Mechanical characterization of aluminium alloys for high temperature applications Part1: Al-Si-Cu alloys

R. Molina, P. Amalberto - Teksid Aluminum
M. Rosso - Politecnico di Torino (Italy)

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 study is aimed to evaluate the mechanical properties at high temperature of Al-Si-Cu aluminium alloys traditionally used for the production of cylinder head castings. The obtained results are very promising, especially for what concerns the modified alloys. In fact, the resistance of base Al-Si-Cu alloy is fairly good up to 150°C, but drops at 250°C, while some interesting improvements have been achieved by modifying the composition of the base alloy with the addition of Mn and Ni, resulting in an increase of strength and ductility at both room and high temperatures. Further studies related to High Cycle Fatigue and creep resistance at high temperature are under way. Moreover, the research will be continued also considering other alloys families, like Al-Mg and Al-Cu and the results will be discussed in a second part of the article.

RIASSUNTO

Con la crescente 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 supportare nuove sfide. In particolare le teste cilindri sono componenti che devono resistere ad alte temperature operative e livelli di sollecitazione sempre più elevati. Questo studio ha lo scopo di valutare le proprietà meccaniche alle alte temperature delle leghe di alluminio Al-Si-Cu tradizionalmente utilizzate per la produzione di teste cilindri e i risultati ottenuti sono molto promettenti, in particolar modo per le leghe modificate mediante appropriate aggiunte di particolari elementi. Il livello di resistenza della lega di base Al-Si-Cu risulta soddisfacente fino a 150°C, ma decresce a 250°C, mentre interessanti miglioramenti sono stati riscontrati modificando la composizione chimica della lega di base con l'aggiunta di Mn e Ni con un conseguente aumento delle proprietà di resistenza meccanica e di tenacità sia a temperatura ambiente che alle alte temperature. Nell'intento di raggiungere sempre più alti livelli di resistenza sono tutt'oggi in corso le caratterizzazioni alle prove di Fatica termica ad alto numero di cicli e resistenza allo scorrimento viscoso (creep) sempre alle alte temperature. Inoltre la ricerca sarà portata avanti considerando altre famiglie di leghe come Al-Mg e Al-Cu con la pubblicazione dei relativi risultati nella seconda parte dell'articolo.

KEYWORDS

Cylinder head; Al-Si-Cu alloys; Mechanical properties; High temperature;Microstructural evaluation.

INTRODUCTION

Aluminium castings are widely used in the automotive industry for several components such as engine blocks and cylinder heads, produced in high volumes, thanks to their favourable combination of low weight, easy machinability, recyclability and low cost.

In the last years the evolution of internal combustion engines has been driven mainly by the need to meet new stringent emissions standards (like Euro 5 or future Euro 6 in Europe) and to improve fuel economy of the vehicles aiming to reduce the amount of CO_2, which is considered a "greenhouse gas" with potential effect on global warming, released to the ambient.

The concept of "Engine Downsizing", in which large displacement engines are replaced by smaller, lighter more efficient units with higher specific ratings, i.e. more power output for unit displacement, has been widely applied, for the development of new engine families.

The increase of specific output, achieved mainly by the application of super or turbocharging and of direct fuel injection concepts also to spark ignited engines, has led to a general increase of mechanical and thermal loads on engine components.

In addition, in the last ten years, also components for light and medium duty diesel engines, which continue to gain market shares in Europe, have started to be cast in aluminium alloys even where, due to the high requirements on strength and durability, cast iron was traditionally used.

Consequently, also requirements for the materials used to produce engine components have grown in terms of mechanical and fatigue resistance at operating temperatures, ductility and resistance to the creep at elevated temperatures.

Developments in aluminium alloys and optimization of casting techniques have lead to improved material properties and functional integration which enable aluminium castings to satisfy the new market requirements and have allowed to replace, in many cases, engine components made with heavy cast iron alloys.

Nevertheless requirements for new products are becoming more and more challenging for conventional aluminium alloys and their further improvement or the introduction of new alloys are under evaluation.

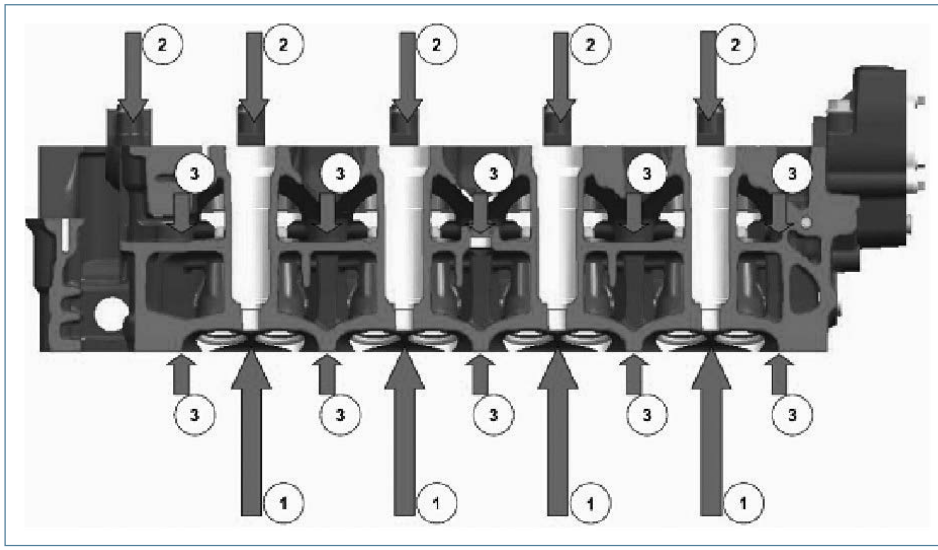


Fig. 1: Forces acting on a cylinder head.

Cylinder heads are, in particular, the engine components in which stress and operating temperature levels have increased most in new downsized engines. The stresses on the cylinders heads in operating conditions are mainly related to the forces indicated in figure 1:

1. Loads due to the pressure peaks in the combustion chamber, that can reach values around 200 bar in diesel engines, resulting in fatigue loading of the structure, in particular on the water jacket side of the flame deck.
2. Dynamic loads from the valve train system, acting mainly on the upper side of the structure, in particular on the supports of the camshaft.
3. Cylinder head bolts loads, generated by the screws connecting the head to the cylinder block. Tightening torque is usually very high in order to ensure proper cylinder head gasket sealing under firing conditions.
4. Thermal loads due to the uneven temperature distribution in the component and thus to non-uniform thermal expansion of the material.

A typical temperature distribution in the cylinder head of a high specific power engine in operating conditions is shown in Fig. 2.

Maximum temperatures can locally exceed 250°C in the flame deck, combustion side (typically between exhaust valves), and

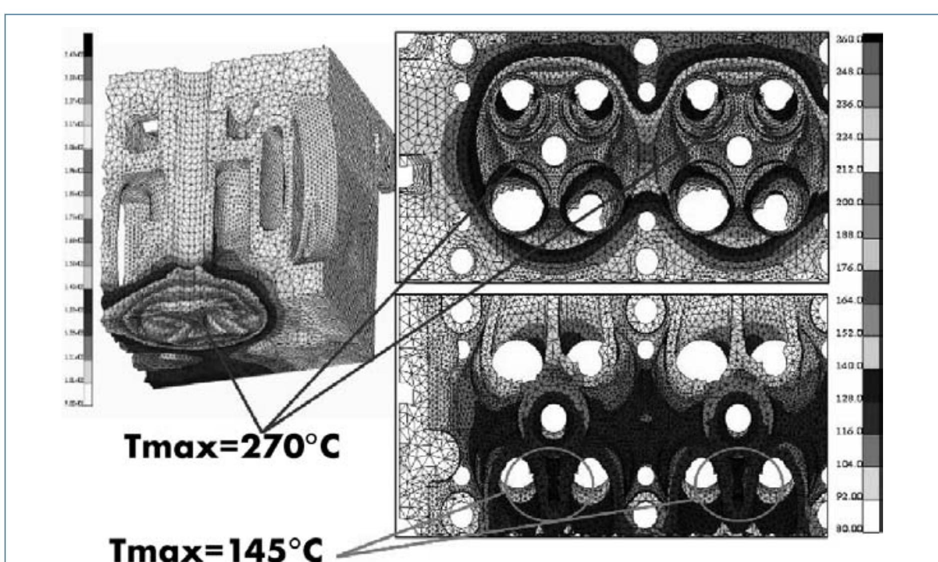


Fig. 2: Temperature distribution in a cylinder head.

reach values around 140°C at the interface with the cooling water jacket.
A typical stress distribution on the water jacket side of a cylinder head, resulting by the combination of the a.m. effects is reported in Fig. 3, showing that areas of high stress concentration are found at the root of the ports, where they intersect the flame deck.

DESCRIPTION OF WORK

The present work summarizes the result of an internal activity, carried out at Teksid Aluminum, in which the mechanical 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.
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 (see Fig. 4), poured in the alloy under evaluation, and, in some cases, from separately cast samples, poured using a specific steel mould (Fig. 5), reproducing the typical cooling conditions found in the 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.

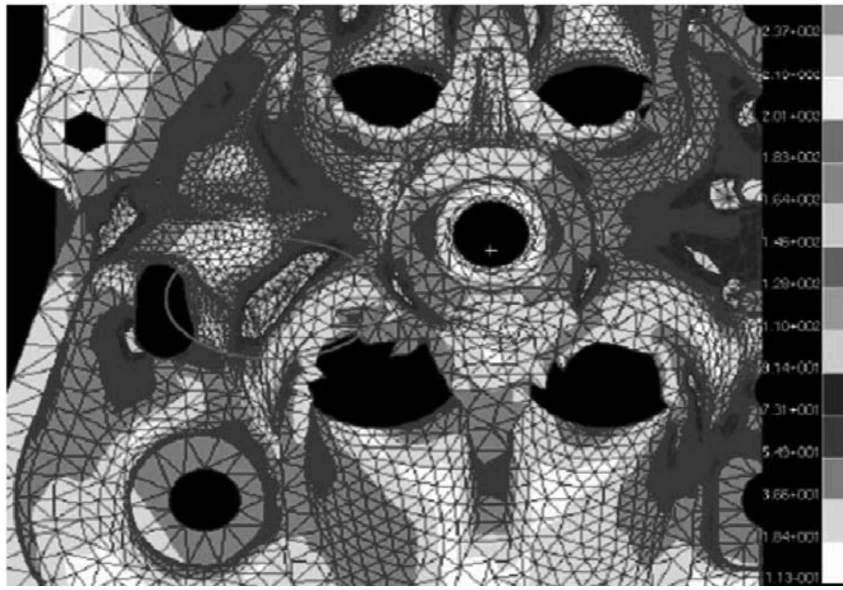


Fig. 3: Stress distribution in a cylinder head.

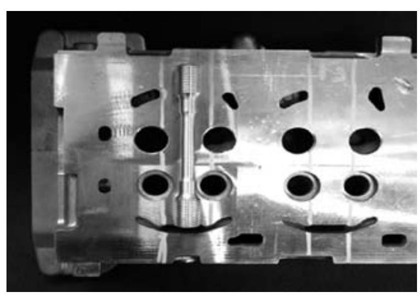


Fig. 4: Test specimen extracted from casting.

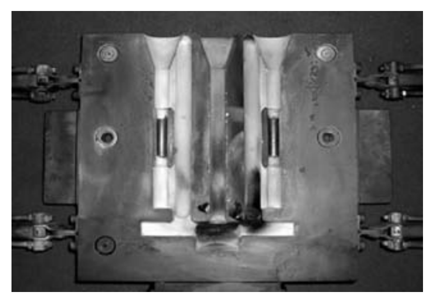


Fig. 5: Mould for separately cast samples.

Fig. 6: RT Tensile test set-up.

Fig. 7: HT Tensile test set-up.

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. 6 and 7.

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

	Chemical composition (%)				Adding elements (%)		Grain refined	Eutectic modification
Alloys	Si	Mg	Cu	Fe	Mn	Ni	TiB2	AlSr
AlSi9Cu1	9.40	0.40	1.05	0.25	< 0.10	0.00	0.05	0.05
AlSi9Cu1Mn	9.40	0.40	1.05	0.25	0.40	0.00	0.05	0.05
AlSi9Cu1NiMn	9.40	0.40	1.05	0.25	0.20	1.00	0.05	0.05

AlSi9Cu1

Baseline alloy, typically used at Teksid Aluminum for diesel cylinder heads. As pointed out in the Al-Si phase diagram, the 9% of silicon provides a good fluidity allowing good filling of complex shapes with relatively low wall thickness, due to the low Liquidus temperature (start of solidification).

In Fig. 8 the binary Al-Si phase diagram is compared to a thermal analysis curve of the alloy. It is evident that respect to thermal analysis this alloy presents a quite short solidification interval, moreover, its considerable high silicon content (9%) allows for an higher amount of eutectic phase solidification compared to a lower silicon alloy like a common AlSi7/A356 with 7% Si.

The content of approx. 1% of copper provides good mechanical properties at high temperature, without affecting significantly elongation at RT.

The cooling curve pointed out shows three transformation phase at three different temperatures during solidification.

Phase α: first germination of alpha-Aluminium nucleus (Aluminum α) T.Liquidus = 585°C;

Phase β: principal Eutectic solidification of Silicon compounds (αAl+Si+Al5FeSi) T.Eutectic= 565/568°C;

Phase β(Al2Cu)': first precipitation of Copper compounds (Al+Al2Cu+Si+Al5FeSi) T. β'= 557/522°C;

Phase β(Al2Cu)'': complex Eutectic solidification of Copper compounds (Al+Al2Cu+Si+Al5Mg8Cu2Si6).

Solidification is completed at approx. 500°C.

With the aim to search for improvement of mechanical properties, at high temperatures especially, the addition of some alloying has been considered and two modification of this alloy have been included in the study:

- AlSi9Cu1 (Mn) – with addition of 0.4% of Mn, aimed to reduce the negative effect of acicular phases containing Fe impurities by transforming them in Fe-Mn intermetallics with more complex shape (Chinese scripts).
- AlSi9Cu1 (Ni-Mn) – with 0.2% Mn and 1% Ni. Where the addition of Ni should provide improved resistance at high temperature.

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. T6 treatments were selected depending on the type of alloy.

T6 HEAT TREATMENT

- Solution phase at 510°C for 6 hours.
- 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° for 6 hours according to the type of alloy.

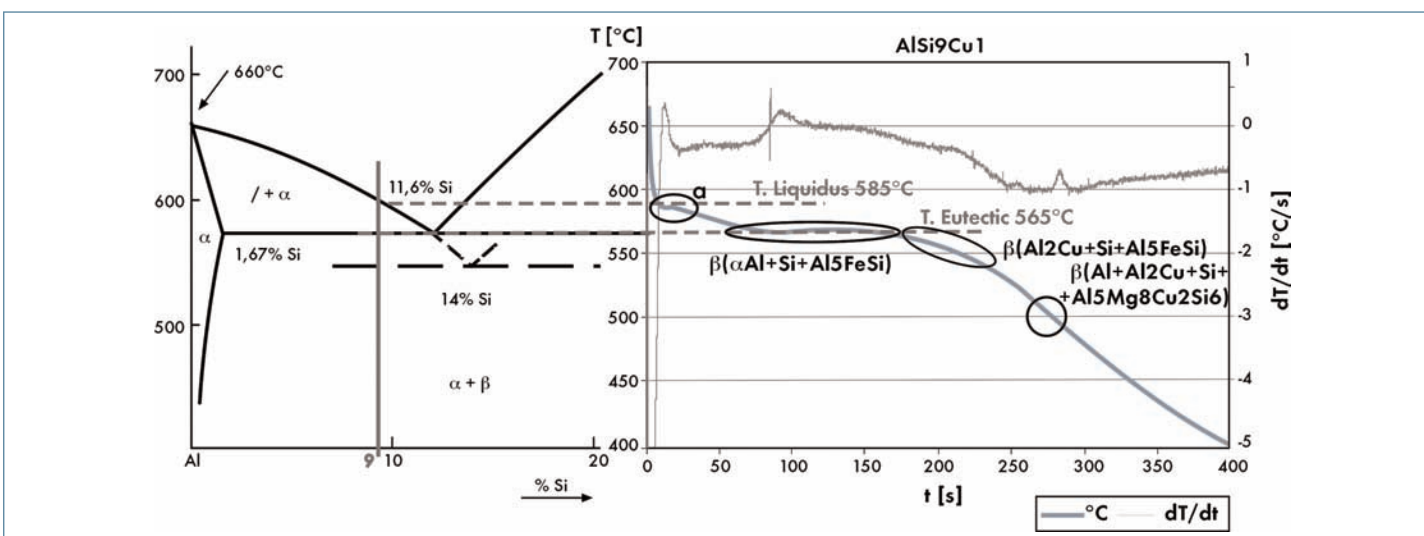


Fig. 8: Al-Si Phase Diagram & Thermal analysis of AlSi9Cu1.

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

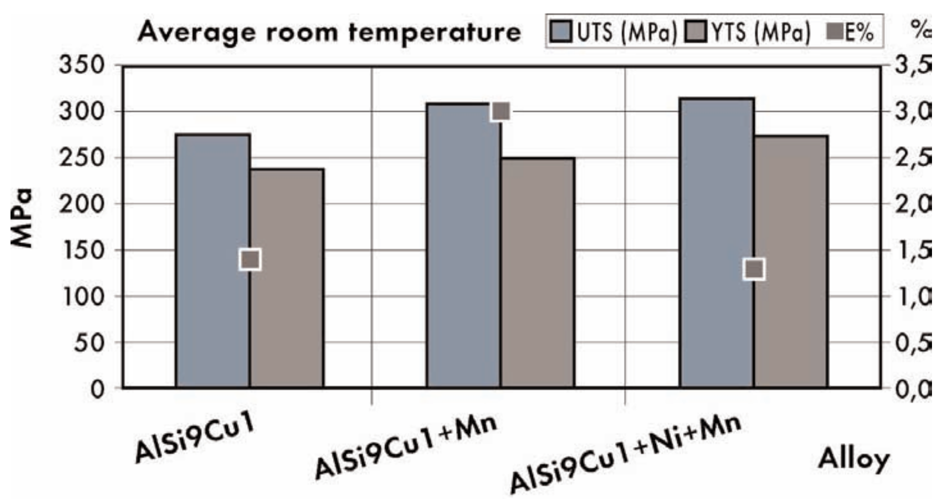
A summary of the test conditions analyzed for the various alloys is reported in table 2, while the results obtained in the tensile tests, as well as on Brinell hardness, at room temperature and at 150 and 250°C are reported in the Figs. 9, 10 and 11. Figures reported in the tables and histograms are 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.

Table 2. Summary of test conditions.

Alloy	Heat treatment	Over-Aging	Characterization condition
AlSi9Cu1	T6	500 h x 150°C 500 h x 250°C	Tensile test (20°C) Tensile test (150°C) Tensile test (250°C)
AlSi9Cu1 Mn	T6	500 h x 150°C 500 h x 250°C	Tensile test (20°C) Tensile test (150°C) Tensile test (250°C)
AlSi9Cu1 NiMn	T6	500 h x 250°C	Tensile test (20°C) Tensile test (250°C)

Tensile test at room temperature

	UTS (MPa)	YTS (MPa)	E%	HB (Ø5 mm-250Kg)
AlSi9Cu1	270	235	1,0	94
AlSi9Cu1 + Mn	305	245	3,0	105
AlSi9Cu1 + Ni + Mn	310	270	1,3	106



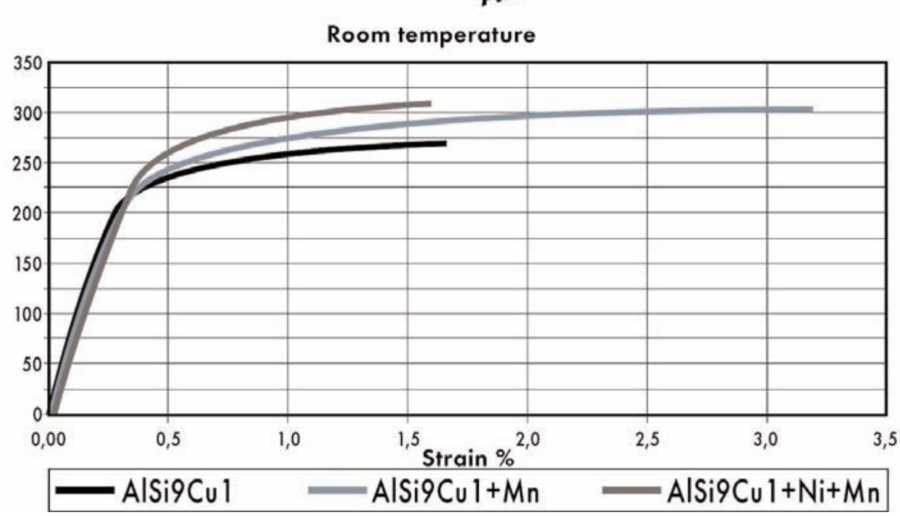


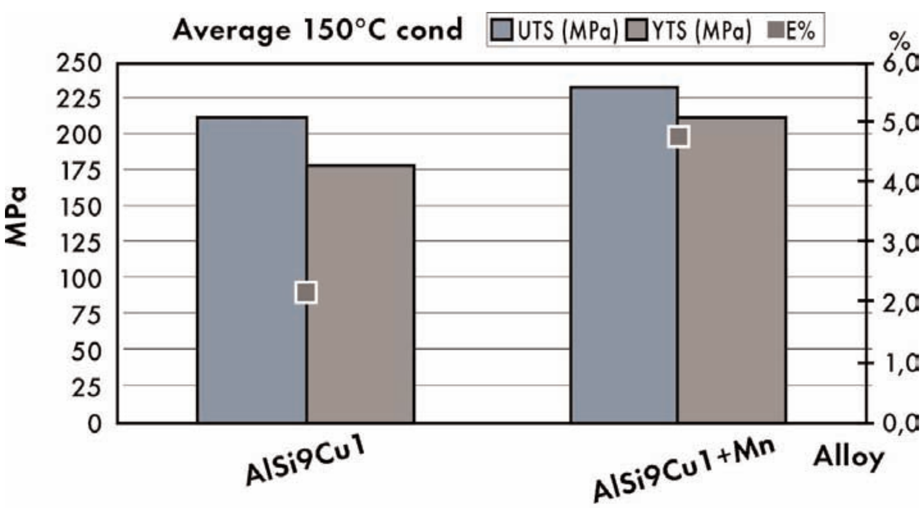
Fig. 9: Tensile test results at RT.

The following considerations can be drawn by the analysis of results obtained at RT (figure 9):

- The behaviour of base alloy AlSi9Cu1 can be improved by the addition of Mn or Mn+Ni: in the first case UTS and elongation increase significantly (reaching respectively 300 MPa and 3%), in the second both UTS (310 MPa) and YTS (270 MPa) grow, while elongation remains stable.
- According to the increase of the strength, the hardness is also improved.

Tensile test at 150°C (conditioning)

	UTS (MPa)	YTS (MPa)	E%	HB (Ø5 mm-250Kg)
AlSi9Cu1	210	178	2,2	94
AlSi9Cu1 + Mn	233	211	4,8	100



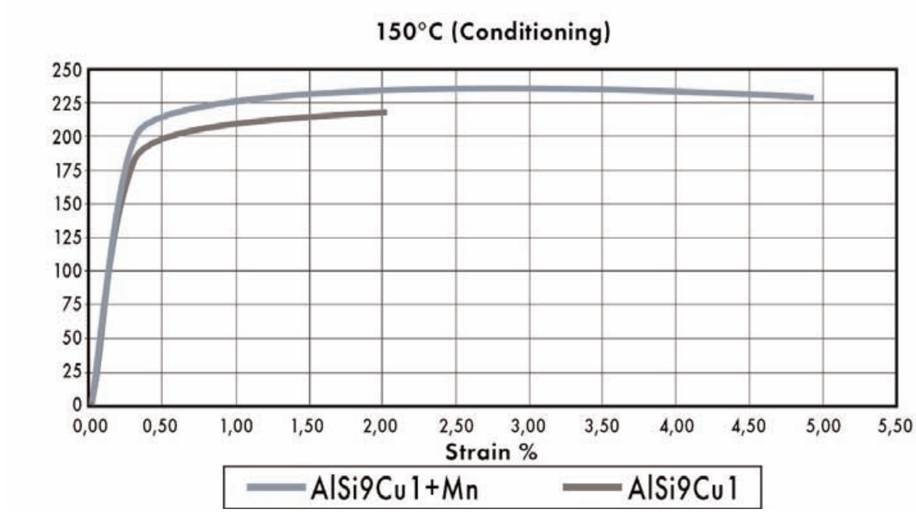


Fig. 10: Tensile test results at 150°C.

At 150°C, Fig. 10, all the alloys show a reduction of tensile properties compared to RT conditions. UTS decreases approximately 20% in average, even if the AlSi9Cu1 (Ni-Mn) modified alloy has not been tested at this temperature, it is confirmed that AlSi9Cu1(Mn) maintains better elongation and UTS compared to the base alloy.

At 250°C, Fig. 11, we can notice a further significant decrease of strength for all the alloys, with dramatic increase of elongation values. From the data in Fig. 11 it is evident that UTS of all the tested alloys drops well below 100 MPa, however the variant with Mn-Ni addition has a slightly better behaviour than the others.

Tensile test at 250°C (conditioning)

	UTS (MPa)	YTS (MPa)	E%	HB (Ø5 mm-250Kg)
AlSi9Cu1	70	54	14,0	51
AlSi9Cu1 + Mn	75	58	21,0	53
AlSi9Cu1 + Ni + Mn	92	66	16,5	62

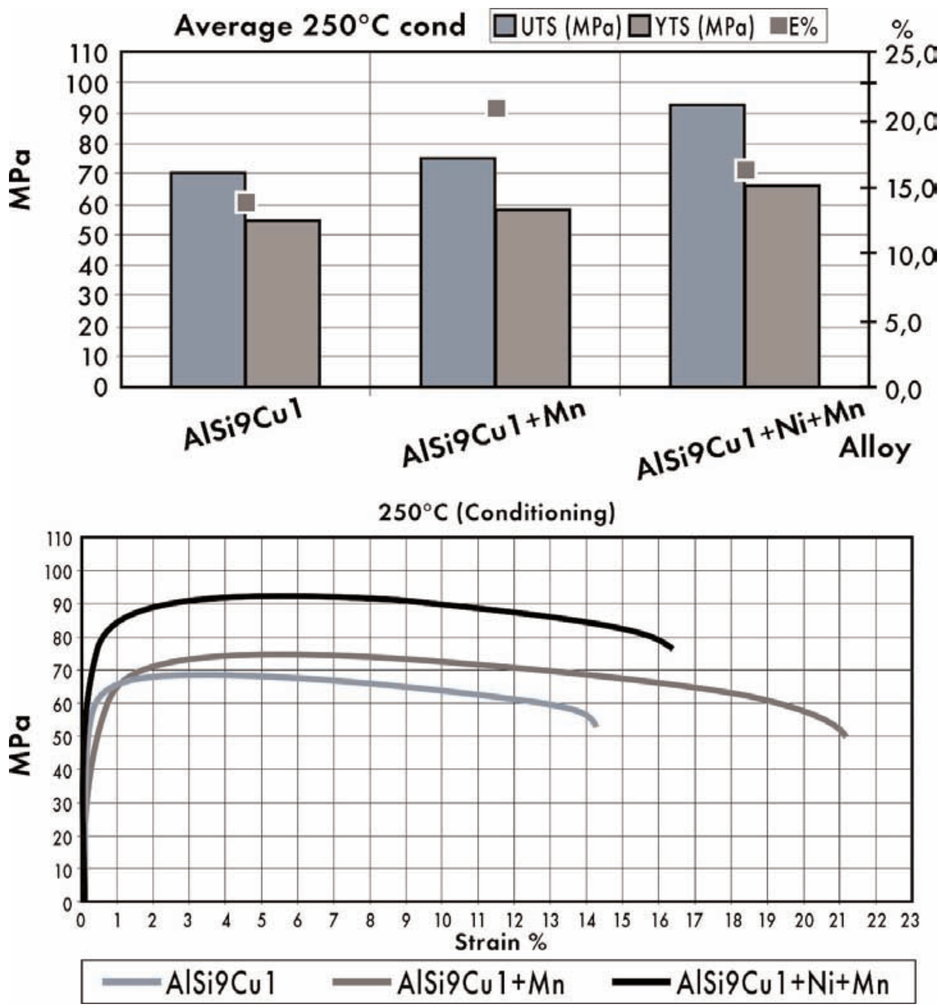


Fig. 11: Tensile test results at 250°C.

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 and a suitable surface preparation of transverse section of samples.

AlSi9Cu1

This type of alloy is characterized by dendrite structure with a homogeneous distribution of eutectic silicon shown in Fig. 12.

By the addition of appropriate elements such as strontium in the liquid metal, it is possible to modify silicon morphological structure from lamellar to globular during the solidification. This modification treatment improves the mechanical properties of the AlSi alloy by reducing the notching effect of needle shaped natural eutectic silicon (Fig. 13).

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 Al_3TiB_2 particles during the melt cooling.

The strengthening effect of Cu in this alloy is linked to precipitation of secondary eutectic phases of $CuAl_2$ intermetallics, shown in Fig. 14. The heat treatment causes the disappearance/solubilisation of $CuAl_2$ while the last solidified phase $Al_5Mg_8Cu_2Si_6$ is partly solubilised.

Silicon particles are rounded and more agglomerated, whilst the iron compound doesn't show any shape modification.

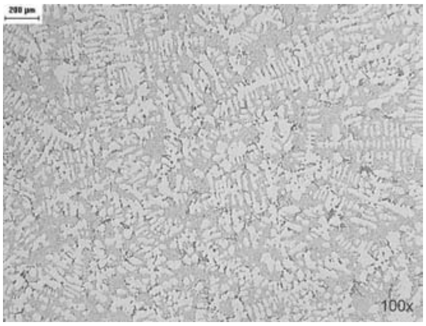


Fig. 12: Typical dendrite structure of AlSi alloys.

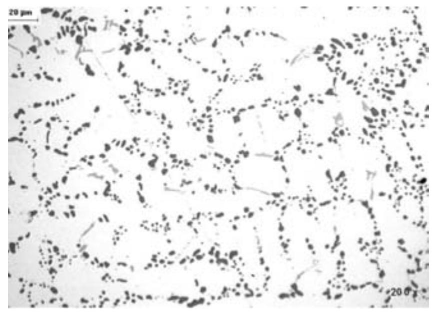


Fig. 13: AlSi9Cu1 – Globular distribution of eutectic silicon.

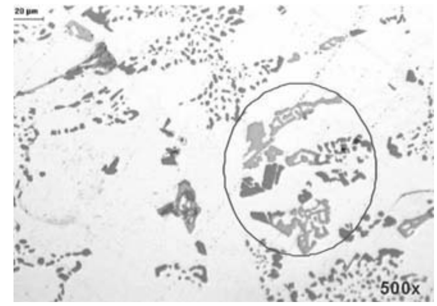
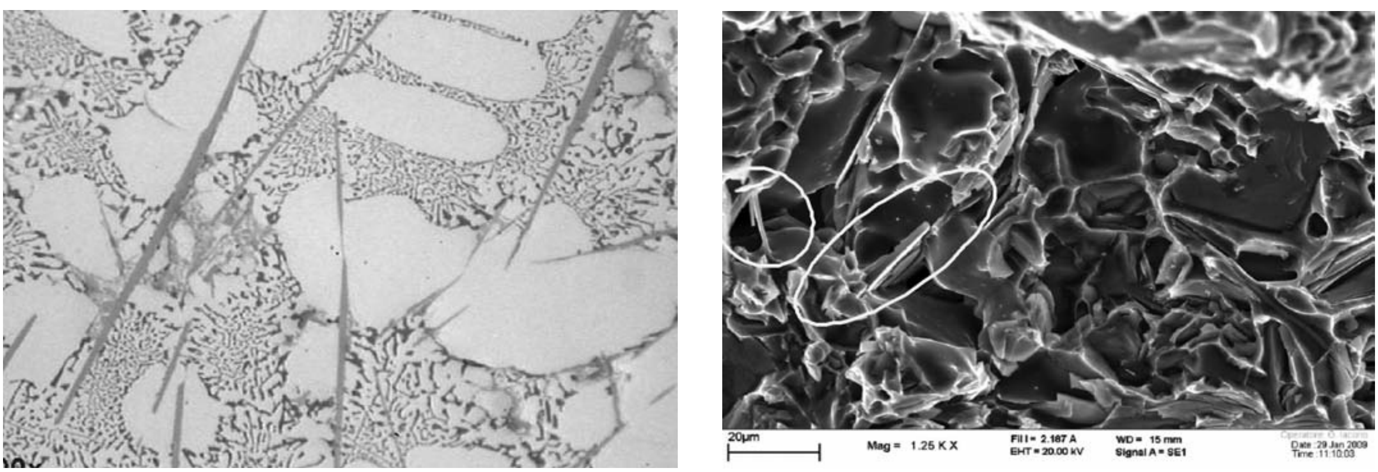
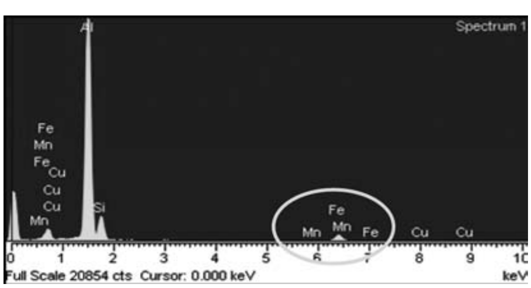
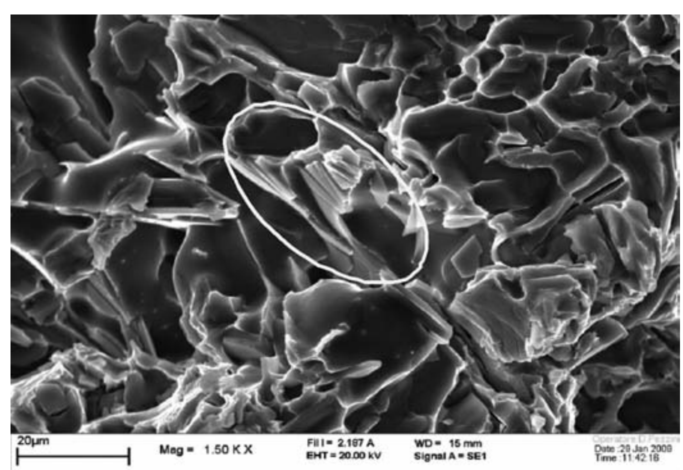


Fig. 14: AlSi9Cu1- Eutectic Cu2 Mg8 Si6 Al5 compound.







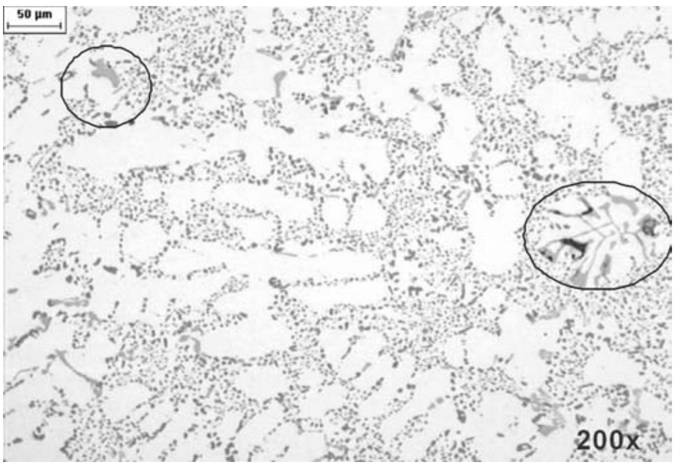
Element	Weight%	Atomic%
Al K	69.77	74.34
Si K	19.87	20.34
Mn K	**0.80**	**0.42**
Fe K	**9.28**	**4.78**
Cu K	0.27	0.12

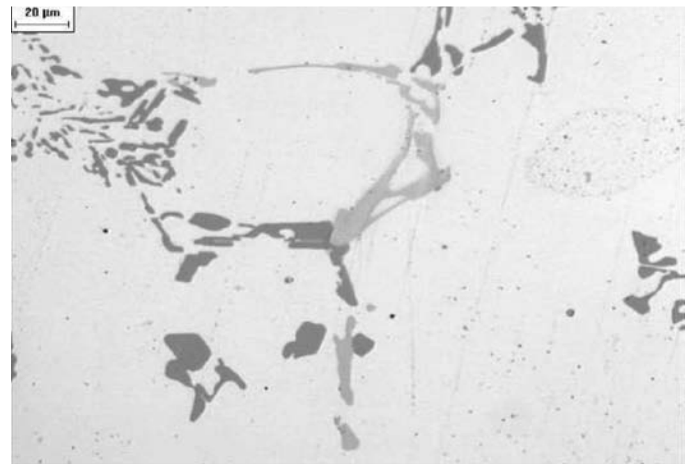
Fig. 15: AlSi9Cu1 Acicular morphology of Fe impurities

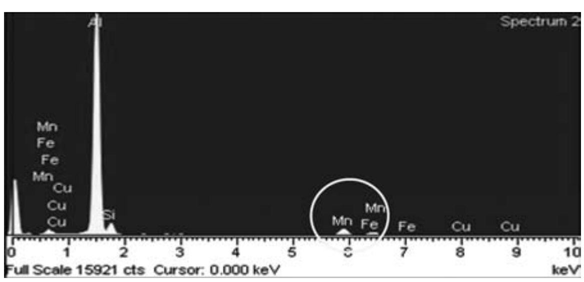
AlSi9Cu1 (Mn)

The presence of iron based precipitates on the AlSi9Cu1 base alloy is evident in Fig. 15, their morphology is of the acicular type and, as it is well known, this type of morphology is quite deleterious, especially for what concerns mechanical characteristics and ductility, in particular the fracture appearance shows the presence of some clivages.

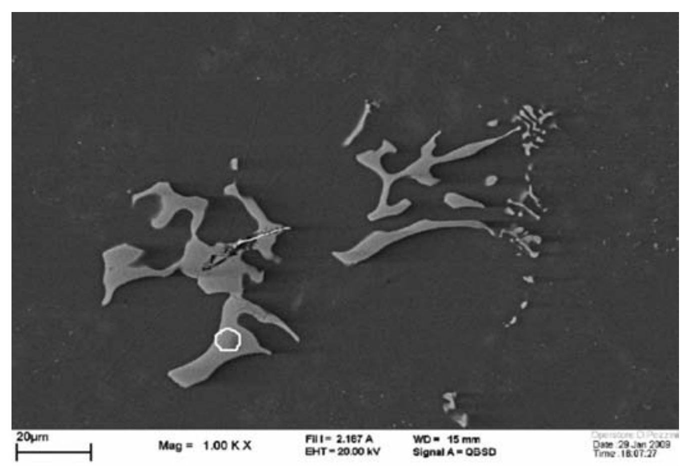
With the addition of Mn the morphology of Fe compound changes from acicular type to complex shape, typical of Fe-Mn intermetallics (Chinese script, Fig. 16), improving the elongation properties of the alloy, due to the reduction of notching effect of Fe needles, the fracture surface now shows the consistent presence of dimples to state higher toughness properties. Because negative effects are not emphasized, it is possible to state that the modification of the base alloy with 0.5 % of manganese is beneficial.

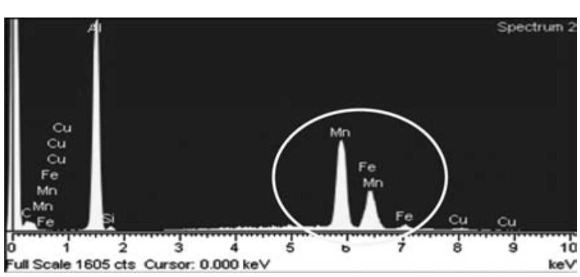






Element	Weight%	Atomic%
Al K	75.70	81.70
Si K	10.83	11.22
Mn K	**9.50**	**5.03**
Fe K	**3.43**	**1.79**
Cu K	0.55	0.25





Element	Weight%	Atomic%
CK	8.93	24.14
Al K	35.37	42.58
Si K	1.03	1.19
Mn K	**38.73**	**22.90**
Fe K	**14.88**	**8.6**
Cu K	1.06	0.54

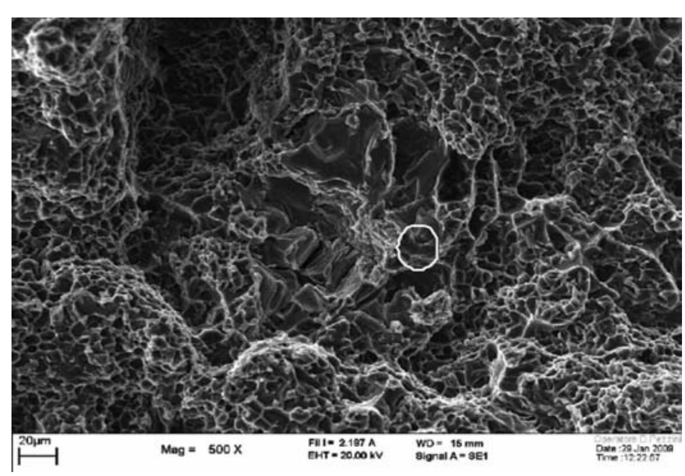
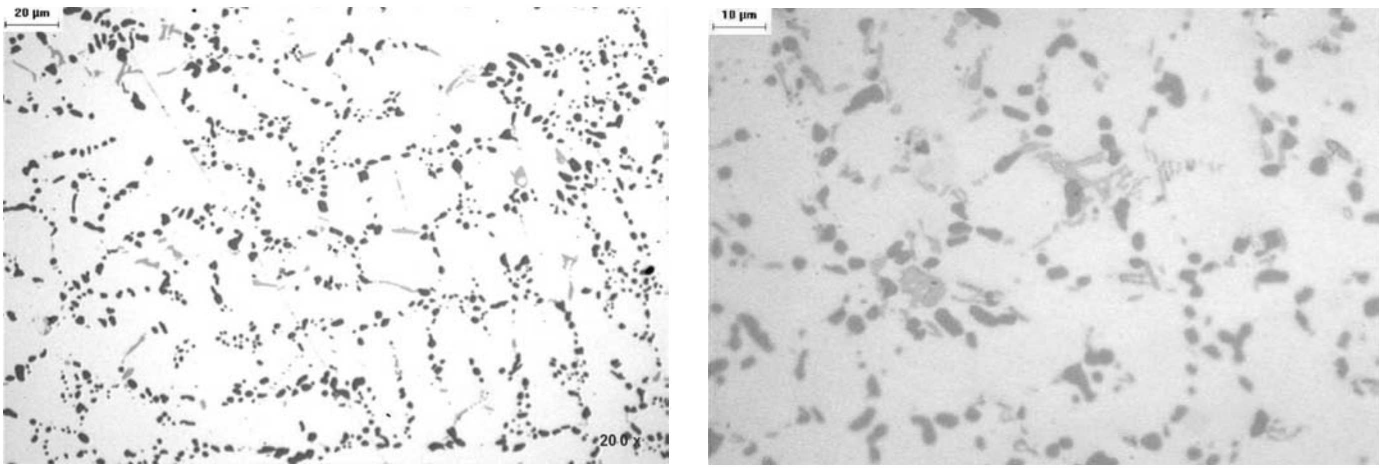
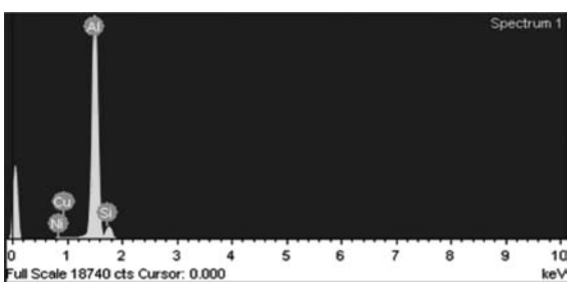


Fig. 16: AlSi9Cu1 Mn - Morphology of Fe-Mn intermetallics

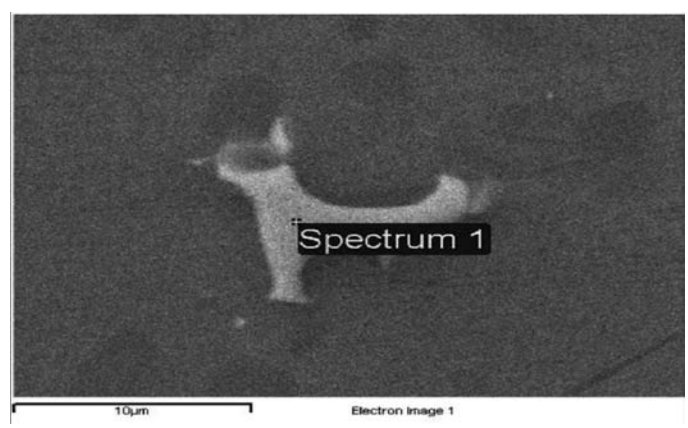
AlSi9Cu1 (NiMn)

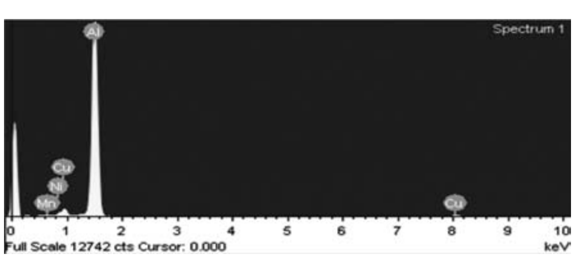
The second studied modification of the base alloy includes smaller Mn amount (0.2%), with the addition of 1% Ni. Also in this case, with respect the basic alloy, the most relevant structure differences are always related to the modification of the morphology of the Fe containing phases, that change from acicular ferrous compound type to complex shape, typical of Fe-Mn intermetallics and the acicular structures are no longer observed. Moreover, the considerable percentage of nickel (1%), with reference to SEM analysis shown in Fig. 17, contributes to the formation of solid solutions and mainly rounded eutectic components. In particular, it seems that nickel ties with copper compound ($CuAl_2$) improving the copper effect on resistance at high temperature.





Element	Weight%	Atomic%
Al K	82.89	84.03
Si K	12.77	15.35
Ni K	**1.8**	**0.51**
Cu K	**2.25**	**0.41**





Element	Weight%	Atomic%
Al K	92.61	96.62
Mn K	**0.66**	**0.34**
Ni K	**1.53**	**0.73**
Cu K	5.20	2.30

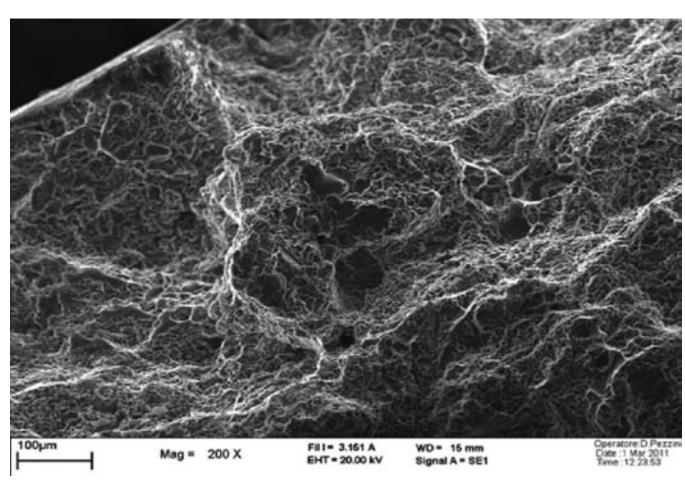


Fig. 17: AlSi9Cu1 NiMn- Morphology of Fe-Mn intermetallics

SUMMARY AND CONCLUSIONS

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

The resistance of base Al-Si-Cu alloy is fairly good up to 150°C (temperature at which the material actually works in the most stressed areas at the bottom of the water jacket of a cylinder head), but drops at 250°C.

Some interesting improvements have been achieved by modifying the composition of the base alloy with the addition of Mn and Ni, resulting in an increase of strength and ductility at both room and high temperature.

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.

Moreover the study will be continued considering other binary alloys, mainly based on Al-Mg and Al-Cu series, to evaluate their real potentiality towards this kind of application. The obtained results will be presented and discussed in a second part of the paper

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