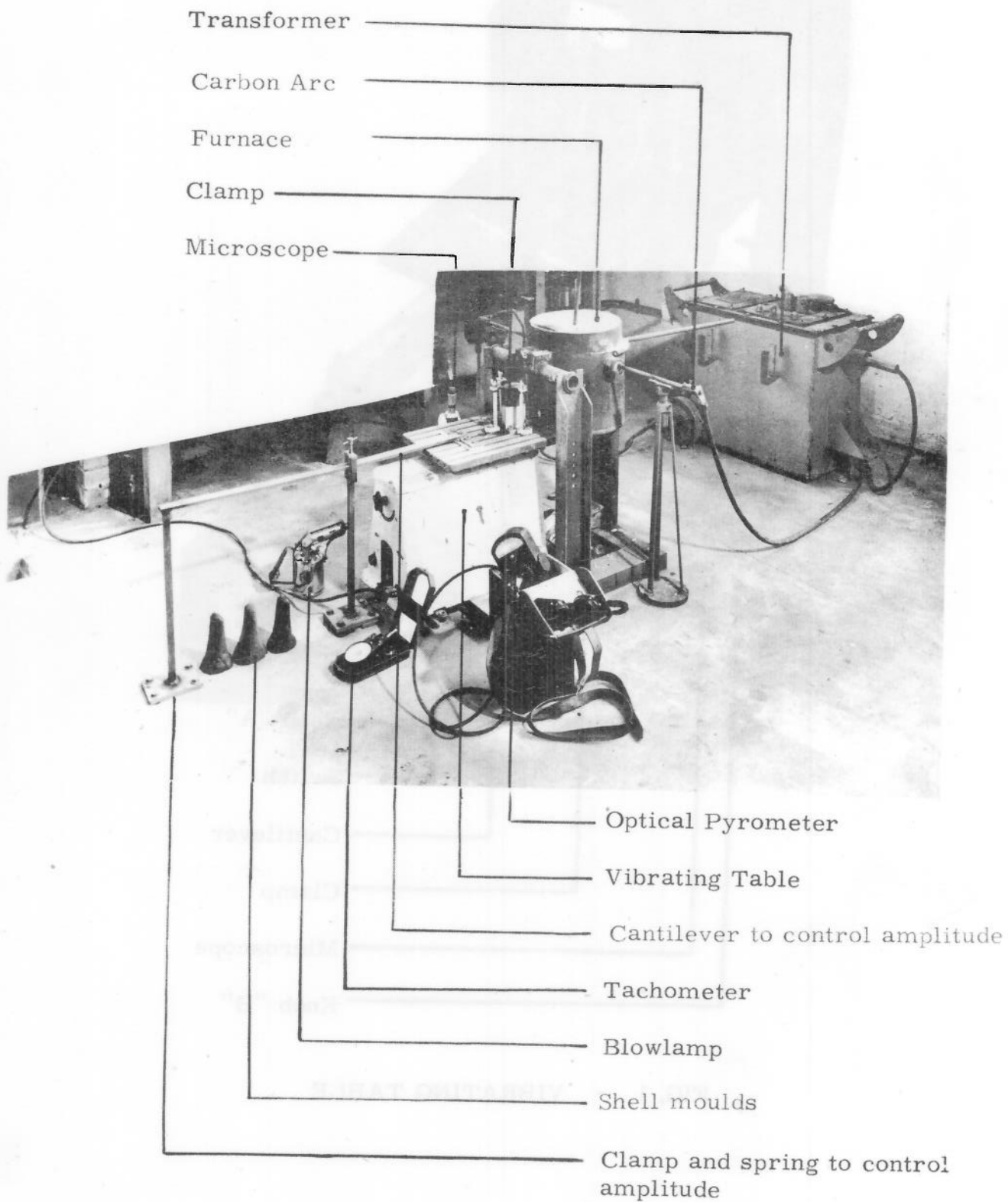


FIG. 2 - ARC FURNACE, ELECTROMECHANICAL VIBRATOR AND FOUNDRY EQUIPMENT

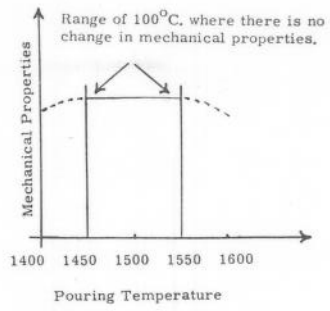


FIG. 3 - EFFECT OF CASTING TEMPERATURE ON MECHANICAL PROPERTIES OF H. R. CROWN MAX (DIAGRAM)

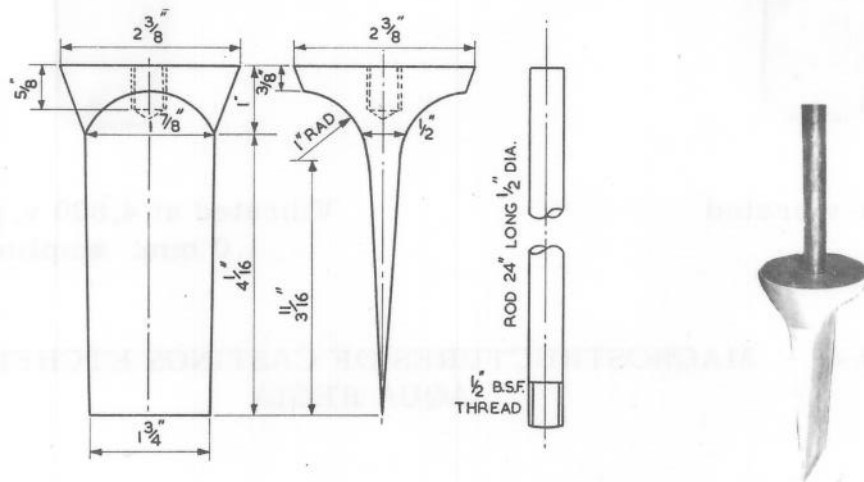


FIG. 4 - PHOTOGRAPH AND DESIGN DATA OF PATTERN FOR TEST CASTING

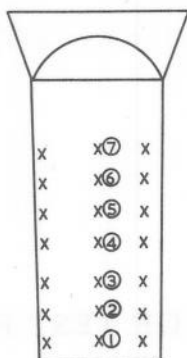


FIG. 5 - DISTRIBUTION OF HARDNESS TESTS



Non-vibrated



Vibrated at 4,800 v. p. m. and
1.0 mm. amplitude

FIG. 6 - MACROSTRUCTURES OF CASTINGS ETCHED IN
AQUA REGIA

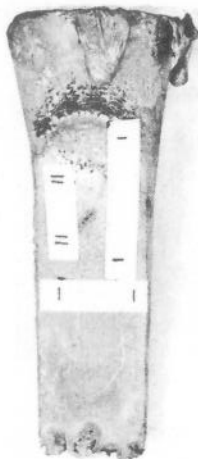
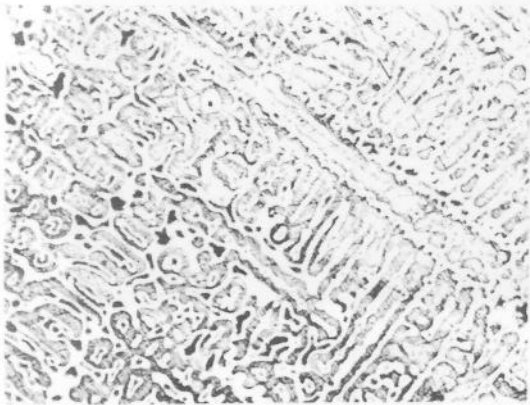
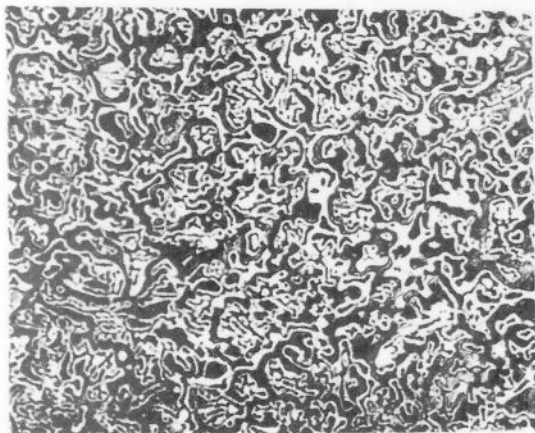
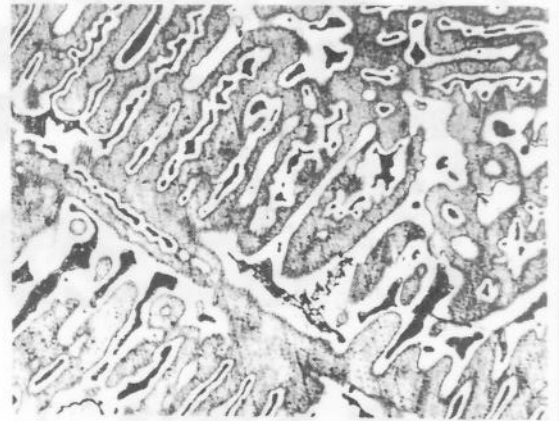


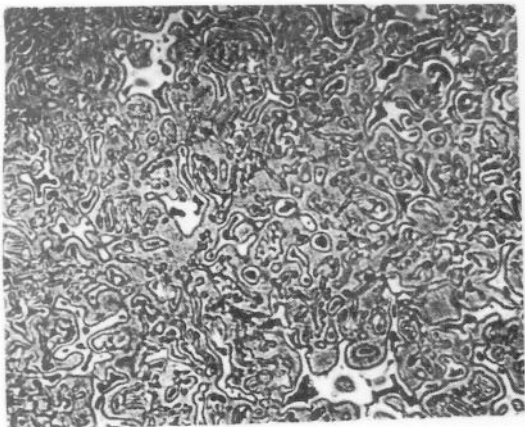
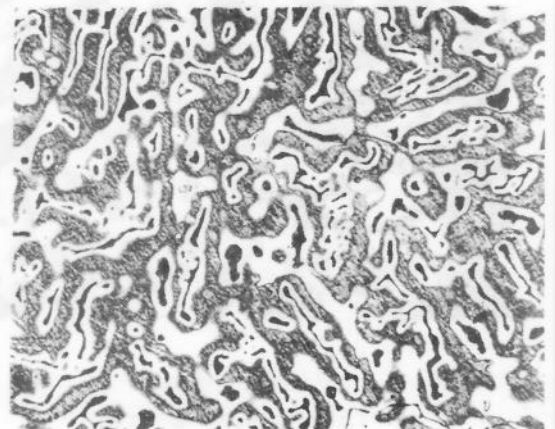
FIG. 7 - POSITION OF TEST PIECES IN TEST CASTING



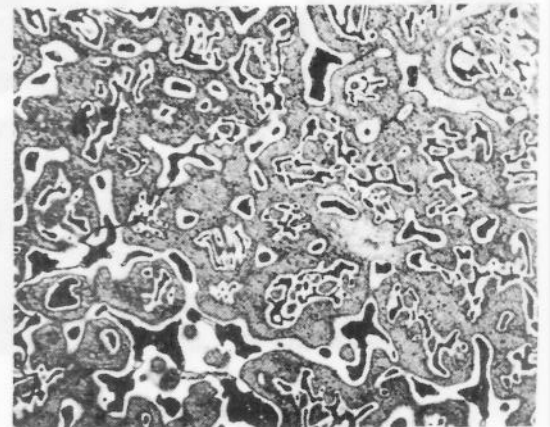
Static



Vibrated at
75 v.p.s. &
2 mm.



100 v.p.s.
& 2 mm.

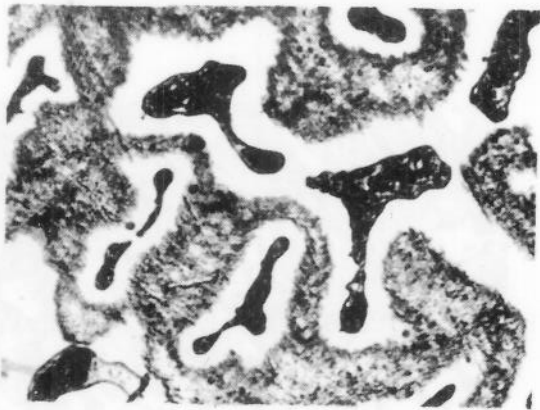


H. R. CROWN MAX

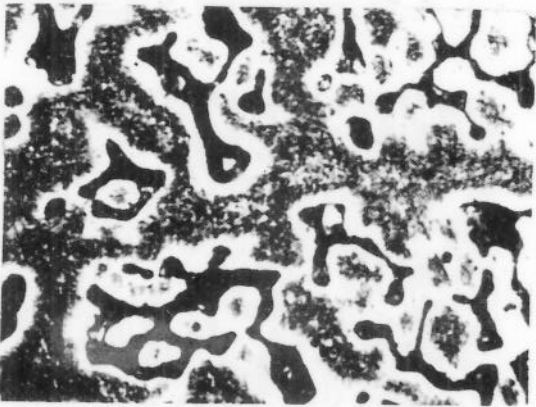
MICROSTRUCTURES OF NON VIBRATED AND VIBRATED CASTINGS
ETCHED IN AQUA REGIA

FIG. 8 - MAGNIFICATION X 100

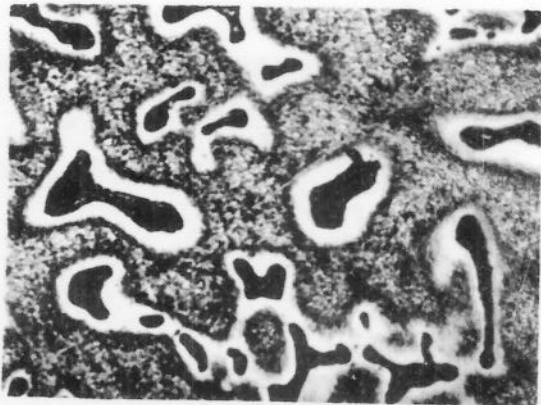
FIG. 9 - MAGNIFICATION X 200



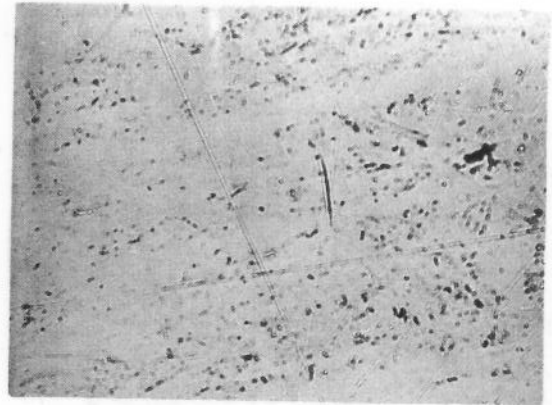
Static



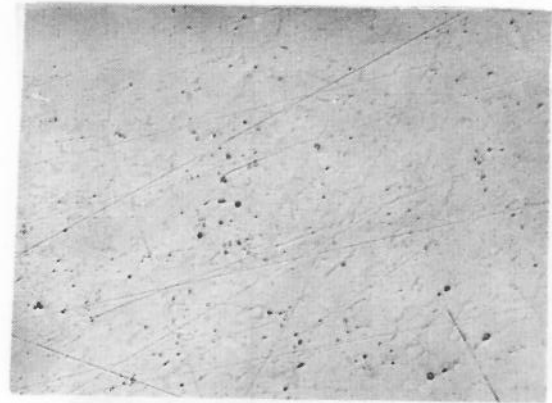
Vibrated at
75 v.p.s. & 2 mm.



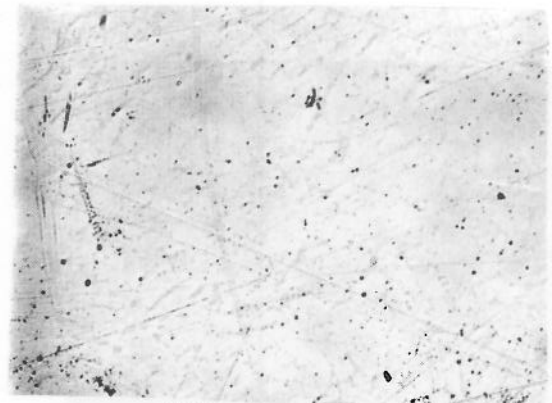
100 v.p.s. &
2 mm.



Static



Vibrated at 75
v.p.s.



100 v.p.s.

H. R. CROWN MAX

FIG. 10 - MICROSTRUCTURES OF NON
VIBRATED AND VIBRATED
CASTINGS ETCHED IN AQUA
REGIA, MAGNIFICATION X 600

FIG. 11 - SURFACE EFFECT OF
CASTINGS AS POLISHED
BUT NOT ETCHED X 100

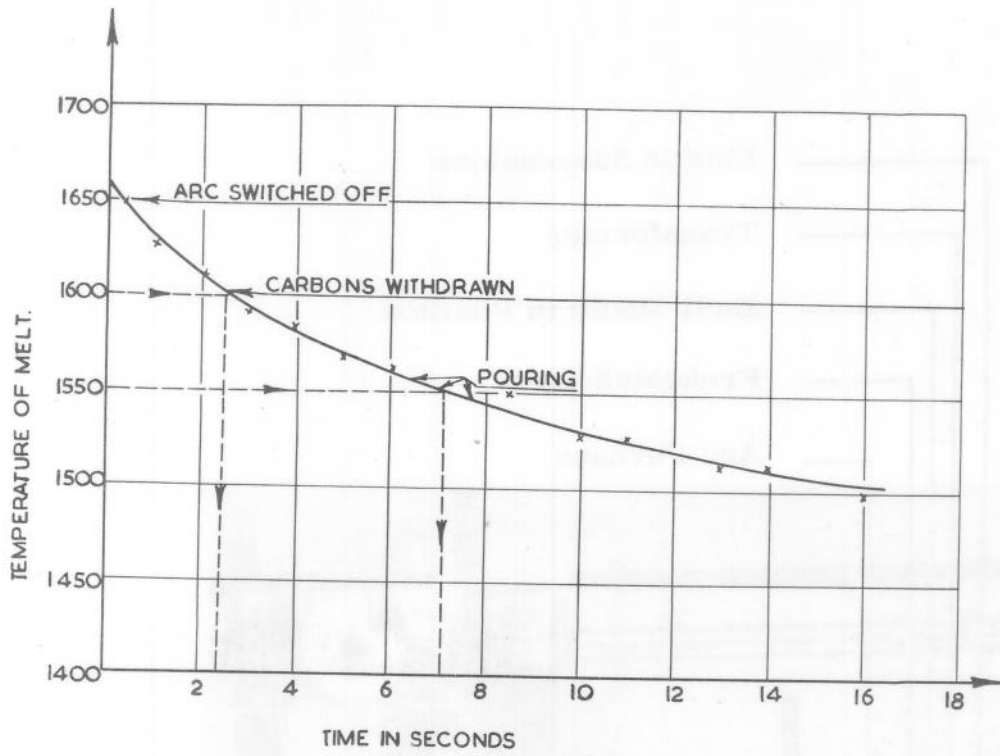


FIG. 12. GRAPH OF RATE OF COOLING OF FURNACE USED TO ESTIMATE TEMPERATURE OF CASTING.

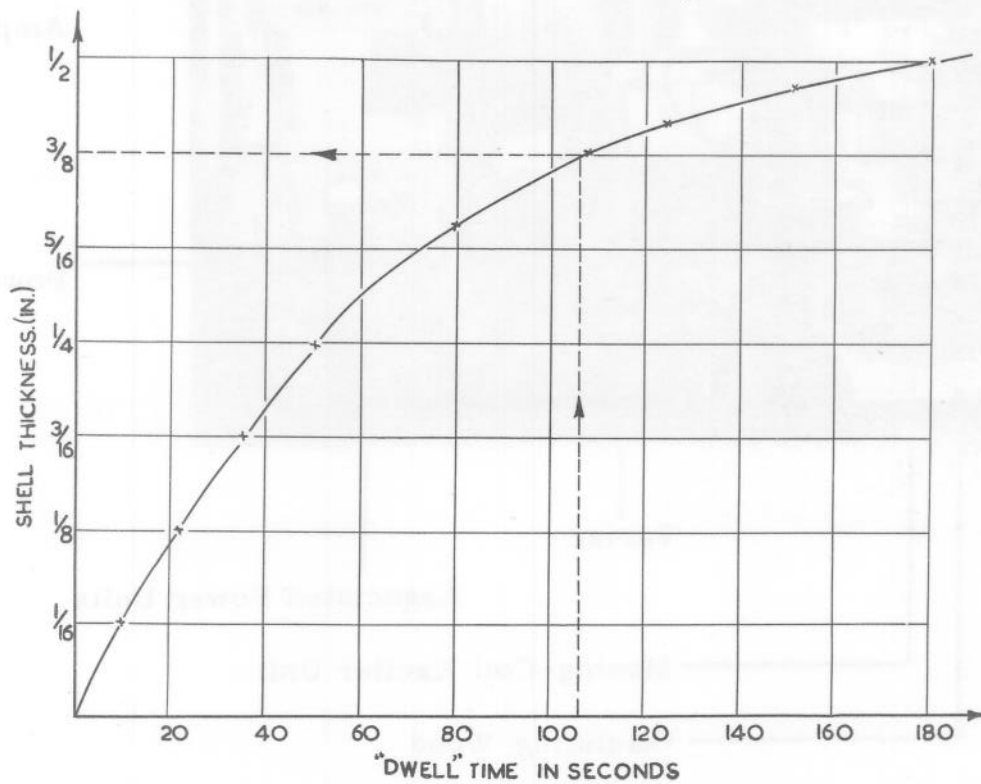


FIG. 13. CONTROL OF THICKNESS OF SHELL MOULD.

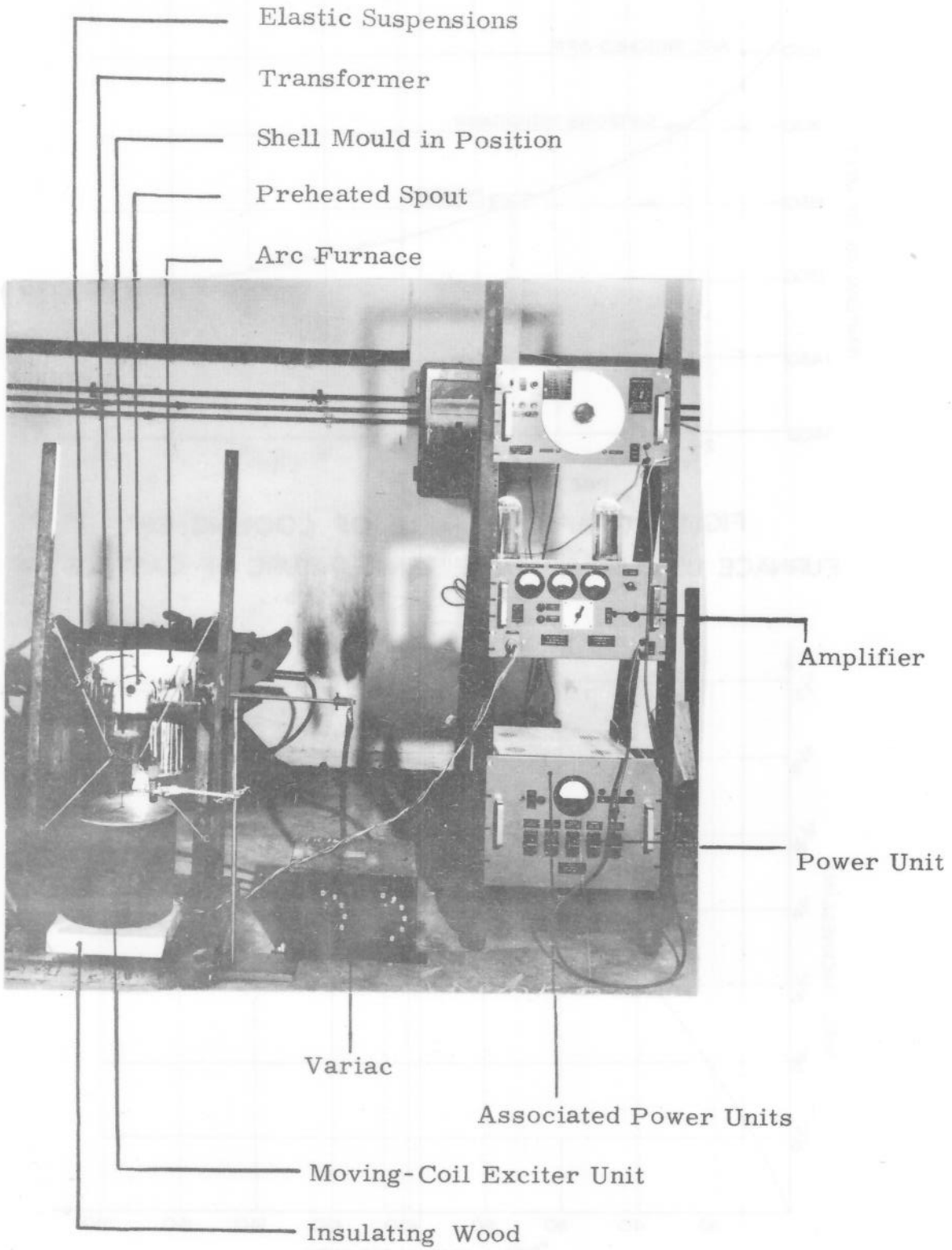


FIG. 14 - ARRANGEMENT OF VIBRATOR, ARC FURNACE AND MOULD

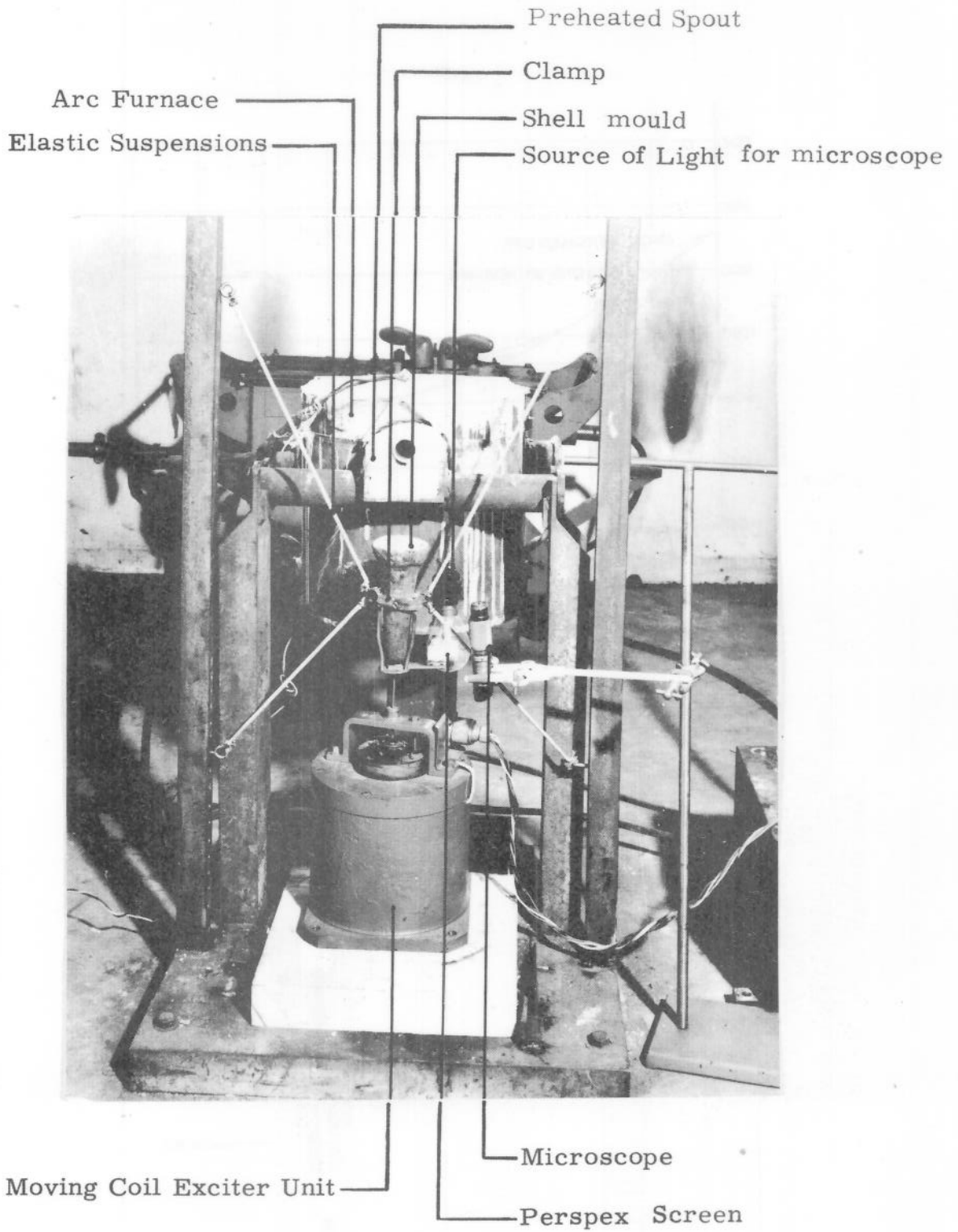


FIG. 15 - ARRANGEMENT OF FURNACE AND MOULD FOR VIBRATING DURING CASTING

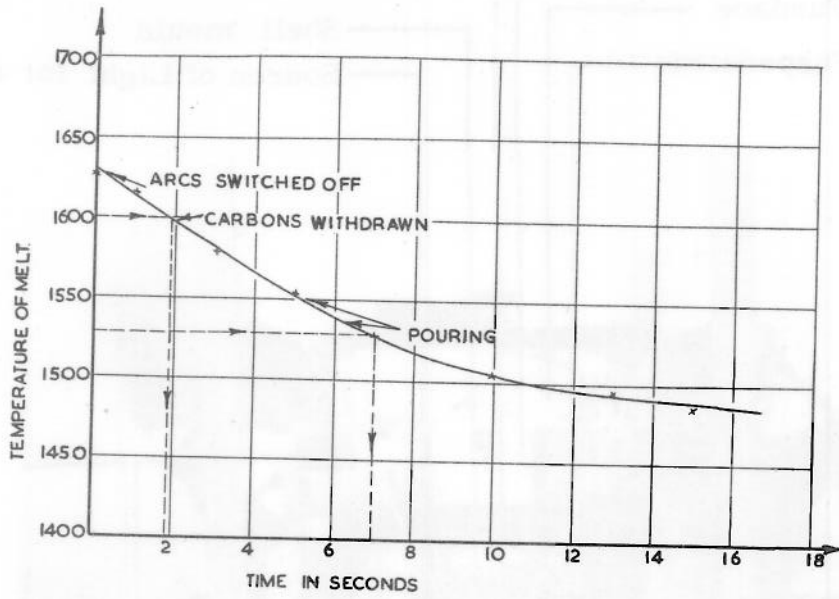


FIG. 16 - RATE OF COOLING OF FURNACE TO CONTROL TEMPERATURE OF OPERATION

MILD STEEL PATTERN

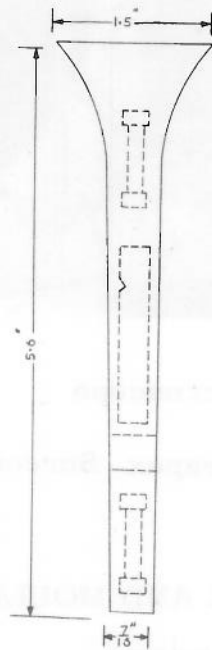


FIG. 17 - POSITION OF TEST PIECES IN CASTING

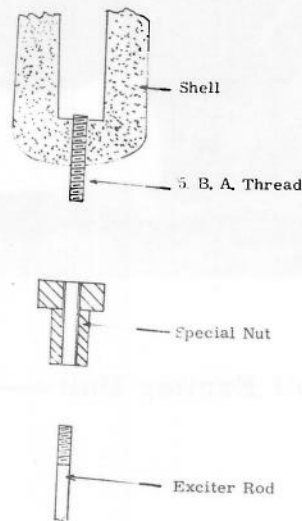
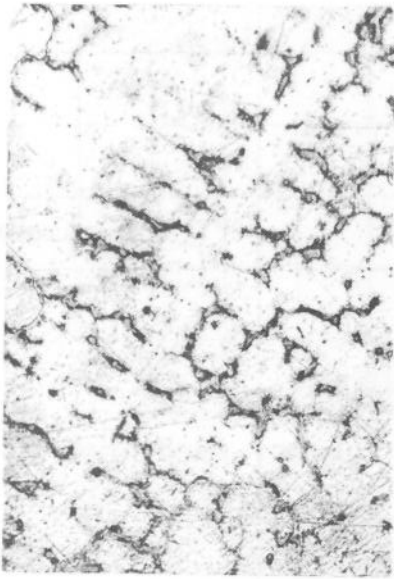


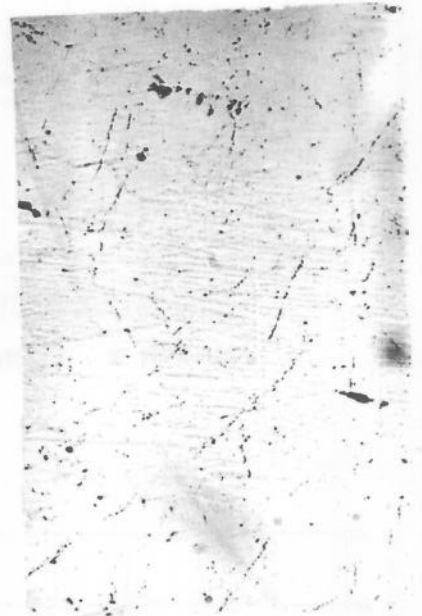
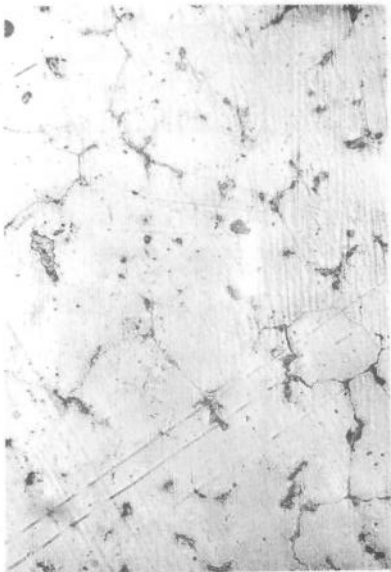
FIG. 18 - ATTACHMENT OF MOULD BOTTOM TO VIBRATOR



Static



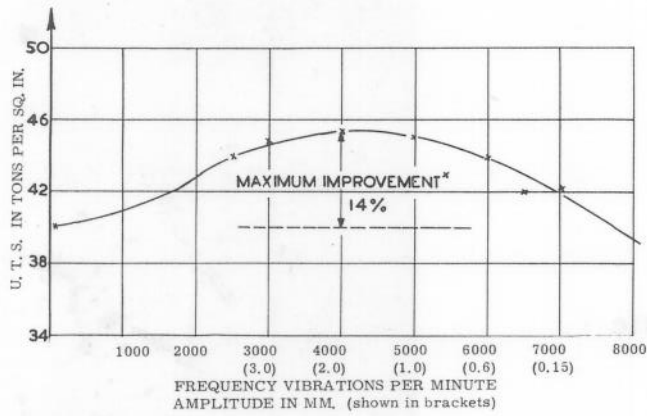
Vibrated
8000 C. P. S.



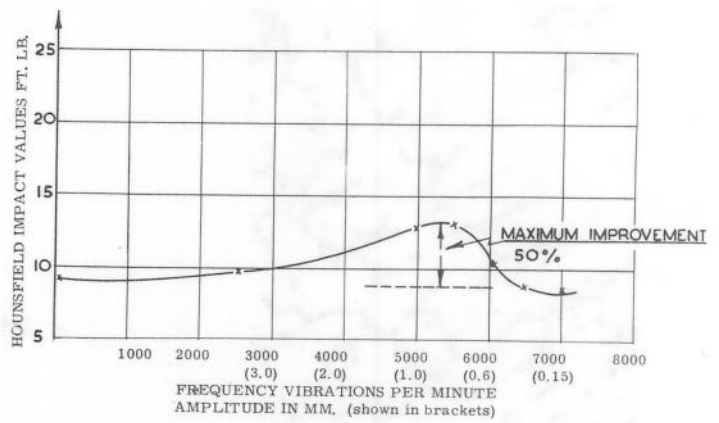
NIMONIC C. 75

FIG. 20 - MICROSTRUCTURE OF
NIMONIC C. 75 X 100
AS ETCHED.

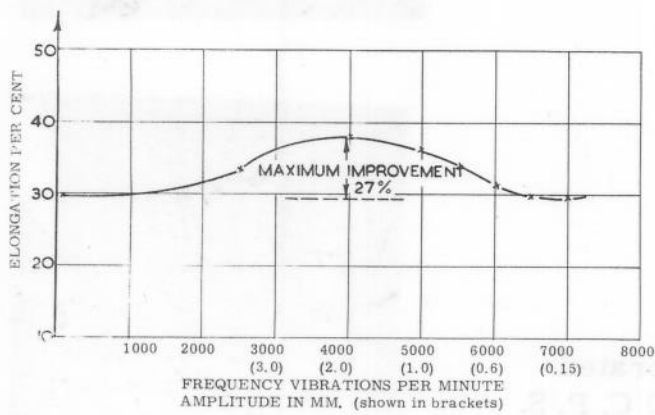
FIG. 21 - NIMONIC C. 75 AS
POLISHED X 100



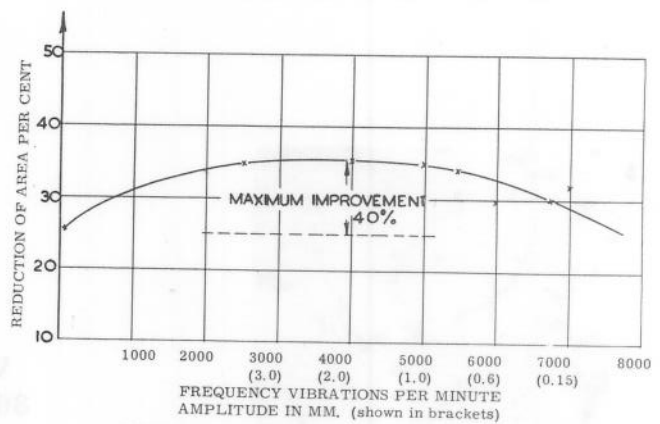
GRAPH.1. ULTIMATE TENSILE STRESS



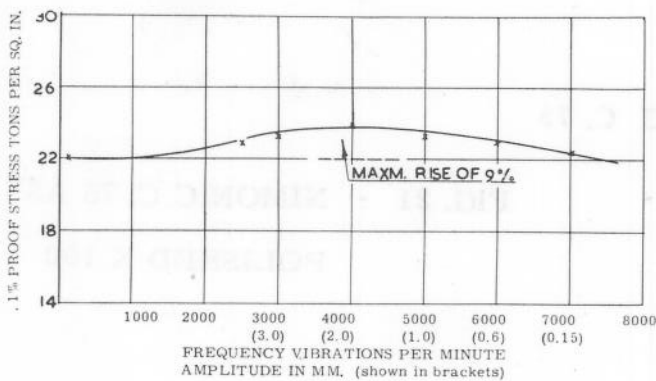
GRAPH 2 IMPACT PROPERTIES



GRAPH.3. ELONGATION

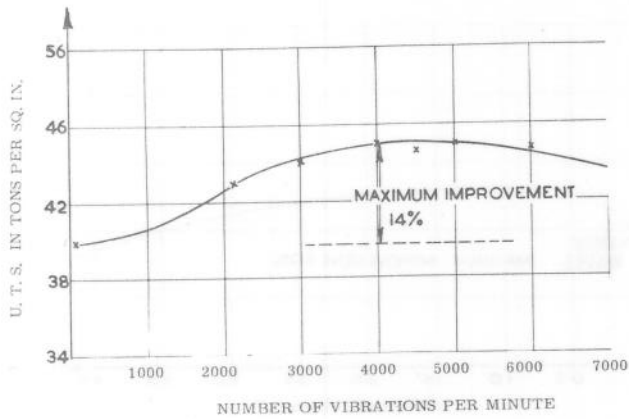


GRAPH.4. REDUCTION OF AREA

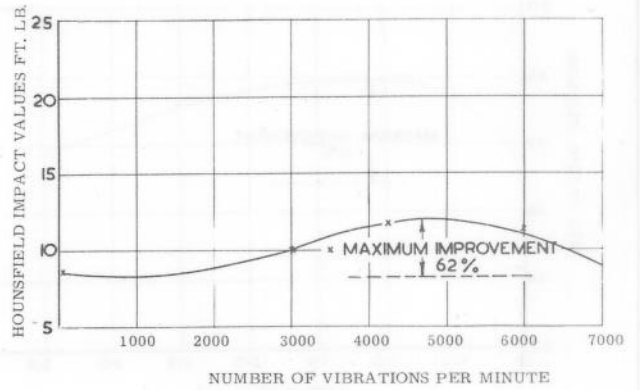


GRAPH.5. .1% PROOF STRESS

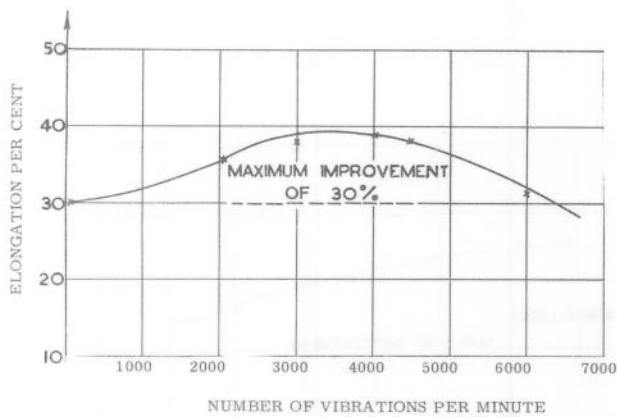
MECHANICAL PROPERTIES OF TEST CASTINGS WITH VARIATION OF FREQUENCY AND AMPLITUDE.



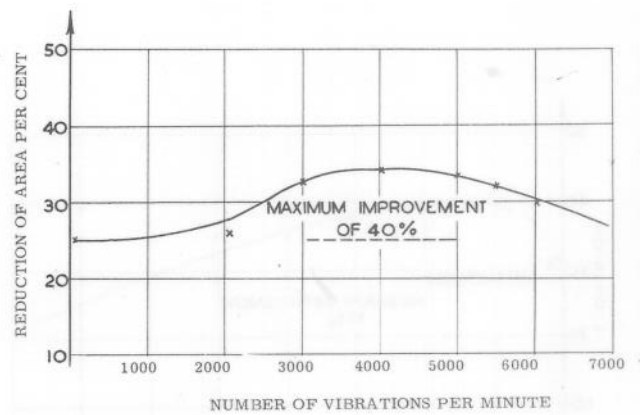
GRAPH. 6. ULTIMATE TENSILE STRESS.



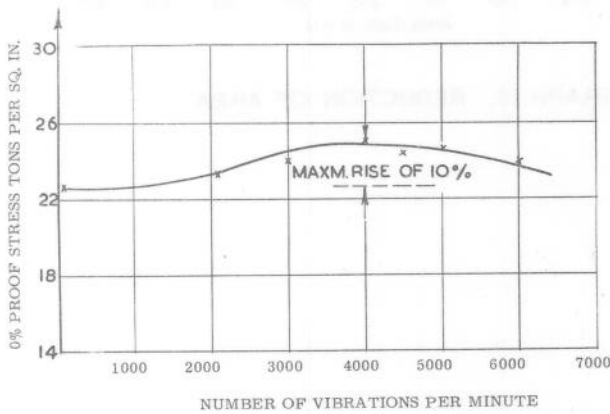
GRAPH. 7. IMPACT PROPERTIES.



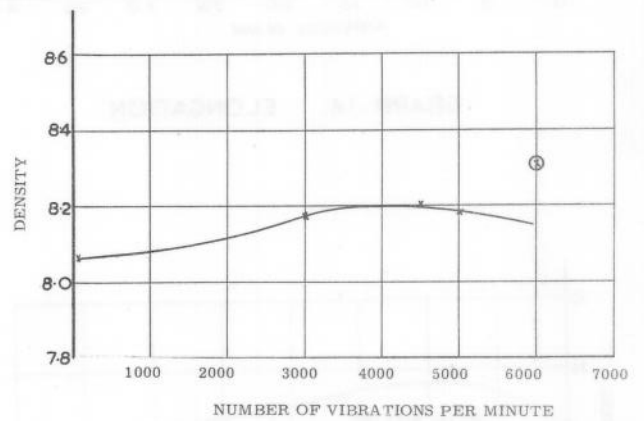
GRAPH. 8. ELONGATION PROPERTIES.



GRAPH. 9. REDUCTION OF AREA.

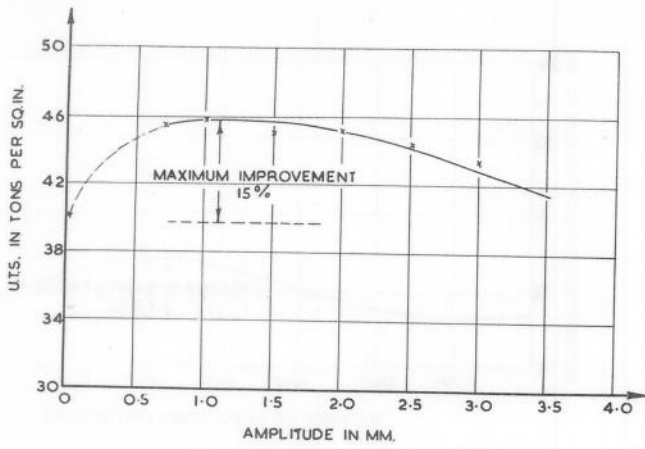


GRAPH. 10. 0% PROOF STRESS.

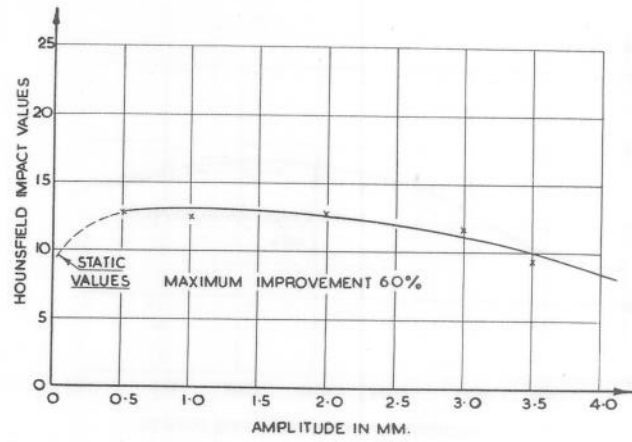


GRAPH. 11. DENSITY OF H.R. CROWN MAX.

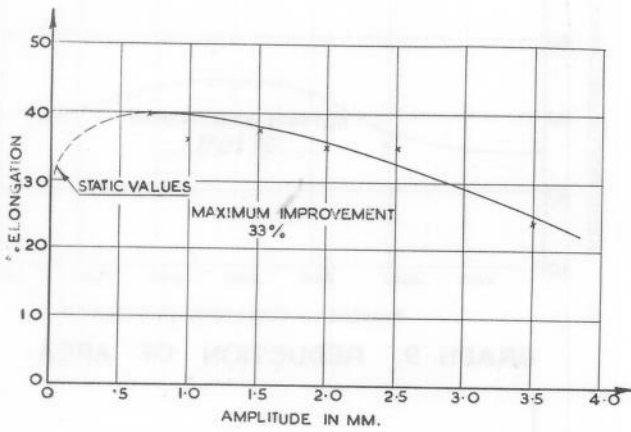
EFFECT ON MECHANICAL PROPERTIES AND DENSITY OF VIBRATION AT FIXED AMPLITUDE AND VARYING FREQUENCY.



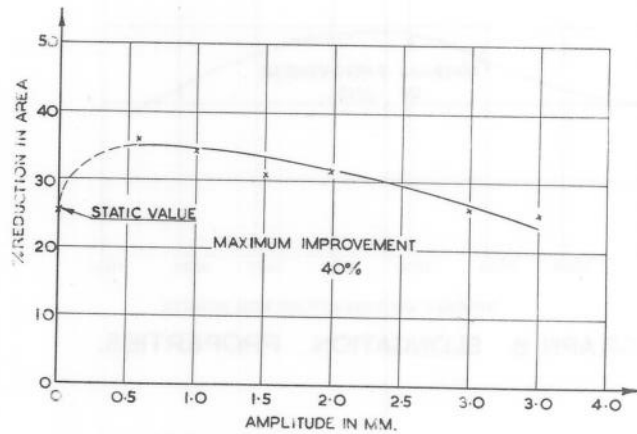
GRAPH.12. ULTIMATE TENSILE STRESS



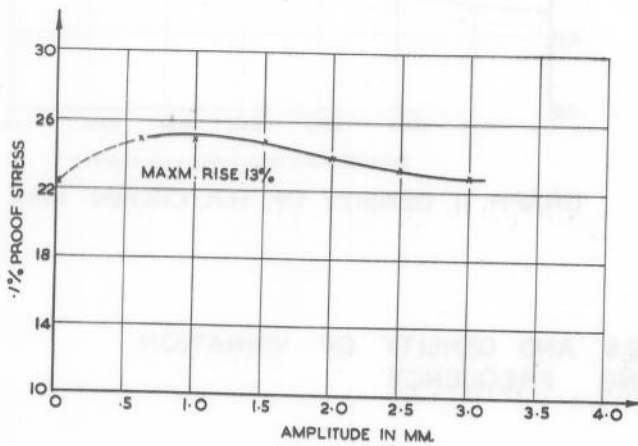
GRAPH.13. IMPACT VALUES



GRAPH.14. ELONGATION

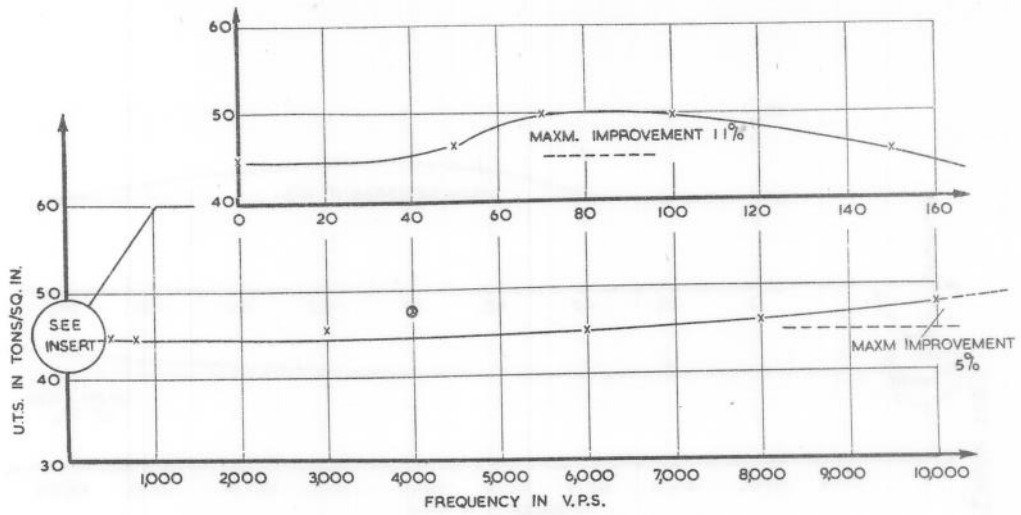


GRAPH.15. REDUCTION OF AREA

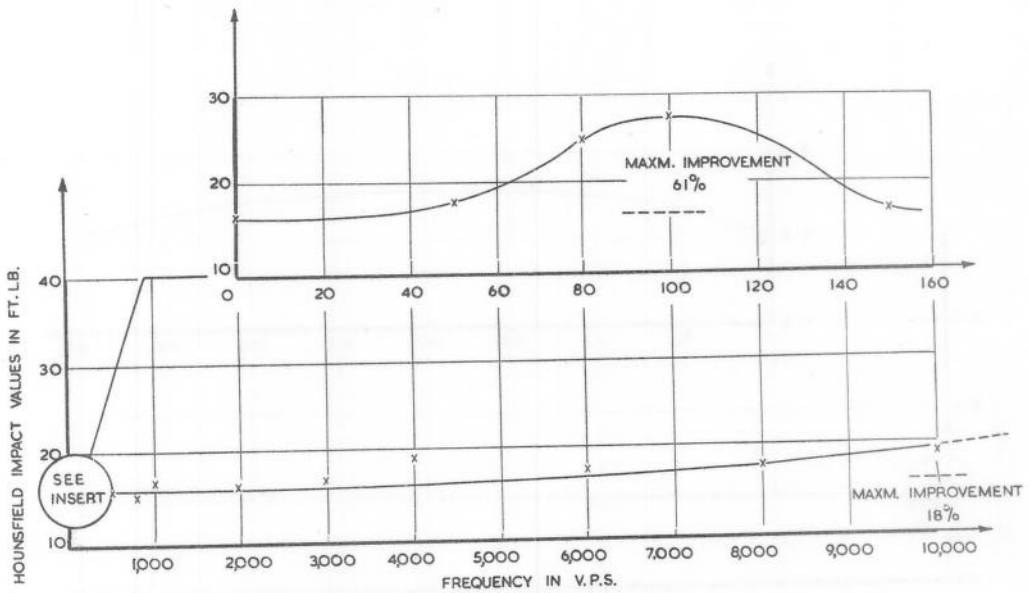


GRAPH 16 .1% PROOF STRESS

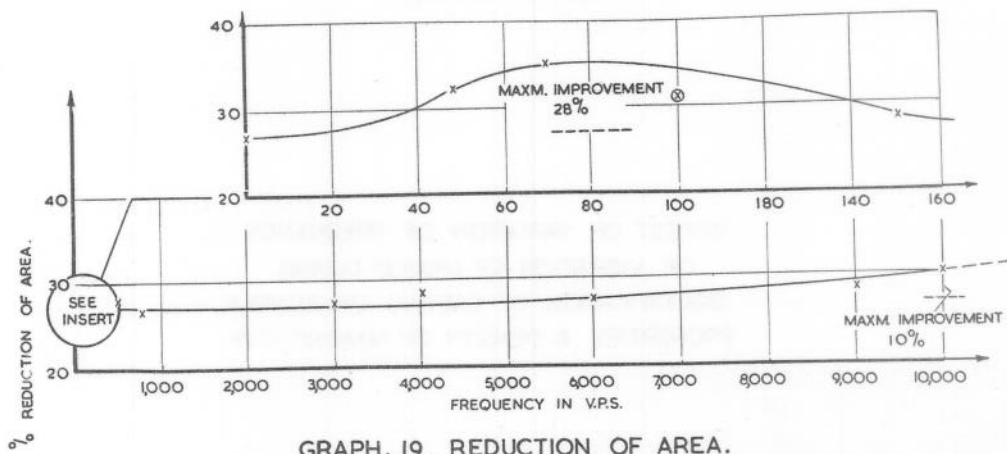
EFFECT ON MECHANICAL PROPERTIES OF VIBRATION AT FIXED FREQUENCY OF 4000 VIBRATIONS PER MINUTE AND VARYING AMPLITUDE.



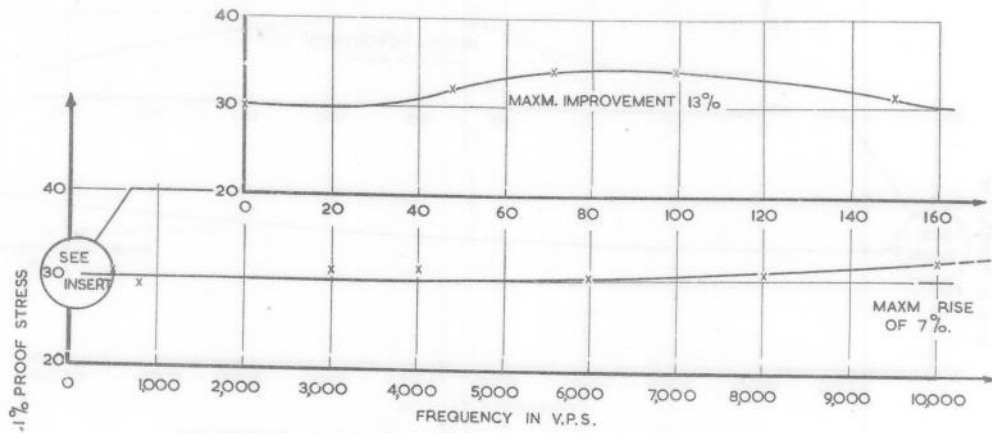
GRAPH.17. ULTIMATE TENSILE STRENGTH.



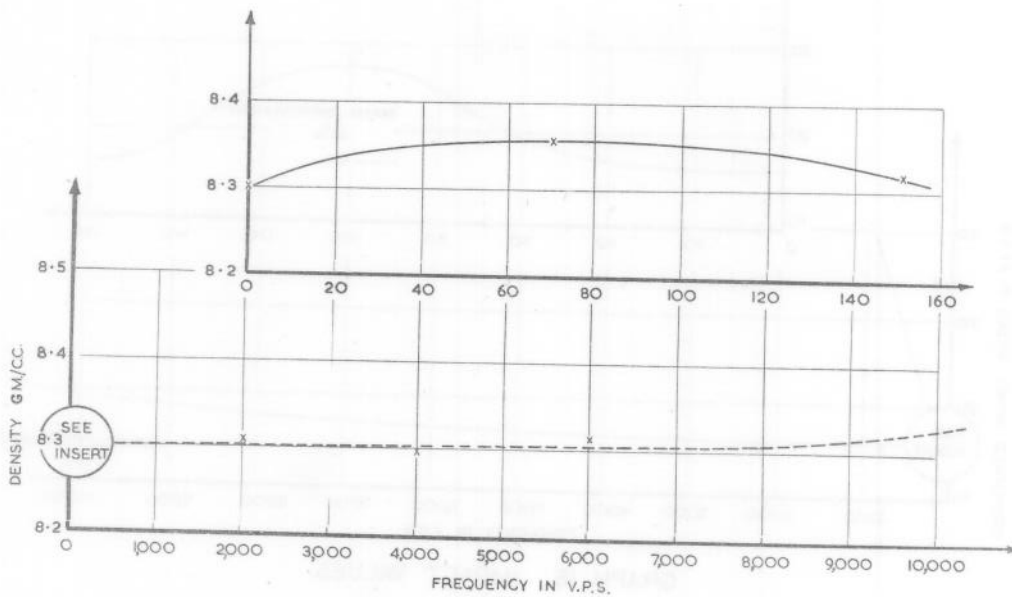
GRAPH.18. IMPACT VALUES.



GRAPH.19. REDUCTION OF AREA.



GRAPH. 20. PROOF STRESS.



GRAPH. 21. DENSITY.

EFFECT OF VARIATION OF FREQUENCY
 OF VIBRATION OF MOULD DURING
 SOLIDIFICATION OF CASTING ON TENSILE
 PROPERTIES & DENSITY OF NIMONIC C.75.