

# THE INFLUENCE OF MELT TREATMENT PROCESS ON THE QUALITY AND PERFORMMANCE OF AL BASED COMPONENTS

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The performance of a mechanical component is often limited by the intrinsic characteristics of the used materials or by weaknesses/limitations inherent to the manufacturing process. Despite their widespread use, casting of aluminum alloys is not easy since they are prone to coarse and heterogeneous structures, usually dendritic. Moreover they are susceptible to hydrogen absorption during melting, requiring a set of processing operations of the liquid metal in order to reduce and control the level of porosity and microstructure after solidification. In the context of the application of aluminum alloys, porosity and mechanical properties are critical factors to the performance of the components. Thus, it becomes important to develop melt treatment techniques that may lead to high sanity and microstructural characteristics that ensure the best possible mechanical performance, without environmental impact, more efficient and easier to control than those existing today.

Ultrasonic vibration treatment (UST) can be a reliable, efficient, fast and environmentally friend melt treatment technique. The experimental results suggest that such technique can increase the actual aluminum alloy density and mechanical properties when compared to traditional melt treatment routes.

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## Introduction

On the last years the demand of cost effective high strength castings for application in industries where superior *strength-to-weight* ratio is a crucial factor, such as the automotive and aeronautical industries, has significantly increased. On this context Al-Si based alloys are the most widely used aluminium alloys for shape casting due to their high fluidity and castability, easy machinability and weldability, good corrosion resistance and mechanical properties. *Caceres et al.* (1) stated that high mechanical strength is usually achieved by the addition of alloying elements such as copper and magnesium as they make the alloys heat treatable, although having a tendency to decrease ductility.

*Ammar et al.* (2) and *Teng et al.* (3) have shown that traditional casting techniques induce high number of defects like porosities, inclusions and coarse microstructure, each of them being characteristic of a specific casting process, that are highly detrimental to the castings mechanical and fatigue properties. They also generate high level of scraped parts. In addition, *Ammar et al.* (2) also stated that fatigue is considered the most common failure mechanism of engineering components and it is responsible for almost 90% of all service failures attributed to mechanical causes. Among casting defects, porosity is considered the key factor controlling the fatigue behavior of Al based castings since they are preferential sites for crack initiation, independently of the loading conditions and the stress applied.

Different studies and models have been developed incorporating the effect of the shape and size of casting defects on the fatigue strength of materials. Some authors proposed simple prediction equations for the fatigue limit with different approaches to obtain the fatigue limit as a function of the defect (4,5,6). However all previous equations assume the defect/pore to be larger than a threshold value that is considered to be around 100  $\mu\text{m}$ . Below this value pores/defects are not the controlling parameter but have an influence similar to other metallurgical constituents, as referred by *Wang et al.* (7).

Foundrymen usually tend to classify porosity as gas holes or shrinkage defects, but in fact, porosities are usually a combination of both. *Gruzleski et al.* (8) as well as *Meidani et al.* (9) have demonstrated that the main source of gas porosities in aluminium castings is hydrogen, which is the only gas with significant solubility in molten aluminium. At solidification point, a large drop in solubility occurs, leading to hydrogen precipitation and development of gas porosities. For this reason, they stated that the hydrogen content in a molten alloy must be kept as low as possible, especially when dealing with high strength casting alloys for critical applications like aerospace or automobile parts.

Taking into consideration the traditional application fields of aluminum alloys, the porosity and mechanical properties are critical factors in the components performance. Thus, it becomes important to develop techniques for treatment of liquid melt leading to a high quality and microstructural characteristics that ensure the best possible mechanical performance of components, without environmental impact, more efficient and easier to control than those existing today.

In the last decades an increasing interest in exploiting the potential of different physical treatment to degas aluminum melts has arise. Such treatment techniques include mechanical or magneto-hydrodynamic stirring and ultrasonic vibration.

Ultrasonic vibration treatment (UST) can be a reliable, efficient, fast and environmentally friend degassing method. Experiments made by Eskin (10) and more recently by Puga *et al.* (11) and Xu *et al.* (12) revealed that it is possible to remove the hydrogen dissolved in aluminium melts by applying acoustic energy to the melt, in order to induce cavitation.

According to Eskin (10), when a liquid metal is submitted to high intensity ultrasonic vibrations, the alternating pressure above the cavitation threshold creates numerous cavities in the liquid metal which intensifies mass transfer processes and accelerates the diffusion of hydrogen from the melt to the developed bubbles.

The main advantages of ultrasonic degassing are the high degassing rate and the reduced environmental impact of the process. Moreover, cavitation promotes the removal of non-metallic inclusions from the melt, playing a major contribution to obtain high sanity castings.

On this work, the effect of ultrasonic degassing on the final density and porosity is assessed. Furthermore, the type of pores, area fraction, average size and maximum size are assessed and their influence on mechanical and fatigue properties of an AlSi<sub>9</sub>Cu<sub>3</sub>(Fe) alloy is presented, for different degassing times. Moreover, other microstructural features, such Si phase and presence of Fe-rich intermetallic compounds, can play also an important role in mechanical behavior, however the main object of this study was the treatment of liquid – degassing in the performance of components.

### **Experimental procedure**

Ultrasonic degassing was performed using the equipment shown in Fig. 1.



Fig. 1 Laboratory unit for ultrasonic degassing.

The ultrasonic device consists mainly of an ultrasonic generator, a transducer, a horn and an acoustic radiator to transmit ultrasonic vibration to the melt. The transducer is capable of converting up to 1.2 kW of electric energy at a resonant frequency up to 25 kHz.

Melting stocks of  $\text{AlSi}_9\text{Cu}_3(\text{Fe})$  alloy (Tab. 1), weighing 4 kg were melted in a resistance furnace equipped with a 170 mm diameter and 180 mm height SiC crucible. Melt temperature was controlled within an accuracy of  $\pm 5^\circ\text{C}$ .

Tab. 1 Chemical composition of alloy

Alloy	Chemical Composition (%wt)							
	Si	Fe	Mg	Cu	Mn	Zn	Sn	Al
<b><math>\text{AlSi}_9\text{Cu}_3(\text{Fe})</math></b>	9,15	0,66	0,18	2,25	0,26	0,47	0,10	Bal.

A 60 mm diameter radiator made of a titanium-based material was introduced in the melt on a length of 50 mm. Degassing tests were conducted using 750 W at a frequency of  $19.8 \pm 0.2$  kHz, during no treatment, 1 and 3 minutes, and melt temperature of  $700^\circ\text{C}$ . Before degassing, and after each degassing period, 15 cylindrical samples with 14 mm in diameter and 110 mm long were cast on a metallic mold and used for mechanical and fatigue testing. At the same time, 3 samples for alloy density evaluation, using the Reduced Pressure Test (RPT) and the apparent density measurement method were cast.

Samples for microstructure characterization were taken from each cast sample by sectioning them perpendicularly to its longitudinal axis at middle of length. They were ground using 1200 SiC paper and polished up to  $1 \mu\text{m}$ . Those samples used for optical microscopy characterization were etched using Keller's reagent to reveal the resulting microstructure.

Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) with quantitative metallographic analysis capability were used to evaluate the shape and grain size of constituents. Image-ProPlus software was used to quantify the area fraction of porosities in fields of 200x.

For tensile testing, the specimens were machined from the as-cast samples according to EN 10002-1:2004 with a gauge length  $L_0$  of 50 mm and a cross-section diameter  $d_0$  of 10 mm. Tensile tests were carried out at room temperature and a strain rate of 0.5 mm/min on a INSTRON testing machine - Model 8874, to obtain yield strength, ultimate tensile strength and strain. At least 12 specimens, with the geometry shown in Fig. 2, were used for fatigue testing for each processing condition. Fatigue tests were performed on a rotating bending machine and life is considered as the number of cycles to rupture.

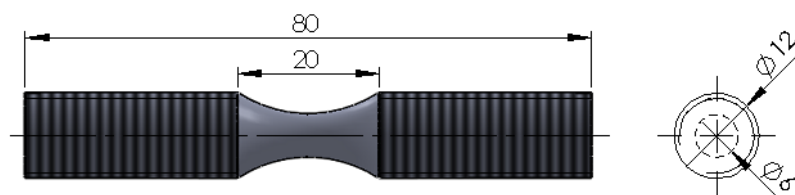


Fig. 2 Rotating bending fatigue specimen.

## Results and discussion

### Density and microstructure characteristics

Degassing evaluation was based in the measurement of samples density by using the RPT test and the apparent density measurement method, as proposed by Gruzleski *et al.* (8). The degassing efficiency  $\eta$  was calculated from equation [1], where  $d$  is the theoretical alloy density ( $2.74 \text{ kg/dm}^3$ ), and  $d_i$  and  $d_f$  are density before and after the degassing treatment, respectively.

$$\eta = \frac{d_f - d_i}{d - d_i} \times 100 \quad [1]$$

Fig. 3 presents the evolution of the alloy density and porosity with processing time. It is clear an increase in density and a reduction on pores area fraction. It is also clear that the kinetics of ultrasonic degassing is time dependent changing as hydrogen is being removed from the melt, confirming the results of other researchers (10,11,12).

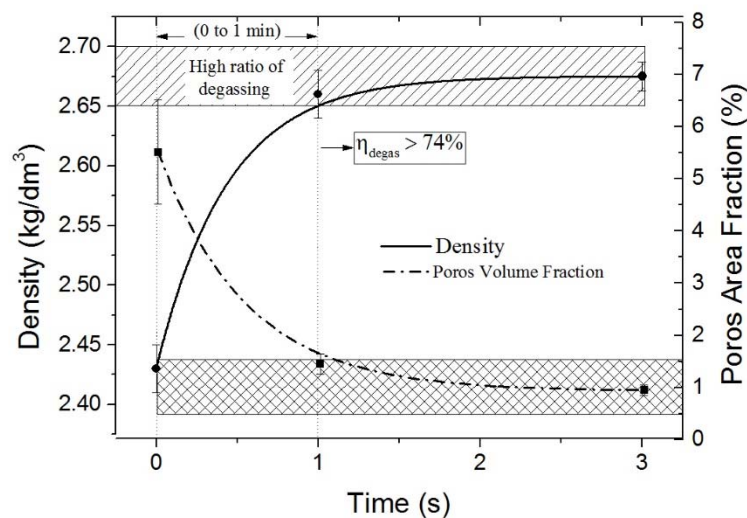


Fig. 3 Alloy density and area fraction of pores as a function of degassing time.

The maximum alloy density ( $2.67 \text{ kg/dm}^3$ ) was obtained after 2 minutes ultrasonic processing (although after 1 minute it was already about 98.5% of the maximum value). In fact it seems that for the electric power ( $750 \text{ W}$ ), frequency ( $19.8 \pm 0.2 \text{ kHz}$ ) and melt temperature ( $700^\circ\text{C}$ ) used on this work, 1 minute is enough to produce the diffusion of hydrogen from the melt to the developed bubbles, for adjacent bubbles to coalesce and grow to a size sufficient to allow them to rise up through the liquid, against gravity, until reaching the surface. For longer degassing times density remained constant, and the difference/balance to the theoretical alloy density is only due to solidification defects. This behavior is due to the mechanism of hydrogen removal from aluminium melts and the effect of acoustic cavitation on that mechanism. In fact, due to the extremely large number of very small bubbles developed in the molten alloy by cavitation, diffusion of hydrogen towards them is very fast.

Tab. 2 shows the density values obtained by the RPT test, and porosity data and SDAS values obtained by image analysis of optical micrographs.

Tab.2 Alloy density, porosity data and microstructural features of cast samples as a function of ultrasonic degassing time

UST min	Density kg/dm <sup>3</sup>	Porosity			Measured SDAS μm
		Pores area fraction (%)	Per mm <sup>2</sup>	Average pore size (μm <sup>2</sup> )	
0	2.43±0.02	5.51±1.0	5	4550	26.12±2.15
1	2.66±0.02	1.45±0.2	2 - 3	890	23.34±1.89
3	2.67±0.01	0.95±0.1	1 - 2	610	25.56±3.01

According to the experimental results, pore size and density were significantly influenced by the ultrasonic processing time. Two important remarks can be drawn from these results:

- The number of large pores, considered the most detrimental for fatigue drastically decreased with the processing time (Fig. 4) as a consequence of the ultrasonic vibration mechanism of cavitation. In fact, after 1 minute processing only small hydrogen bubbles with diameter below 22 μm still remained.
- Porosity resulting from shrinkage seems also to have been reduce in size (Fig. 4 (c)). In fact some of the large pores observed in materials are shrinkage pores. The microstructures presented on Fig. 4, obtained from polished surfaces, show that large shrinkage porosity seems to have almost disappeared ultrasonic processing. As explained by Monroe (13), shrinkage porosity needs not only hot points to start developing, but also dissolved hydrogen. When feeding is cut off and the metal continues to solidify the pressure in the remaining metal pool decreases while segregation causes the gas content to increase. In those places where hot spots occur, porosity is nucleated, but gas must be available for its development. Thus shrinkage pores start and develop depending on available dissolved hydrogen.

These remarks are very important for fatigue evaluation since both pores area fraction and their geometrical characteristics are important as fatigue crack risers.

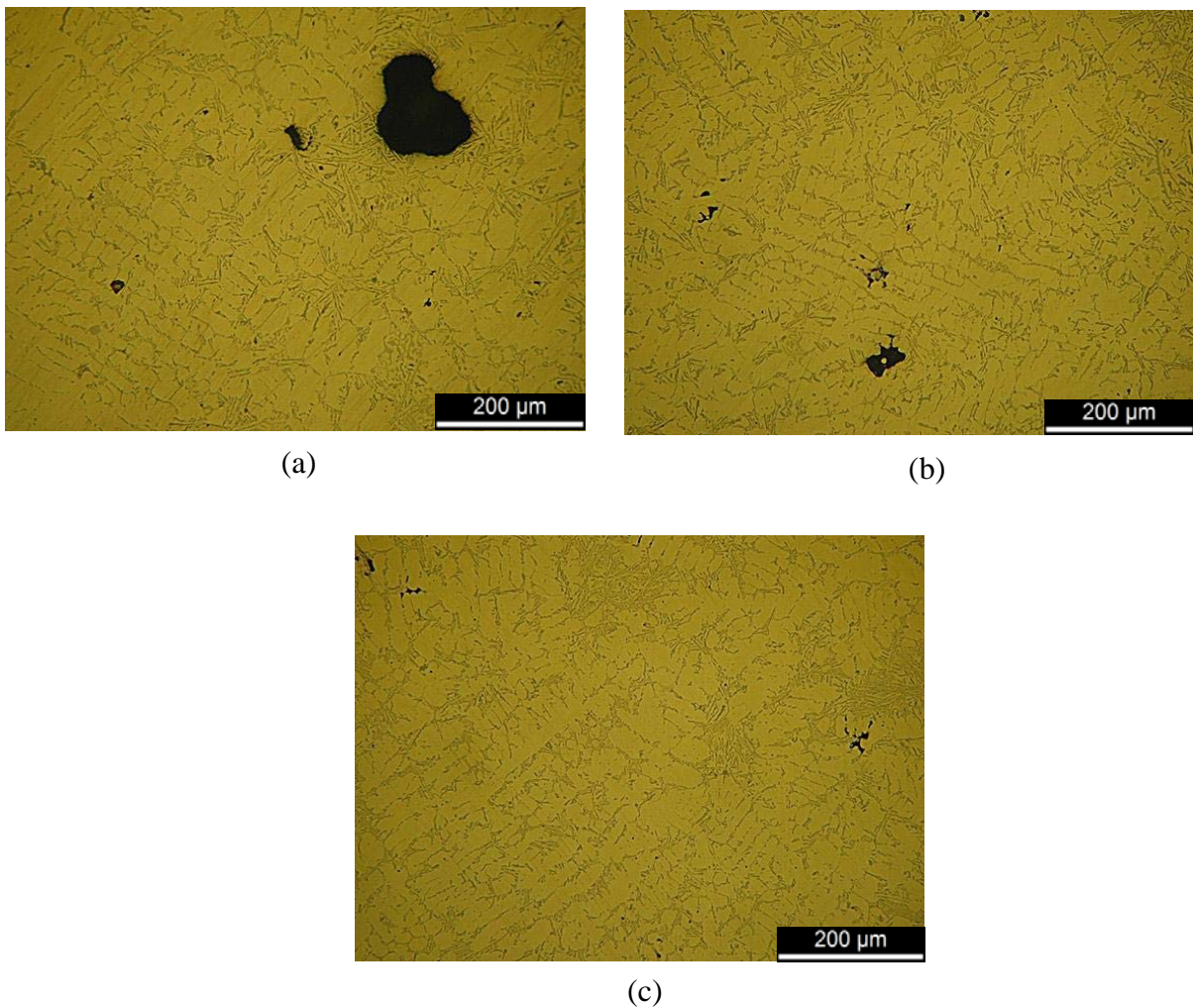


Fig. 4 Pores characterization as a function of degassing time. (a) Without degassing (no treatment); (b) 1 minute US degassing; (c) 3 minutes US degassing.

### *Mechanical and fatigue properties*

Fig. 5 shows the results of static tests. It is quite clear that ultrasonic processing had no significant effect on static properties. In fact it is widely reported that porosity has a small effect on static properties, in opposition to what is observed on fatigue properties (Fig. 6). Moreover, only in castings with large pores and high area fraction of porosity they play significant role on the mechanical properties. Other metallurgical features, particularly SDAS, which is known to affect the mechanical properties of aluminum alloys, also seems not to be prone to ultrasonic processing, since their value remained almost constant for processing times up to 3 minutes (Tab. 2).

The lower elongations measured in the samples are mainly due to the casting defects and the large unmodified eutectic Si particles, with needle-like morphology, characteristic of alloy without process of modifications Si and refinement of grain.

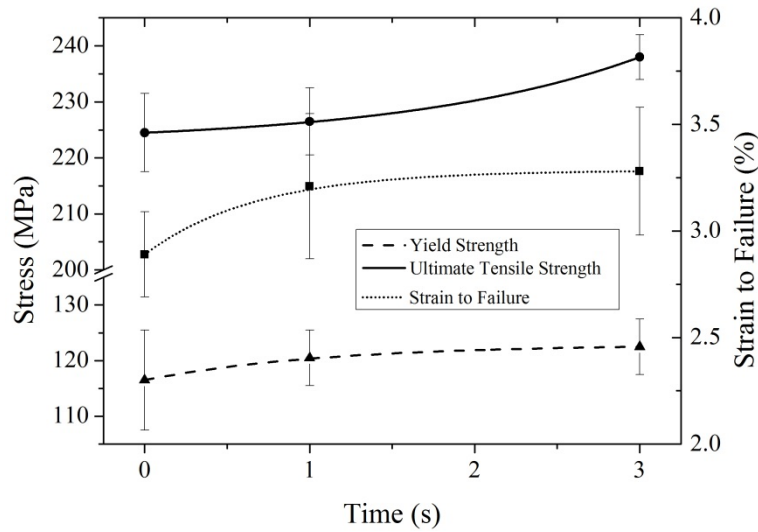


Fig. 5 Yield Strength, Ultimate Tensile Strength and Strain to Failure function of time of degassing.

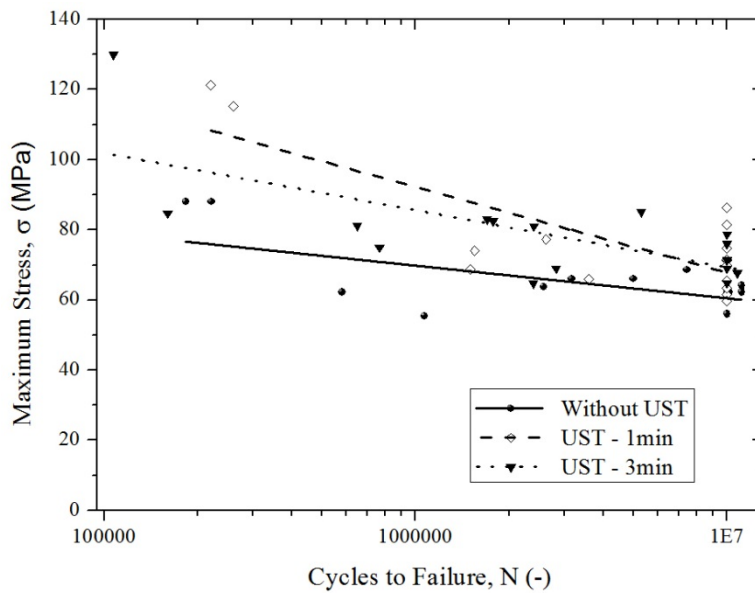


Fig. 6 S-N curve as a function of degassing time.

Regarding to Fig. 6, it can be seen that fatigue limit increased about 25% for 1 min US processing and no significant further increase was observed for 3 minutes processing. The experimental results of the fatigue tests were characterized by high degree of scatter. As presented in Tab. 2 the maximum area of the pores and their area fraction suggest be the cause probably of lower limit of fatigue. To evaluate the data experimental were used a set equations, proposed by some authors, which can predict the evolution of fatigue limit with those variables studied. Although of typical fatigue limit can be seen for iron or titanium based alloys, for aluminum based alloys S-N curve it is not common to reach a plateau. For this reason a conventional value for fatigue life is chosen at  $10^7$  cycles. Moreover, according to Murakami (15) fatigue



prediction models based on defects are commonly used for different types of materials.

In Fig. 7 are represented properties variation (fatigue limit, average pore size, and pores area fraction) as a function of degassing time, according equations proposed by:

(1) De Kazinczy (16) in which the equation proposed allow to determine the fatigue limit as a function of yield stress ( $\sigma_{ys}$ ) used a constant representing the defect geometry ( $k$ ), and the defect size ( $d$ ). This model is agree with experimental results (Fig. 7), since average defect size decreases with degassing time (Tab. 2) at approximately in the same proportion.

(2) Costa (17) which developed a model where both volume fraction of defects as well as their size (diameter) is taken into consideration on fatigue limit. This model is also in line with experimental results since both volume fraction of pores as well as average size of porosity (Tab. 2) decrease with degassing time at approximately in the same proportion.

Thus, when ultrasonic vibration is applied, the changes in pore geometrical features (average dimension and area fraction) are able to increase fatigue limit of the Al alloy. This increase is fatigue limit is experimentally verified but may also be properly predicted by using most common fatigue limit prediction equations.

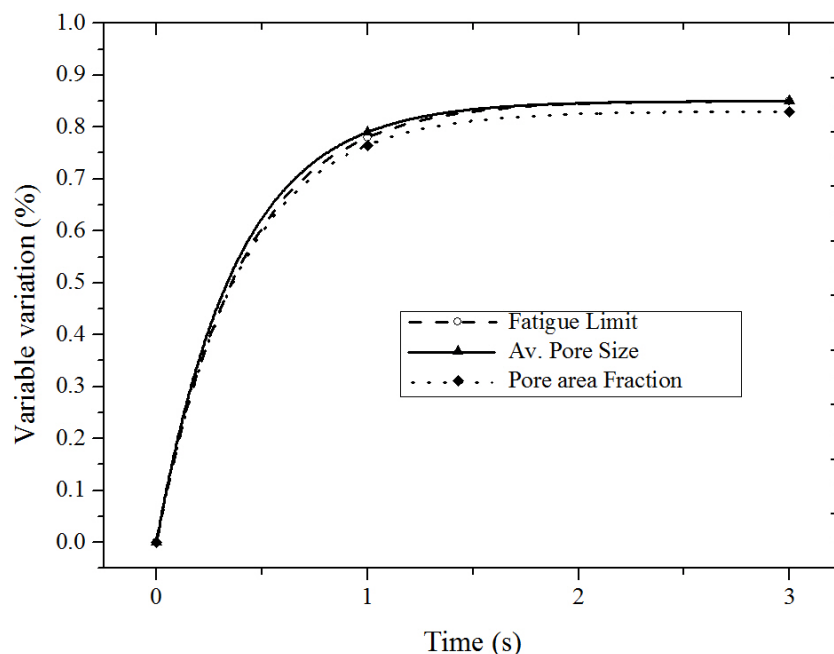


Fig. 7 Properties variation (Fatigue Limit, Average Pore Size and Pores area Fraction) as a function of degassing time. Fatigue limit is multiplied by a material dependent factor ( $k=3.4$ ) as suggested by fatigue prediction equations. This factor is a material constant.

Wang *et al.* (7) have shown that when porosity size become very small its influence on fatigue limit may become of the same level of other micro structural constituents such as SDAS, eutectic silicon lamellae thickness, etc. In the present study SDAS

measurements were performed to verify if other metallurgical constituents, besides porosity, changed with ultrasonic degassing time and could then be the responsible for the reduction on fatigue limit verified. Previous studies of *Puga et al.* (11, 14) have shown that when ultrasonic vibration is used metallurgical features change with electric power and melt temperature but they are not affected by the degassing time. Thus, a change in SDAS or other metallurgical features other than porosity was really not expected.

A SEM micrograph example of the fracture surfaces of the fatigue specimens is shown in Fig. 7. The region of crack initiation, steady crack growth and final failure can be characterized. A detailed study of the crack initiation site at 300x of magnification showed that fatigue initiation took place at the porosities and was located close to the specimen surface. As it was expected, although the porosity level does not have a substantial influence on static properties, it has a substantial effect on fatigue properties and in particular on fatigue limit.

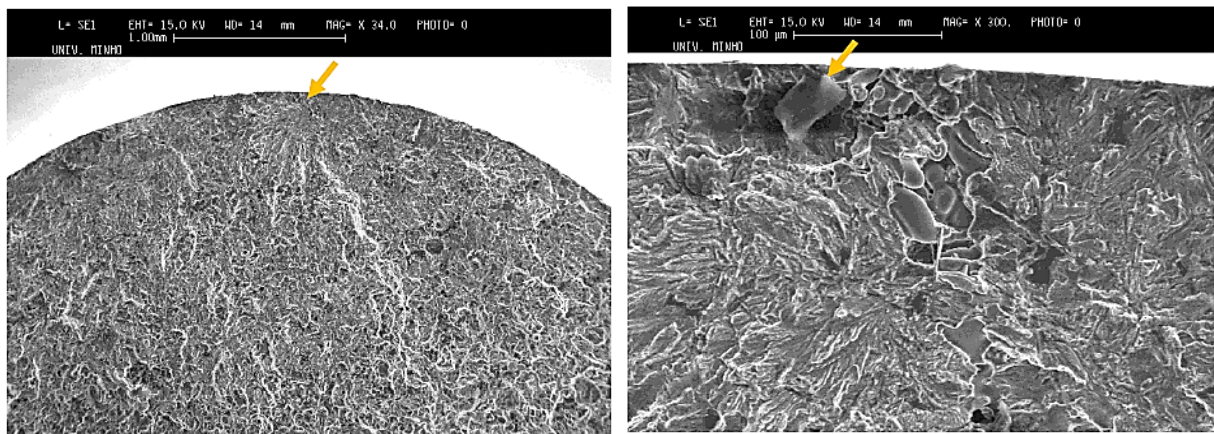


Fig. 7 SEM images. (a) Magnifications of 34x; (b) Magnifications of 300x.

## Conclusions

The main conclusions of this work can be drawn as follows:

- Ultrasonic degassing seems to be effective in reducing porosity of castings;
- Ultrasonic degassing seems to act on porosity area fraction as well as on pores dimension so that it becomes effective for fatigue improvement;
- Ultrasonic degassing does not change SDAS spacing;
- Porosity has a small effect in static properties contrary to what is observed on fatigue properties;
- Changes in porosity dimension nearly reach the fatigue threshold value for porosity as a controlling fatigue parameter.

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## References

- 1) Caceres, C.H., Svensson, I.L., Taylor, J.A.. "Strength-ductility behaviour of Al-Si-Cu-Mg casting alloys in T6 temper", *International Journal of Cast Metals Research* 15, pp. 531-543, 2003.
- 2) Ammar, H. R., Samuel, A.M., Samuel, F.H., "Effect of casting imperfections on the fatigue life of 319-F and A356-T6 Al-Si casting alloys", *Materials Science and Engineering A* 473, pp. 65-75, 2008.
- 3) Teng, X., Mae, H., Bay, Y., Wierzbicki. T., "Pore size and fracture ductility of aluminum pressure die casting", *Engineering Fracture Mechanics* 76, pp. 983-996, 2009.
- 4) Tanaka K., Nakai Y., Yamashita M., "Fatigue growth threshold of small cracks", *International Journal Fracture* 17 (5), pp. 519–33, 1981.
- 5) Lukas P, Kunz L, Weisse B, Stickler R., "Non damaging notches in fatigue", *Fatigue Fracture Engineering Materials Structures* 9(3), pp. 195–204, 1986.
- 7) Wang Q.G., Apelian, D., Lados, D.A., "Fatigue behavior of A356/357 aluminum cast alloys. Part II – Effect of microstructural constituents", *Journal of Light Metals* 1, pp. 85-97, 2001.
- 8) Gruzleski, J.E., Closset, B.M., "The Treatment of Liquid Aluminium-Silicon Alloys", AFS, Des Plaines, IL, USA; 1990.
- 9) Meidani, A.R.N., Hasan, M., "A study of hydrogen bubble growth during ultrasonic degassing of Al-Cu alloy melts", *Journal of Materials Processing Technology* 147, pp. 311-320, 2004.
- 10) Eskin, G.I., "Ultrasonic treatment of light alloy melts", 1st ed. Amsterdam: Gordon and Breach Science Publishers, 1998.
- 11) Puga, H., Barbosa, J., Seabra, E., Ribeiro, S., Prokic, M., "The influence of processing parameters on the ultrasonic degassing of molten AlSi9Cu3 aluminium alloy", *Materials Letters* 63, pp. 806-808, 2009.
- 12) Xu, H., Jian, X., Meek, T., Han, Q., "Degassing of Molten Aluminium A356 Alloy Using Ultrasonic Vibrations", *Materials Letters* 58, pp. 3669-3673, 2004.
- 13) Monroe, R., "Porosity in Castings", AFS Transactions, Schaumburg, IL USA, 2005.
- 14) Puga, H., Costa, S., Barbosa, J., Ribeiro, S., Prokic, M., "Influence of ultrasonic melt treatment on microstructure and mechanical properties of AlSi9Cu3 alloy", *Journal Materials Processing Technology*, 211, pp. 1729-1735. 2011.
- 15) Murakami Y. "Metal fatigue: effect of small defects and non metallic inclusions", Oxford: Elsevier; 2002.
- 16) De Kazinczy F., "Effect of small defects on the fatigue properties of medium-strength cast steel", *Journal of the Iron and Steel Institute*, pp. 851-855, 1970.
- 17) Costa, N., Machado, Silva, F., "A new method for prediction of nodular cast iron fatigue limit", *International Journal of Fatigue* 32 (7), pp. 987-995, 2010.