Modeling the influence of pores on fatigue crack initiation in a cast Al-Si alloy

P. Baicchi[1], G.Nicoletto[1] and E. Riva[1]

[1] Dept. of Industrial Engineering - University of Parma ,Viale G.P. Usberti, 181/A - 43100 Parma – Italy, e-mail: baicchi@ied.unipr.it, gianni.nicoletto@unipr.it, enrica.riva@unipr.it

ABSTRACT. *Recently, the fatigue behavior of cast Al-Si alloys have been extensively studied for the increasing practical relevance. The fatigue behavior of these Al-alloys depends on a number of mechanical and microstructural factors, in particular on casting porosity. The present work is aimed at identifying a strategy for determining the actual impact of porosity on the fatigue response of a cast part, considering that a degree of porosity is inevitable for a standard casting process. Fatigue experiments have been carried out on a cast AlSi7Mg alloy, (equivalent to A356), subjected to a standard T6 heat treatment. Light microscopy was used to characterize the material microstructures and porosity. Casting pores were then considered as micro stress concentrators and the influence of their shape, exactly reproduced from micrographs, on K_t determined by a linear elastic finite element analysis (FEA). Equivalent notch geometries were then considered and the influence of notch plasticity verified by elasto plastic FEA.*

INTRODUCTION

Aluminum alloys are often used in applications that require a low weight, (i.e. aircraft and automotive industry) because they have mechanical properties lower than steels but an excellent specific strength (i.e. strength-to-weight ratio). The most used Al–alloys for casting applications are Al-Si alloys, [1]. The mechanical properties of Al-Si alloys can be controlled by small addition of Mg or Cu and then strengthened (i.e. up to 30 times stronger than pure aluminum) by a precipitation hardening treatment that forms Mg_2Si or Al_2Cu phases, [1]. The strength properties of Al-Si-Mg alloys can also be affected by inoculation (e.g. Ti, B) and modification. Addition of a small quantity of Sr produces a fine distribution of small rounded eutectic silicon particles with an improvement of strength.

However, the casting production route introduces defects, such as gas porosity and shrinkage, that can have a dominant influence on the fatigue behavior of Al-Si alloys as demonstrated by some recent studies, [2-7]. The negative effect of porosity in particular the pore size on fatigue life of A356-T6 has been pointed out by Wang et al. [3]. Lee and al. [4] also considered the influence of porosity on cast A356 alloy and found a dominating effect. After inspection of the fracture surfaces of the failed specimens the influence was rationalized using the average size of the fatigue critical pore. In [7], Lee and al. proposed a model that describes the S/N curve as a function of a pore-affected stress parameter. He used the finite element method to evaluate the stress concentration at actual pores and generalized the observation including pore location with respect to the free surface and the possible contribution of notch plasticity.

In this paper the previous results are examined in the light of a fatigue characterization of a cast AlSi7Mg (equivalent to A356) using rotating bending tests. A microstructural characterization and a classification of casting porosity is performed on metallographic sections in the as-cast conditions with a digital image analysis software. Selected microscopic images of porosities are selected and the associated local stress concentration determined by the finite element method. The potential influence of porosities on fatigue crack initiation is discussed.

EXPERIMENTAL DETAILS

Characterization of material porosity

The material of this study is the AlSi7Mg alloy (equivalent to A356), modified with Sr obtained by a sand casting process. A typical microstructure is shown in Fig. 1. It is characterized by a primary Al matrix (α-phase) together with an Al+Si eutectic phase located between the secondary dendrite arms. This eutectic phase is characterized by a distribution of small, rounded particles because a small amount of Sr was added to the molten metal (Fig. 1). Measurement of secondary dendritic arm spacing (SDAS) provided an average value of 60 μm.

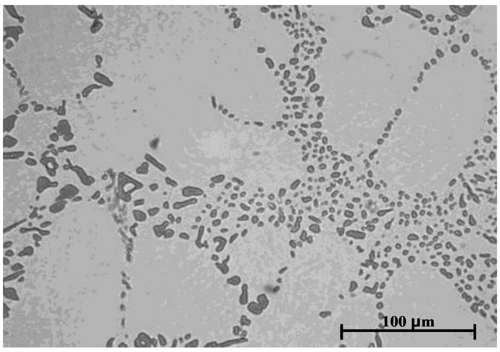

Fig. 1 Microstructure of AlSi7Mg. Etched with 0.5% HF

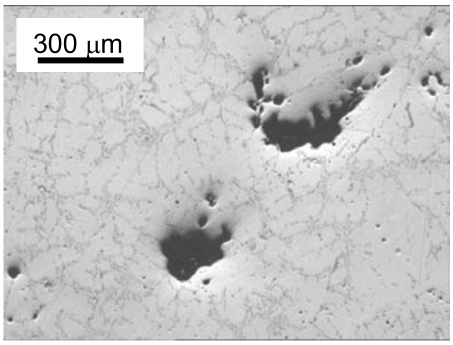

Fig. 2 Examples of shrinkage porosity.

Formation of porosity and shrinkage cavities is almost inevitable in the sand casting process. Quality of the casting is therefore strictly related to porosity control. Formation of casting porosity is due to: i) shrinkage during solidification or ii) gas trapping [1]. Shrinkage porosity develops due to the difference in density between solid and liquid phases of pure aluminum that cause a 7% decrease in volume during the solidification (5% - 6% for aluminum alloys). Gas trapping occurs during the solidification process because hydrogen, formed in the reaction between liquid aluminum and water vapor, is expelled by solidified material. The liquid becomes supersaturated with gas and bubbles may become trapped when it solidifies. An example of the shrinkage porosities found in this cast AlSi7Mg is shown in Fig. 2. They are highly irregular in shape and randomly distributed. Their size is in the range of several tens to hundreds of microns, [4,7].

A image analysis software was applied to many micrographs like Fig.2 to statistically characterize gas and shrinkage porosity. The role of porosity on fatigue is intuitively dependent on its size and Murakami and others have considered the parameter $\sqrt{A}$, where A is the projected area of the pore measured directly from metallographic samples, as is the unique measure representative of the pore severity. Porosity of different morphologies for the same area A is however found in castings.

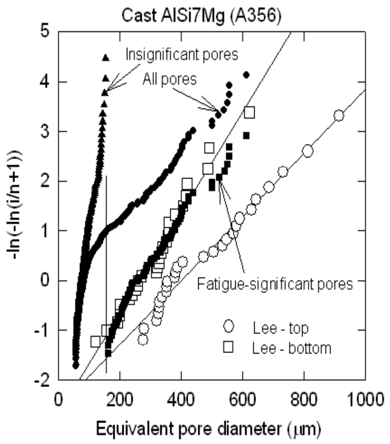

Fig. 3 Extreme value plot of equivalent pore size of an AlSi7Mg

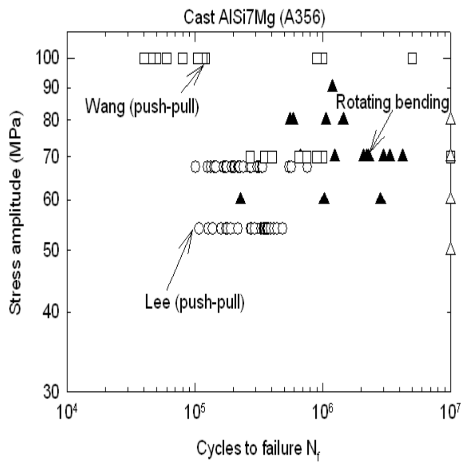

Fig. 4 Comparison of rotating bending fatigue results on cast A356 with push-pull tests results from the literature

To compare and correlate the present porosity data with data from the literature, the equivalent diameter parameter $d_e = (4A/\pi)^{1/2}$ with A as the projected area of the pore. The equivalent diameters of the pores responsible for fatigue crack initiation were measured from the fatigue fracture surfaces in [7]. The extreme value distribution, [8], is assumed in Fig. 3 to describe the equivalent dimension of the fatigue-generating porosities measured on the fracture surfaces reported by Lee, [7]. The pore diameters are distributed along two different lines, each representative of the two batches of specimens extracted from the top and the bottom parts of the casting. This evidence confirms that the different parts of the same casting had different porosity content and explains the observed fatigue lives.

The equivalent size distribution of all porosities measured on metallographic sections of the present cast A356 is plotted in the same EV diagram of Fig. 3. No filter on pore size is applied and the distribution of Fig. 3 shows a not linear trend that appears a combination of two linear distributions. The inflection point is at an equivalent size of about 150 μm, which is about the minimum pore size that originated a fatigue fracture in [7]. Therefore, the present data were split and re plotted in the same diagram. The two sets are now linearly distributed and one pore size distribution overlaps the fatigue critical porosity of the bottom part of the casting. The second porosity distribution is linear but is not apparently relevant for the fatigue process.

Fatigue tests

Fatigue tests were performed to characterize the fatigue resistance of cast AlSi7Mg at 10^7 cycles. Smooth rotating bending specimens with a minimum cross section diameter of 6 mm were tested at 50 Hz. A stair-case procedure was adopted with test interruption at 10^7 cycles. The results of the experiments are shown in Fig. 4 (i.e. filled triangle = rupture, open triangle = run out), along with the push-pull fatigue tests on the same cast alloy reported in the literature.

The present results are coherent with the previous results: the previous analysis of material porosity summarized in Fig. 3 showed the presence of an equivalent distribution of pores as the best material of [7]. The relatively longer lives found here is directly attributed to the type of loading used in the tests. Even if the population of defects is similar, the 6-mm-dia rotating bending specimen used here highly stress a smaller volume of material compared to the 5-mm-dia push-pull specimen of [3,7].The main conclusion of these tests is that the size distribution of porosity is the dominating factor controlling the fatigue performance of the cast AlSi7Mg.

MODELING THE INFLUENCE OF POROSITY

The fatigue experiments of this study confirm the critical role of porosity in controlling the fatigue of the cast AlSi7Mg. Now the possibility of rationalizing the influence of porosity on material behavior by modeling is examined. Although previous studies considered the equivalent diameter of the porosity as the main characterizing parameter of the pore severity, a role of pore morphology would also be theoretically expected when the actual irregular geometry of porosity found in castings is observed, see Fig. 2. For example, pores of equal area could greatly differ in terms of theoretical stress concentration depending on their actual shape and the loading direction. To study this aspect the finite element method was used.

FE Modeling of pores and shrinkage

The finite element analysis of the stress distribution around pores was conducted with the commercial software ABAQUS (HKS Inc., Pawtucket, RI, USA). The aim was the evaluation of the micro-stress and strain concentration at pore critical points. The AlSi7Mg alloy was assumed to be, initially, a linear elastic material (i.e. modulus of elasticity: 69 GPa and Poisson's ratio: 0.3) and then an elastic-plastic material, (i.e. tangent modulus: 69 GPa and yield stress: 200 MPa). Fig. 5 shows how a typical porosity was reproduced from a micrograph with vectorial 2D software and spline curves and then imported in the FE software for meshing and analysis.

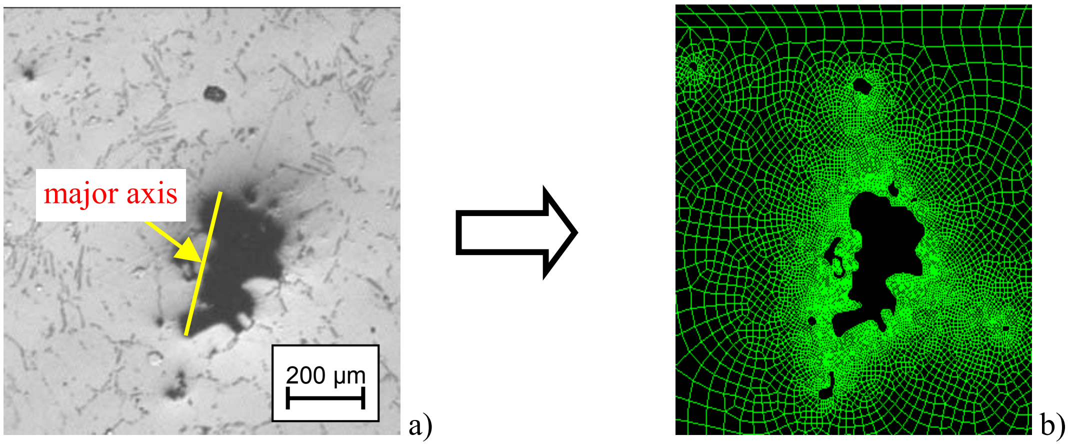

Fig. 5 a) Image of a porosity and b) finite element model of the pore.

The mesh of Fig. 5b is characterized by parabolic quad element. The plane strain 2D model was loaded with a unitary far-field stress in two perpendicular directions. The region surrounding the pores is modeled with a refined mesh so as to increase the accuracy of the calculation (see Fig. 5). Solutions for the local stress/strain distribution around pores were calculated and the results were presented in terms of stress along the load direction.

Theoretical stress concentration

Different pore morphologies were identified and analyzed. Here the discussion is limited to the shrinkage porosity of Fig. 5. The stress concentration factor K_t (i.e. ratio between the maximum stress and the far-field stress) of the pore is found to depend on load direction. The critical points determined with the elastic finite element analysis are shown in Fig. 6a and 6b, respectively.

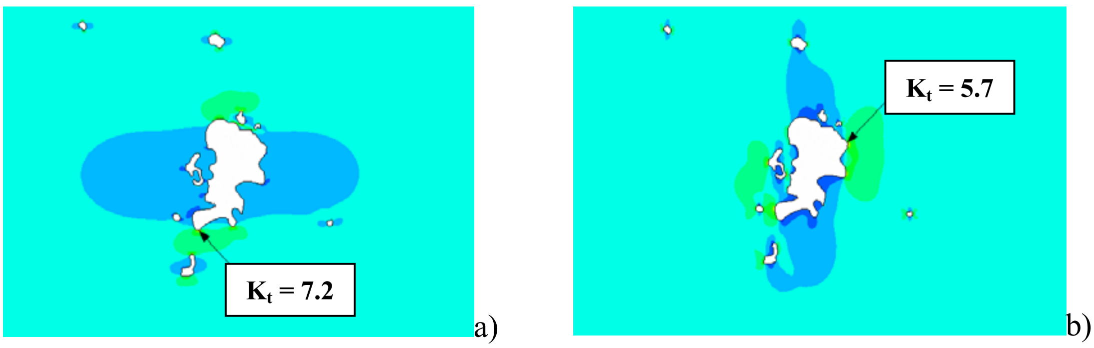

Fig. 6 Theoretical stress concentration at a shrikage pore
a) loading in horizontal direction b) loading in vertical direction

The theoretical stress concentration is found to be always very high and controlled by the maximum size of the porosity, transverse to the loading direction, and by the local notch root radius, which is typically very small. The determined K_t values of this study agree with the data reported in [7].

Equivalent notch

The computational approach leading to the results of Fig. 6 is however cumbersome to be used in practice. Especially useful would be a simple method to determine an equivalent notch effect due to porosities found by metallographic inspection of actual castings, without the need of fatigue testing. One such approach is due to Murakami, [8], with the square root of the porosity area, which has proved very valuable in practice. Lee, [7], adopted the equivalent diameter approach. In both cases the reference equivalent geometry is a circular (or spherical) hole giving the same theoretical stress concentration factor, independent of load direction. The theoretical stress concentration factor is expected, however, to be quite small compared to the value reported in Fig. 6. Apparently, a size effect correction will be required.

Here the adoption of the elliptical notch geometry defined by the maximum transverse dimension (i.e. *2a*) and the minimum local radius (i.e. ρ) as a more representative equivalent geometry than the equivalent circular hole is considered. Fig. 8 shows examples of representative ellipse extraction from the shrinkage porosity. The analytical solution for the elastic stress concentration of an ellipse in a plate in tension is given by [9] as

$$K_t = 1 + 2\sqrt{\frac{a}{\rho}} \tag{1}$$

To give an equivalent output of the previous analysis of porosity, Fig. 8 shows the stress maps of computed stress distribution in plates containing the approximating ellipses for the two cases of Fig. 6 and the theoretical stress concentration factor K_t. It can be appreciated that the proposed approach accurately represents the theoretical stress concentration of an actual porosity.

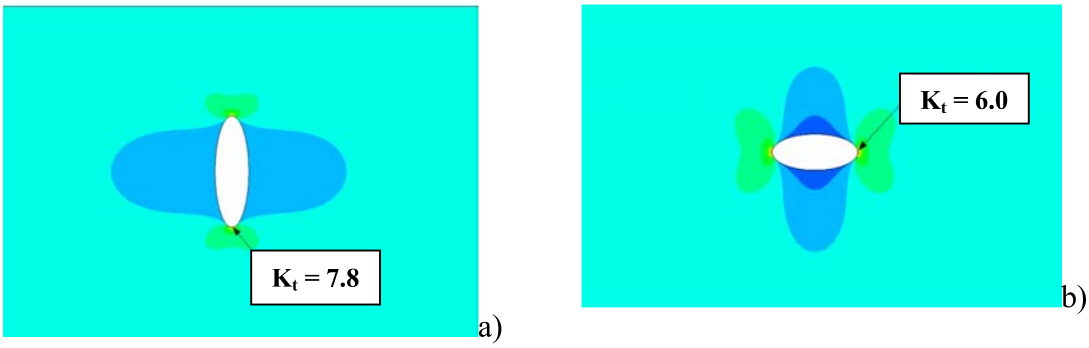

Fig. 8 Theoretical stress concentration at ellipses equivalent to porosity
a) shrinkage porosity of Fig. 6a b) gas porosity of Fig. 7a

Role of notch plasticity

Nonetheless, it is expected that the elastic stress concentration factor K_t of pores represents only one of the factors that affect the fatigue response of cast AlSi7Mg. Micro notch plasticity is expected to have a significant role even at relatively low stress levels associated to fatigue loading. The results of an elasto plastic finite element analysis of equivalent notches are now examined in the light of the effective stress concentration concept.

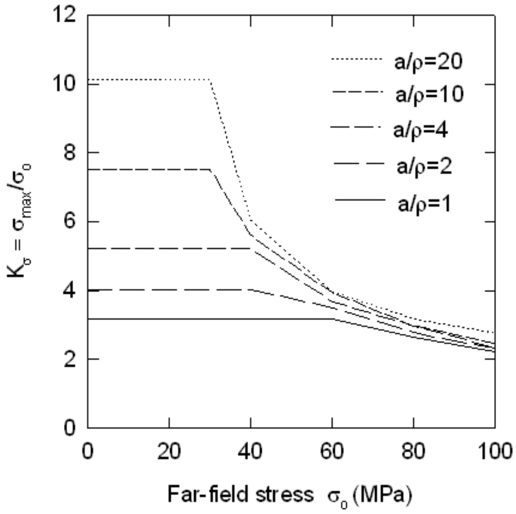

Fig. 9 Evolution of the elastic-plastic stress concentration factor K_σ as a function of the applied far-field load for equivalent ellipses (semi axis/root radius a/ρ)

Fig. 9 shows the evolution of the effective stress concentration factors, K_σ defined as the ratio of maximum elastic-plastic stress σ_{max} and the far-field stress σ_o as a function of the far-field stress σ_o for a circular hole and ellipses of different severity. While the major semi axis dimension is equal to the circular hole radius, ellipse severity is controlled by the root radius ρ. The K_t considered ranges from about 3 to 10. When only elastic deformation occurs at the notch root, $K_\sigma = K_t$. When the far-field stress is increased to the levels used for fatigue testing (60 – 100 MPa in Fig. 4), plasticity develops at the notch root of all realistic notches. Fig. 9 shows that K_σ evolves to quite similar values, independently of notch severity, to a value that is close to the case of the equivalent circular pore. This proves that, as a first approximation, the equivalent diameter obtained from the pore area used in [7, 8] can be a reasonable measure of the pore significance in fatigue.

The present conclusion about the role of casting pore plasticity, their size and shape and the usefulness of the equivalent pore diameter confirms recent studies where it was reported that the shape of pores and inclusions has a negligible effect on fatigue performance in cast aluminum alloys. Additionally, size effect and residual stresses are that should be considered together with the phenomenon of non propagating notch cracks, [8].

CONCLUSIONS

Based on the consideration that a degree of porosity is inevitable in an industrial casting process, the present work has presented a strategy for determining the role of porosity on the fatigue response of a cast Al-alloy.

Microscopy was used to characterize the porosity content and fatigue test results on smooth specimens confirmed that the present material conforms to cast Al-alloys reported in the literature. A pore was assumed equivalent in terms of stress concentration to an ellipse having the major axis and the notch root radius extracted from the metallographic inspection. Elastic stress concentration at casting porosity was determined with linear elastic finite element analysis was found to be higher than 5.

Previous approaches based on the equivalent pore diameter have been analyzed and compared to the present elliptical hole approximation. While different under the elastic assumption, the circular hole and elliptical hole approximations converge if micro notch plasticity is considered as in the case of relatively high fatigue stress amplitudes.

ACKNOWLEDGMENTS

This work has been developed in the framework of the activities of MATMEC, one of Emilia-Romagna regional net-laboratories (http://www.diem.ing.unibo.it/matmec/).

REFERENCES

1. Askeland, D. R. (1994) *The science and engineering of materials*, PWS Publishing Company, Boston,
2. Skallerud, B., Iveland, T., Harkegard, G. (1993) *Eng. Fract. Mech*. **44** 857-874.
3. Wang, Q. G., Apelian, D., Lados, D. A. (2001) *Journal of Light Metals* **1**, 73-84.
4. Yi, J. Z., Gao, Y X., Lee, P. D., Flower, H. M., Lindley, T C. (2003) *Metall. Trans.* **34a**, 1879-1890.
5. McDowell, D.L., Gall, K., Horstemeyer, M.F., Fan, K. (2003) *Eng. Fract. Mech*. **70** 49-80
6. Yi, J.Z., Y.X., Gao, P.D., Lee, Lindley, T.C. (2004) *Materials Science And Engineering* **A386** 396-407
7. Y.X., Gao, Yi, J.Z., P.D., Lee, Lindley, T.C. (2004) *Fatigue Fract Engng Mater Struct*, **27**, 559-570
8. Murakami, Y. (2002) Metal Fatigue: Effects Of Small Defects And Nonmetallic Inclusions, Elsevier, Oxford
9. Peterson, R. E. (1974) Stress Concentration Factors. John Wiley & Sons, New York.