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Effect of heat treatments on mechanical properties and fracture behavior of a thixocast A356 aluminum alloy

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The effect of different heat treatments (T5 and T6) on mechanical properties, fracture behavior and damage evolution of A356 Thixocast aluminum alloy have been examined in detail in the present work. Tensile tests of the material have been performed in the as cast and as treated conditions in order to observe the different fracture behavior in consequence of the heat treatments. Optical and scanning electron microscopy techniques have been used to characterize the microstructure and fracture surfaces of the specimens. Finally, the precipitation processes of the material have been analyzed by hardness and electrical conductivity measurements and EDS analysis has been used to characterize the different phases in the as-thixo and as-treated conditions. © *2004 Kluwer Academic Publishers*

1. Introduction

The thixocasting technology is now widely used in the production of components designed for the automotive industry. One of the major reasons is that it permits the design of products characterized by lower weights and very complex geometries in a single step cycle with respect to traditional techniques and materials. By using thixoforming it is also possible to improve the tool life, the mechanical properties of the components and realize net shape products [1]. The alloys from the Al-Si system are the most widely used in the foundry industry thanks to their good castability and high strength to weight ratio; the microstructure of such materials consists of a primary phase, aluminum or silicon and an eutectic mixture of these two elements. These materials contain many impurities: such alloying elements partly go into solid solution in the matrix and partly form intermetallic particles during the solidification process [2]. Among cast aluminium alloys, A356 ranks as one of the commercially important alloys used in automotive applications, on account of its excellent casting characteristics and good mechanical properties. For these reasons, the A356 is one of the candidate alloys to perform the shaping of aluminium alloys in the semisolid state or thixocasting that has become a widely accepted industrial process in the last years [3]. Thixotropic aluminium alloy used at a liquid fraction of around 50% presents, with respect to its 100% liquid homologue used in conventional high pressure die casting, three major difference [4]: (i) a much higher viscosity, that permits to inject the material at relatively high speeds; (ii) a lower heat content allowing a considerable increase in production rate; and (iii) less contraction during solidification reducing risering problems.

The very good mechanical properties are due to the globular microstructure which results very fine and homogeneous and is accompanied with very low levels of voids produced during the solidification process [5, 6]. By using heat treatments the mechanical properties of such material can be strongly improved [2, 7]. The aim of this work was to study the effect of T5 and T6 heat treatments on the mechanical properties of A356 thixocast alloy and to correlate the mechanical behaviour to the microstructural evolution.

2. Experimental procedure

The material under investigation has the following composition (wt%): Si = 6.5%, Fe = 0.5%, Cu = 0.03%, Mn = 0.03%, Mg = 0.4%, Ni = 0.03%, Zn = 0.05%, Pb + Sn = 0.03%, Ti = 0.2%, Sr = 0.05%, Al = bal. The material was supplied under the form of thixoformed bars, produced by electromagnetic stirring by Aluminium Pechiney (France) and their dimensions were 200 mm length and 18 mm diameter. The specimens were solution treated at 540°C for 1, 2, 4, 8, 16 h and then aged at 160 and 200°C while other specimens were aged at the same temperatures without solution treatment (T5). The heat treatment effects were analyzed by hardness measurements (HRF) and electrical conductivity measurements, which were performed by employing a Foster probe on the sample surfaces in order to understand the hardening mechanisms and the precipitation. The tensile specimens were subjected to the same treatments and then tested. In this case the

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typical gage dimensions were 25 mm in length and 6 mm in cross section. The tensile tests were carried out by using an INSTRON 4507 testing machine, the tensile strain rate was calculated as 0.001 s^{-1}. The yield stress was based on a 0.002 plastic strain offset; for optical and scanning electron microscopy observations (OM and SEM), specimens were ground with silicon carbide paper and polished with one micron diamond paste. EDS analysis was conducted on samples (after tensile tests) in a Philips XL40 SEM equipped with a LaB6 filament to identify the different type of phases present in the as-cast condition and after solution treatment at 500°C for 4 h. This information would have helped to understand the fracture mechanisms. An etch of one part 40% hydrofluoric acid to 20 parts water was found to contrast the constituents of the A356 alloy well, and was used for microscopic observations.

3. Results and discussion

Fig. 1 shows the as-cast microstructure of the A356 aluminium alloy sample. The microstructure of the electromagnetically stirred bars is composed of solid matrix globules (this part remained solid during the heating in the semisolid region) surrounded by the eutectic region (that was liquid). The eutectic of the studied system contains Si, Fe and Mg particles embedded in Al. The shape of these constituents is elongated and irregular as in a typical eutectic structure. During solution heat treatment at 540°C some physical changes occur (Fig. 2): the coarsening and spheroidizing of the silicon particles, coarsening: formation of small precipitates inside the solid phase (not visible in the as cast state), and the shrinking and eventual disappearance of the phases inside the eutectic region. The hardness and electrical conductivity of the material were plotted versus time at the solution temperature of 540°C. The hardness shows an increase for the lower times followed by a softening at the higher ones, after 8 h the hardness levels off indicating that the aluminium matrix is saturated, the result is confirmed by the electrical conductivity measurements. The slight increase in hardness is due to the enhanced solution hardening mechanisms of Fe and Mg due to their high solubility at 540°C, after 8 h, the coarsening of Si phase results in the drop to minimum hardness.

The mean equivalent diameter of the Si particles was measured for all the solution times (Table I) indicating

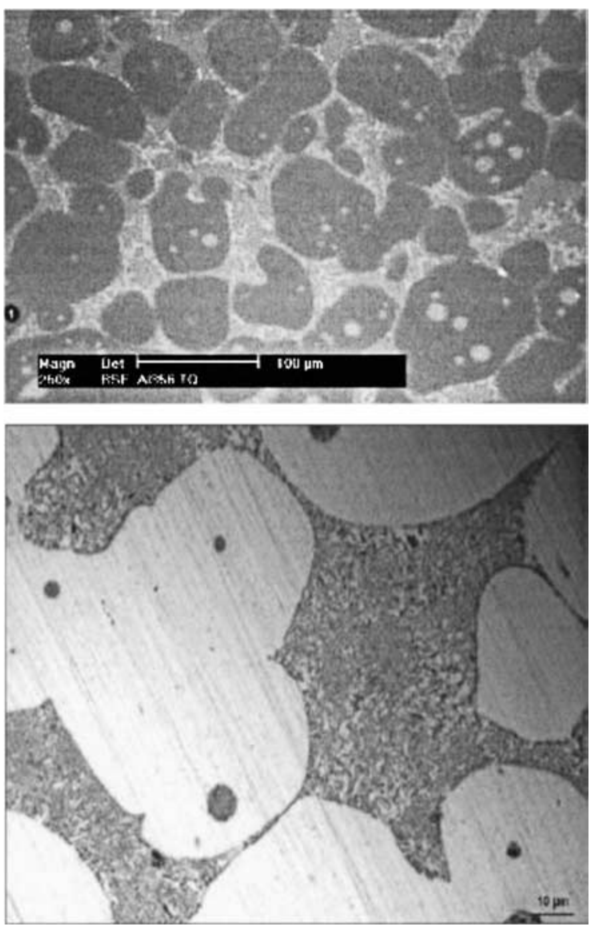

Figure 1 Microstructure of the as-thixo A356 aluminium alloy showing the semisolid structure of the material.

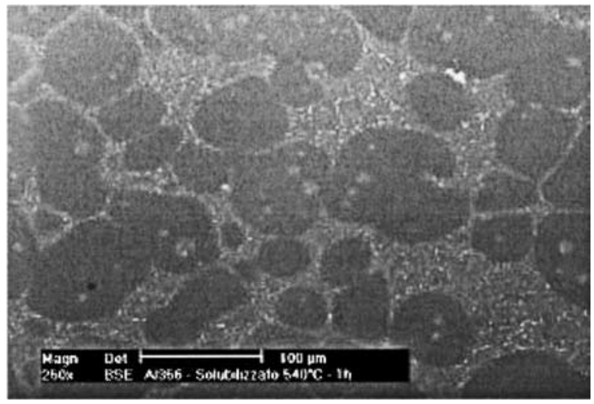

Figure 2 SEM image of the as-solutioned alloy (540°C, 1 h) showing the modifications due to the heat treatment.

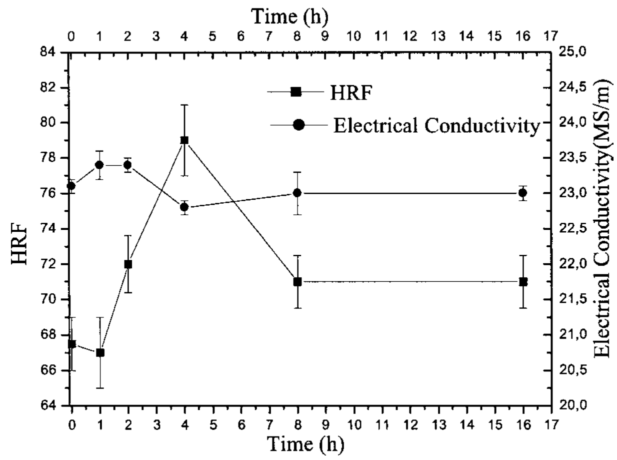

Figure 3 Plot of HRF and electrical conductivity vs. time in the solution state at 540°C.

TABLE I Equivalent diameter of the Si particles measured for different times of solution treatment at 540°C

Time (h)	Equivalent diameter (μm)
1	1.9 ± 0.8
2	2.3 ± 1.2
4	2.8 ± 1.2
8	3.1 ± 1.9
16	3.2 ± 1.5

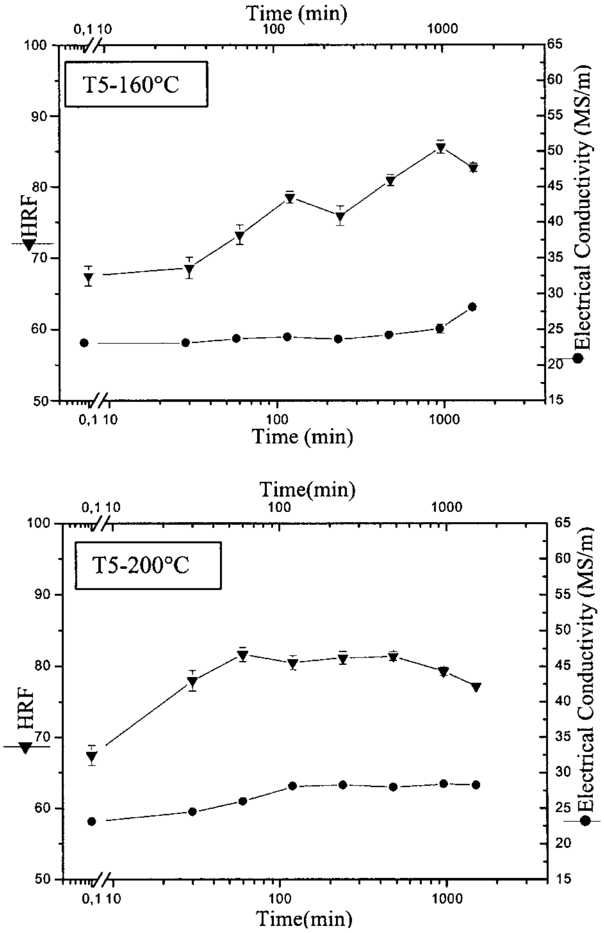

Figure 4 Plot of HRF and electrical conductivity vs. time of ageing at 160 and 200°C in the T5 condition.

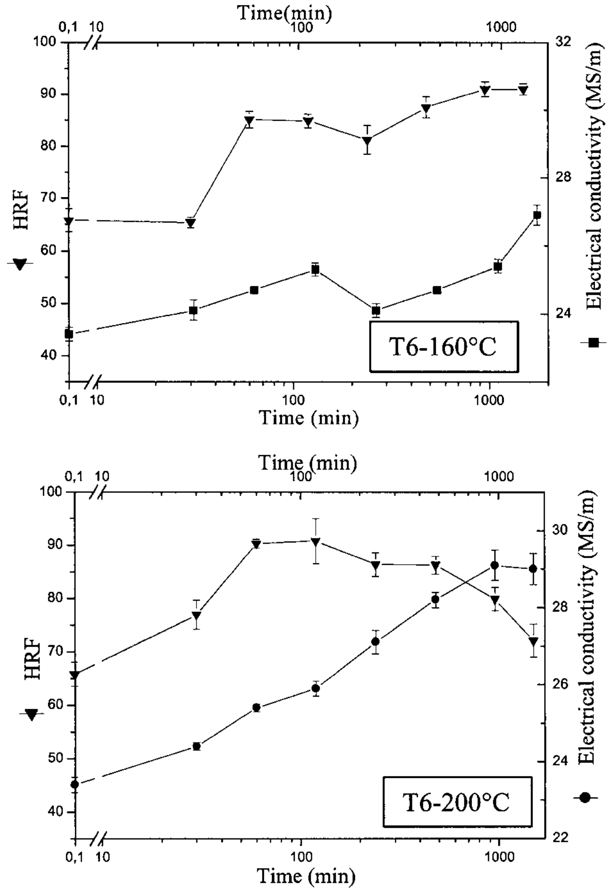

Figure 5 Plot of HRF and electrical conductivity vs. time of ageing at 160 and 200°C in the T6 condition (after solution treatment at 540°C, 1 h).

that the sferoidization of such phases is accompanied with the softening of the material.

In Figs 4 and 5 the aging curves are plotted for the different treatments at 160 and 200°C for the material in the T5 and T6 conditions. The curves show higher levels of hardness at the same time and temperature of treatment for the material in the T6 condition. It can be seen that at 200°C overaging starts after 2 h while at 160°C hardness increases continuously to a maximum reached after 1 day in both T5 and T6 conditions.

Finally the microstructure of the material was characterized by employing EDS analysis. In the as-thixo state the EDS revealed that (Fig. 6): the α globules are constituted by aluminium and Mg in small quantity (point 1), the eutectic phase (zone 2) is constituted by phases rich of Fe and Mg, the Fe is combined with the other elements to form different phases such as α-AlFeSi or lamellar particles $Fe_2Si_2Al_9$ or $FeAl_3$, Mg is combined with aluminium to form Mg_2Al_3 or Mg_2Si. In the darker zone of the eutectic phase (point 3), Si in lamellar structure and Mg_2Si particles were recognized. The EDS spectra were finally used to characterize the material in the as solutioned state (540°C, 1 h). In the eutectic zone of Fig. 7 darker particles due to the sferoidization and growth of Si particles were recognized, a reduction of Mg content in the eutectic region was revealed, caused by the dissolution of Mg_2Si phase in consequence of solution treatment. The described situation is more cleared by observing the microstructure of the material reported in Fig. 8.

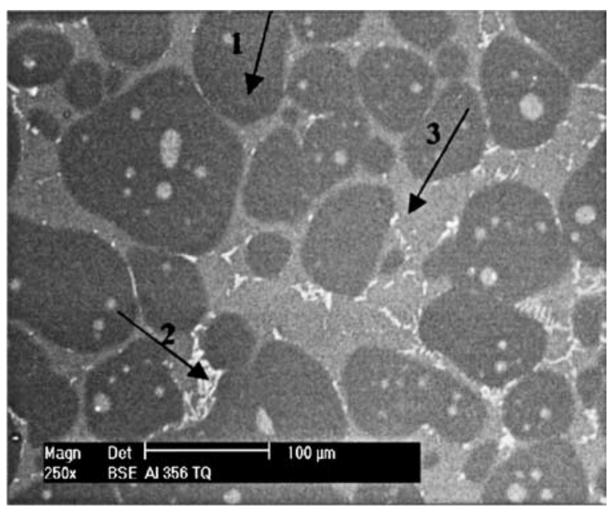

Figure 6 SEM image of the as-thixo A356 aluminium alloy showing the different phases analyzed by employing EDS.

After solution treatment the specimens were artificially aged at 160 and 200°C; tensile tests were performed in both T5 and T6 conditions: the relative results are reported in Table II. The YS and UTS increase with increasing time in both the tested conditions; in the T5 condition the UTS is comparable with that measured for the T6 one. In the T6 condition an increase of ductility at the lower times of treatment can be highlighted together with an increase in YS and UTS. The T5 samples do not exhibit ductility values comparable

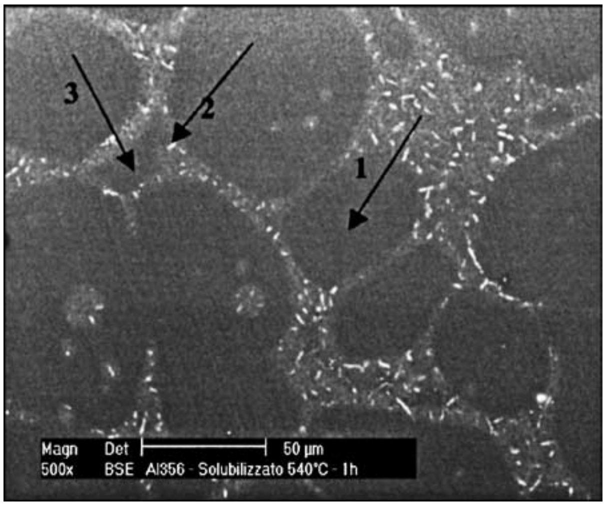

Figure 7 SEM image of the as-solutioned (540°C, 1 h) A356 aluminium alloy showing the different phases analyzed by employing EDS.

TABLE II Mechanical properties of A356 aluminium alloy obtained by tensile tests in different treatment conditions

Specimens condition	Yield stress (MPa)	UTS (MPa)	A (%)	Young modulus (GPa)
As-thixo	104	241	12	78
Solution 1 h	106	231	18	92
T6 at 160°C, 0.5 h	115	243	20	79
T6 at 160°C, 4 h	127	245	18	90
T6 at 160°C, 25 h	153	264	16	86
T6 at 200°C, 0.5 h	111	236	16	91
T6 at 200°C, 4 h	154	257	15	89
T6 at 200°C, 25 h	247	297	3	85
T5 at 160°C, 0.5 h	103	239	12	77
T5 at 160°C, 4 h	107	236	12	81
T5 at 160°C, 25 h	129	244	6	98
T5 at 200°C, 0.5 h	104	238	12	84
T5 at 200°C, 2 h	150	252	9	90
T5 at 200°C, 25 h	201	280	5	88

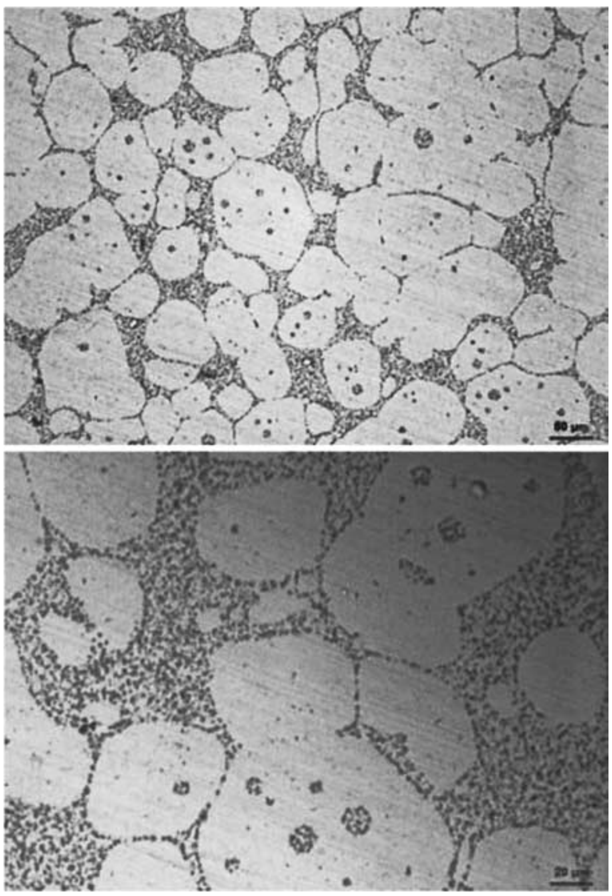

Figure 8 Optical pictures of as-solutioned alloy showing the spheroidization of the analyzed particles.

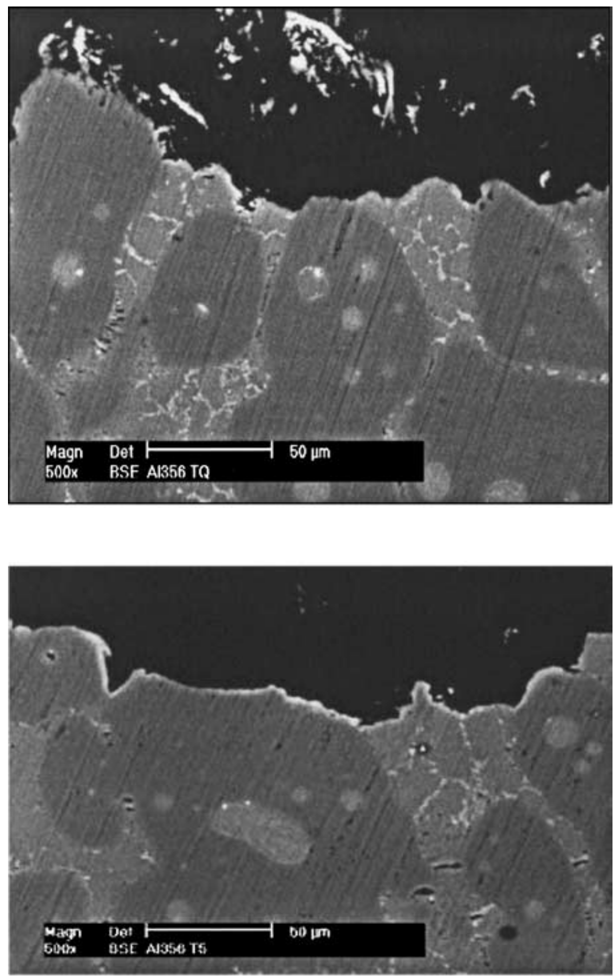

Figure 9 Fractures around the globules in the eutectic region for the A356 alloy in the as-received and T5 conditions.

with those measured for the T6 condition, the principal effect of this treatment being, in fact, the increasing of the ductility of the material with an increase in mechanical properties respect to the as-thixo alloy. From this point of view the best conditions appear (T6 ones) to be 160°C 4 h and 200°C 4 h.

An extensive evaluation of longitudinal sections of tensile tested samples was finally carried out by scanning electron microscopy. In all the observed conditions the fracture propagates in the eutectic region around the globules (Fig. 9). The fracture surfaces of the as thixo and T5 specimens revealed a brittle behaviour as clearly shown in Fig. 10. On the contrary, the specimens in the T6 condition revealed a ductile behaviour demonstrated by the presence of dimples around the bigger particles visible in the microstructure (Fig. 11). The described behaviour was evidenced in all the fracture surfaces and was due to the solution treatment prior of the ageing one of the material (Fig. 12).

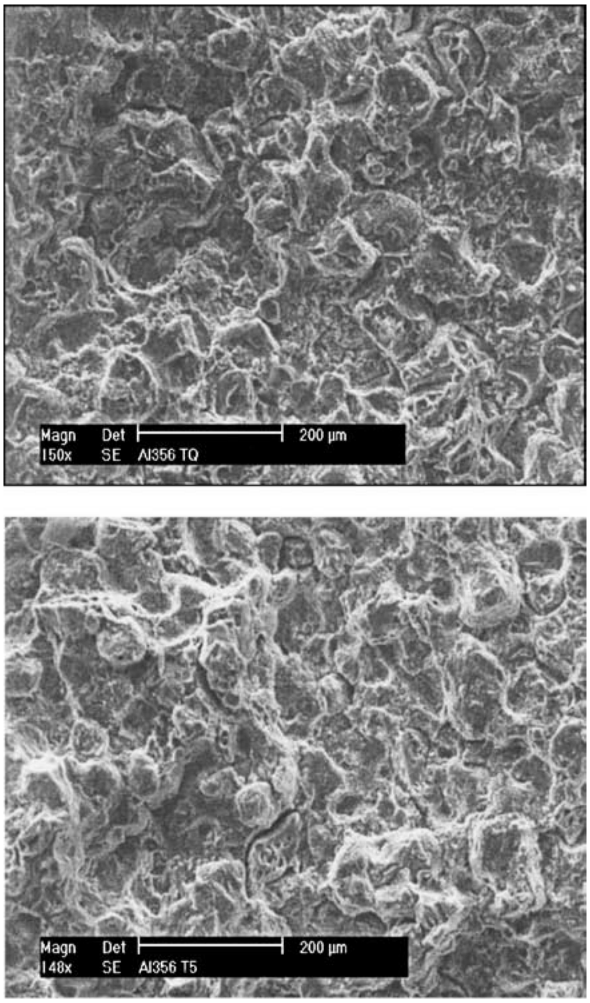

Figure 10 Fractures surfaces around the globules in the eutectic region for the A356 alloy in the as-received and T5 conditions.

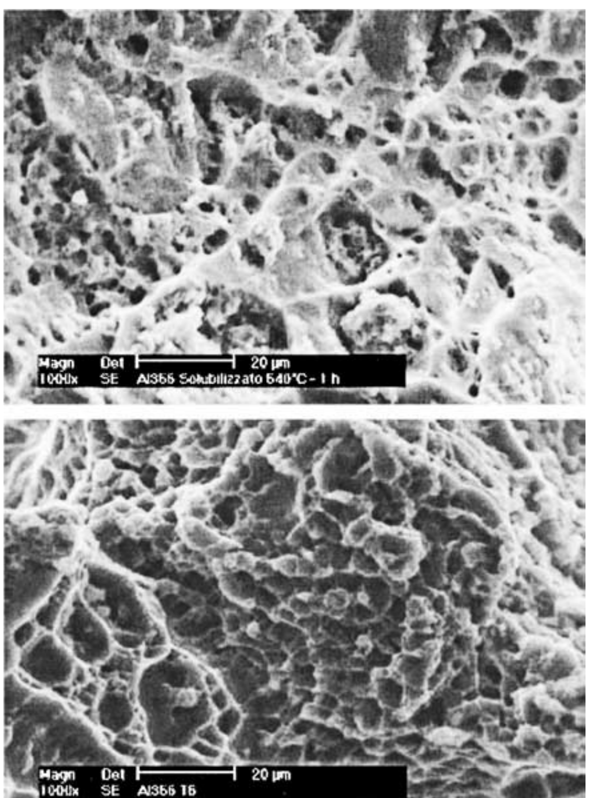

Figure 11 Dimples formation on the fracture surface of the T6 treated samples showing high ductility levels.

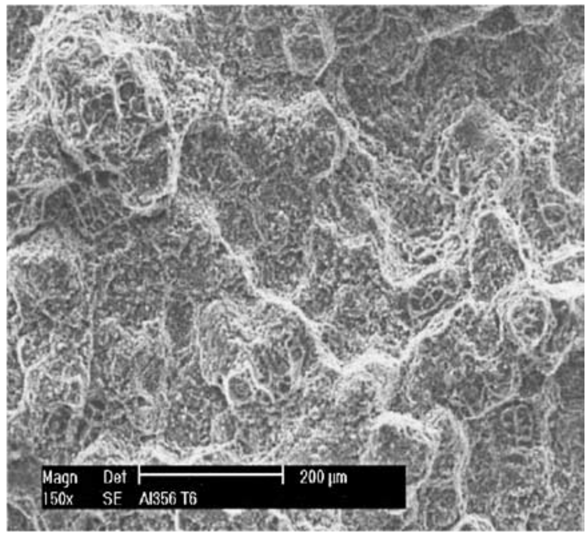

Figure 12 Fracture surface of the T6 A356 aluminium alloy showing different behaviour respect to the as-thixo and T5 conditions.

4. Conclusions

A wide study of the effect of heat treatments on mechanical properties of a thixocast A356 aluminium alloys was carried out and described in the present paper. The material was analyzed by using hardness and tensile tests as well as optical and electron microscopy (SEM). The main conclusions can be summarized as follows:

(i) A good ductile behaviour is revealed by the specimens after solution treatment thanks to the sferoidization of silicon particles due to the heat treatment. The spheroids favours the plastic deformation until fracture.

(ii) During treatment at higher temperatures different microstructural phenomenon take place: in particular, on lower times the hardening of the material is predominant due to dissolution of intermetallic particles in the matrix, whereas on higher times softening is more relevant thanks to the spheroidization of particles.

(iii) The ageing treatment both in the T5 and T6 conditions produces an increase in mechanical properties of the material. With respect to this, it was observed that YS and UTS do not differ for the temperatures of 160 and 200°C, while ductility differs very much from one temperatures and the other.

(iv) The analysis of fracture surface showed a ductile behaviour in the specimens after T6 treatment, while it revealed a brittle behaviour in the as-thixo and T5 ones with fracture which propagate preferentially in the eutectic region around the primary globules in all the tested conditions.

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