FATIGUE PROPERTIES OF A CAST ALUMINIUM ALLOY FOR RIMS OF CAR WHEELS

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Abstract

Thanks to the potential weight saving, aluminium castings are good candidates for automotive, electronic, aeronautic, sport equipments and other high performance products. At present, one of the main limits to a wide use of aluminium alloys for these applications is a lack of complete understanding of their fatigue behaviour and of the relationships to microstructural features, particularly as far as casting alloys are concerned.

In this paper, the rotating bending fatigue behaviour of a cast Al-10Si-0.6Cu alloy has been investigated. The specimens for both the fatigue tests and the microstructural analyses have been drawn directly from the rims of car wheels. The wheel design influences the microstructure of the alloy, conditioning the cooling rate during solidification and, of consequence, may have important effects on the wheel fatigue performances.

Measurements of the sizes of the microstructural constituents, such as secondary dendrite arm spacing and of porosity, have been also carried out by means of optical microscopy, supported by an image analysis software.

Rotating bending fatigue tests have been performed on specimens with different types of notches. In this way, after the fatigue tests, it was possible to study the effect of the wheel design and so, of stress concentrations, on the fatigue life.

Riassunto

Le leghe di alluminio da fonderia sono ampiamente utilizzate per molteplici applicazioni nell'industria automobilistica ed aeronautica, in articoli sportivi, nell'elettronica ed in impieghi dove sono richiesti materiali ad elevate prestazioni. Uno dei fattori che impediscono un più vasto uso dell'alluminio in questi settori industriali è la limitata disponibilità di dati sul comportamento a fatica ed in particolare sulle correlazioni tra questo tipo di sollecitazione e le caratteristiche microstrutturali e geometriche del componente.

In questo lavoro è stato studiato il comportamento a fatica a flessione rotante di una lega da fonderia Al-10Si-0.6Cu, impiegata per la produzione di cerchioni per autovetture. I provini per le prove meccaniche e per le analisi metallografiche sono stati ricavati direttamente dai componenti. È stato dimostrato che la geometria ed il disegno dei cerchioni, ottenuti per fusione in conchiglia, hanno una forte influenza sulla microstruttura della lega nelle varie parti del pezzo, in quanto condizionano la velocità di solidificazione e di raffreddamento del materiale e di conseguenza hanno significativi effetti sul comportamento a fatica in esercizio.

Sono state eseguite osservazioni al microscopio ottico ed analisi di immagine con misure della spaziatura dendritica secondaria (SDAS) e delle dimensioni delle microporosità residue.

Le prove di fatica a flessione rotante sono state condotte su provini con differenti tipologie di intaglio, eseguendo successivamente le osservazioni al SEM delle superfici di frattura. In tal modo è stato possibile studiare l'effetto localizzato dei difetti, della concentrazione localizzata delle tensioni e della geometria dei cerchioni sulla resistenza a fatica.

INTRODUCTION

The application of aluminium alloy castings in many mechanical components, especially for cars and rail vehicles, has gradually increased in the last years, thanks to the great potential of these materials as replacements for ferrous alloys.

In particular, for those applications in which the necessity of high mechanical properties is combined with the need of a substantial weight saving, aluminium castings seem to be extremely interesting solutions.

Moreover, the opportunity of producing cast components in a finished or semi-finished shape permits a high reduction of the production costs.

The lower mechanical properties and reliability of the aluminium cast alloys can be principally caused by the presence of defects and inhomogeneities, which could be preferential fatigue initiation sites.

Also, a lack of complete understanding of the fatigue behaviour of aluminium cast alloys, does not allow a full exploitation of the potential weight and cost savings distinctive of these materials.

The mechanical properties of aluminium castings have been studied correlating them with microstructure and, as a consequence, with the cast processing parameters, since the 1940s [1].

Cast pores are preferential crack initiation sites in these materials and, so, they have been considered as the main parameter to study because of their influence on the mechanical properties. Secondary dendrite arm spacing (SDAS), inclusions and grain size are also considered to be important microstructural factors to understand the mechanical behaviour of cast alloys.

Recently, many studies have been carried out on the influence of microstructure and microporosity on the mechanical properties of aluminium cast alloys. In some cases, the influence of casting pores and of secondary dendrite arm spacing on the fatigue crack initiation and propagation in cast

aluminium alloys has been evaluated [1-6].
It is well known that, controlling the cooling rate during solidification of cast structures, it is possible to control the microstructural constituent sizes, in particular secondary dendrite arm spacing.
Flemings [7] found that the SDAS of cast structures usually has a stronger influence on mechanical properties than the grain size has. Increasing the cooling rate during solidification SDAS decreases and, generally, mechanical properties increase.
B. Zhang et al. [1], found that fatigue cracks initiated from porosity in the material solidified at slow cooling rates, while, as cooling rate increased, the fatigue cracks initiated from near-surface eutectic microconstituents.
Porosity has been observed to affect fatigue life of cast alloys, in particular at an high number of cycles; eutectic microconstituents, instead, affect fatigue life particularly at a low number of cycles (high stresses) [4].
This research has been carried out in order to obtain a better understanding of the relationship between cast design, which develops continuously, microstructural characteristics and mechanical properties of cast aluminium alloys. In particular, the fatigue behaviour of a cast aluminium-silicon alloy has been investigated. As the material came from the rims of two car wheels with different shapes, the effect of the rims dimensions on microstructure has been studied. Rotating bending fatigue tests have been performed on specimens un-notched and with different notches, in order to evaluate also the stress concentration effect of different notch tip radii. The fatigue strength reduction factors have been investigated according to notch theory as presented in [8].

MATERIAL AND EXPERIMENTAL PROCEDURE

The material investigated was a Al-10Si-0.6Cu cast aluminium alloy. Samples have been directly drawn from the rims of two cast wheels (named “A” and “B” respectively); the two shapes were different, especially concerning the rim section: the minimum thickness changed, in fact, from about 25 mm for rim of wheel A to 15 mm for rim of B (see Fig. 1, a-b). The wheels had been cast in a partially cooled metallic shell and were used in the as-cast condition.
The mechanical properties of the alloy, evaluated by the wheels supplier in previous tests, have been reported in Tab. I; in Tab. II the chemical composition has been summarised.
Microstructural characterisation of the material has been carried out by standard metallographic grinding and polishing; measurements of secondary dendrite arm spacing have been also carried out on samples cut from different parts of the two wheels. In order to estimate the maximum occurring defect size, the pore size has been studied by means of a software for image analysis; the results have been then elaborated.
Rotating bending fatigue tests, at a frequency of 200 Hz, have been then performed. Specimens with three different notches and un-notched have been tested, in order to evaluate the material behaviour in presence of stress concentration effects comparable to those in the fillets between two rims.

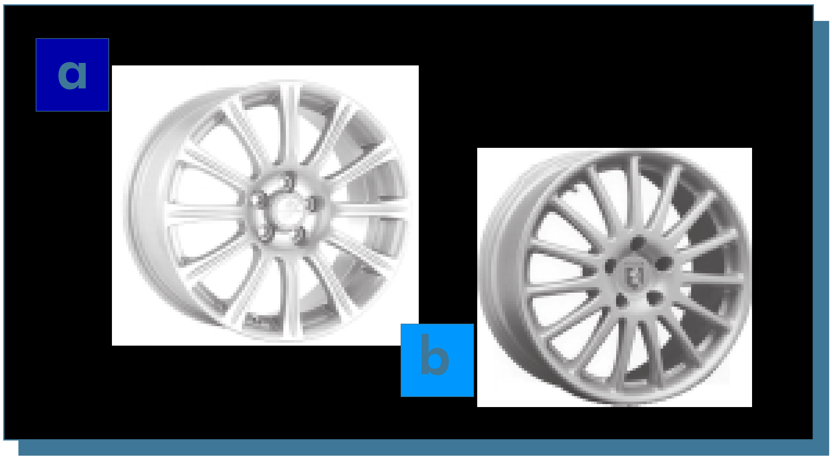


Fig. 1: Different design of the two cast aluminium wheels: a) wheel A); b) wheel B

TABLE I. MECHANICAL PROPERTIES OF THE CAST ALLOY

	Ultimate Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Young’s Modulus (GPa)
Value	220	160	15.0	72

TABLE II. CHEMICAL COMPOSITION OF THE ALUMINIUM CAST ALLOY

Chemical element	Wt, %
Si	10.7
Cu	0.6
Mn	0.35

The stress concentration factors calculated for these three different geometries (named, respectively, R1, R2, R3) have been summarised in Tab. III [9].
Finally, in order to understand the fatigue nucleation and propagation mechanisms, fractographic analyses have been performed on selected fatigue fractured specimens.

TABLE III. STRESS CONCENTRATION FACTORS OF THE THREE DIFFERENT SPECIMEN GEOMETRIES

Specimen	Notch tip radius (mm)	K_t
R1	10	1.11
R2	4	1.26
R3	1.5	1.68

RESULTS

Microstructure

Representative optical micrographs have been gathered in Fig. 2. In Tab. IV, the values of secondary dendrite arm spacing (SDAS), measured for the two different rims, and different parts of wheel "A", have been reported (medium values obtained from twenty optical microscopy measurements).

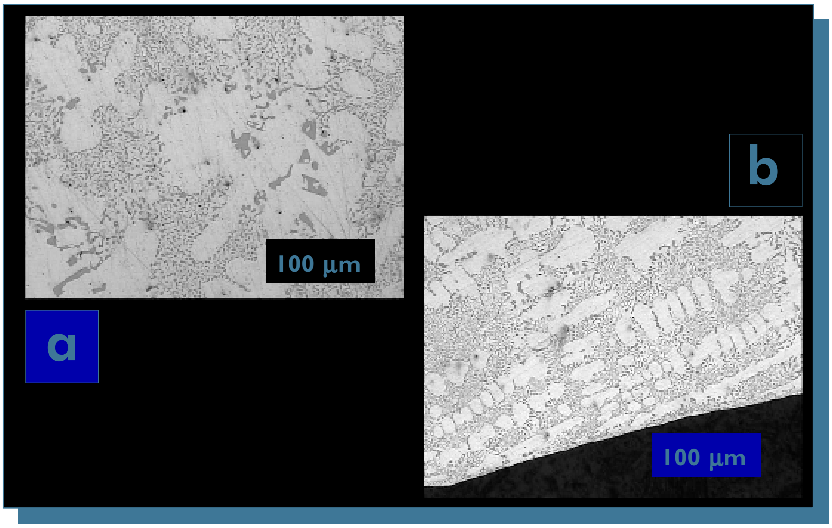


Fig. 2: Optical micrographs of the dendritic structure of the cast Al-Si alloy: a) rim drawn from wheel A; b) rim from wheel B

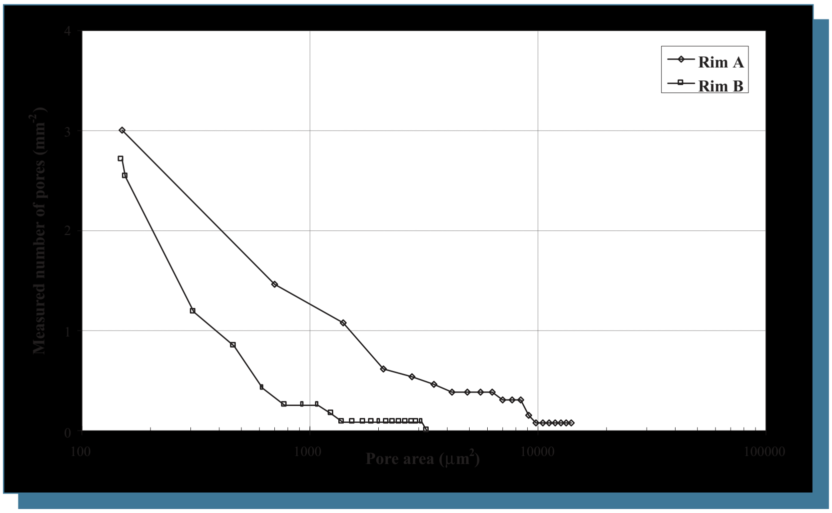


Fig. 3: Measured number of pores (per square mm) as a function of pore area in the material drawn from the rims of the wheels A and B)

TABLE IV. MEAN VALUES OF SECONDARY DENDRITE ARM SPACING MEASURED IN DIFFERENT PARTS OF THE TWO WHEELS

	SDAS (μm)
Wheel A	
Hub	74.8
Rim	46.5
Wheel B	
Rim	36.0

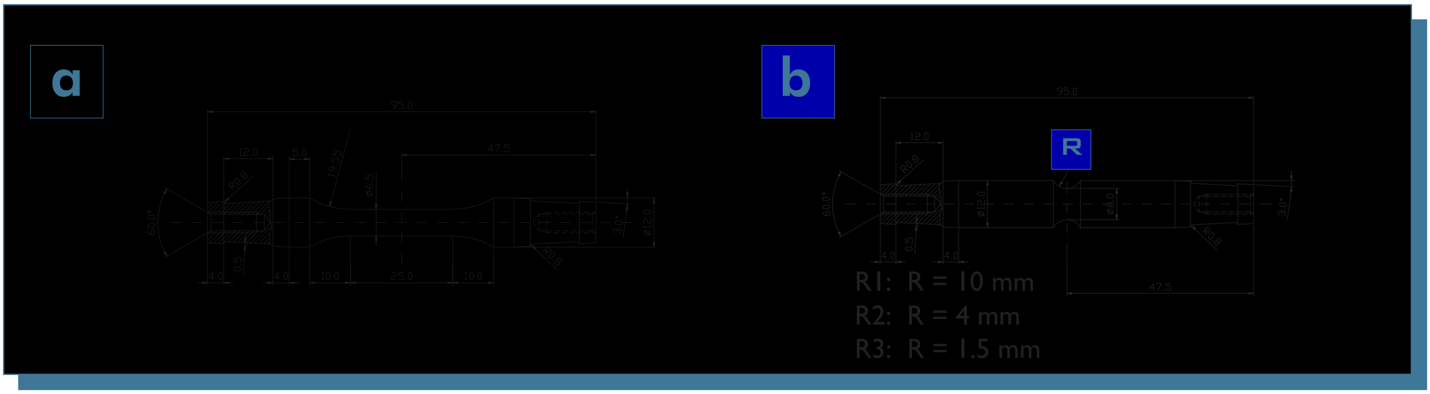
The SDAS measured for the rim of wheel B is clearly lower than that of rim of wheel A, due to rim B lower thickness, which induces higher cooling rates during solidification.

In Fig. 3, has been reported a diagram of the measured number of pores observed in the material drawn from the two different rims. It is important to note that porosity had the typical shape of solidification shrinkages. The rims of wheel A clearly present a higher porosity level.

ROTATING BENDING FATIGUE TESTS

Rotating bending fatigue experiments (R = -1) have been conducted at 200 Hz; for the rims of wheel A un-notched specimens have been used. The specimen geometries used for the fatigue tests have been shown in Fig. 4.

Fig. 4: Specimen geometries used in the fatigue tests (all dimensions in mm); a) un-notched specimen, b) notched specimens, respectively: R1, R2, R3



The results of this first serie of tests have been elaborated in the Wöhler curve of Fig. 5.

Another serie of tests have been carried out on the notched specimens drawn from wheel B (see Fig. 4 -b). The three Wöhler curves, drawn by these further tests, have been reported in Fig. 6.

As presented in [10], in order to estimate the reduction of fatigue resistance induced by the presence of a notch, the following equation can be used:

$$k_f = \frac{k_t}{\sqrt{\left(1+\frac{b}{r}\right)}} \qquad (1)$$

Hence the fatigue strength of notched components (as a function of nominal stress) turns out to be:

$$\sigma^{(notched)}_{A,\,2\cdot10^6} = \left(\frac{\sigma^{(un\text{-}notched)}_{A,\,2\cdot10^6}}{k_t}\right) \cdot \sqrt{\left(1+\frac{b}{r}\right)} \qquad (2)$$

Where *r* is the notch tip radius and *b* is a coefficient characteristic of the material.

A best fitting of the experimental data permitted us to find optimal values of the fatigue limit of the material (un-notched specimens, $N = 2{\cdot}10^6$) and of *b* using the eq. (2). The results of this analysis have been reported in Tables V-VI.

According to these data it is possible to evaluate the "notch sensitivity" of this material, i. e. the ratio k_f/k_t as a function of the notch tip radius.

In Fig. 7, the trend of the k_f/k_t as a function of the notch tip radius has been plotted.

Unfortunately, in geometrically complex components (as the car wheels), the nominal stress values cannot be defined, and only local stresses are available from numerical or experimental investigations. As a consequence, in order to take into account the reduced fatigue notch sensitivity, the local stresses should be reduced by a function of notch tip radius and material parameter b. For a proper fatigue strength prediction it is possible to compute the "effective value" (σ_{eff}) of stress at notch. σ_{eff} is function of (and lower than) peak stress value, according to eq. (3):

$$\sigma_{eff} = \frac{\sigma_{peak}}{\sqrt{\left(1+\frac{b}{r}\right)}} \qquad (3)$$

In Fig. 8 the Wöhler curves as a function of the effective stress value for the three series of specimen have been reported.

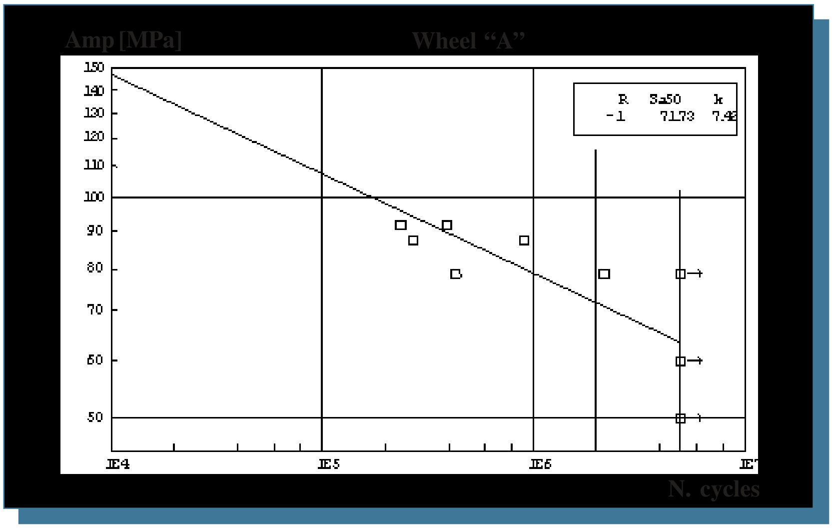


Fig. 5: Stress amplitude versus fatigue life for wheel "A"; un-notched specimen

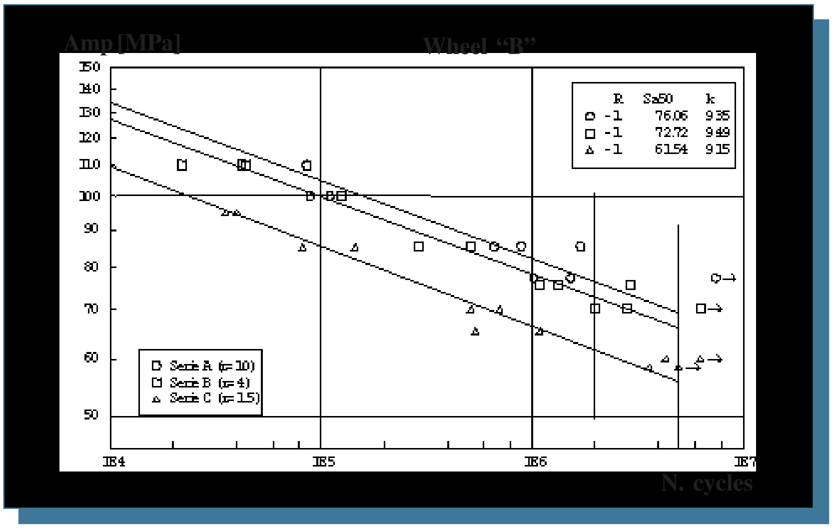


Fig. 6: Stress amplitude versus fatigue life for the three notched specimens drawn from wheel B

TABLE V. EXPERIMENTAL AND ESTIMATED FATIGUE STRENGTH OF NOTCHED SPECIMEN AT $2{\cdot}10^6$ CYCLES

Specimen	r (mm)	K_t	$\sigma_{A,\,2\cdot10^6}$ (MPa) (experimental	$\sigma_{A,\,2\cdot10^6}$ (MPa) (eq. 2)
A	10	1.11	76.1	76.6
B	4	1.26	72.7	71.8
C	1.5	1.68	61.5	61.9

TABLE VI. MATERIAL PARAMETERS FOR FATIGUE NOTCH BEHAVIOUR PREDICTION

$\sigma_{A,\,2\cdot10^6}$ (MPa) (eq. 2)	b (mm)
81.25	0.96

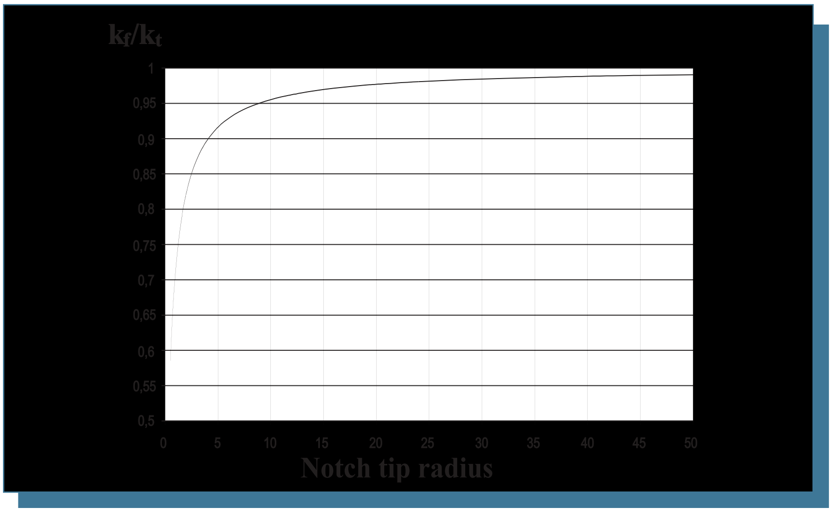


Fig. 7: Evaluation of k_f/k_t as a function of the notch tip radius

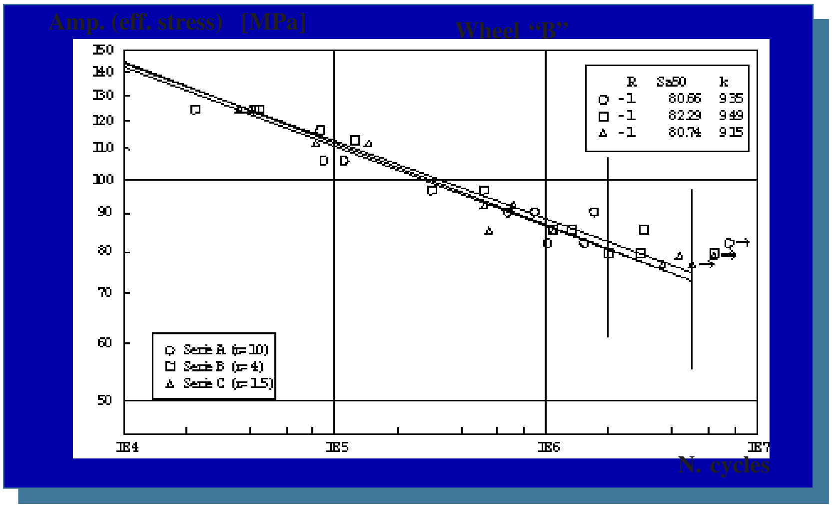


Fig. 8: Wöhler curve as a function of the effective stress value for the material drawn from wheel B

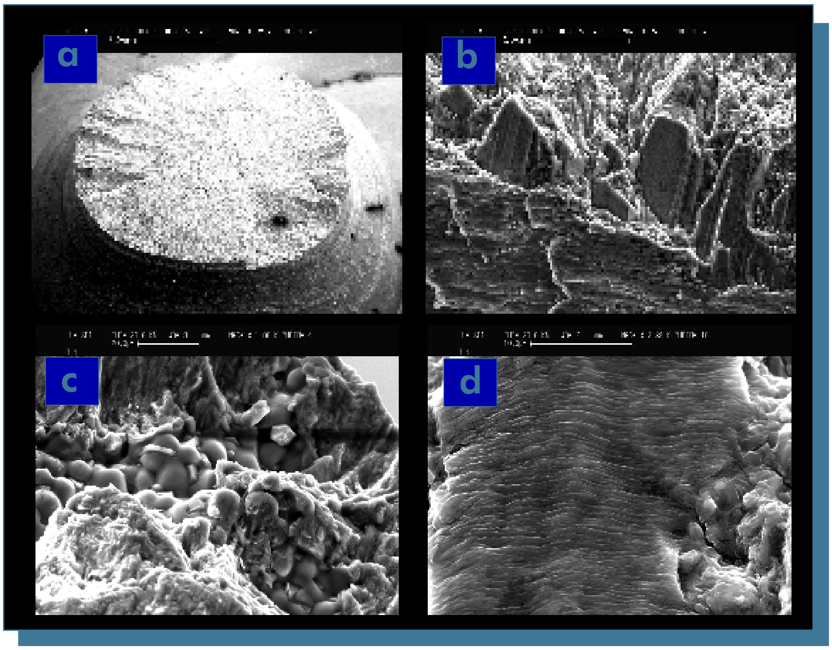


Fig. 9: SEM topographies of the fatigue fracture surfaces; a) a typical fracture surface; b)-c) fatigue nucleation sites: b) scratch caused by machining, c) near surface eutectic microconstituents; d) region in the first stage of growth, with typical fatigue striations

As can be clearly seen from Fig. 8, the Wöhler curves tend to superimpose one upon another, forming a unique curve, when σ_{eff} is concerned, (while it is not so when peak values are considered); this curve represents the fatigue resistance of the material correspondent to the wheel B. It follows that eq. 3 (instead of eq. 2) can be used when peak local values are available (instead of nominal stress values).

The fatigue resistance of the material drawn from wheel B is clearly higher than that of the material from wheel A, in particular at a high number of cycles.

FRACTOGRAPHY

A SEM micrograph showing a typical fracture surface generated during the fatigue tests, has been showed in Fig. 9-a. These fracture morphology has been frequently observed both from specimens from wheel A and from wheel B. Crack initiation has been usually observed in correspondence of surfacial defects as porosities and scratches due to specimens machining.

SEM fractographs at different steps of the crack propagation have been reported in Fig. 9 – (b,c,d).

As can be seen in Fig. 9-c another typical crack initiation site has been observed in near-surface eutectic microconstituents.

DISCUSSION

The experimental results confirm obviously that the fatigue resistance decreases as the notch tip radius increases. Anyway, the lower fatigue resistance observed in the material drawn from wheel B could not be determined simply by the coefficient k_t, because the peak stress value does not always control the failure mechanisms. In order to understand in which measure the fatigue strength is reduced by stress concentration effects, it has been necessary to study the fatigue behaviour of specimens with three different notch tip radii, comparable to those existent in wheel B.

Worth noting is the high dispersion of the as-obtained results, which is probably caused by microstructural defects and inhomogeneities, characteristic of cast alloys.

After the experimental tests it was possible to evaluate both the fatigue resistance of the material and the fatigue strength reduction as a function of the notch tip radius and microstructure parameters.

As a consequence, after that it has been obtained with a FEM analysis the peak stress value, it is possible to calculate also the effective stress value, which controls the fatigue behaviour.

Regarding the fracture surface analysis, two potential crack nucleation sites have been observed: surfacial porosities and near-surface eutectic microconstituents. Also scratches and microscopic notches caused by the tool during specimen machining should be considered.

From a comparison between Fig. 5 and Fig. 8 it is possible to note that samples drawn from wheel A show a lower fatigue resistance than the ones drawn from wheel B, in particular at lower stresses (high number of cycles); we had no information on the fatigue behaviour of the material from wheel A at high stresses (higher than 100 MPa), due to a low bending stiffness caused by the geometry of this first serie of specimens (see Fig. 4 -a).

It's important to note that the wheel A was characterised by a different geometry, with thicker rims than wheel B; the consequent lower cooling rate during solidification caused a slight coarser microstructure (larger secondary dendrite arm spacing).

Secondary dendrite arm spacing (SDAS) is a parameter that characterises the medium dimensions of dendrites in cast alloys; in literature it is possible to find several data [1,4,5] regarding the effect of SDAS on mechanical properties.

Dendritic structure controls the precipitates and inclusions morphology in the cast alloys; higher cooling rates, reducing secondary dendrite arm spacing, reduce also the formation of interdendritic shrinkages and, so, of the consequent porosities. Also for this reason, as SDAS decrease, mechanical properties increase. Obviously, the best conditions are insured by extremely fine dendritic structure and absence of porosity.

Our results, obtained both from microstructural analyses and from fatigue tests, substantially confirmed what it has been found in literature; the lower fatigue properties of the material from wheel A have been due to its different geometry that, causing lower cooling rates during solidification, caused the formation of a coarser dendritic microstructure, which affects mechanical properties of cast alloys.

CONCLUSIONS

The fatigue behaviour of a cast aluminium/silicon alloy for car wheels has been investigated. In particular, the relation between rim thickness, material microstructure and fatigue properties has been evaluated. Rotating bending fatigue tests have been performed on specimens un-notched and with three different notches, in order to evaluate also the fatigue strength reduction caused by different notch tip radii. The investigation allowed to draw the following conclusions:

1) The aluminium cast alloy of wheel "A" showed a coarser dendritic microstructure, with larger secondary dendrite arm spacing. The porosity level in rims of wheel "A" was also higher.
2) Samples drawn from wheel A showed a lower fatigue resistance than the ones drawn from wheel B, in particular at lower stresses (high number of cycles).
3) The lower fatigue properties of the material from wheel A have been related to the different geometry of this wheel that, causing lower cooling rates during solidification, caused the formation of a coarser dendritic microstructure (larger secondary dendrite arm spacing), which mainly affects mechanical properties of cast alloys.
4) The cast alloy showed low notch sensitivity. Fatigue stress reduction was lower than stress concentration factor, and, so, a notch theory has been used.
5) This research has confirmed that the marketing necessity of a continuous development of the cast design should be always accompanied by an accurate analysis of the consequent changes in cooling rates and solidification mechanisms, that strongly influence microstructural parameters, and of geometrical influence on stress distribution, valuable by the stress concentration effects.

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