JOURNAL OF MATERIALS SCIENCE **35** (2000) 3327–3335

Effect of low frequency vibration on macro and micro structures of LM6 alloys

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This study summarises research into the effect of low frequency mechanical vibration on the macro and microstructures of LM6 [Al-Si 12.30%] alloy. Vibration at varying frequencies between 15 and 41.7 Hz and amplitudes between 0.125 and 0.5 mm has been applied to both unmodified and metallic sodium modified LM6 alloys during solidification. The effect of low frequency vibration on the grain size, shrinkage pipe and eutectic silicon were analysed using quantitative metallography. The results indicated that

(1) The pipe in the ingot was reduced by vibration with increasing frequency and amplitude.
(2) Pipe elimination was more effective with increasing time of vibration of the liquid.
(3) Vibration with increasing frequency and amplitude produced grain refinement.
(4) Vibration caused coarsening in the eutectic silicon in unmodified and sodium modified LM6 alloy, the extent of which increased with increasing vibration time.
(5) Primary silicon in LM6 alloys was coarsened by vibration.

1. Introduction

Aluminium-Silicon alloys are one of the most commonly utilised foundry alloys because they offer many advantages such as excellent castability, high strength-to-weight ratio, wear and corrosion resistance, pressure tightness and good weldability [1–4]. Applications of these alloys have included automotive cylinder heads, engine blocks, aircraft components and pipe fittings. The mechanical properties of Aluminium-Silicon alloys are related to the grain size, and the shape, size and distribution of the discontinuous phase of the castings. Coarse grain, eutectic silicon, and cavities all reduce the tensile strength, the ductility and the impact strength of the alloys. If the macro- and microstructures are controlled, they should have excellent mechanical properties [5–10].

In the foundry, it is possible to improve properties of alloys by suitable chemical, physical and mechanical treatment, applied either in the molten state or at a suitable stage of solidification. In the chemical treatment, small amounts of titanium and boron are added to the melt to obtain grain refinement [11, 12]. However, if residual refiner compounds remain in the castings they produce hard spots. The addition of sodium or strontium to the melt results in modification due to change of eutectic silicon from plate-like to a branched fibrous form: the tensile strength, ductility and hardness of Aluminium-Silicon alloys are improved [6, 7, 13–17]. However, some recent studies [3, 9, 10, 18, 19] have reported that modified castings are more prone to microporosity than unmodified castings.

A review of the literature [20–47] reveals that the application of mechanical, sonic and ultrasonic vibration has a number of notable effects such as grain refinement, increased density, degassing, shrinkage, and the shape, size, and distribution of the second phase. Vibrational energy has been used in many processes within the metallurgical and engineering field's [20]. According to the review by Shukla *et al.* [21], the application of vibration during solidification was first studied in 1868 by Chernov who set a mould of steel into motion by a gentle reciprocal rocking action, which resulted in refinement of the primary austenite structure. Following this a number of metals and alloys have been treated with vibration during solidification [20–47].

The main effect of vibration on the structure of solidifying metals and alloys is the suppression of columnar growth and the formation of small equiaxed grains. Aluminium-Silicon castings showed refinement of grain size when solidified under vibrating conditions [20, 22–26]. Pillali [25] applied vibration at a frequency of 12 Hz and amplitude of approximately 10 mm on sodium modified and unmodified aluminium-silicon alloys during solidification. He showed that vibration refined the eutectic silicon in the structure of unmodified alloys. In contrast, eutectic silicon was coarsened by vibration in sodium modified alloys. Vibration at 50 Hz and an amplitude of 0.5 mm was applied to a

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eutectic aluminium-silicon alloy by Abd-El Azim [23]. He concluded that vibration refined the eutectic silicon in unmodified alloys, but coarsened it in sodium modified alloys. However, Burbure *et al.* [24] pointed out that vertical sinusoidal vibration at 50 Hz with a maximum amplitude of 5 mm gave coarsened silicon needles which became increasingly short and thick in unmodified aluminium-silicon alloys. Fisher [20] also explained that the eutectic silicon in Al-8%Si and LM6 alloys was coarsened at frequencies of 12 Hz and above.

The object of the present work is to study the effect of low frequency mechanical vibration on the macro and microstructure of LM6 alloy. Vibration of varying frequencies and amplitudes has been applied to both unmodified and sodium modified LM6 alloy during solidification.

2. Experimental procedure

The vertical mode of vibration is the most common because it has a strong influence on the solidification of the casting by fragmentation of the growing grains [27]. Therefore it has been used successively for pure metals and alloys [20, 23, 25, 28, 29]. Horizontal vibration is relatively uncommon. Campbell [27] indicated that oscillatory rotations are suitable only for ingots or castings having rotational symmetry. This mode is unusual in that it can operate most effectively at very low frequencies, typically 0.1–10 Hz.

There are three practicable methods of application of vibration:-

1] vibration of the whole of the mould,
2] vibration of liquid, and
3] electromagnetic induction.

TABLE I Application of vibration at different frequencies and amplitudes to the unmodified and modified LM6 alloy

Frequency [Hz]	Amplitude [mm]	Angular frequency [Rad/sec]	T, Period [Sec]
41.7	0.125		
	0.250		
	0.375	261.7	0.024
	0.500		
31.7	0.125		
	0.250		
	0.375	198.9	0.031
	0.500		
21.7	0.125		
	0.250		
	0.375	136.1	0.046
	0.500		
15.0	0.125		
	0.250		
	0.375	62.8	0.1
	0.500		

Vibration of the complete mould is the most convenient of all processes influencing solidification. This method gives good results for low frequency and high amplitude vibrations. But, its effectiveness is limited by the reflection of the energy at the mould casting interface, particularly for ultrasonic frequencies. Moreover, the contraction of the casting causes an air gap between casting and mould.

The insertion of a probe into the liquid is also a possibility, but, there are a several important aspects that require consideration. A water-cooled probe gives rise to shower effects. The wetting of the vibrating probe by the melt is important to transfer energy. Southgate [30] used a vibration probe which was electrically heated in order to transmit the vibration directly to the liquid metal without passing through any solidifying or pasty intermediate region, which would have attenuated severely the acoustic waves. The heating of the vibration probe also prevented solid metal adhering to the probe [27].

Vertical vibration of the mould was applied to the alloys and the treatments used are listed in Table I.

Melting of LM6 alloy, the chemical composition of which is given in Table II was achieved using a graphite-clay crucible in a gas-fired Morgan type furnace. For those alloys which were to be modified, 0.035 wt% metallic sodium [98.9% purity] was added into the melt at 730°C. Grain refinement of LM6 alloy was carried out by the addition to the melt at 730°C of 0.5 wt% Foseco Nucleant2, which contains titanium and boron in the ratio of 6 : 1. Both unmodified and modified LM6 melt were poured into the graphite mould [200 mm deep with a diameter tapering from 75 mm at the top to 65 mm at the bottom] in both static and dynamic conditions. To determine the effect of vibration during long solidification times the mould was insulated with kaowool: it was vibrated only at a frequency of 41.7 Hz with an amplitude of 0.5 mm. Cooling curves were obtained for both static conditions and for vibration at a frequency of 41.7 Hz and an amplitude of 0.5 mm [48].

The volume and depth of the shrinkage pipes in the solidified ingots were measured. Subsequent sectioning of the ingot often did not coincide with the centre line and therefore the pipes shown in the photographs sometimes indicate pipe volume and depth which seems to differ from the actual values obtained by direct measurement.

Each ingot was sectioned vertically as near to the centre line as possible and one of the halves was machined to a good surface finish for etching in order to examine the macrostructure. The grain size of the etched ingots was assessed by a linear counting technique [48]. Nine metallographic samples were cut from one of the two halves and they were prepared metallographically for examination in the optical microscope [48].

TABLE II Chemical composition of LM6 alloy

	Elements wt. Pct.										
Alloy	Si	Mg	Cu	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
LM6	12.30	0.05	0.07	0.35	0.14	0.01	0.02	0.01	0.01	0.01	Balance

The coarseness of the eutectic silicon in the alloy was evaluated by measuring the average distance between the silicon particles by either the line intercept method for flake silicon, or the areal method for fibrous silicon. Each value of spacing was measured from the average of twenty-five individual measurements. The average inter-particle spacing for the ingot was taken from nine metallographic samples. The average spacing [λ] is given by,

$$\lambda = \left[\frac{1}{M}\right]\left[\frac{L}{N_0}\right] \quad \text{For flake silicon}$$

$$\lambda = \left[\frac{1}{M}\right]\sqrt{\left[\frac{A}{N_0}\right]} \quad \text{For fibrous silicon}$$

where, M is the Magnification, N_0 is the Number of flakes or fibres counted, A is the Area, and L the Length of the intercept line.

3. Experimental results

3.1. Thermal analysis

The solidification times for the unmodified alloy, vibrated at 41.7 Hz and with an amplitude of 0.5 mm, were reduced by approximately 24% in comparison to the static casting.

3.2. Pipe formation

Effect of vibration and grain refinement of the alloy on pipe formation is shown in Figs 1 to 3. Grain refinement with Nucleant2 did not affect the volume and depth of the pipe. The volume of the pipe decreased with increasing vibration frequency and amplitude. However, vibration at the higher frequencies of 31.7 and 41.7 Hz required only an amplitude of 0.125 mm to cause a decrease. Vibration at the lower frequencies of 15 and 21.7 Hz did not have a very large effect on the depth of pipe, Fig. 3. Vibration of the insulated ingot at a

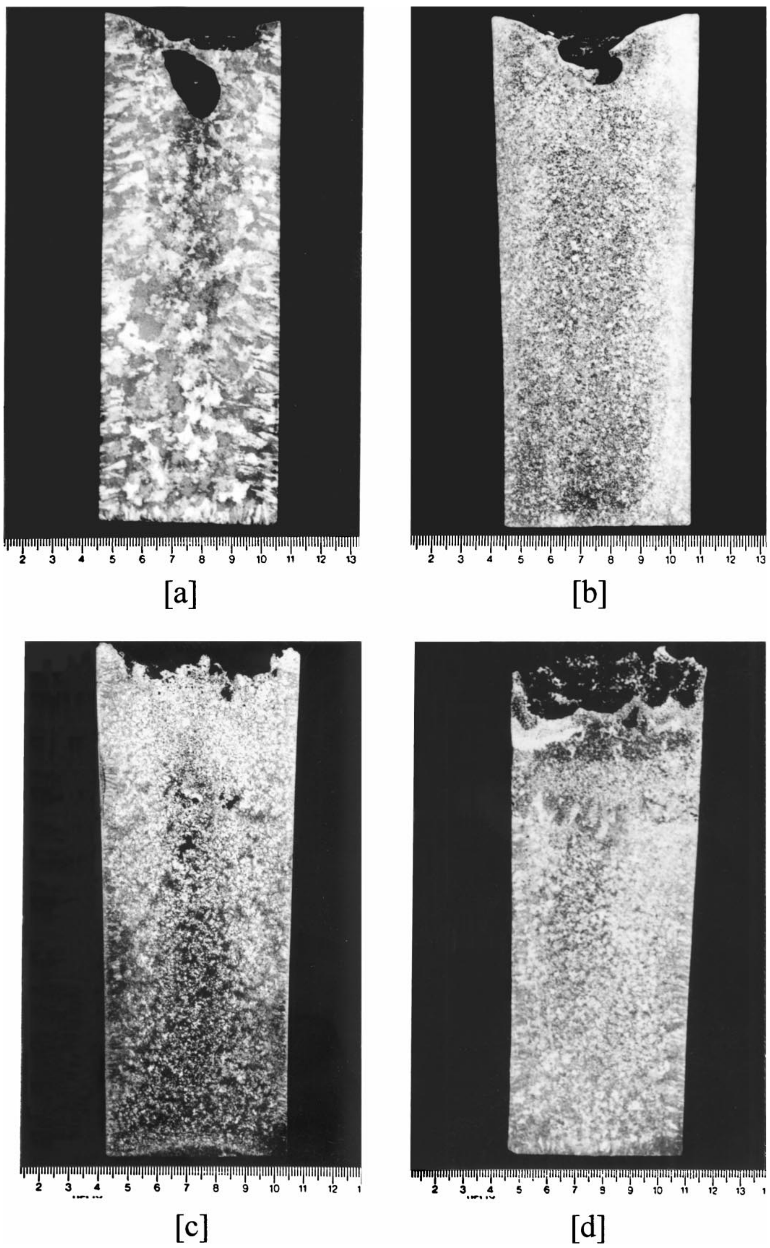

Figure 1 Ingot section of LM6 alloy. [a] In static condition, [b] Grain refined with nucleant2, [c] Vibrated at 41.7 Hz and 0.5 mm, [d] Vibrated at 41.7 Hz and 0.5 mm and insulated.

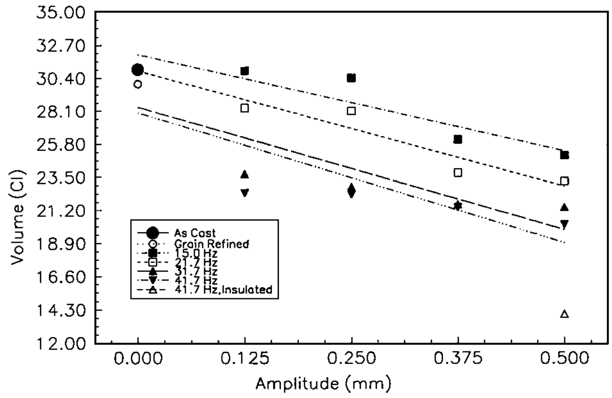

Figure 2 Variation of volume of pipe in LM6 alloy as a function of vibration.

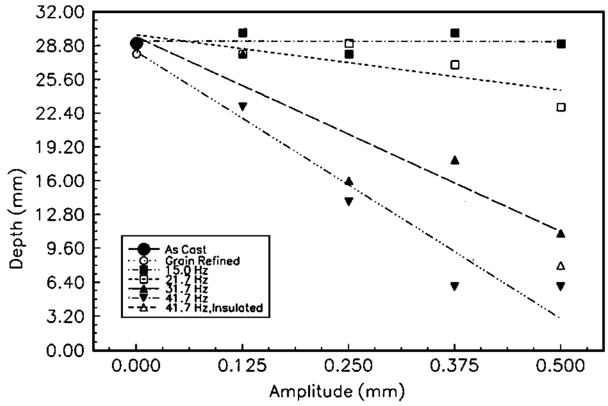

Figure 3 Variation of depth of pipe in LM6 alloy as a function of vibration.

frequency of 41.7 Hz and amplitude of 0.5 mm showed a 55% reduction in the pipe volume, Fig. 1d.

3.3. Grain structure and size

The structure of the ingot in the as cast condition, shown in Fig. 1a, exhibits coarse equiaxed grains in the centre and columnar grains elongated from the chill zone towards the centre. The effect of vibration on the grain size is presented in Fig. 4. Vibration at 15 and 21.7 Hz did not give an appreciable reduction in grain size but a significant decrease in grain size took place when the vibration frequency was increased to between 31.7 and 41.7 Hz and to amplitudes between 0.375 and 0.5 mm. At a frequency of 41.7 Hz and 0.5 mm amplitude the grain size decreased from 3.9 mm to 1.18 mm.

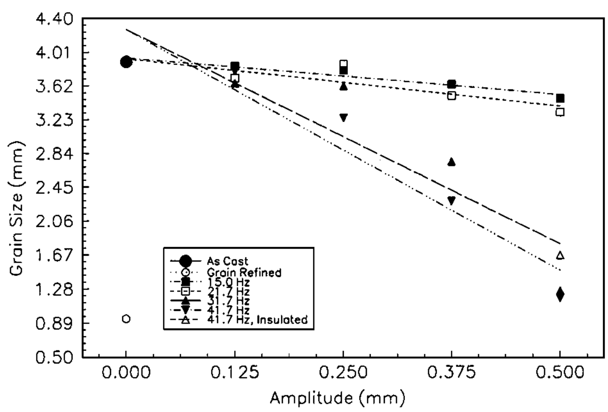

Figure 4 The grain size of LM6 alloy.

It should be noted that a grain size of 0.94 mm was obtained by the addition of Nucleant2. Insulation together with vibration of the mould at 41.7 Hz and 0.5 mm amplitude resulted in fine grains (Fig. 1d) of size 1.67 mm.

3.4. The effect of vibration on silicon morphology and interparticle spacing

3.4.1. Unmodified alloys

The eutectic structure of the alloy in the as cast condition contains relatively coarse silicon flakes embedded in an aluminium matrix, Fig. 5. Some polyhedral and cuboids of primary silicon can also be seen in the microstructure. Vibration with increasing frequency and amplitude coarsened the structure by the separation of silicon flakes at branches in the eutectic silicon, in unmodified alloys: flake silicon became rounded and thickened, Fig. 6. Interparticle spacing measurements in the unmodified alloy also supported the coarsening of eutectic silicon under low frequency vibration. The addition of Nucleant2 to the unmodified alloy caused a 25% reduction in the interparticle spacing, Fig. 7. Only at frequencies in excess 31.7 Hz and amplitudes in excess of 0.375 mm has vibration affected the spacing. The interparticle spacing has increased by a factor of 35% from 8.17 to 11.07 μm after vibration at the highest intensity, reaching 12.55 μm in the insulated mould. The primary silicon has also coarsened with vibration.

3.4.2. Sodium modified alloys

The morphology of the silicon has changed from a plate to a fibrous form as can be seen in the microstructure shown in Fig. 8 for the modified alloy. The primary silicon in the microstructure has completely disappeared due to suppression of the eutectic temperature; the eutectic point has been shifted to higher silicon content by the decrease of the eutectic temperature. Thus modification by metallic sodium has caused the alloy to become slightly hypoeutectic.

Vibration of the sodium-modified alloy has caused a coarsening of the fibrous eutectic silicon, Fig. 9; the interparticle spacing of fibrous silicon in the alloy has also increased. Fig. 10 shows the effect on the interparticle spacing of increasing vibration intensity; the mean value has increased by a factor of 83% from 2.10 to 3.85 μm after vibration at 41.7 Hz and 0.5 mm amplitude.

The effect of modification due to sodium has almost disappeared due to oxidisation, in the insulated mould, vibrated at a frequency of 41.7 Hz and amplitude of 0.5 mm. The eutectic silicon in flake form and primary silicon have also appeared in the alloy. Thus vibration has prevented the fibrous silicon structure forming in the sodium-modified alloy. Vibration of the insulated mould caused 215% increase in spacing.

4. Discussion

4.1. Pipe formation

Silicon in the aluminium silicon alloys decreases the solidification contraction from 6.6% for commercial pure aluminium to 3.8% for Al-12%Si alloy [1, 32]. Vibration with increasing frequency and amplitude decreased the pipe, Figs 2 and 3.

Figure 5 The microstructure of LM6 alloy taken from sample 5 (×400).

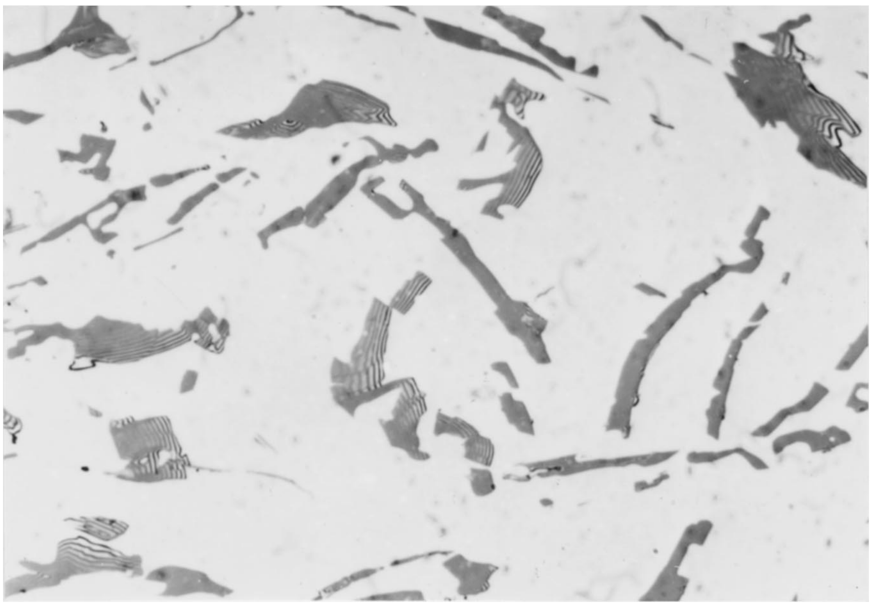

Figure 6 The coarsened eutectic silicon in unmodified LM6 alloy. Vibrated at 41.7 Hz and 0.5 mm. Taken from sample 9 (×1000).

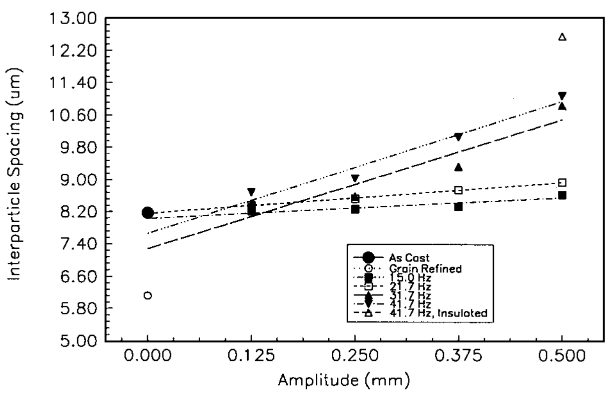

Figure 7 Interparticle spacing in unmodified LM6 alloy as a function of vibration.

Fig. 1c shows a completely equiaxed grain structure in an ingot produced during vibration at a frequency of 41.7 Hz and amplitude of 0.5 mm. The transition of the grain structure from columnar to equiaxed form has occurred by detachment of tiny grains or dendrites on the mould wall, which have moved to the centre of ingot, so decreasing the temperature gradient from the centre to the outside of the ingot. Irani and Kondic [34] explained that the feeding process is controlled by both the total solidification time and by the temperature gradients. The elimination of the pipe by mechanical vibration agrees with the study of Richards and Rostoker [29], and Fisher [20]. Fisher [20] pointed out that mechanical vibration reduced the solidification time of Al-Si8% and LM6 alloy. Only one investigator [33] has reported that increasing frequency between 40 and 50 Hz with an amplitude of 1 mm produced a larger shrinkage and made the pipe flatter and wider.

4.2. Grain refinement

Vibration of the alloy during solidification caused grain refinement, Fig. 4, in agreement with other workers

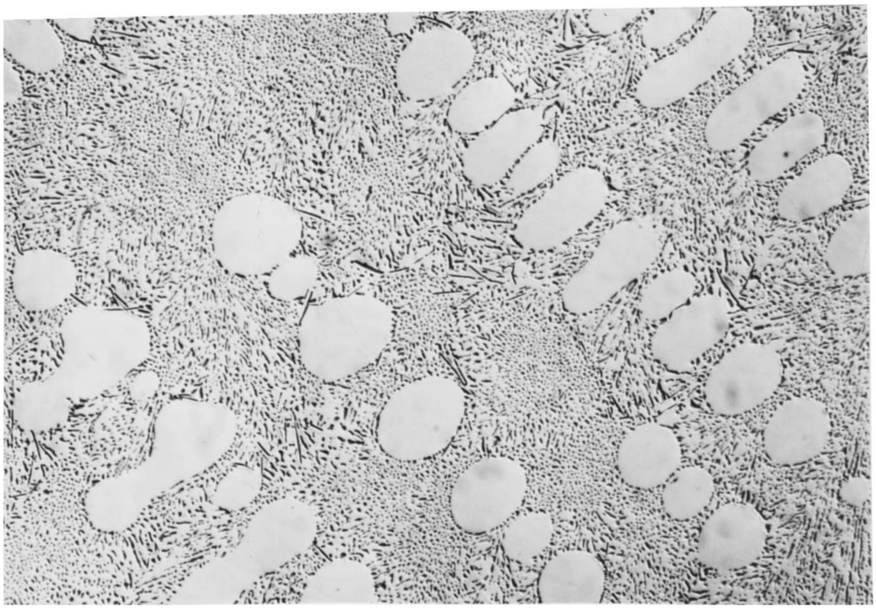

Figure 8 The microstructure of sodium modified LM6 alloy. Taken from sample 9 (×400).

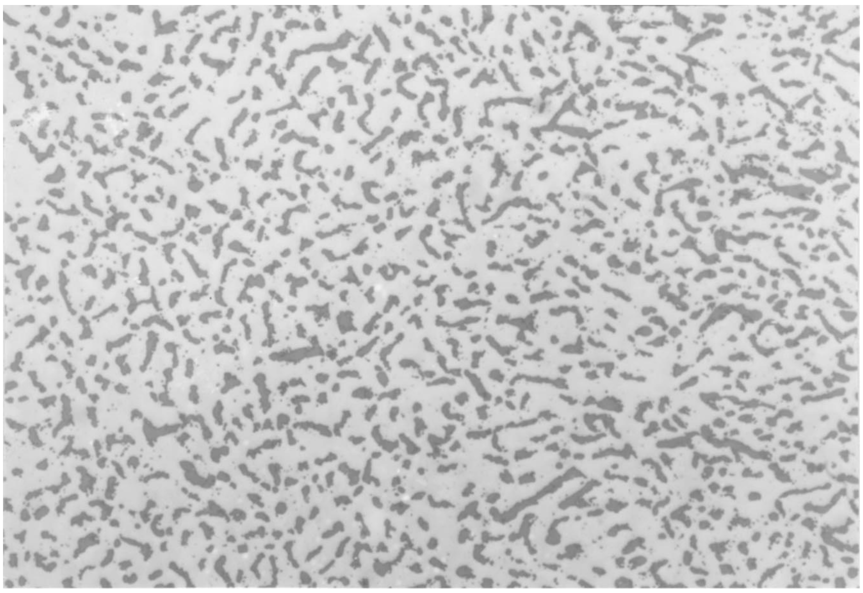

Figure 9 The coarsened eutectic silicon in sodium modified LM6 alloy. Vibrated at 41.7 Hz and 0.5 mm. Taken from sample 8 (×400).

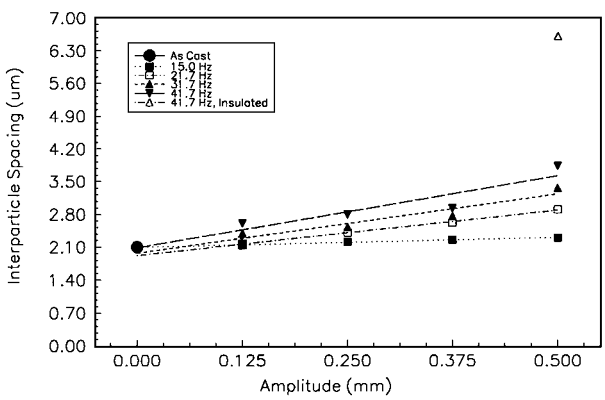

Figure 10 Interparticle spacing in sodium modified LM6 alloy as a function of vibration.

[20, 22–24, 29]. Burbure *et al.* [24] found grain refinement in LM6 alloy when vibrated at 50 Hz while grain refinement in Al-12%Si alloy vibrated at a frequency of 50 Hz and amplitude of 0.2 mm was obtained by Abd-El-Azim [23]. Unfortunately no quantitative measurements were made in their work. Garlick and Wallace [22] vibrated Al-12%Si alloy at 60 Hz, and found grain refinement, but the eutectic cells were considered to be individuals grains. Richards and Rostoker [29] have shown that vibration of Al-4.35%Cu-1.28%Si alloy at a frequency of 60 Hz and 0.5 mm amplitude caused a reduction in grain size by as much as 10 : 1. Fisher [20] showed experimentally that a reduction in grain size of Al-8%Si alloy with vibration at a frequency of 29 Hz is approximately 8 : 1.

The grain refinement mechanism that occurs under conditions of low frequency vibration as used in this study can be explained as follows:

1. *Flow around dendrite arms:* The flow of liquid metal occurs by either laminar or turbulent motion. Since, in this study the flow is caused by forces which are approximately simple harmonic, then the maximum

Reynold's number [R_e] according to Campbell [27] is

$$R_e = \frac{2\pi d \rho f a}{\eta}$$

where $d =$ the diameter of the dendrite arm [5×10^{-4} m], $\rho =$ the density of liquid [2.5×10^3 kgm^{-3}], $\eta =$ the viscosity of the liquid [1.3×10^{-3} Nsm^{-2}], $f =$ the frequency [Hz], $a =$ the amplitude.

Campbell [27] considered that flow is laminar below a Reynold's number of 10, and turbulent above 10^3, while between these values it is mixed. The Reynold's number used in the present experiment lies between 9.05 and 100.6, and thus the flow of liquid should be mixed.

2. *Bending stress:* The vibration induced movement of the liquid between the solid dendrites subjects the growing dendrites to bending stresses. These dendrites have very little strength and ductility because the temperature is so close to the melting temperature. Fragmentation occurs due to impact of the liquid with the dendrites, and the small crystals generated by fracture of the dendrites which will act as nuclei are carried to the centre of the casting. At the same time, detached dendrites will assist in damaging neighbouring arms. In order for these crystals to grow, the centre of the melt should be constitutionally undercooled. Many researchers have suggested this theory of fragmentation during vibration [35, 37–41].

3. *Increase in temperature fluctuations:* In static casting conditions, thermal convection arises from both temperature differences in the melt and pouring momentum, both of which produce density instabilities which cause fluid motion [36]. However, the motion of liquid under mechanical vibration is much stronger, and increases these temperature fluctuations. Since remelting at the necks of dendrite arms may occur, and since the many small dendrites are carried to other parts of liquid by convection currents, the temperature gradients decrease even faster and the melt temperature drops more rapidly. Thus fine dendrites act as a nuclei for equiaxed grain formation. The remelting mechanism is also supported by the result of Jackson [40] *et al.* who found that a "washing" of liquid on growing crystallites or dendrites caused remelting at the neck of dendrites and the detachment of many crystals.

4. *Showering of dendrites:* The movement of liquid during vibration disturbs the surface of the ingot as explained above, so that the dendrites that are attached to the liquid surface will be dispersed into the liquid. These detached dendrites impinge on each other and on those still attached to the wall, causing further extensive dendrite damage, and consequently grain refinement occurs. Therefore, this "showering mechanism" is also responsible for grain refinement and contribution to the formation of equiaxed grains. The shower effects earlier suggested by Balandin and Yakovlev [42], and then Southin [43] showed experimentally that vibration of many pure metals and alloys in a mould at 50 Hz, resulted in grain refinement produced by "showering" of dendrites.

5. *Reduction of solidification time:* Cooling curves of the alloy were obtained during solidification and vibration at a frequency of 41.7 Hz and amplitude of 0.5 mm. The total solidification time of the alloy was reduced by vibration. Genders [44] and Fisher [20] also found that the total solidification time of LM6 and Al-Si8% alloys was reduced by low frequency vibration.

Fragmented dendrites created by turbulence of the liquid, temperature fluctuations, bending stresses and flow of liquid around dendrite arms, are carried to the other parts of liquid, in particular to the central region of the mould, where they act as nuclei. As this solid is replaced by liquid, the temperature of liquid and the temperature gradients decrease even faster. Therefore, the temperature in the mould drops more rapidly and heat will be extracted faster from the mould.

As the temperature of liquid decreases below the solidification temperature many small equiaxed crystals form everywhere in the casting in agreement with Chalmers [45, 46] "Big Bang" theory. This mechanism also operates during vibration producing grain refinement. Genders [44] and Fisher [20] also found that the total solidification times of LM6 and Al-8%Si alloys were reduced by low frequency vibration.

The gas bubbles in the liquid might behave in a "hard" manner, because of the surface tension. They have a high momentum and they can also damage dendrites leading to grain refinement, as explained by Campbell [41].

Grain refinement can also occur by cavitation, which takes place during the negative pressure part of the vibration cycle [20, 30, 47, 49]. The growth of the cavities in one half-period reduces the temperature in the cavity so that crystal nucleation can occur in this region when the temperature drop is sufficient. During the second half-period, as a result of compression of the cavities the crystal can be torn off the cavity surface and the surge wave carries the nuclei into the melt. If the cavities do not grow, they usually collapse on the positive pressure of the cycle, generating large local pressures. This cavitation collapse results in a refinement through dispersion of solid particles that act as heterogeneous nuclei, through the remaining liquid [30, 37, 47].

In conclusion grain refinement in LM6 alloy seems to be operated by many mechanisms, but fragmentation is one of the most important under low frequency vibration.

4.3. The effect of vibration on silicon morphology and interparticle spacing in unmodified and sodium modified alloy

Vibration mainly caused coarsening of the eutectic silicon in both unmodified and modified alloy. In the unmodified aluminium-silicon alloys, eutectic silicon is the faceted phase and grows ahead of the aluminium at the eutectic temperature. The movement of liquid around growing silicon flakes, resulting from the vibration induced bending stress causes fracture in the silicon, which has a very little strength. The broken silicon flakes "swim" to other parts of the liquid, and during this travel, become increasingly thickened and broadened, Fig. 6. The silicon in the microstructure of the unmodified ingot that was insulated and vibrated at

41.7 Hz and 0.5 mm has the largest size because of the long solidification time.

Coarsening of the eutectic silicon depends on intensity of vibration and also on the solidification rate and the presence of large silicon particles are evidence for the increase of the silicon diffusivity in the liquid by vibration.

In sodium or strontium modified eutectic aluminium-silicon alloys growth occurs with a more or less planar solid-liquid interface [50]. The silicon is not a leading phase into the liquid for the growth of eutectic. Thus, fragmentation cannot be effective in these alloys under low frequency vibration. The growth of silicon in sodium modified alloys proceeds after the initial nucleation event, sodium inhibiting nucleation build up at the growth front [14, 51, 52], and preventing the silicon growth front producing a fibrous structure. Low frequency vibration might disturb the solid-liquid interface of silicon, and as a consequence silicon attachment to the silicon sites is encouraged and hence a coarser structure develops. This effect is more dominant when the intensity and duration of vibration increased.

Abd-El-Azim [23] obtained a refinement in the eutectic silicon in Al-12%Si alloy when vibrated at frequency of 50 Hz and amplitude of 0.5 mm, and explained that the silicon flakes become short and fine, and appear in groups of radiating form whereas the cuboids of primary silicon disappear. The eutectic silicon in the sodium-modified alloy was coarsened with increasing intensity of vibration. In contrast, strontium modified alloy showed a refinement of the eutectic silicon with vibration. Burbure *et al.* [24] has shown that silicon needles become short and thick with an increase in vibration amplitude at a frequency 50 Hz. Fragmentation of silicon flakes and increased diffusion rate was given for the cause of coarsening. Fisher [20] explained that the eutectic silicon in Al-8%Si and LM6 alloy coarsened at a frequency of 12 Hz and above, and interparticle spacing increased; however no quantitative measurements were made. Pillali [25] pointed out that vibration of Al-Si alloys at the frequency of 12 Hz and amplitude of approximately 10 mm resulted in a refinement in eutectic silicon. However, vibration of sodium modified Al-Si alloys at the same intensity caused a coarsening. In conclusion, some of the researchers [20, 24] have found coarsening of the eutectic silicon under low frequency vibration while the others [23, 25] obtained refined eutectic silicon. However, in this study, the result of coarsening of fibrous silicon obtained by the addition of sodium under low frequency vibration is in good agreement with the studies by Abd-El-Azim [23] and Pillai [25].

5. Conclusion

The main conclusions deduced from this work on the effect of low frequency vibration on the macro and microstructure of LM6 alloy may be summarised as follows.

[1] The pipe found in the ingot was eliminated with vibration at an increasing frequency and amplitude. But vibration at the highest frequencies and amplitudes produced large holes on the top of the ingot. Pipe elimination was more effective with increased vibration time.

[2] Vibration with increasing frequency and amplitude had a grain refining effect. The grain size was reduced by about 52% by vibration at 41.7 Hz and 0.5 mm amplitude. However the grain size with Nucleant2 was decreased by a factor 76%.

[3] The microstructures observed and the measurement of the interparticle spacing in unmodified and sodium modified alloy suggest:

a] Vibration caused coarsening in the eutectic silicon in both the unmodified and the sodium modified alloy, but that considerable coarsening occurred with vibration at higher frequencies and amplitudes.

b] Coarsening increased with an increasing vibration time of liquid: the interparticle spacing in both unmodified and modified alloy was increased by vibration. However, vibration of the insulated ingot at a frequency of 41.7 Hz and an amplitude of 0.5 mm produced high interparticle spacing as can be seen in Figs 7 and 10, because the insulated ingot has a longer solidification time and vibration time of liquid than the un-insulated ingot.

c] Primary silicon was coarsened by vibration.

d] Vibration gave a considerable improvement, i.e., a decrease in the grain size and the pipe volume, but produced coarse eutectic silicon in LM6 alloy. Coarse eutectic silicon decreases the mechanical properties. Therefore, vibration at frequencies up to 41.7 Hz and amplitudes up to 0.5 mm should not be used for castings of LM6 alloy.

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Received 6 May
and accepted 14 December 1999