DYNAMIC SOLIDIFICATION OF SAND-CAST ALUMINIUM ALLOYS

P. Appendino *, G. Crivellone, C. Mus**, S. Spriano***

***Politecnico di Torino - Dipartimento di Scienza dei Materiali ed Ing. Chimica - Torino**

**** Teksid Aluminium S.p.A. – Via Umberto II, 3/5 - Carmagnola**

Abstract

The effect of low-frequency mechanical vibration, applied during the solidification process, on the microstructure and mechanical performance of aluminium sand-casting was investigated. Both green-sand moulds and chemically bounded sand moulds were used. The vibration was applied to the moulds along the vertical axe. The investigated acceleration range was included between 0.1g and 15g. The effect of different sections and cooling rate was considered, as well as the influence of using different amplitude at constant acceleration. The microstructure and porosity of the ingots was evaluated by optical microscopy and image analysis. The mechanical properties were investigated by tensile tests performed both on cylindrical and different section flat specimens. Microstructure modification of dynamically solidified castings was achieved, consisting on a refined or a completely non-dendritic microstructure, with a globular aspect and quite rare dendrite fragments. The effective threshold acceleration in order to modify the microstructure of the different section considered was assessed. The ingots presenting modified microstructure revealed interesting mechanical performance, that means mainly higher fracture strain.

Riassunto

Vengono qui presentati i risultati della sperimentazione condotta su getti in lega d'alluminio colati in forme in sabbia. Sono stati studiati gli effetti sulla microstruttura e sulle caratteristiche tensili di vibrazioni meccaniche a bassa frequenza applicate durante la fase di solidificazione. Per le forme si è usato sia terra verde che sabbia legata chimicamente. La sollecitazione vibrazionale è stata applicata lungo l'asse verticale della motta. Il range di accelerazione investigato varia da 0.1g a 15g. E' stato valutato l'effetto della velocità di raffreddamento considerando sezioni di diverso spessore. Si è anche valutata l'influenza di differenti ampiezze a parità d'accelerazione.
L'esame microstrutturale e le misure di porosità sono stati condotti con microscopio ottico ad analisi d'immagine.
Le caratteristiche meccaniche sono state misurate con prove di trazione quasi statica sia sulle provette cilindriche che su quelle piatte di differente spessore.
La solidificazione dinamica dei getti ha determinato modifiche microstrutturali in generale affinando la struttura dendritica fino, in alcuni casi, a mostrare una microstruttura con aspetto globulare e rari frammenti detritici.
I getti con microstruttura modificata mostrano caratteristiche meccaniche interessanti soprattutto nell'elevata capacità di deformazione a rottura.

INTRODUCTION

The aim of this work was to obtain a modification of the microstructure of sand-cast aluminium alloys by mechanical vibration. The final goal consists in an improvement of the mechanical performance of sand castings and at this purpose a non-dendritic microstructure is preferable. Traditional methods utilised in order to obtain this effect are rapid cooling rate and addition of grain refining elements. Alternatively we employed dynamic solidification condition, by applying a mechanical vibration to the sand moulds. Because of the expensive equipment required and size limitation, this method was not widely used up to now. Nowadays the new development of dynamic system technology, with low investment, could permit new interesting large-scale industrial application.

The effect of dynamic condition during the solidification of castings was investigated in literature from a long time (1868), but it was not completely clarified due to the wide number of different equipment and materials employed and the often non-systematic investigations and data reports performed [1, 2]. A dynamic state can be applied both by mould vibration (along a vertical, horizontal or rotational axe) and just by casting vibration. Cooled and uncooled probes or magnetic fields can be used at this purpose, but they present technological disadvantages [3, 4]. A wide frequency and amplitude range, obtained by these different equipment, were randomly explored by different authors, starting from low mechanical vibration (1Hz-1 cm) up to high ultrasonic waves (30000 Hz-10μm) [1]. Most of the data refer to graphite, cast iron or steel moulds [1].

In this work vertical low-frequency vibration of sand moulds was applied to A356 alloy castings, according to the interest on automotive application. Sand moulds, bound by thermosetting polymer, present a sufficient mechanical strength for this purpose.

Several data confirm that grain refinement of pure metals by dynamic solidification requires strong acceleration [1,5]. In the case of pure aluminium this means that an acceleration of 4×10^4 g must be

applied. On the other hand, suppression of columnar growth on alloys presenting dendritic solidification can be obtained by applying low or medium acceleration (0.1 g - 2×10^3 g). Grain refinement and non-dendritic microstructure by dynamic solidification was explained in literature considering a higher nucleation frequency by fragmentation of primary dendrite arms, but the discussion on the cause of dendrite fragmentation is still open [7]. Some mechanical effects, like bending stress and fracture of primary arms, turbulent liquid flow around dendrite arms and showering mechanism due to impingement of detached dendrites were supposed [1]. Other authors reported that the main cause was the damage of dendrites due to gas bubbles and cavitation effects [1]. This is also the main cause of refinement in the case of pure metals, where a planar front solidification is involved and quite high accelerations are necessary. Finally thermodynamic aspects, like remelting at the neck of dendrites, due to local recalescence produced by stirring, and reduction of solidification time were also considered [6].
Discordant data were reported about the secondary effects of dynamic solidification. Some authors underlined a decrease of pipes and shrinkage porosity, due to a decrease of the temperature gradient and solidification time [7]. This effect can be related to a higher liquid flow around dendrite arms and to small dendrites carried around in the liquid. At this regard smaller feeders could be employed in the case of dynamically solidified ingots. Furthermore the dynamic state of the liquid causes also a degassing effect. The ingot soundness can take advantage of this issue or it can be a source of higher gas porosity depending of feed-head design.

MATERIALS AND METHODS

The A356.0 alloy was used and its average chemical composition was: Si 6.2%wt, Mg 0.3%wt, Fe max 0.2%, Ti max 0.2%, Al balance. The alloy was modified by Na and the modifier was added, to the melt bath, hour after hour in order to avoid that the modification effect was lost.
Both green-sand moulds and chemically bounded sand moulds (cold box system) were used. Green-sand means a simple mixture of sand-silica, clay (calcium bentonite) and water: pressure was applied to the sand in order to compact it firmly against the face of the pattern. The cold box systems used worked with phenolic resin and isocyanate component, cured by a vaporised amine catalyst.

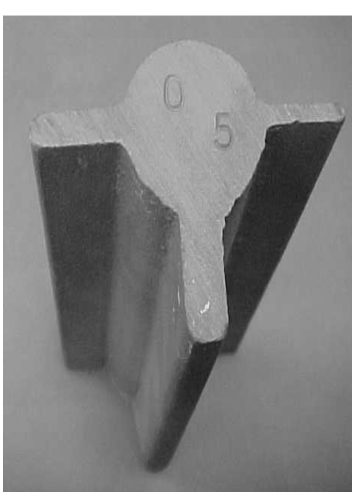

Fig. 1: The photograph reproduces the shape of the prepared ingots. They were formed by a central conic body and three lateral ribs of different sections

The vibration equipment employed consisted of a 900kg heavy machine (2m/s maximum speed, 60g maximum acceleration and 3000Hz maximum frequency). The vibration was applied to the moulds along the longitudinal axe, as a sinusoidal wave. The frequency range explored started from 5 up to 350 Hz and the amplitude range was included between 1×10^{-5} and 1×10^{-3} m. The peak acceleration can be obtain by using equation (1):

$$a = 4\,\pi^2 f^2 x \qquad (1)$$

a = peak acceleration
f = frequency
x = peak to peak amplitude
It was explored the peak acceleration range included between 0 and 15g. The vibration was applied to each ingot for 5 minutes. The melt temperature was checked before each casting and it was of minimum 717 and maximum 733 °C.
The ingot shape can be observed in figure 1. It consisted of a conic shape central body (maximum and minimum diameter 60-40mm) and three rectangular ribs of different section (mm x mm): 5x20 (thin), 7x20 (medium) and 9x20 (thick). This ingot shape was selected in order to investigate the effect of the different vibration parameters on samples of different section and cooling rate. One ingot, representative of each vibration condition tested, was sectioned along the longitudinal axe and twelve metallographic specimens were obtained. In fact for each ingot the microstructure of the top, centre and bottom of the central conic body and of the three rectangular ribs was observed.
The porosity of the ingots was evaluated by image analysis, performed on low magnification microphotographs, as ratio between pore and massive area. Tension tests were performed on three ingots for each vibration condition employed. From each ingot one cylindrical specimen was obtained from the conic central body and three rectangular samples (3-5-7mm thick) were cut from the lateral ribs. All the tensile samples were prepared according to ASTM normative B557-94 ("Standard test methods of Tension Testing Wrought and cast Al and Mg alloy products"). The tests were performed by controlling the cross slide speed with a nominal strain rate of 10^{-3} s^{-1}. All the ingots were thermally treated, before cutting the tensile specimens, according to the T6 condition (solution at 540°C for 4 hours; quench in cold water within 25 seconds; ageing at 160°C for 4 hours).

RESULTS AND DISCUSSION

J.Campbell [1] reported an extensive review about the effects of vibration on solidifying metals, containing useful amplitude-frequency maps. By using these figures the theoretically serviceable conditions, in order to obtain microstructure modification, can be approximately found. The lower limit corresponds to the lowest stress sufficient to bend roots, while the upper limit is the threshold beyond which surface standing wave patterns, with melt ejection, can occur. The amplitude-frequency range included between these two limits can be effective or not, depending on material mould, cooling rate, material and dimension of the ingot, type of the equipment employed.

In this work we tested the conditions reported in figure 2. The range included between 0.1-2.5g was explored in the case of green-sand castings, because of the limited strength of these moulds, while accelerations up to 15g were tested in the case of chemically bounded moulds. In fact this type of mould showed good firmness up to 18g. In the case of 3 and 5g we compared the effects of the same acceleration obtained by using two different frequency-amplitude pairs, one close to the lower and one to the upper theoretic limit.

Considering the microstructure of the α-aluminium phase, all the castings solidified by using acceleration lower than 2.5g presented a dendritic microstructure quite close to the static reference, as well as all the casting solidified by using low amplitude vibrations. In fact no significant microstructure modification was observed on the castings solidified at 3 or 5g, obtained by using vibration conditions close to the lower theoretic limit (Figure 2). On the contrary the castings solidified at 5g or higher acceleration, obtained by using amplitudes close to the upper theoretic limit (Figure 2), showed a non-dendritic microstructure both in the central conic body and in the lateral ribs. In figures 3, 4 and 5 the microstructure of the medium thick ribs was reported as an example. All the microphotographs referred to the central part of the rib. It could be observed that while the static ingot (Figure 3) showed a typical dendritic microstructure with long primary arms, the specimen solidified at 5g (Figure 5) presented a substantially non-dendritic aspect. In the case of the ingots solidified at 3g a sort of intermediate microstructure was observed in the lateral ribs, while the central conic shaped had a non-dendritic aspect. In the case of the medium thickness rib solidified at 3g (Figure 4), dendrite fragments were distributed in the matrix with a higher frequency than in the specimens submitted to higher accelerations during the solidification. Furthermore the microstructure of this sample had a refined aspect respect to the static one, with a SDAS of about 40μm respect to the average value of 28μm in the static specimen. This gradient of microstructure modification versus the casting thickness can be explained by considering that thicker is the section of the ingots and slower is the cooling rate, as consequence longer is the time of vibration during the solidification. So it can be expected that the same acceleration will be more effective on thicker and slow cooled section. The metallographic specimens related to the ingots solidified at very high acceleration showed a completely non-dendritic microstructure, with a globular aspect and quite rare dendrite fragments, as in the case of figure 6 (central conic body solidified at 15 g). In any case the microstructure was not significantly refined by using very high acceleration.

So as first it was assessed that the microstructure modification can be obtained, in the investigated cases, by using 3g or higher acceleration during the solidification process, that means that polymeric bounded sand moulds have to be employed. In the second place the use of an acceleration just higher than the assessed threshold and obtained in condition close to the

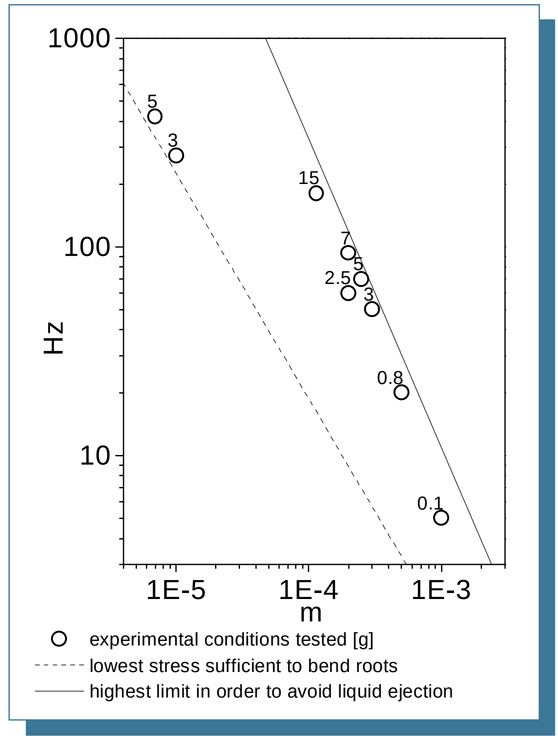

Fig. 2: Vibration condition tested. The two lines represent the lower and upper theoretic limits

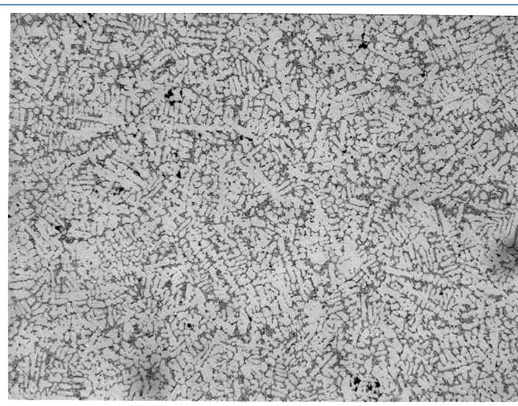

Fig.3: Microstructure of the medium thickness rib of a static ingot. Typical dendritic aspect. - 25x

upper theoretic limit, seams to be effective in order to refine the microstructure in thinnest sections and to obtain a non-dendritic microstructure in the thickest ones. Slightly higher acceleration allows to completely modifying the ingot microstructure, while on the contrary the use of quite high accelerations does not present any significant advantage.
Considering the Si phase morphology it could be noted that the eutectic Si presented a well-modified aspect in all the samples. Furthermore a slight coarser cell dimension was registered in the specimens related to the solidification at 3g or higher acceleration (Figure 7-8). The effect of dynamic condition of solidification on the morphology of the eutectic Si, in modified and un-modified alloys, is a controversial argument in literature [1,1]. In any case data in agreement with our observations are reported in several papers [2,3,4,5]. In these cases authors supposed that the vibration disturbs the envelopment and poisoning layer, that is reach in the modifier element, on the silicon growth front. As a consequence, the silicon diffusion to the growing silicon site is facilitated and hence a coarser structure develops. This effect can be avoided by short time of vibration. In any case it seams to have a moderate effect in the cases investigated in this research.
The porosity of the static and dynamically solidified ingots was evaluated by quantitative image analysis on the metallographic specimens. It was observed that an increment in the acceleration, applied during the solidification process, involved an increment in the average porosity both in the central conic body and in the lateral ribs. The effect was more evident increasing the thickness of the section considered. In figure 9 the data obtained on the thinnest ribs were reported as an example. The almost linear trend of the porosity respect to the acceleration applied could be observed also by comparing the porosity on the top, centre and bottom area of the different ribs. In the most of the cases reported on figure 9 the top showed a higher porosity than the bottom. This trend was not reproduced in thicker sections, where in some cases the bottom presented a porosity peak. The position of the pores along the longitudinal axes can be an indication of the occurrence of a degassing effect due to the mechanical vibration. It seams that in thinner section it was easier to obtain sound ingots and that the most of the pores were confined on the top. This means that opportune feeders could probably avoid them. By comparing the same acceleration obtained at low and high amplitude, it could be remarked that in the thinner sections the samples obtained in

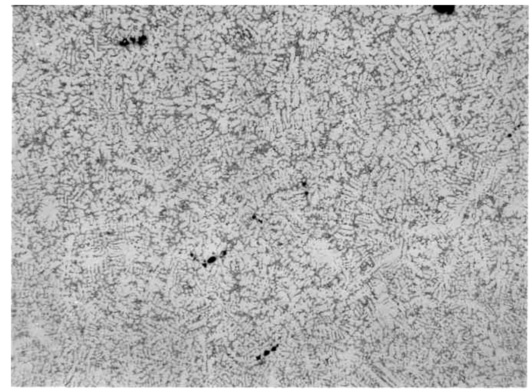

Fig. 4: Microstructure of the medium thickness rib of an ingot obtained by applying 3g acceleration (high amplitude). Refined aspect - 25x

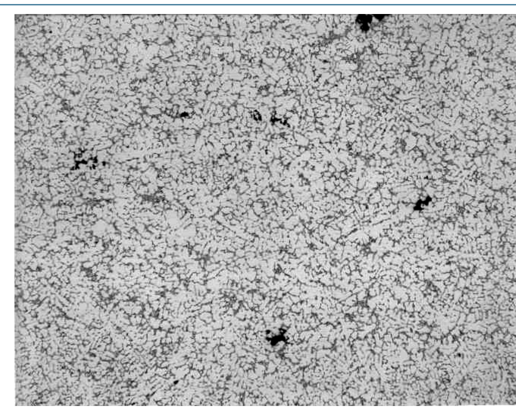

Fig. 5: Microstructure of a medium thickness rib of an ingot obtained by applying 5g acceleration (high amplitude). Non-dendritic aspect - 25x

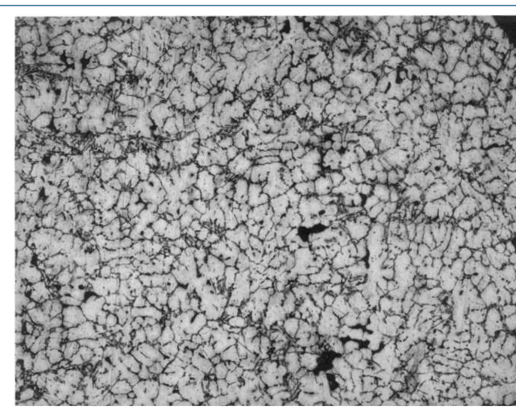

Fig. 6: Microstructure of the conic shape central body of an ingot solidified by applying 15 g. Non-dendritic microstructure - 32x

vibration condition close to the upper theoretic limit (high amplitude) presented a lower porosity. This is less evident as thicker was the section considered, in any case the highest level of average porosity was registered in the case of the central conic body of the ingot solidified at 5g at low amplitude (2.7%). These data are in agreement with some published results [6] where an enlargement and coagulation mechanism of the gas bubbles, due to vibrational treatment, and the preferential location of the pores on the top of the ingots was also reported. So it must be considered that when un-degasified melts are dynamically solidified, feeder dimension, location

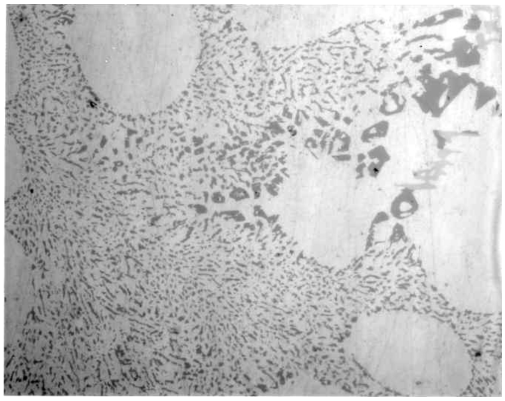

Fig. 7: The microphotograph reproduces the eutectic Si morphology in the conic central body of a static ingot. The alloy was modified by Na - 500x

Table 1. Mechanical data obtained on flat specimens

Tensile sample thickness [mm]	Acceleration applied	Y		UTS		E %	
		average value [MPa]	St.Dev	average value [MPa]	St.Dev	average value [%]	St.Dev
3	a=0	252	0	284	6	2.4	0.6
	a=3g (low amplitude)	246	4	281	8	2.6	1.0
	a=5g (low amplitude)	228	7	267	4	2.9	0.8
	a=3g (high amplitude	248	4	300	8	4.0	0.8
	a=5g (high amplitude)	250	1	282	7	1.8	0.7
	a=7g (high amplitude)	243	4	293	7	4.0	0.4
5	a=0	239	7	274	1	2.3	0
	a=3g (low amplitude)	237	6	272	8	2.6	0.5
	a=5g (low amplitude)	227	5	265	7	2.7	0.6
	a=3g (high amplitude)	238	10	279	13	3.5	1.0
	a=5g (high amplitude)	242	2	272	0	1.8	0
	a=7g (high amplitude)	233	3	269	3	2.3	0.2
7	a=0	226	2	260	1	2.6	0.4
	a=3g (low amplitude)	232	2	262	7	2.1	0.6
	a=5g (low amplitude)	215	6	250	8	2.4	0.3
	a=3g (high amplitude)	223	3	264	5	2.7	0.5
	a=5g (high amplitude)	224	3	253	1	1.7	0
	a=7g (high amplitude)	220	5	253	2	1.8	0.1

and design have to be strictly controlled in order to confine pores in uncritical zones. Alternatively by pouring well-degasified melts, dynamical solidification could be effective in order to minimise shrinkage [6,6].

Tensile tests were performed both on cylindrical specimens cut from the central conic body of the ingots and on flat samples sectioned from the lateral ribs. The tensile tests executed on the cylindrical specimens didn't show any remarkable difference between static and dynamically solidified ingots. The fracture occurred in any case at about 0.7% strain; the yield (Y) and ultimate tensile strength (UTS) average values were respectively close to 217 MPa and 230 MPa. In table 1 the results obtained on the flat samples were summarised. The average values obtained on three samples were reported, with the indication of the standard deviation (SD). In figure 10 two stress-strain curves related to static and dynamically solidified specimens (5mm thick) are reported as an example. It can be underlined that 3mm thick specimens solidified at 3 or 7g (high amplitude) showed an increment of the 66% in the elongation (E) respect to the static reference, with any significant decreasing in the Y value and also an increment in the UTS value. Also considering the 5 mm thick specimens a better behaviour of the specimens obtained at 3g (high amplitude) respect to the static reference can be observed and 52% of the increment in the elongation (E) was reached

Fig. 8: The microphotograph reproduces the eutectic Si morphology in the conic central body of an ingot solidified by applying 5g (high amplitude). The alloy was modified by Na - 500x

(Figure 10). These data could be related to the microstructure modification observed on these types of samples. The correlation between SDAS of cast structures and the fracture strain is sufficiently strong and confirmed from many examples found in the literature [7,8] and the presence of a non-dendritic microstructure seams to produce a similar effect.

This effect is of special significance considering that the fracture strain is the referring specification for the mechanical designer since the safety component, realised by using cast aluminium alloy, has to be verified in the crash resistance. The difference between static and dynamically solidified specimens is less evident in the case of thicker tension specimens (flat 7mm thick and cylindrical samples). This can be related to the higher porosity observed on these specimens respect to the static ones. In any case it could be supposed that the dynamically solidified specimens presented a higher deformation capability, considering that in spite of

a higher porosity they showed a mechanical behaviour closed to the static reference. Unfortunately porosity enhancement probably hid the effect of microstructure on the mechanical performance also in the case of 5g (high amplitude) thin tension samples. According to metallographic observation the specimens solidified in condition closed to the lower theoretic limit (3 and 5g at low amplitude) didn't show any remarkable difference respect to the static reference, both in the case of thin and thick sections.
So, considering that the main objective of this research was to verify the effect of dynamic solidification on the microstructure of sand-castings, it can be concluded that once assessed, case by case, the threshold acceleration to be overcome, dynamic solidification allows to refine or completely modify the microstructure. The feeder design must be opportunely modify in order to avoid gas porosity. Furthermore the preliminary mechanical data obtained evidenced an improvement of the fracture strain of dynamically solidified sand castings.

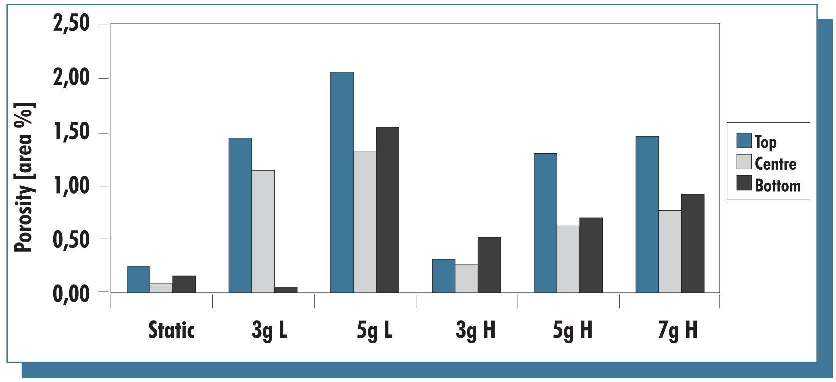

Fig. 9: Porosity data obtained on the thin lateral ribs of static and dynamically solidified ingots. L= low amplitude; H= high amplitude

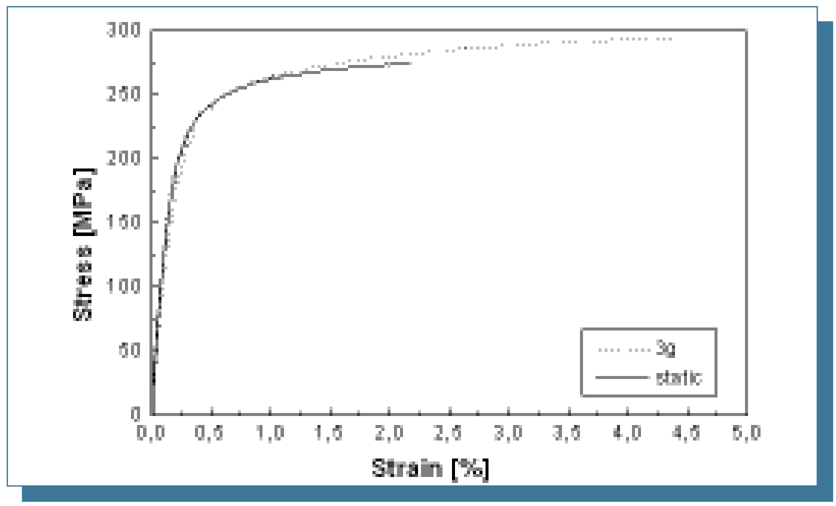

Fig. 10: Stress-strain curves related to tensile tests performed on static and dynamically solidified (3g high amplitude) medium thickness ribs

CONCLUSIONS

Microstructure modification of aluminium sand castings was achieved by low-frequency mechanical vibrations. In fact, while in the static condition the tested castings showed a typical dendritic microstructure with an average SDAS of 40µm (medium thickness ribs), on the contrary dynamically solidified samples, prepared at low acceleration, showed a dendritic microstructure with a refined aspect (average SDAS of 28µm). The use of higher accelerations allowed obtaining a completely non-dendritic microstructure, with a globular aspect and quite rare dendrite fragments. The threshold acceleration to be employed depends on casting section and cooling rate, it was closed to 3g in the case considered.
The ingots presenting modified microstructure revealed interesting mechanical performance, that means mainly higher fracture strain.

Thanks

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