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Tensile behavior and impact toughness of an AlSi3MgCr alloy

Marialaura Tocci[a*], Annalisa Pola[a], Lorenzo Montesano[a], Mattia Merlin[b], Gian Luca Garagnani[b], G. Marina La Vecchia[a]

[a] *Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38, 25123, Brescia, Italy*
[b] *Department of Engineering (DE), University of Ferrara, Via Saragat 1, 44122, Ferrara, Italy*

Abstract

Recently, an innovative AlSi3Mg alloy with Cr and Mn additions was developed for the production of truck wheels by means of a non-conventional hybrid technique, which combines features of both low pressure die casting and forging processes. The presence of both Cr and Mn leads to the formation of an intermetallic phase rich in Cr, Mn and Fe with a globular or dendritic morphology. Furthermore, proper solution treatments cause the formation of dispersoids in the aluminium matrix. These dispersoids are responsible of enhancing the alloy performance due to dispersion hardening mechanism. In the present work, the tensile properties and the impact toughness of the alloy in as-cast and different heat-treated conditions were studied. Moreover, tensile and impact strength tests were performed on A356 samples in T6 condition machined from traditional LPDC wheels, whose results were compared with the performance of the innovative alloy. Fracture surfaces of tensile and Charpy specimens were observed by Scanning Electron Microscopy (SEM) in order to identify the role of the Cr-Mn containing intermetallic particles in the failure mechanism and the influence of the heat treatment parameters. Considering the static properties, the innovative alloy showed remarkable values of tensile strength, while ductility was improved only after heat treatment optimization. Poor impact toughness values were measured and the microstructural analysis confirmed the presence of coarse intermetallic secondary phases, acting as crack initiation and propagation particles, on the fracture surfaces.

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Keywords: Al-Si-Mg alloys; tensile test; impact test; fracture surface

* Corresponding author. Marialaura Tocci Tel.: +39-030-371-5415; fax: +39-030-370-2448.
E-mail address: m.tocci@unibs.it

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1. Introduction

Al-Si-Mg alloys are the most common aluminum alloys used for automotive castings (Zapp et al. (2002); Miller et al. (2000)). These materials are characterised by excellent castability, good corrosion resistance, high elongation and significant strength, particularly after proper heat treatments. In the last decades, the light weighting of cars and trucks has become a very widely discussed theme (European Aluminium Association (2013)) and the object of several researches performed by both the academic and the industrial world. The design of more efficient processes and the development of stronger and lighter materials enhance the reduction of weight of cars and trucks components, allowing the reduction of fuel consumption and toxic emissions in atmosphere. For these reasons, an innovative AlSi3Mg alloy with Cr and Mn addition was developed for the production of truck wheels by means of a non-conventional hybrid technique, which combines features of both low pressure die casting and forging processes (Tocci et al. (2015)). The aim is the light-weighting of this component by enhancing the mechanical properties of the alloy due to a particular efficient casting technology and the presence of Cr and Mn as strengthening elements. In fact, in Al-Si alloys, Fe is a common impurity which forms brittle needle-like intermetallics, known as β-Al_5FeSi, which are harmful for mechanical properties, particularly for tensile and fatigue behaviors (Seifeddine et al. (2008); Mahta et al. (2005); Kim et al. (2006)). Instead, Cr and Mn additions lead to the formation of globular or polygonal intermetallics (Mahta et al. (2005); Shabestari (2004); Taylor (2012)) that are less detrimental for mechanical properties than the acicular β-Al_5FeSi phase. Nevertheless, the presence of a significant amount of intermetallic phase can still represent a limit to the mechanical performance of the Cr-containing alloy and deeper investigations are needed to evaluate its effect.

In addition, heat treatment is also a key factor to consider in order to optimise the performance of any Al-Si-Mg alloy and several authors examined the effect of heat treatment parameters and chemical composition on microstructure, mechanical properties and precipitation sequence for Al-Si-Mg alloys (Sjolander and Seifeddine (2010)). For instance, Wang et al. (Wang and Davidson (2001)) studied the effect of Mg content on both solidification and precipitation behaviour of AlSi7Mg casting alloy, while Li et al. (Li et al. (2004)) investigated the ageing behaviour of Al-Si alloys with Mg and Cu addition with particular attention to the precipitation sequence. Conversely, when Cr and Mn are present in the alloy composition it was found that they do not interact significantly with Mg during ageing treatment. In fact, it was recently demonstrated that Cr-containing dispersoids already form in AlSi3Cr alloy during the solution treatment and that they contribute to the dispersion hardening of the material (Tocci et al. (2017)).

Despite the abundant information in scientific literature about this topic, heat treatment optimization is a constant issue for industrial production in order to reach a good compromise between strength and ductility. For these reasons, in the present paper tensile properties and impact toughness were investigated for the innovative AlSi3Cr alloy by changing time and temperature of the ageing treatment. Particular attention was paid to the role of intermetallic particles and the effect of ageing treatment parameters. Furthermore, the optimised performance of this alloy was compared with the properties of the commercial A356 casting alloy, currently used for the production of car wheels, in order to better evaluate the suitability of the alloy for this application.

2. Materials and methods

The alloy under investigation is an Al-Si-Mg alloy developed for the production of truck wheels by a non-conventional hybrid technique (Tocci et al. (2015)), combining features of both low pressure die casting (LPDC) and forging processes. The chemical composition is among those of the conventional alloys for LPDC and forging. In particular, the concentration of the main alloying elements is shown in Table 1.

Table 1. Main alloying elements (wt. %) for the studied alloy.

	Si	**Mg**	**Cr**	**Mn**	**Fe**	**Al**
AlSi3Cr	3.158	0.558	0.276	0.120	0.123	Balance

All the samples were drawn from the same position of the wheel (rim). Samples to be tested in as cast condition were directly machined to the proper shape for tensile and Charpy impact tests, while other samples were first machined as cylinders, heat treated and then machined to the final shape.

Solution and aging treatments were performed in air in two different furnaces, in order to guarantee an optimal temperature control and homogeneity in the heating chamber. Heat treatment temperatures were chosen according to solidus temperature measured by DSC measurements (Tocci et al. (2015)) and best practice for this group of aluminium alloys (Davis (1993)). During the heat treatment, the temperature was additionally monitored by a thermocouple placed inside an aluminium sample in the furnace chamber. Samples were solution treated for 3 h at 545 °C, then water quenched at 65 °C to have optimal quenching conditions (Davis (1993)) and subsequently aged at 165 °C and 190 °C for different times between 1 and 8 h. Between quenching and ageing treatment, the samples were kept at -20°C in order to avoid natural ageing.

Microstructural characterization was carried out by both a Leica DMI 5000 M optical microscope (OM) and a LEO EVO 40 scanning electron microscope (SEM), equipped with an energy X-ray dispersive spectroscopy probe (EDS).

Vickers microhardness measurements were performed on as cast, quenched and aged samples using a Shimadzu indenter with an applied load of 1.9 N and a loading time of 15 s. At least 20 measurements were performed on each sample in order to guarantee a reliable statistic.

Tensile tests were performed at room temperature on as cast, quenched and aged samples using an Instron 3369 testing machine with a load cell of 50 kN. The crosshead speed was 1 mm/min in the elastic field and 2 mm/min in the plastic field. Accurate elongation values were obtained using a knife-edge extensometer fixed to the specimens' gauge length.

Charpy impact tests were performed at room temperature on as cast, quenched and aged samples using a CEAST instrumented pendulum with an available energy of 50 J. U-notched samples with standard dimensions (10 mm x 10 mm x 55 mm) were used. Data were acquired using a DAS 64k analyser.

The fracture surfaces of tensile and impact specimens were observed and analysed by SEM.

Tensile and impact strength tests were also performed on samples drawn from a commercial A356 LPDC wheels in the T6 condition in order to be compared with the innovative AlSi3Mg alloy.

3. Results and discussion

3.1 Microstructural analysis

The typical microstructure of the AlSi3Cr alloy in the as cast condition is illustrated in Fig. 1 at two different magnifications. It consists of a primary dendritic phase with a small amount of a eutectic mixture. Moreover, intermetallic particles with a globular or dendritic morphology are also present (see arrows in Fig. 1b). These particles are usually indicated as the α-Al(Fe,Mn,Cr)Si intermetallic phase, which forms when Cr and/or Mn are added to the alloy composition (Taylor (2012); Mondolfo (1976)).

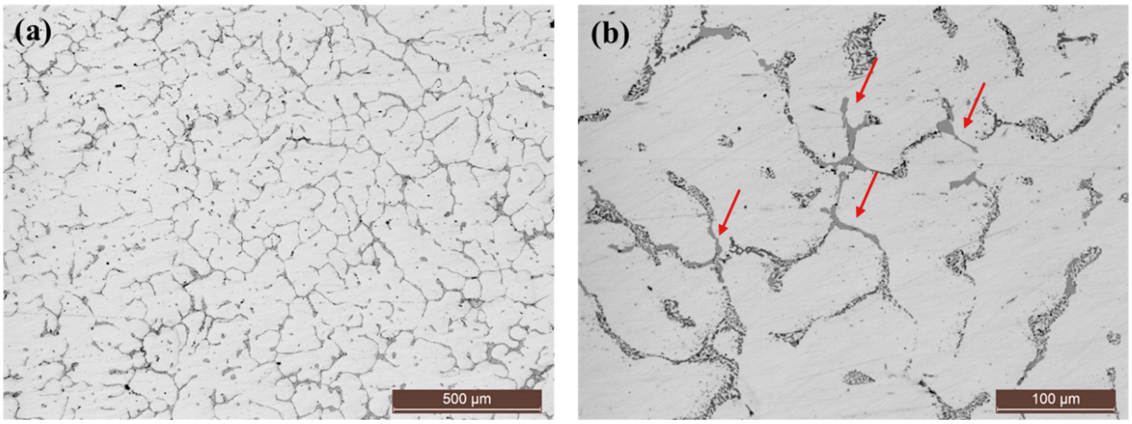

Fig. 1. Typical microstructure of the AlSi3Cr alloy in the as cast condition at two different magnifications.

After heat treatment, the expected spheroidisation and coarsening of Si eutectic particles takes place (Fig. 2). In addition, as explained in a previous work by the authors (Tocci et al. (2017)), also the formation of Cr-containing dispersoids takes place in the aluminium matrix during solution treatment. It was demonstrated that they are responsible of an increase in material hardness, also affecting both tensile properties and toughness (Seifeddine et al. (2008); Kim et al. (2006); Li et al. (2011)).

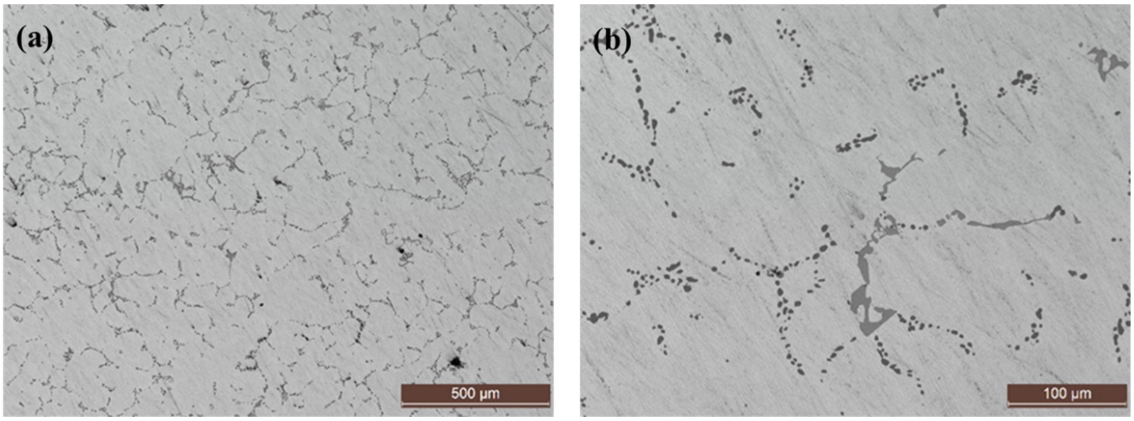

Fig. 2. Typical microstructure of the AlSi3Cr alloy in aged condition (1 h at 165°C) at two different magnifications.

3.2 Hardness and tensile properties

The average values of Vickers microhardness of tensile properties of the AlSi3Cr alloy in as-cast condition are summarised in Table 2.

Table 2. Mechanical properties of the AlSi3Cr alloy in the as cast condition.

	HV0.2	UTS (MPa)	YS (MPa)	El (%)
Average	73	202	106	5,3
Standard deviation	2	2	2	0,5

The influence of the aging time on the Vickers microhardness of the studied alloy for the two considered aging temperatures, 165 °C and 190 °C, is shown in Fig. 3. As expected, it appears that the peak condition is reached earlier when ageing is performed at 190 °C rather than at 165 °C (Sjolander and Seifeddine (2010)). In fact, in the former case peak hardness is reached after 4 h and in the latter case after 6 h of treatment. Accordingly, over ageing occurs earlier when the heat treatment is performed at higher temperature, while the peak hardness is about 130 HV for both the ageing temperatures.

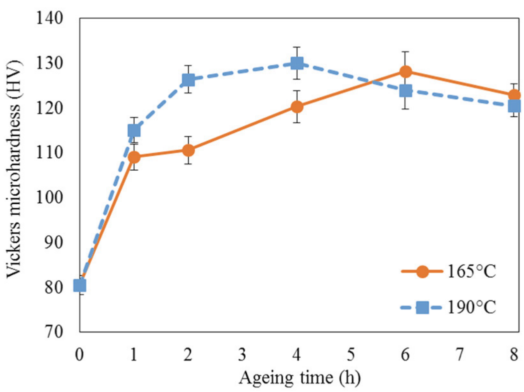

Fig. 3. Ageing curves of AlSi3Cr alloy for ageing at 165°C and 190°C.

In order to investigate the evolution of the mechanical properties according to the aging time, tensile tests were performed on specimens in the same conditions.

It was found that the AlSi3Cr alloy shows a remarkable increase in strength after the ageing treatment, reaching values of UTS between 320 and 360 MPa and values of YS between 275 and 330 MPa (Fig. 4a-b). On the other hand, a loss in ductility is expected as drawback of any increase in material strength and hardness; in fact, in most heat-treated conditions, the AlSi3Cr alloy shows poor elongation values. However, as shown in Fig 4c, it is possible to reach elongation values between 4% and 6% with ageing treatments between 1 h and 4 h at 165 °C.

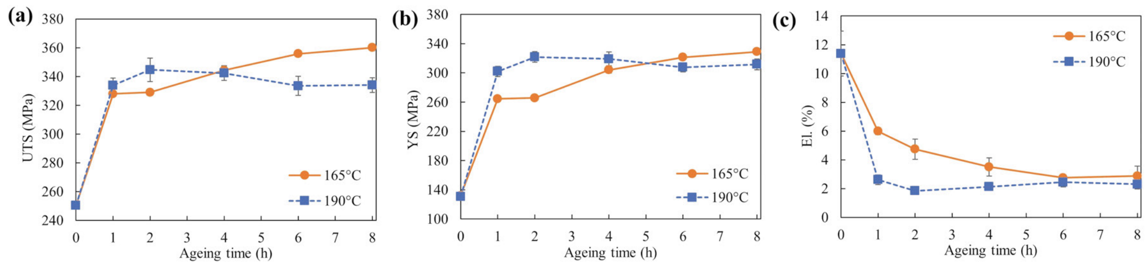

Fig. 4. (a) UTS, (b) YS and (c) elongation of the AlSi3Cr alloy in the selected heat-treated conditions.

Material ductility is affected by different parameters such as the presence of brittle Si eutectic particles, of α-Al(Fe,Mn,Cr)Si intermetallics and of Mg_2Si precipitates after the ageing treatment. Particularly, in as cast condition brittle Si particles and Fe-containing intermetallics are known to be responsible for crack propagation during the evolution of the fracture processes (Seifeddine et al. (2008)). After heat treatment, spheroidisation of Si particles and formation of precipitates take place. The former is reported to be positive for tensile properties (Zhang et al. (2002)), while the latter is responsible of a loss in ductility of the α-Al matrix (Sjolander and Seifeddine (2010)).

A mainly ductile fracture mechanism of the matrix is observed from SEM analysis of the fracture surfaces after tensile tests in all the selected heat-treated conditions (Fig. 5). A transcrystalline fracture, typical for Al-Si alloys (Warmuzek (2004)) with visible traces of micro-deformation (dimples), can be observed.

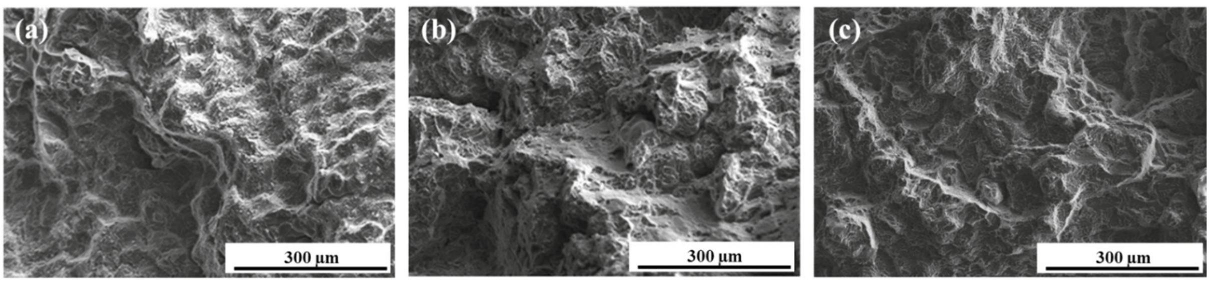

Fig. 5. Fracture surface of AlSi3Cr tensile samples in (a) as cast, (b) as quenched and (c) aged condition (1h 190°C).

Intermetallic particles containing Fe and Cr were sometimes detected on the fracture surfaces, as shown in Fig. 6a-b (EDS analysis in Table 3). They appear to be small and not cracked and this supports the idea that they play a marginal role in fracture initiation. As reported by some authors (Kim et al. (2006); Park et al. (1994); Dowling and Martin (1976)), α-Al(Mn,Cr,Fe)Si intermetallics are not cut by dislocations, which instead create a circle around the particles and moves around them during tensile tests, bypassing the obstacle. It is believed that the same mechanism is taking place for the studied alloy, in particular when globular intermetallic particles are present. Therefore, the main failure mechanism involves the fracture of eutectic Si particles rather than of intermetallics particles. This supports what is already reported by different authors about the positive contribution to tensile properties of the modification of intermetallic morphology due to Cr and Mn addition to Al-Si-Mg alloys (Seifeddine et al. (2008); Kim et al. (2006); Li et al. (2011)). Therefore, it appears that intermetallic particles are not critical for tensile behaviour for AlSi3Cr alloy and that most of the ductility is lost due to precipitation of hardening Mg_2Si phase.

Unfortunately, it is not possible to identify the presence of dispersoids, which are too small to be observed by SEM. In addition, areas where α-Al matrix emerges were detected on the fracture surface (Fig. 6c), as demonstrated by EDS analysis (Table 3). Here traces of plastic deformation in α-aluminium solid solution can be observed as very small dimples, likely in correspondence of dispersoids or precipitates (Warmuzek (2004)).

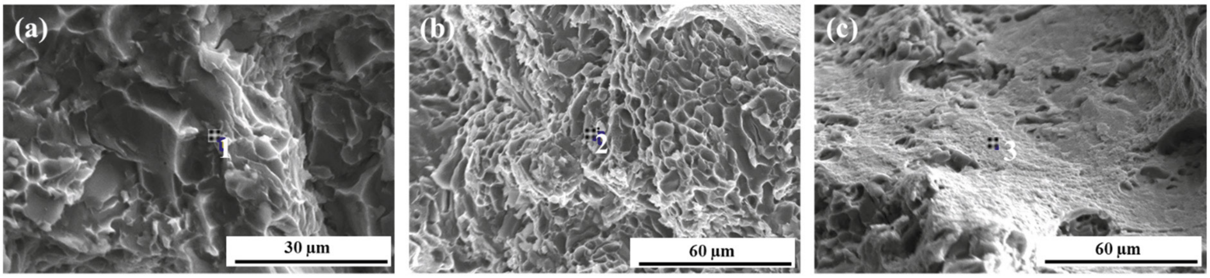

Fig. 6. Intermetallic particles on the fracture surface of AlSi3Cr tensile samples in (a) as cast, (b) aged condition (1 h at 190 °C). (c) Detail of fracture surface of aluminium matrix in as quenched condition.

Table 3. EDS analysis (wt. %) on intermetallic particles on fracture surface.

	Mg	Al	Si	Cr	Mn	Fe
1	0.49	48.81	22.98	0.43	0.35	26.94
2	--	33.87	2.97	14.98	10.34	37.85
3	0.79	96.75	2.13	0.33	--	--

3.3 Impact toughness

The mean values of total impact energy, with standard deviations, obtained on the U-notched samples in as-cast condition was equal to 2.43 ± 0.14 J. Moreover, the mean impact energies of the samples obtained after solution treatment and also after ageing performed at both 165 °C and 190 °C are summarized in Fig. 7.

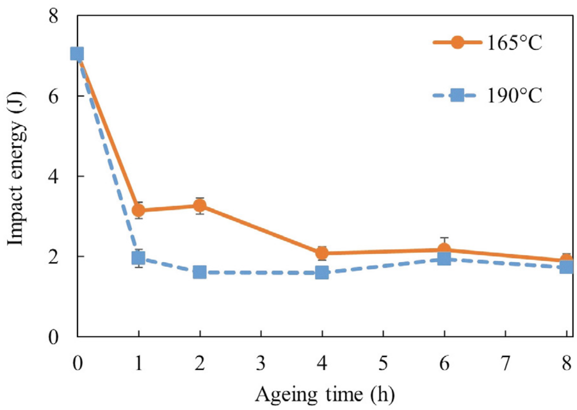

Fig. 7. Total impact energy for AlSi3Cr samples in different conditions.

Solution treatment performed at 545 °C for 3 h increases impact energy values with respect to the as-cast condition. This is mainly due to the spheroidisation of eutectic Si particles and the dissolution of Mg_2Si particles during the solution treatment; in fact, it is well-known that solution treatment reduces the number of critical points for crack initiation and therefore leads to the enhancement the energy absorption of the alloy (Elsebaie et al. (2011)). Similarly, the partial decomposition of some Fe-containing intermetallics can positively contribute to increase the material toughness by diminishing sharp edges at the interface with the matrix. Nevertheless, after ageing treatment, a severe drop in materials properties takes place due to the precipitation of β'-Mg_2Si particles. These particles, with their brittle behaviour, increase the micro-stresses, reducing the α-Al strain so that micro-cracks are more likely to originate (Zhang et al. (2002); Dieter (1986); Smallman and Ngan (2007); Merlin et al. (2009)).The highest values of the absorbed impact energy were measured in the samples aged at 165 °C for short aging times, while after 6 and 8 h of ageing very similar values were recorded. In addition, almost constant values of the impact energy were found after ageing treatment at 190 °C, regardless of the aging time, probably due to the fast precipitation of the hardening Mg_2Si particles.

SEM images of the fracture surfaces are shown in Fig. 8 and a typical ductile morphology can be identified for the as-cast and the selected heat-treated conditions. Preliminary analyses show that dimples formed around the Si eutectic particles as a result of the plastic deformation of the α-Al matrix.

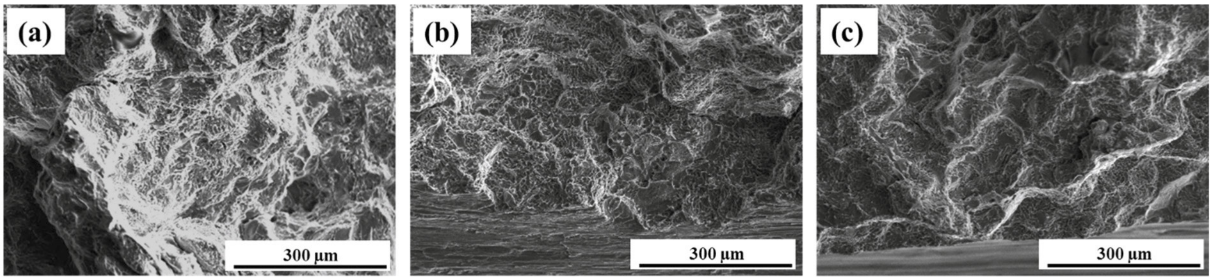

Fig 8. Fracture surfaces of AlSi3Cr impact samples in (a) as cast condition, (b) as quenched condition, (c) aged condition (1h ageing at 190°C).

Cracked intermetallics were observed on the fracture surfaces of the analyzed samples and a details of cracked particles are depicted in Fig. 9; the chemical composition of the particles as measured by EDS is reported in Table 4. They surely play an important role in both crack initiation and propagation during the impact tests (Elsebaie et al. (2011); Merlin et al. (2009)). The precipitation of Mg_2Si particles seems to be not effective in increasing the impact properties of the alloy; in fact, only the samples aged at 165 °C for 1 h show a slight increase of the absorbed impact energy if compared with the as-cast ones.

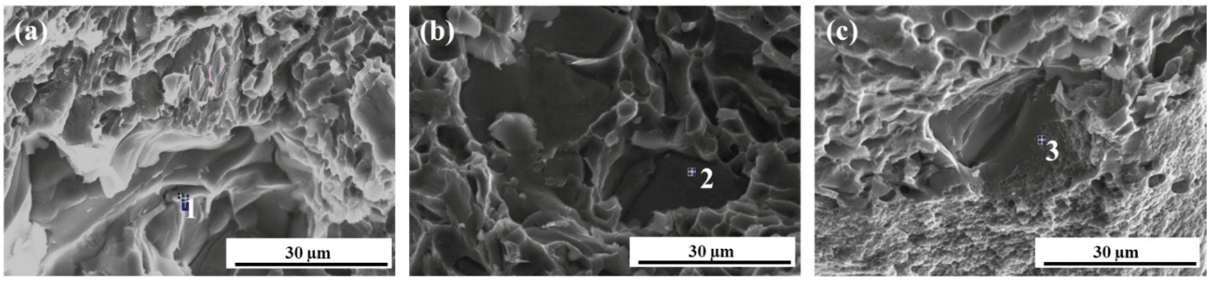

Fig. 9. Cracked intermetallic particle on fracture surface of sample samples in (a) as-cast condition, (b) as-quenched condition, (c) aged condition (1 h ageing at 190 °C).

Table 4. EDS analysis (wt. %) of the intermetallic particle depicted in Fig.9.

	Mg	Al	Si	Cr	Mn	Fe
1	0.66	92.06	4.16	1.24	0.60	1.28
2		61.20	13.47	9.91	4.15	11.26
3		64.08	3.55	12.48	5.49	14.39

In comparison with the analysis on tensile specimens, it appears that intermetallics are much more abundant on fracture surface from impact tests. They appear therefore more critical for material toughness, while for tensile properties it can be observed that hardening and strengthening of the matrix due to ageing is the most critical factor affecting material ductility.

3.4 Preliminary comparison with a conventional A356 alloy in the T6 condition

Tensile and impact tests were performed also on samples drawn from wheels produced by LPDC process with the traditional A356 alloy in the T6 condition (solution treatment at 540 °C for 4 h and ageing treatment at 155 °C for 2,5 h). In particular, the obtained results were compared with the performance of the innovative alloy in the optimised heat-treated condition (ageing for 1 h at 165 °C). Data are collected in Fig.10.

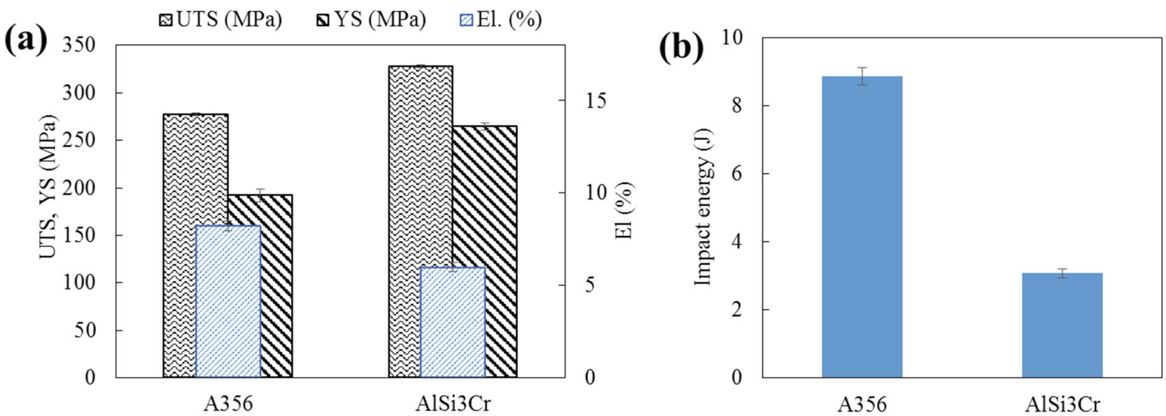

Fig. 10. (a) Tensile properties and (b) impact toughness of A356 and AlSi3Cr alloys.

It can be observed that UTS and YS are significantly higher for AlSi3Cr than for A356 alloy. On the other hand, a slightly lower elongation is also recorded.

More evident is the difference in impact toughness for the studied materials since A356 alloy can absorb three times the energy absorbed by AlSi3Cr alloy. It is believed that the coarse intermetallic phase present in the innovative alloy is particularly detrimental in impact tests, as demonstrated also by the presence of fractured intermetallics on the surface of tested specimens (Fig. 9). Nevertheless, deeper investigations are needed to better evaluate also the role of the different Si content on impact toughness and what affects most the crack initiation rather than the crack propagation in order to improve AlSi3Cr performance.

Conclusions

Tensile properties and impact toughness were studied for an AlSi3 alloy containing Cr and Mn in different heat treated conditions. Particular attention was paid to the influence of intermetallic phases, which form due to the presence of Fe, Cr and Mn, on the mechanical performance of the material. It was found that the alloy show remarkable tensile strength in most heat treated conditions, while elongation can reach values very similar to that of the conventional A356 alloy for selected aged conditions. The fracture mechanism was mainly ductile and intermetallic particles appear to play a marginal role in fracture initiation. On the other hand, poor impact toughness values were measured because, in this case, intermetallic secondary phases act as crack initiation and propagation particles. This was demonstrated by the presence of coarse cracked intermetallic particles on the fracture surfaces in as cast and heat treated conditions.

The study of mechanical performances of the innovative AlSi3Cr alloy still needs further investigation, but the data collected in the present work can be very helpful for the identification of proper applications for this material.

Acknowledgments

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