

Mechanical characterization of aluminium alloys for high temperature applications

Part 2: Al-Cu, Al-Mg alloys

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ABSTRACT

New challenges for the Aluminium alloys used for the production of castings for automotive engine components are coming from the evolution trend of Internal combustion engines towards higher specific power output. Cylinder heads, in particular, have to withstand higher operating temperatures and stress levels. The present article is the continuation of a study aimed to evaluate the mechanical properties at high temperature of Al-Cu and Al-Mg families of aluminium alloys to evaluate their suitability as a potential alternative to the Al-Si-Cu alloys traditionally used for the production of cylinder head castings.

RIASSUNTO

Con l'inarrestabile evoluzione dei motori endotermici e il relativo aumento delle potenze specifiche, le leghe di alluminio utilizzate per la produzione di componenti per propulsori automobilistici sono chiamate a fronteggiare nuove sfide. In particolare le teste cilindri sono componenti che devono resistere ad alte temperature operative e livelli di sollecitazione sempre più severi. Questo articolo è il proseguimento di uno studio focalizzato alla valutazione delle proprietà meccaniche ad alta temperatura delle leghe di alluminio appartenenti alle famiglie Al-Cu e Al-Mg ed alla valutazione della loro idoneità come potenziale alternativa alle leghe Al-Si-Cu tradizionalmente impiegate per la produzione di teste cilindri.

KEYWORDS

Cylinder Head; Al-Cu alloys; Al-Mg Alloys; Mechanical properties; High temperature; Microstructural evaluation.

INTRODUCTION

The call for the reduction of pollution and for a better and more severe control of the emissions, together with the demand for fuel economy, constitutes the driving force for the research in light-weighting of cars. In this more and more competitive scenario aluminium alloys and related forming technologies represent a strategic key.

In the vol. n. 29-1, April 2011, of *Metallurgical Science and Technology Journal* [1] a preliminary article was published, it represents the first part of this paper and contains a deep analysis of the motivation of the interest for Al alloys for high temperature applications, as well as the description of the evolution of modern engine concept and design. The consequence of these changes and evolutions are the preeminent requirements for the search and development of new or modified aluminium alloys able to better guarantee higher strength, performances and reliability at high temperature.

In these two papers (part 1 and part 2) the study and the characterisation activities related to the evaluation and development of Al alloys resistant to high temperatures are presented. The research aims to attain possible improvements of strength limits especially in the case of high thermo-mechanical stresses, namely in engine components, like cylinder heads, in which operating load and temperature levels have increased most in new downsized engines [2-6].

The first part of the paper was dealing about the primary AlSi9Cu1 (A354) alloy, chosen as a reference for comparative basis of properties of the new considered alloys. The alloys have been chosen also taking into account their suitability for gravity and low pressure die casting processes. On these basis the new considered alloys are belonging to the AlMg and AlCu groups, always as primary alloys.

In particular the tensile properties at room temperature, at 150°C and at 250°C were accounted as main aspects and the test experimental procedure is the same already adopted for the first part of the work and it has been already illustrated in the related paper.

DESCRIPTION OF WORK

The preliminary work summarizes the result of an internal activity, carried out at Teksid Aluminum, in which the mechanical

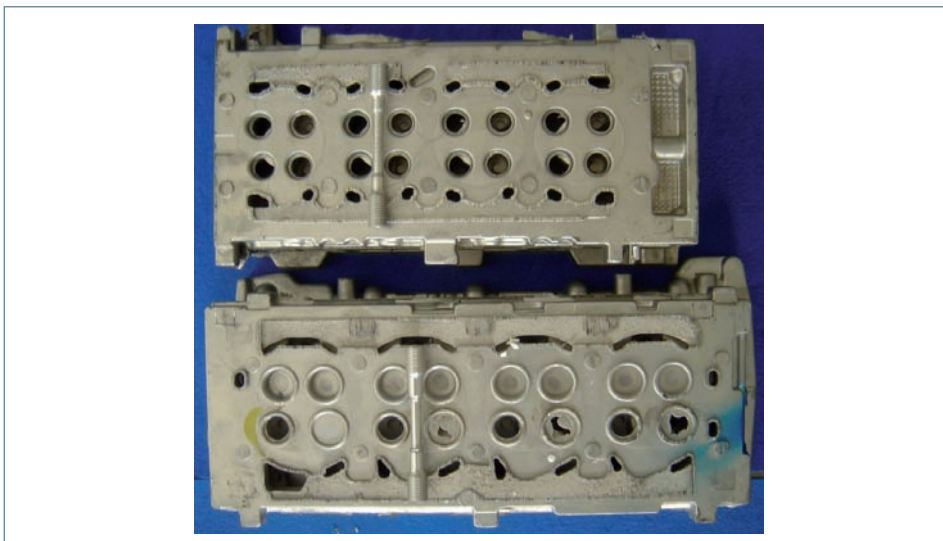


Fig. 1: Test specimen extracted from casting.

behaviour at elevated temperature of an Al-Si-Cu alloy (A354 family), typically used today for diesel cylinder heads cast in Gravity Semi-Permanent Mould (GSPM), has been evaluated and the possibility of a further development of this alloy to improve its resistance to high temperatures has been studied.

In addition these results were taken as a basis for a comparative study focused on two different families of alloys, Al-Mg and Al-Cu. They both are known for their good thermal stability, but they are not normally used for the production of castings in GSPM or Low Pressure Die Casting (LPDC); the evaluation of their capability to undergo these processes constitute the main purpose of this part of the work.

The following properties have been considered for the comparison:

- ▶ tensile strength properties at room temperature (RT);
- ▶ tensile strength properties at 150°C (Typical condition found at the cooling fluid interface);
- ▶ tensile strength properties at 250°C (Typical condition found in the combustion chamber);
- ▶ Hardness data for each test condition.

Test specimens have been taken both from the flame deck of actual cylinder head castings, Fig. 1, poured in the alloy under evaluation, and, in some cases, from separately cast samples, poured using a specific steel mould, Fig. 2, reproducing the typical cooling conditions found in the

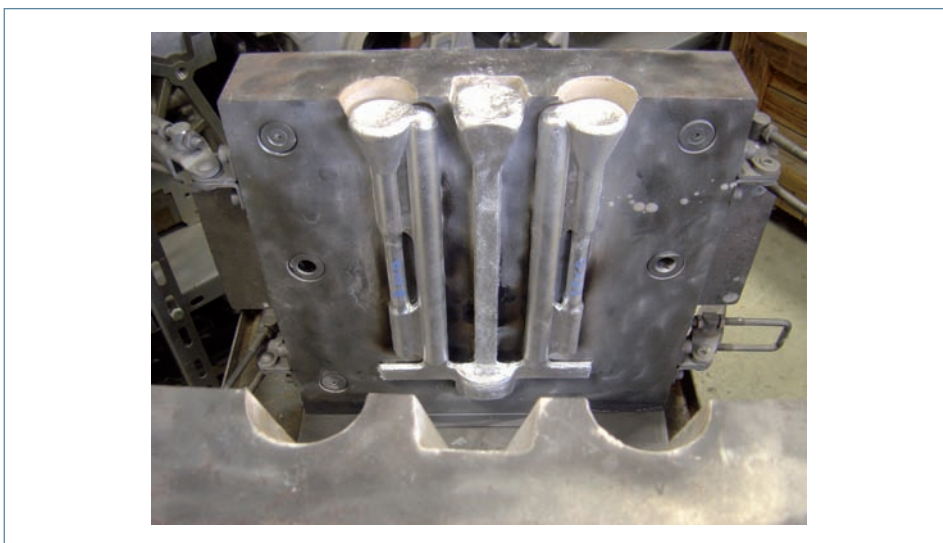


Fig. 2: Mould for separately cast samples.

bottom part of a cylinder head casting close to the drag of the mould, so that a similar microstructure can be reproduced. Mechanical tests have been performed on a Zwick Z100/TL3S tensile testing machine, equipped with data acquisition system for the recording of stress-strain curves. For the High Temperature (HT) tests a tubular furnace positioned around the specimen under test has been used; in order to ensure temperature setting consistency and to avoid temperature

gradient along the test bar, the control system of the furnace uses three thermocouples positioned in the middle and at the ends of the test bar. Specially designed extensometer in stainless steel connected to optical position measuring system has been used to measure elongation during the HT tests. RT and HT test set-ups are shown in Fig. 3 and Fig. 4.

CHOICE OF THE ALLOY SYSTEMS TO BE STUDIED

The following primary alloys, characterized by low content of impurities, Fe in particular, and whose composition is summarized in Table 1, have been used for the study:

Table 1. Alloys Composition

Alloys	Chemical composition (%)								Grain refined
	Si	Mg	Cu	Fe	Mn	Ni	Sc	Zr	TiB2
AlMg3Si Mn	1.00	3.30	0.00	0.15	0.20	0.00	0.00	0.00	0.015
AlMg3Si Sc-Zr	1.10	3.30	0.00	0.100	0.00	0.00	0.00	0.15	0.025
AlCu5	0.00	0.00	4.00	0.15	0.20	1.00	0.00	0.00	0.015

ALMG3

The first system is related to aluminum-magnesium alloys, primary AlMg3. In the base version AlMg3SiMn the main alloying elements of the alloy are:

- Magnesium from 2.7 up to 3.5% wt%.
- Silicon from 0.9 up to 1.3 wt%.
- Manganese about 0.2 wt%.
- Iron, as impurity, 0.1 wt% max.

The binary Al-Mg family alloys are already quite well known for their very considerable mechanical properties and good corrosion resistance, clearly depending on the magnesium contents, higher magnesium means better properties, a negative aspect could be related to their cost, higher than the Al-Si based alloys.

Manganese is introduced in these alloys mainly to compensate the negative effect of Fe impurities to keep always high mechanical properties without sacrificing their typical corrosion resistance.

The Al rich end of the phase diagram of the base alloy, Al-Mg, is illustrated in Fig. 5; it is evident that at room temperature intermetallic Al₃Mg₂ particles can segregate from α solid solution, while,

when operating at high temperature the alloys are mainly monophasic, because of the solution effect, with consequent changes in properties.

Possible modifications of the base alloy can include the addition of scandium together with zirconium, both have an evident strengthening effect, because they form complex aluminides, that is phases of the type Al₃(Zr_xTi_{1-x}), which have an anti-recrystallization effect and consequently can be considered as self-ageing and are stable from a thermal point of view [7-10]. The role of Sc and Zr in helping to nucleate the aluminum alloy can be explained by the duplex nucleation model. According to the binary Al-Sc equilibrium phase diagram (Fig. 6), at the Al-rich end there is an eutectic reaction between α -Al and Al₃Sc phase; and the eutectic composition is at the low level of 0.35 at% Sc. Under the condition of non-equilibrium solidification, Sc mainly tends to form Al-Sc solid solutions. The Al₃Sc phase is a stable heterogeneous particle and can intensively refine aluminum grains when the

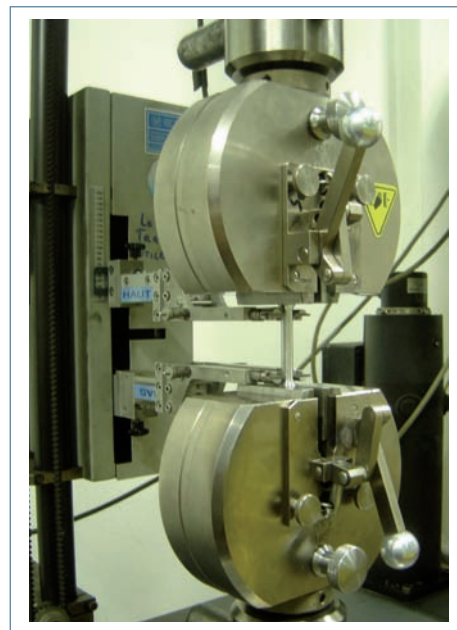


Fig. 3: RT Tensile test set-up.



Fig. 4: HT Tensile test set-up.

concentration of Sc in the melt exceeds the critical limit. The effect of Sc is amplified by the simultaneous addition of Zr by concentration fluctuation and microstructure wave in the melt due to interaction of Sc and Zr.

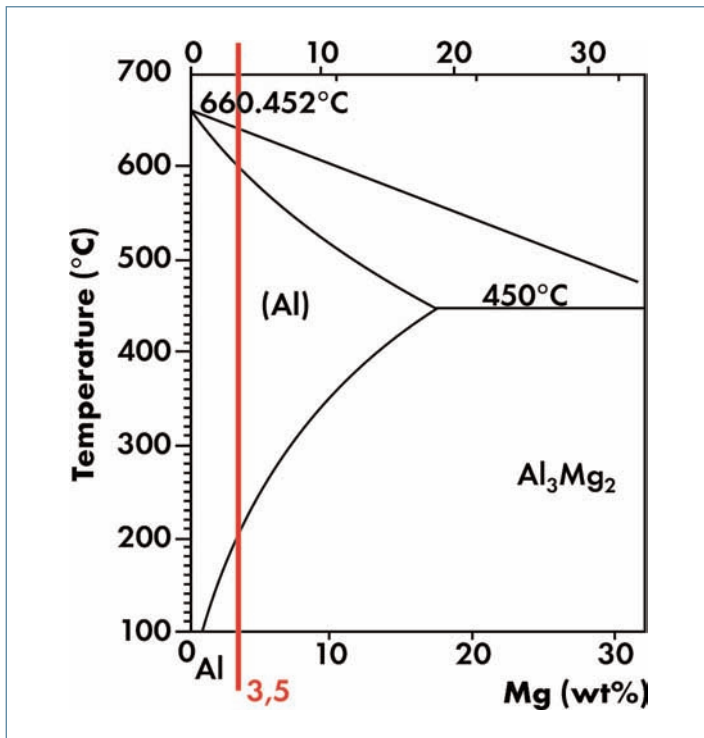


Fig. 5: Al-rich end of the Al-Mg phase diagram.

ALCU5

The second reference system was chosen based on the primary AlCu5 alloy, it is characterized by a very low impurity content and by the presence of important alloying, like Ni, which increase the cost of the alloy. This type of alloy is well known for its hot resistance; then it is traditionally employed for components working in heavy conditions.

The copper characterises this primary alloy as main element and gives excellent mechanical performance. The contribution of Cu involves a slight increase of the density, reduces the coefficient of linear thermal expansion and more significantly electrical and heat conductivity. The Al rich end of the Al-Cu phase diagram (Fig. 7) shows the decrease of Cu solubility in α -Al solid solution at decreasing temperatures; as it is very well known, this effect is exploited for alloy strengthening by heat treatment.

The main elements in AlCu5 are:

- ▶ Copper in percentage from 4.0 to 5.0% wt
- ▶ Nickel in percentage from 0.9 to 1.1% wt
- ▶ Manganese in percentage approx. 0.20% wt
- ▶ Iron (impurity) less than 0.15% wt

Al-Cu alloys are generally considered difficult to cast due to their tendency to hot

tearing; components made with this family of alloys are usually produced by the sand casting process in which solidification speed is relatively low.

During the present study, some prototype cylinder heads have been cast with AlCu5 alloy using a modified GSPM steel mould and, after a careful set-up of process parameters and feeding system, castings without internal defects or cracks were produced.

HEAT TREATMENT AND CONDITIONING

All the cylinder head castings and the separately poured samples have been heat treated before the tests in order to maximize the aluminium alloy's properties. T5 or T6 treatments were selected depending on the type of alloy.

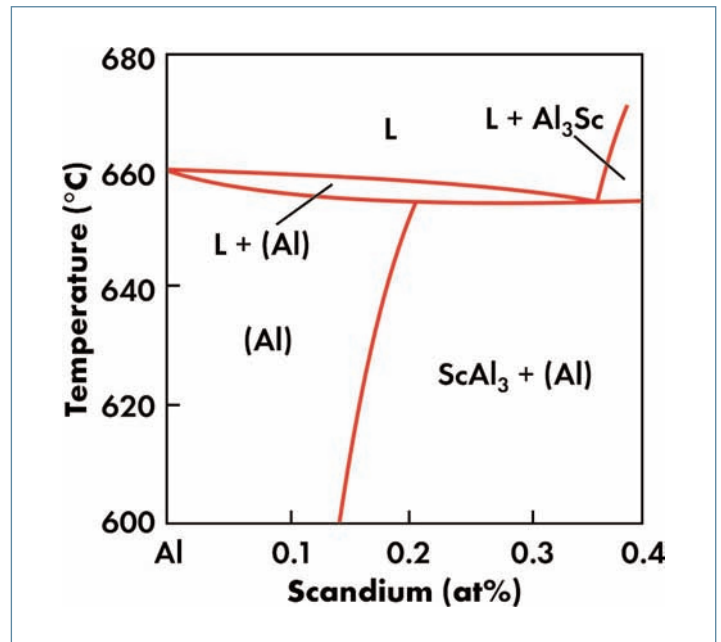


Fig. 6: Al rich end of the Al-Sc equilibrium diagram.

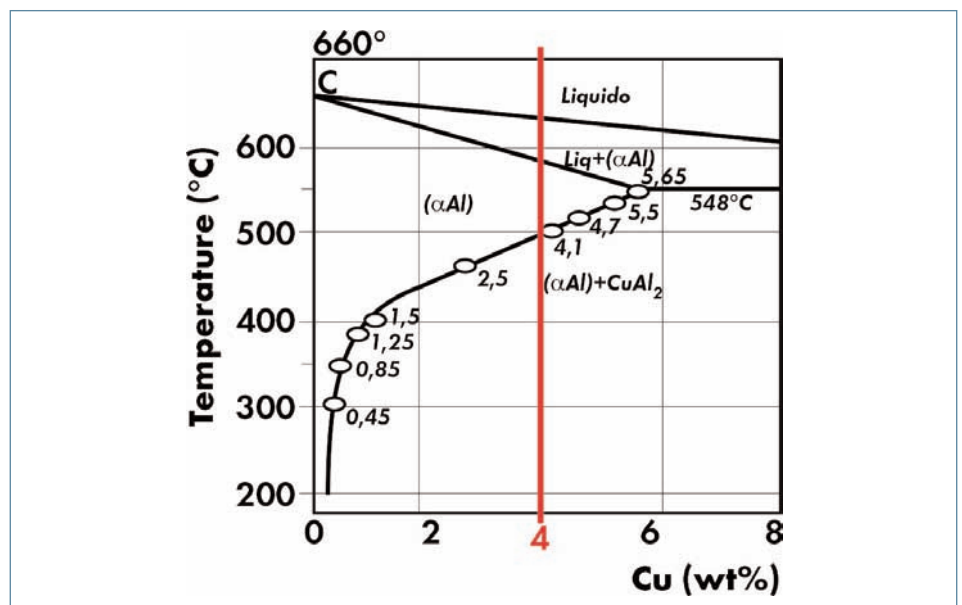


Fig. 7: Al rich end of the Al-Cu Phase Diagram.

T6 HEAT TREATMENT

- Solution phase at 540°C for 8 hours for Al-Cu and Al-Mg alloys.
- Quenching in hot water (80°C), at the end of the solution phase in order to freeze the state of solution in alloy elements.
- Precipitation hardening at 225°/240°C for 6/8 hours according to the type of alloy, Al-Cu or Al-Mg alloys

T5 HEAT TREATMENT

- Precipitation hardening at 200°C for 8 hours for the AlMg3Si (Sc-Zr) alloy.
- Before the tensile testing at HT (150 – 250 °C) all the test samples have been pre-conditioned at the test temperature for 500 hours, in order to reproduce the “in service” conditions of the over-aged material and the microstructural “damages” caused by long exposure to high temperatures.

MECHANICAL TESTS RESULTS

A summary of the test conditions analyzed for the various alloys is reported in Table 2:

Table 2: Summary of test conditions

Alloy	Heat treatment	Over-Aging	Characterization condition
AlMg3Si Mn	T6		Tensile test (20°C)
AlMg3Si Sc-Zr	T5		Tensile test (20°C)
		500 h x 150°C	Tensile test (150°C)
		500 h x 250°C	Tensile test (250°C)
AlCu5	T6	500 h x 150°C	Tensile test (20°C)
		500 h x 250°C	Tensile test (250°C)

Results obtained in the tensile tests at RT and HT are reported in the tables and histograms are the average values measured for each set of tested specimen, while the stress-strain curves show the results of a single specimen representative of the typical behaviour of the alloy.

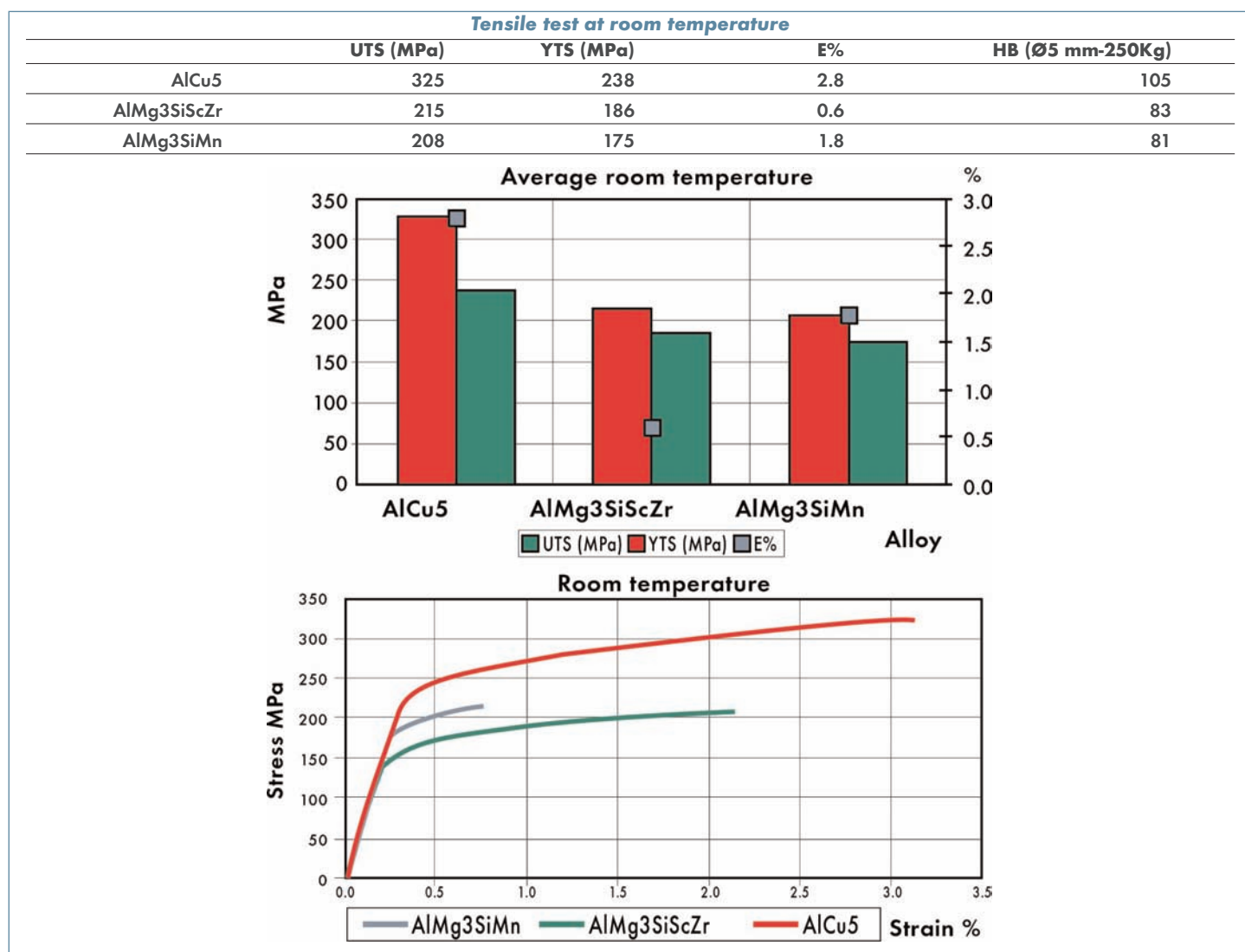


Fig. 8: Tensile test results at RT.

The following considerations can be drawn by the analysis of results obtained at RT:

- AlCu5 alloy shows the highest values for UTS (> 320 MPa), good elongation (around 3%) and YTS (around 240 MPa).
- Both AlMg3Si alloys show levels of UTS (around 210 MPa) and YTS (around 180 MPa) lower than the others.

At 150 °C all the alloy show a reduction of tensile properties compared to RT conditions. UTS decreases approx. 20% in average:

- Maximum UTS and YTS values are found again for AlCu5 alloy (around 250 MPa and 210 MPa respectively); elongation remains acceptable.
- AlMg3Si(Sc-Zr) shows lower values for UTS and YTS, but very high elongation (approx. 12%).

At 250°C we can notice a further significant decrease of strength for all the alloys, with dramatic increase of elongation to fracture values.

- AlCu5 is the only alloy to stay well over 100 MPa as YTS, with UTS around 140 MPa.
- AlMg3Si shows a lower decay in performances, maintaining UTS values around 100 MPa and very high elongation.

MICROSTRUCTURAL EVALUATION

In order to get a deeper understanding of the behaviour of the different alloys, a microstructural evaluation was performed on the specimen after the tensile test.

Another important practice to improve the mechanical properties and casting characteristics is to introduce inoculating compound like titanium and boron. This treatment of grain refinement allows to have a fine distribution of first dendrite's germination, due to nucleation of Al₃TiB₂ particles during the melt cooling.

AlMg3Si

This type of aluminium alloys is characterized by a dendritic structure with the significant presence of eutectic Magnesium compounds located into interdendritic region.

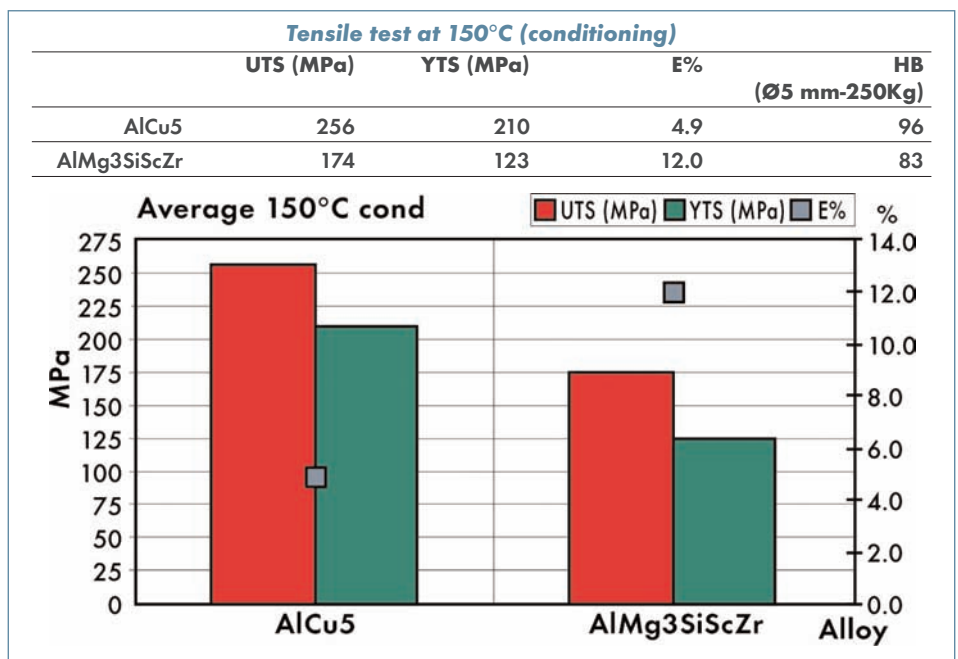


Fig.9: Tensile test results at 150 °C.

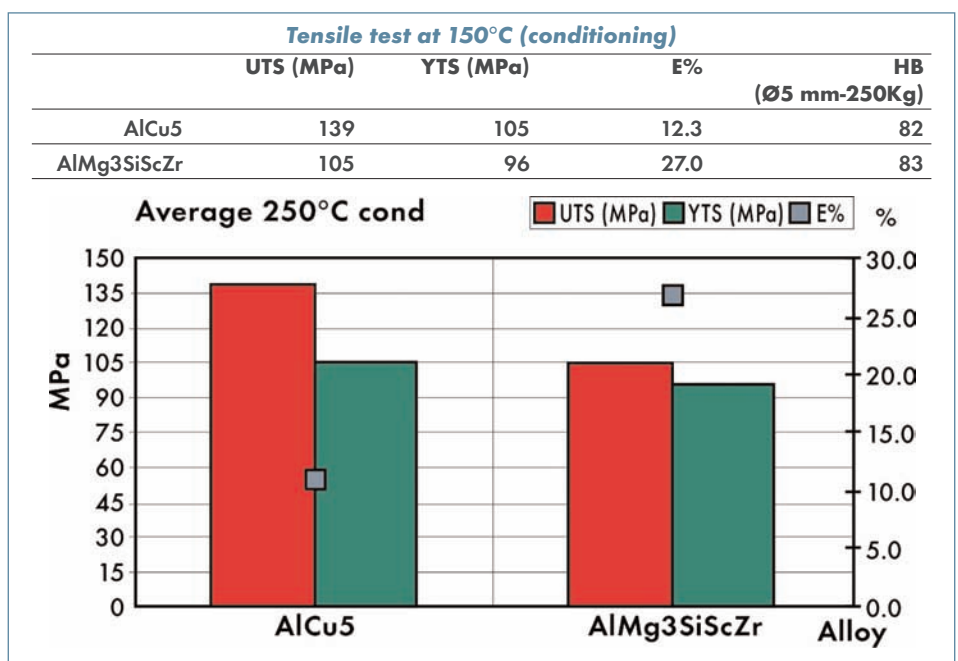


Fig.10: Tensile test results at 250 °C.

Since the alloy contains an inoculating element like titanium (200 ppm), the grain size is small.

From micrography (Figures 11 and 12) we can recognize the unchanged precipitation hardening eutectic compound Mg₂Si, even if the most important eutectic phase is the precipitation of Al₈Mg₅, which is difficult to recognize because for the most part is dissolved by solution treatment.

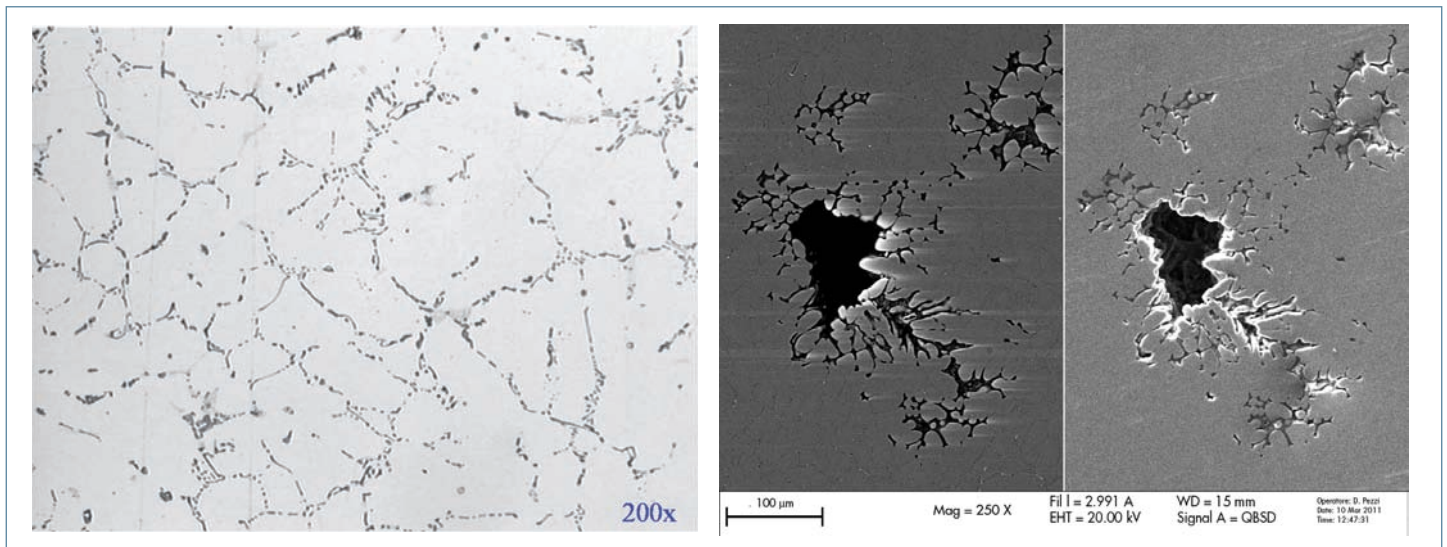


Fig.11: Microstructure of Al-Mg alloys, showing some shrinkage porosity.

AlCu5

This Aluminum-Copper alloy presents a typical dendritic structure accompanied by eutectic Cu compounds located in the interdendritic region.

Since the alloy contains an inoculating addition like titanium (150 ppm), the grain size is small.

Both micrographies (Figures 13 and 14) show a homogeneous eutectic distribution of CuAl₂; we can appreciate that the T6 treatment causes the solution of a large quantity of this eutectic phase, undissolved CuAl₂ is rounded.

The Cu₃NiAl₆ compound are not affected by heat treatment.

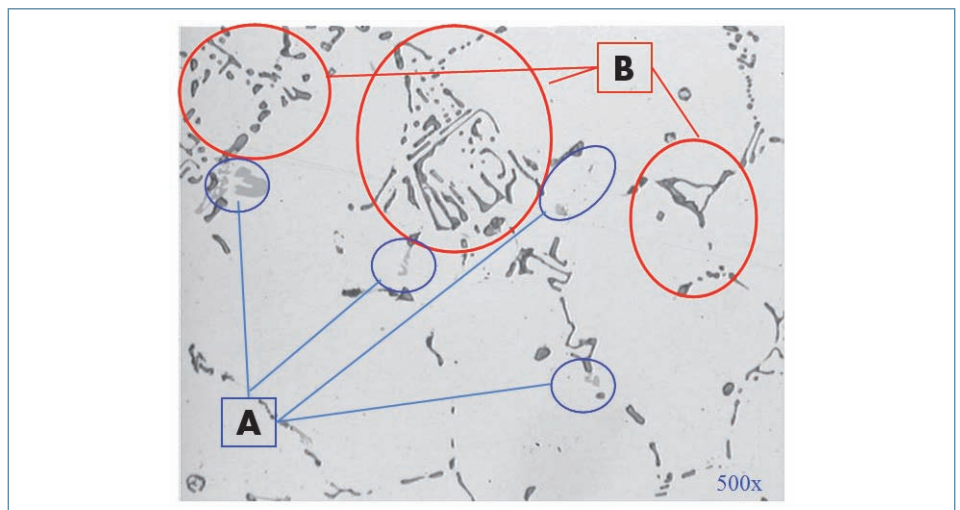


Fig.12: AlMg3Si - Intermetallic compounds: a) Al₈Mg₅ highlighted in blue - b) Mg₂Si highlighted in red.

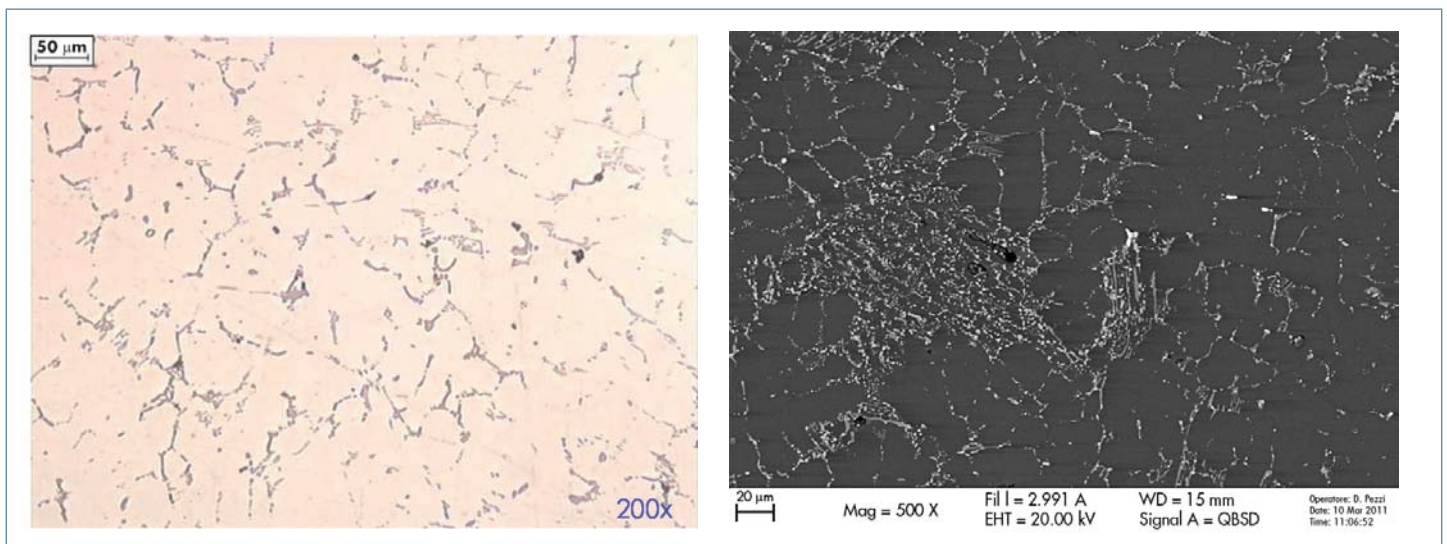


Fig.13: Microstructure of Al-Cu alloys.

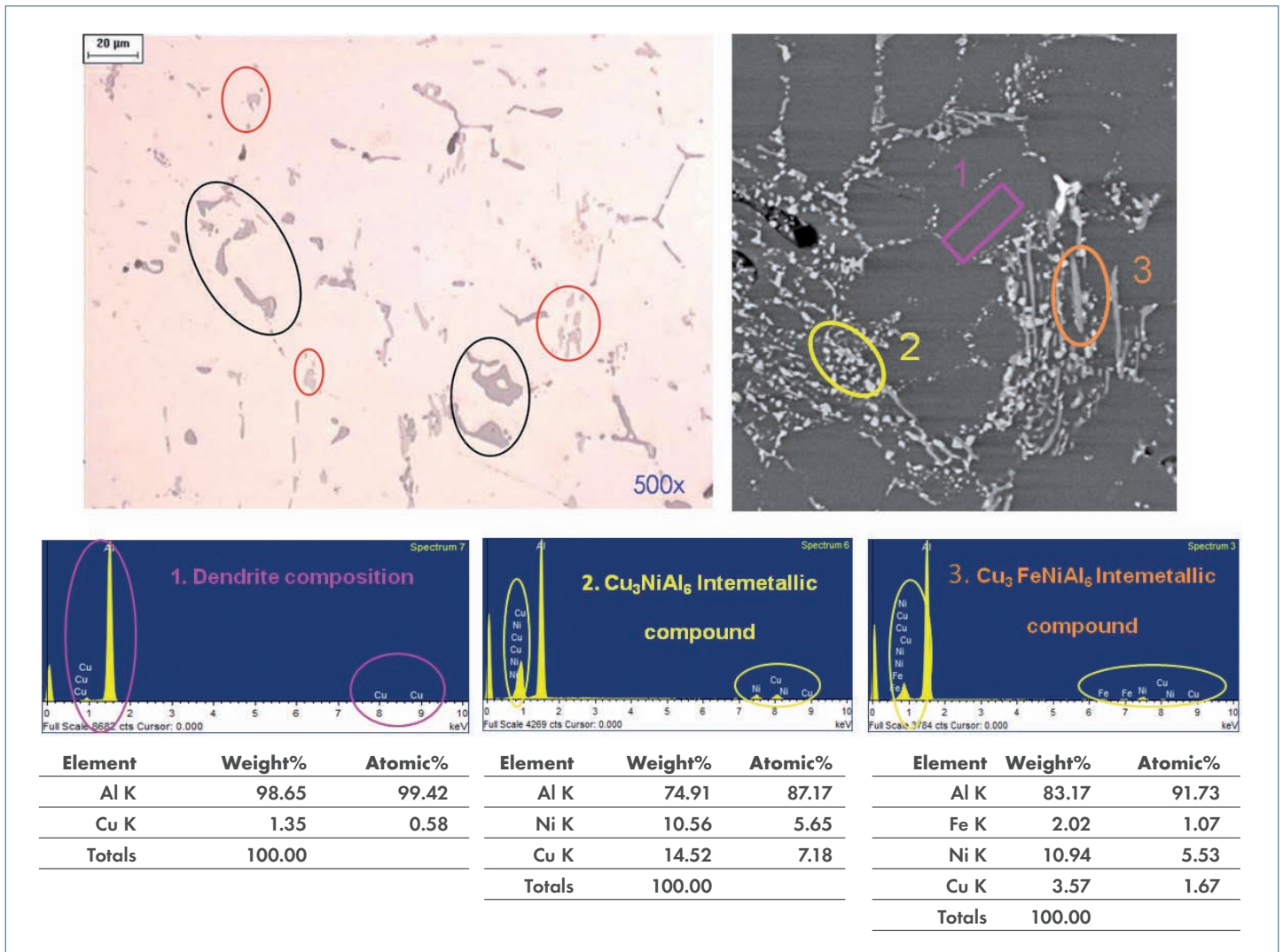


Fig. 14: AlCu5 - Intermetallic compounds: a) CuAl2 highlighted in red - b) Cu3NiAl6 highlighted in black

SUMMARY AND CONCLUSIONS

The mechanical behaviour of Aluminum alloys, measured by means of tensile test, is strongly influenced by the test temperature and by the exposure time at high temperatures.

Among the tested Aluminum alloys, the AlCu5 alloy showed the better performances at both room and high temperature and can provide adequate strength (UTS around 140 MPa) even at 250 °C.

Despite the reported worse castability properties than conventional Al-Si alloys, it was possible to obtain sound cylinder head castings using GSPM process with steel mould, by careful set-up of process parameters.

The main drawback of this type of alloys appears to be the high cost (50-60% more than Al-Si-Cu primary alloys), that allows, at present, their use only for premium or motorsports, low volume applications.

Alloys of the Al-Mg family considered in the present study did not completely meet the expectations: they showed actually a lower decay of performances as the temperature raised (and better stability over long exposures), but they were penalized by the low level of strength measured at room temperature (only approx. 70% of the others). They showed, on the other side, very good ductility.

A deeper study of heat treatment parameters is probably needed to increase their properties at room temperature.

Since their cost is, at present, very high (almost double than Al-Si alloys for the versions with Sc and Zr), their application for high volume cylinder head castings is not economically viable.

Based on the results achieved in the present study it was decided to continue the evaluation of the considered alloys also in terms of High Cycle Fatigue and creep resistance at high temperature. This activity is at present on-going.

ACKNOWLEDGMENTS

The authors wish to thank the personnel at Teksid Aluminum R&D and testing Labs and Dario Pezzini of Materials Laboratory of Politecnico di Torino, Alessandria branch, for their precious contribution to the work.

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