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CHARACTERISATION OF A 6082 ALUMINUM ALLOY AFTER THIXOFORMING

KARAKTERIZACIJA ULITE ALUMINIJEVE ZLITINE A 6082 PO POSTOPKU "THIXO"

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The heat treatment response and the microstructure of a 6082 aluminum alloy produced by thixoforming were investigated. The initial microstructure was characterised by globular dendrites separated by a low volume fraction of "liquid" (i.e. of eutectic). The heat-treatment response was investigated by testing the alloy in the form of thixoformed bars. The analysis of the hardness variation with ageing time and the electrical conductivity measurements suggested that the hardening of the alloy reflected the presence of coherent zones or semi-coherent precipitates at low temperature (160 °C) and the precipitation of equilibrium phases at high temperature (210 °C). These preliminary studies were partially repeated on samples obtained by sectioning a large component of more complex shape. The small fraction of liquid available at the thixoforming temperature was found to result in the formation of voids and hot-cracks in some locations of the component. The heat-treatment response was quite similar to that observed by testing thixoformed bars, even if the microstructure, and consequently the initial value of the hardness, was substantially less homogeneous in the component.

Keywords: aluminum alloys, thixoforming, heat treatment

Raziskan je vpliv toplotne obdelave na mikrostrukturo thixoforming ulite zlitine A 6082. Začetna struktura je bila iz globularnih dendritov, med njimi pa malo evtektika. Vzorci za preiskave so bili odrezani od ulitih palic. Evolucija trdote in elektro prevodnosti kažeta, da je utrditev posledica nastanka koherentnih in polkoherentnih izločkov do 160 °C, pri 210 °C pa nastajajo ravnotežne faze. Uvodne preiskave so bile preverjene na preizkušancih iz večjih ulitkov z bolj zapleteno obliko. Pokazalo se je, da zaradi majhne količine evtektika nastajajo votline in razpoke. Odgovor na toplotno obdelavo je bil sicer enak kot pri palicah, čeprav sta bili mikrostruktura in trdota manj homogeni v ulitku.

Ključne besede: aluminijeve zlitine, postopek "thixo", toplotna obdelava

1 INTRODUCTION

In recent years thixoforming has been extensively evaluated as a cost-effective process for the production of automotive components. During thixoforming the alloy is formed in the semisolid state, i.e. its microstructure consists of globular dendrites in a eutectic-type liquid matrix. The forming temperature is obviously in the solidification interval[1,2]. The semi-solid state is characterised by a pseudoplastic and thixotropic behaviour (i.e. its viscosity decreases when the stirring speed and the shear stress are increased)[1,2].

The thixoforming process consists of two separate steps: the alloy is firstly solidified in the form of billets, characterised by the typical semi-solid microstructure of globules and eutectic. During the second step the billets are reheated at the forming temperature and injected in to a die. One of the major advantages of this process over conventional forming techniques is the possibility of obtaining near-net-shape components[1]; the lower temperature of injection, when compared with traditional die casting, results in reduced energy loss and deterioration of the die. The duration of the production cycle is reduced when compared with die casting, another advantage resulting from the lower temperature of the injection. Minor solidification shrinkage and the reduced formation of cracks and defects are further advantages over conventional casting techniques. On the basis of these potential advantages, thixoforming is now gaining importance as an alternative to the conventional forming processes. Different aluminium alloys have been considered as candidates for semi-solid forming processes: alloys such as Al-7Si-0.3Mg (A356) or Al-7Si-0.6Mg (A357) can be thixoformed without any particular problem to give components with complex shapes[1,3,4]. Wrought aluminium alloys of the 2XXX (Al-Cu-Mg), 6XXX (Al-Mg-Si) or 7XXX (Al-Zn-Mg) families were also considered[1,5,6].

The Al-Mg-Si alloys are widely used for extrusion, with smaller quantities available in the form of plate or sheet. These materials are medium-strength alloys for structural applications, and are characterised by good weldability and corrosion resistance[7]; in general the amounts of Mg and Si result in the formation of a quasi-binary alloy Al-Mg_2Si. Even if these materials are widely considered as wrought alloys, thixorming experiments on the 6061 alloy were carried out[8]. The results of this study showed that the injection window is quite narrow and that there is a deleterious effect of liquid entrapments in the globules. Nevertheless, in the T6 condition (solution treatment and artificial ageing) the mechanical properties of the thixoformed component, when compared with the conventional extruded one, were considered to be acceptable, while the fatigue strength was even improved.

The 6082 alloy is a member of the 6XXX group that contain Mg and Si in excess of 1.4%; a typical feature of these alloys is the high strength developed after solution treatment-quench and artificial ageing. A small addition of Mn is beneficial in promoting a fine grain size. In particular, the relatively high Si content is thought to improve the ageing response, an effect commonly explained by a refining effect on the size of the precipitated Mg_2Si and by the additional precipitation of Si particles.

The conventional ageing temperature for alloys in the 6XXX family is close to 170 °C. In contrast with the behaviour observed in many other heat-treatment Al alloys, a permanence at room temperature after solution treatment is considered detrimental in light of the reduced mechanical properties measured after ageing[7].

The aim of the present study was to investigate the microstructure and the heat treatment response of a 6082 alloy produced by thixoforming.

2 EXPERIMENTAL PROCEDURES

The investigated alloy (composition given in **Table 1**) was produced by EFU GmbH (Germany) in the form of thixoformed bars (10 mm in diameter); after thixoforming the bars were water quenched to room temperature. The samples used for ageing tests and microstructural investigations were obtained directly by sectioning the thixoformed bars.

Table 1: Chemical composition of the investigated alloy (wt.%)
Tabela 1: Kemična sestava preiskovane zlitine

Si	Mg	Mn	Fe	Cu	Cr	Zn	Ti	Pb	Al
1.12	1.06	0.69	0.29	0.02	0.01	0.01	0.01	197ppm	bal

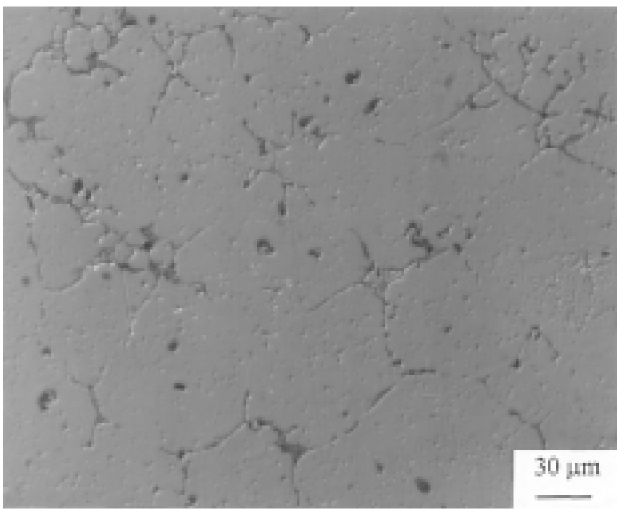

Figure 1: Microstructure of the as-thixoformed alloy (bars)
Slika 1: Mikrostruktura palice ulite po postopku "thixo"

A component (in this case a conrod) was produced in order to verify the possibility of obtaining defect-free parts with complex shapes by thixoforming. After thixoforming the component was cooled in the die.

All the samples, obtained either from the bars or the component, were heat treated in air and then quenched in water. The solution treatment temperature was 530 °C; ageing temperatures, either for T5 (artificial ageing directly after thixoforming) and for T6 (artificial ageing after solution treatment) tempers, were 160, 170, 185 and 210 °C.

Optical microscopy and scanning electron microscopy (SEM) were used to investigate the evolution of the microstructure after heat treatments; the samples were etched with the Keller reagent.

3 EXPERIMENTAL RESULTS

3.1 Heat-treatment response of thixoformed bars

The initial microstructure after thixoforming is illustrated in **Figure 1**. The structure is characterised by globular dendrites separated by a low volume fraction of "liquid" (i.e. of eutectic). **Figure 2** shows the size distribution of the globules in the thixoformed bars. Solution treatment at 530 °C, for 0.5-8 h, results in a progressive reduction of the amount of eutectic phase and in its spheroidisation. The average size of the globules of α-phase (solid solution of Mg and Si in Al) increases with solution treatment time (**Figure 3**). Hardness measurements, after ageing at 160 °C, indicated that a solution treatment time over 2-4 h does not result in any significant increase in the final hardness (**Figure 4**). For this reason, a solution treatment time of 2 h was considered a good compromise between the necessities of reducing the solution- treatment time and of maximising the amount of alloying elements available in the solid solution.

SEM analysis of the solution-treated samples (**Figure 5**) showed the existence of different families of precipitates; in particular, Mn-rich primary particles and

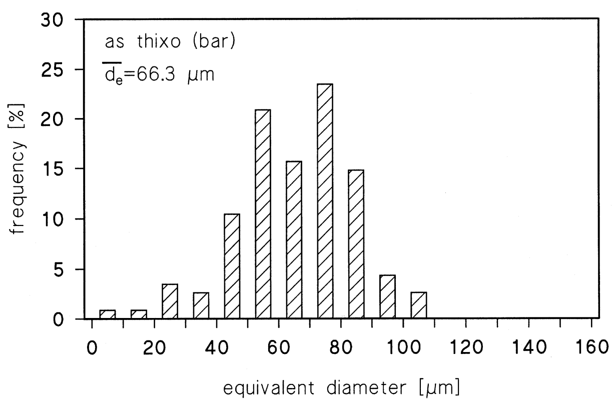

Figure 2: Size distribution of the globules after thixoforming (bars)
Slika 2: Velikostna porazdelitev globulov v liti palici

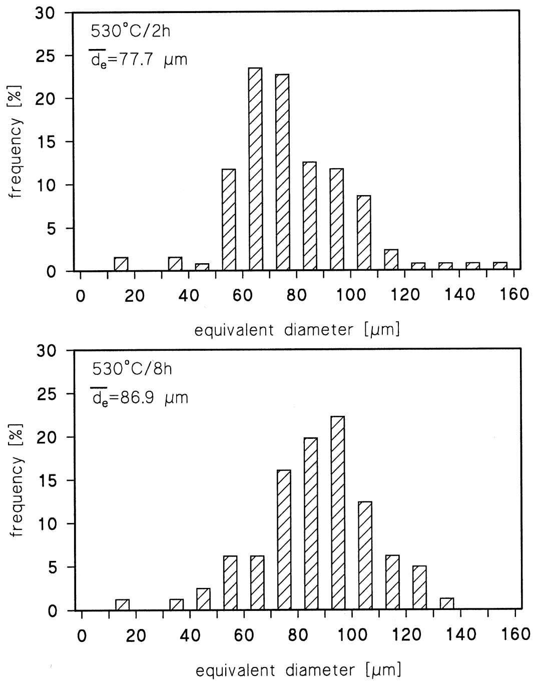

Figure 3: Effect of solution-treatment time at 530 °C on the average size of the globules
Slika 3: Vpliv žarjenja pri 530 °C na povprečno velikost globulov

Mg_2Si were easily distinguished. The presence of Mg_2Si can be justified since even prolonged holding at the solution temperature cannot be expected to result in the complete passage of Si and Mg into the solid solution.

Artificial ageing at 160, 170, 185 and 200 °C after the solution treatment at 530 °C-2h gave the hardness curves shown in **Figure 6**. Since the peak hardness at 160 °C, as illustrated in **Figure 4**, was quite close to 100 HRF, the other measurements were carried out using the HRB scale. An increase in the ageing temperature, as expected, means the peak in the hardness can be obtained after shorter treatments, even if ageing at 210

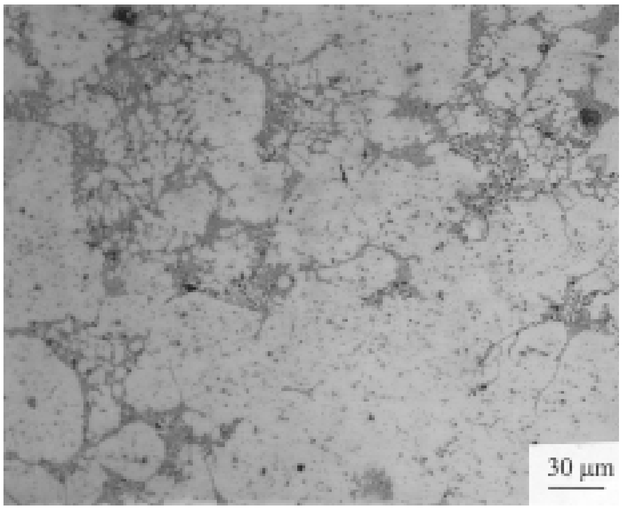

Figure 5: Microstructure of the solution treated material (SEM)
Slika 5: Mikrostruktura raztopilno žarjene zlitine

°C, and, to a lesser extent, at 185 °C, also results in over ageing.

Figure 7 shows the variation of electrical conductivity with ageing time; after ageing at 210 °C a sharp increase in the electrical conductivity is observed, this increase is much less pronounced when ageing at 160 °C.

3.2 Heat-treatment response of the component

A preliminary study of the microstructure at various locations on the component was carried out by optical and electron microscopy. This analysis revealed that thixoforming produced a quite inhomogeneous structure; in particular, the amount of eutectic was found to substantially decrease with increasing distance from the inlet. **Figure 8** illustrates the shape of the conrod and the hardness in various positions on the component. Since

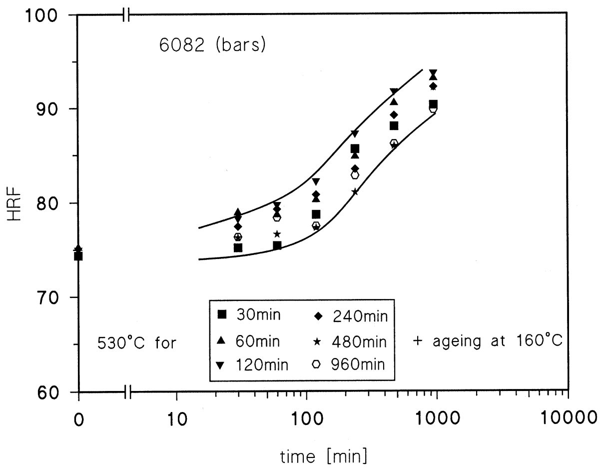

Figure 4: Ageing curves at 160 °C for different solution treatment times
Slika 4: Krivulje staranja pri 160 °C za različne čase žarjenja

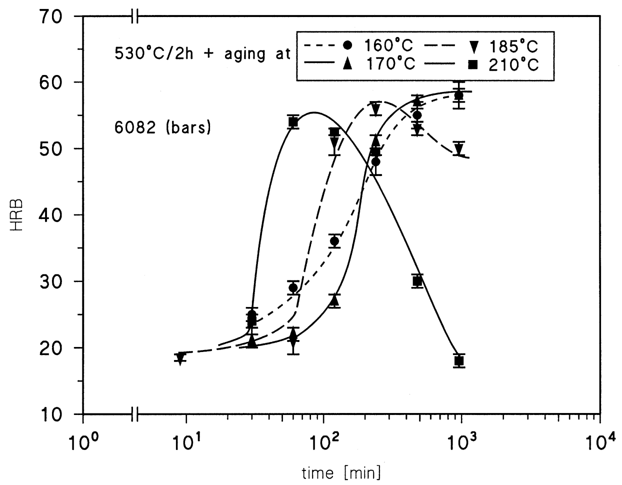

Figure 6: Ageing curves at 160, 170, 185 and 210 °C (bars)
Slika 6: Krivulje staranja pri 160, 170, 185 in 210 °C (palica)

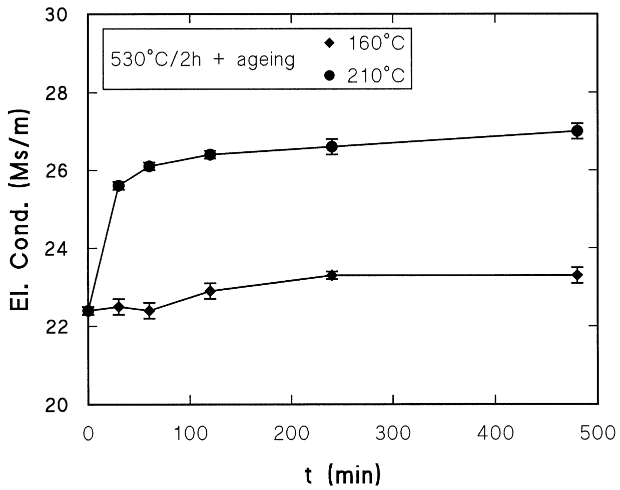

Figure 7: Electrical conductivity for different ageing times (160 and 210 °C)
Slika 7: Električna prevodnost pri različnih časih staranja pri 160 in 210 °C

one of the aims of the study was to evaluate the ageing response directly after thixoforming, and the initial hardness at some locations on the conrod was quite low (typically around 66 - 67 HRF), the hardness was measured using the HRF scale rather than the HRB scale. It is quite clear that the variation in hardness is due to the differences in microstructure (i.e. in eutectic content), while the size of the globules was found to be similar to that observed in the thixoformed bars (**Figure 9**). An example of the microstructure of the conrod is illustrated in **Figure 10**. Remote voids and cracks were detected in the rings as well as in the prismatic part of the conrod.

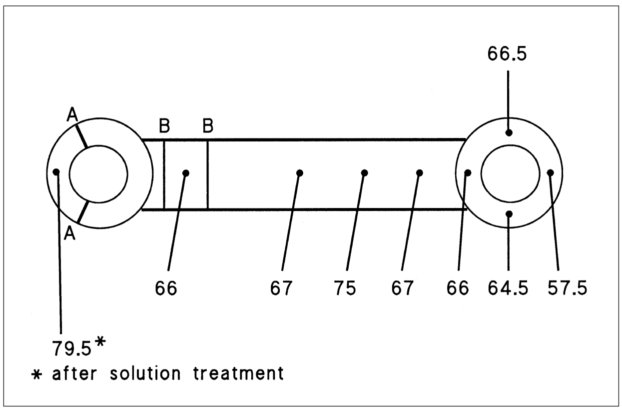

Figure 8: Shape of the component (conrod) investigated in this study; samples obtained from the parts indicated by the AA and BB labels were used to analyse the effect of ageing after solution treatment (AA) or directly after thixoforming (BB). The figure also illustrates the hardness (in HRF) at the surface of the conrod
Slika 8: Oblika raziskanega ulitka (conrod). Vzorci, označeni z AA in BB, so bili porabljeni za preiskave staranja po raztopilnem žarjenju (AA) ali po litju (BB). Navedena je tudi trdota (HRF) na površini ulitka.

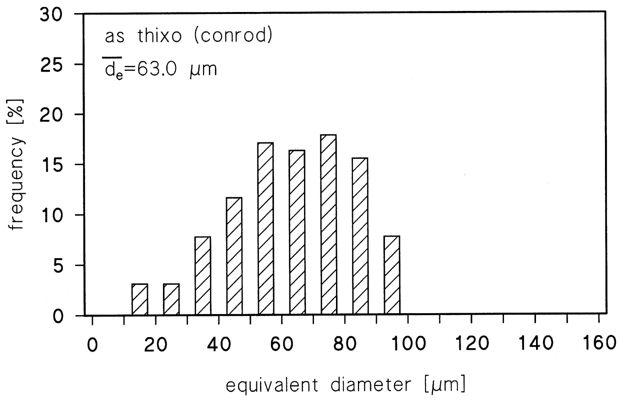

Figure 9: Size distribution of the globules in the conrod (location AA)
Slika 9: Velikostna porazdelitev globulov na lokaciji AA ulitka

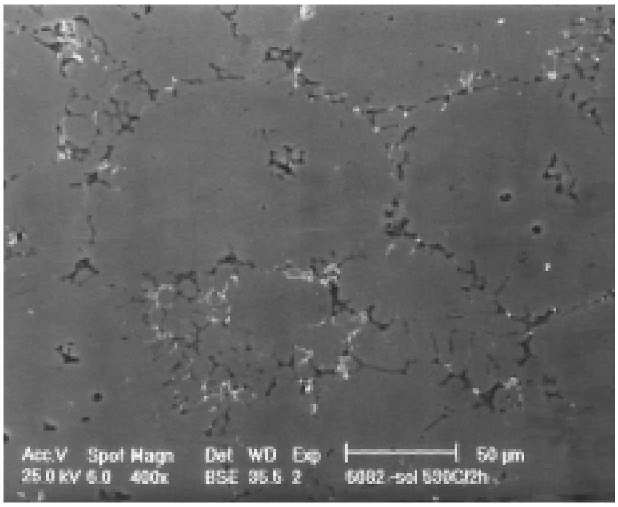

Figure 10: Microstructure of the conrod; one of the zones particularly rich in eutectic is shown
Slika 10: Mikrostruktura ulitka na področju, ki je zelo bogato z evtektikom

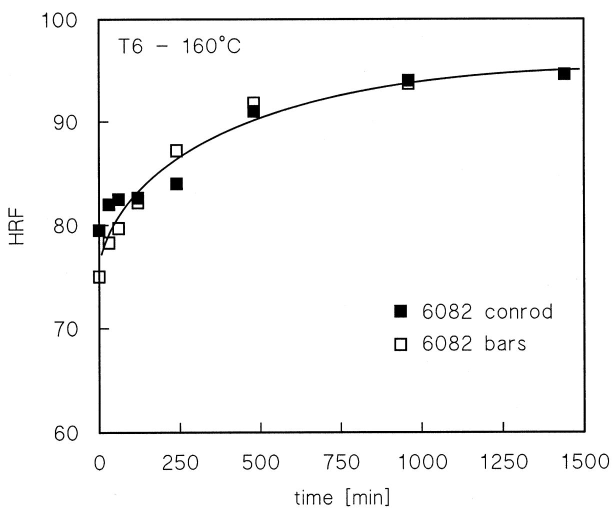

Figure 11: Comparison between ageing curves at 160 °C for the bars and the conrod
Slika 11: Primerjava krivulj staranja pri 160 °C iz palice in iz ulitka

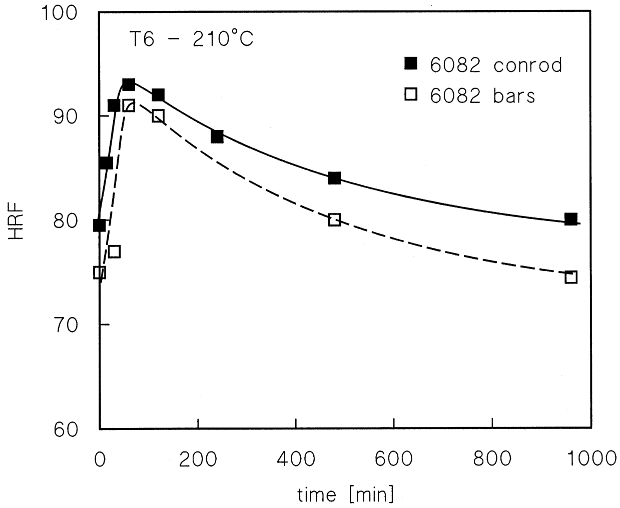

Figure 12: Comparison between ageing curves at 210 °C for the bars and the conrod

Slika 12: Primerjava krivulj staranja pri 210 °C iz palice in ulitka

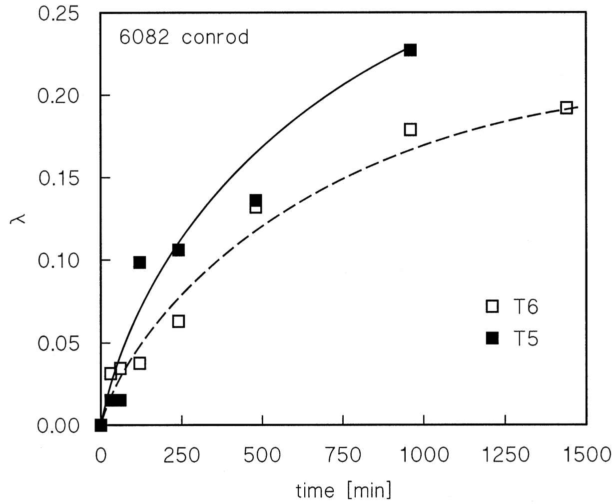

Figure 14: Normalised hardness increase with ageing time at 160 °C for T5 and T6 conditions (conrod)

Slika 14: Normalizirana rast trdote pri staranju pri 160 °C za pogoje T5 in T6 (ulitek)

The samples machined from the A-A part were artificially aged at 160 °C and 210 °C. The curves exhibit a marked similarity with those observed by testing the bars, even if the initial value of the hardness (i.e. the hardness after solution treatment at 530 °C-2h) was slightly different. The peaks in hardness were reached for similar ageing times and did not differ appreciably for the two different product shapes (bars and conrod) (**Figures 11 and 12**).

In order to verify if heating at temperatures above 530 °C during the thixoforming process and the subsequent cooling in the die could be assimilated in to a solution treatment, samples cut from the BB part of the conrod were aged at 160 and 210 °C without previous solubilisation. The T5 treatment resulted in ageing curves quite similar in shape to those obtained after the T6 treatment, even if the difference in initial hardness makes a direct comparison rather difficult (**Figure 13**). **Figures 14 and 15** illustrate the same ageing curves represented in normalised form, using:

$$\lambda = \frac{H - H_0}{H_0} \tag{1}$$

where H is the hardness after a given ageing duration, and H_0 is the hardness of the initial state (as thixoformed or solution treated respectively). Analysis of **Figures 14 and 15** suggests that ageing at 210 °C after solution treatment produces a faster precipitation, while over ageing occurs for a shorter time of exposure;

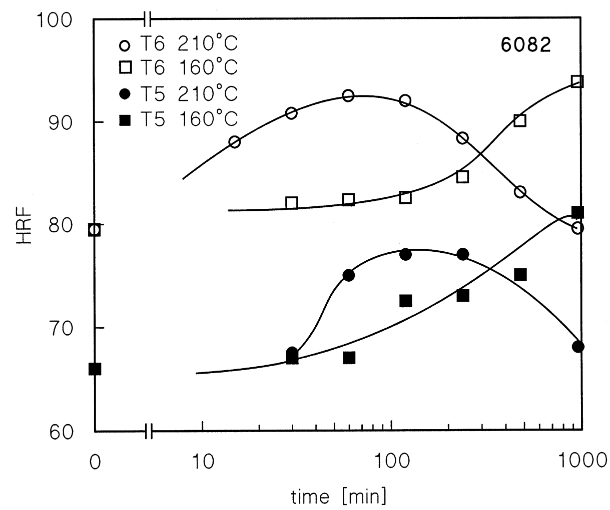

Figure 13: Comparison between T5 and T6 conditions; ageing at 160 and 210 °C (conrod)

Slika 13: Primerjava med pogoji T5 in T6. Staranje pri 160 in 210 °C, ulitek

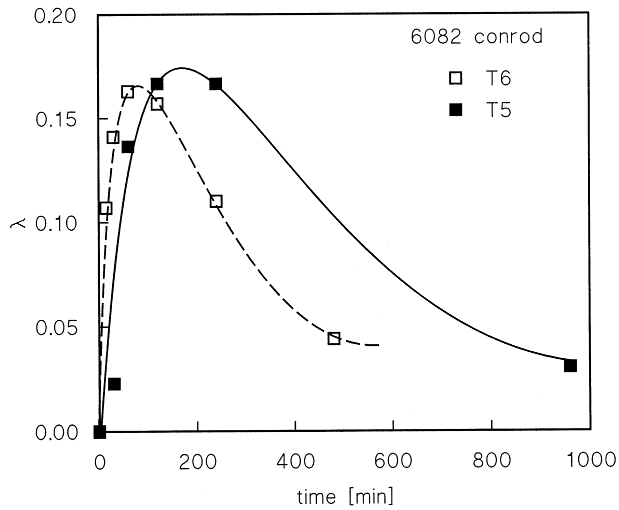

Figure 15: Normalised hardness increase with ageing time at 210 °C for T5 and T6 conditions (conrod)

Slika 15: Normalizirana rast trdote pri staranju pri 210 °C za pogoje T5 in T6 (ulitek)

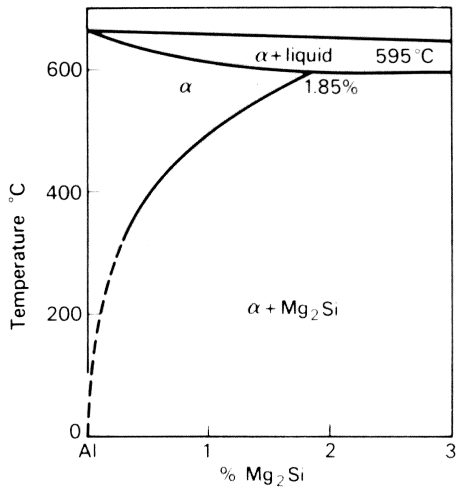

Figure 16: Al- Mg_2Si phase diagram[7]
Slika 16: Fazni diagram Al-Mg_2Si[7]

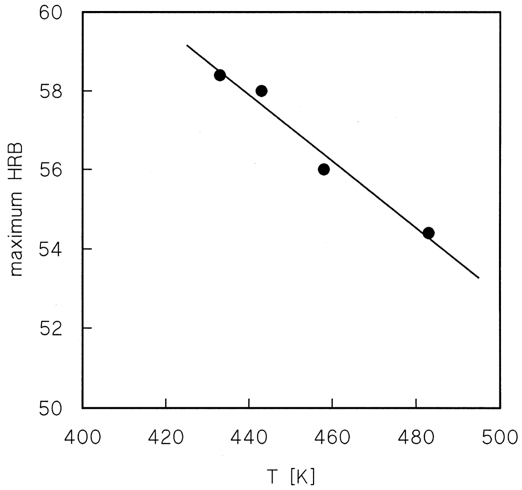

Figure 18: Peak hardness as a function of absolute ageing temperatures
Slika 18: Maksimalna trdota v odvisnosti od absolutne temperature staranja

on the other hand, a continuous increase in hardness is obtained for ageing at 160 °C.

4 DISCUSSION

4.1 Analysis of heat-treatment response

The analysis of the microstructure of the thixoformed alloy clearly revealed that the amount of eutectic (i.e. of the "liquid" component during thixoforming) is quite low. The ternary Al-Mg-Si phase diagram can be represented in the form of the quasi-binary Al-Mg_2Si diagram represented in **Figure 16**[7]. The analysis of the pseudo-binary diagram clearly shows that the alloys in this family can be thixoformed with a certain difficulty, due to the narrow window of temperatures above 595 °C in which the solid α-phase coexists with the liquid phase. In particular, it has been shown[9] that the amount of liquid is close to 50% around 640 °C and that an increase of just 10 °C is enough to cause melting of the alloy. A decrease of 10 °C, on the other hand, reduces the amount of liquid by up to 20%. It is quite clear that a similar behaviour makes thixoforming of large components with complicated shapes a difficult task. Actually, this analysis is fully consistent with the porosity and cracks detected in the component.

The present study has confirmed that after thixoforming the 6082 alloy it is possible to substantially increase the hardness (that is, for a defect free component, the tensile strength) by means of proper heat treatments, the same as normally used for extrusion alloys.

The results of the experimental ageing treatments carried out on thixoformed bars could then be used to obtain a more general, and particularly useful even if

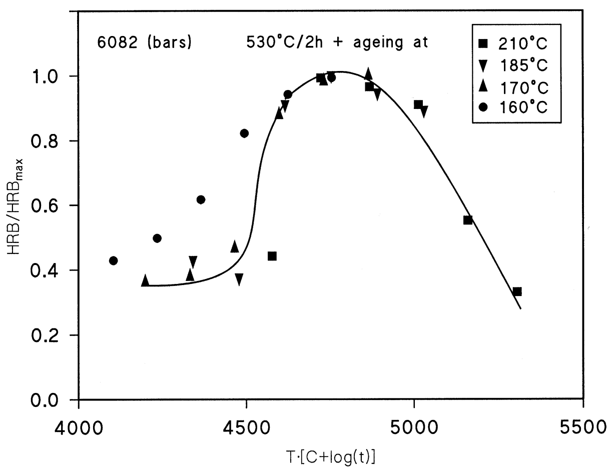

Figure 17: Normalised hardness as a function of the P parameter
Slika 17: Normalizirana trdota kot funkcija parametra P

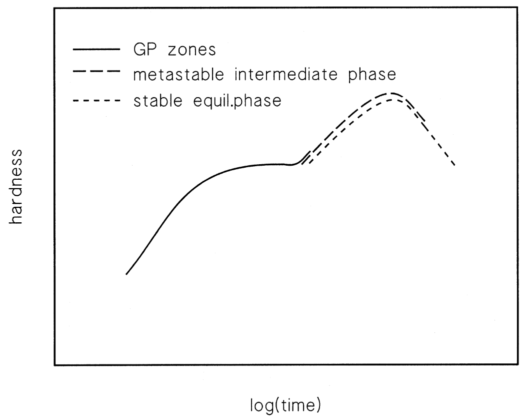

Figure 19: Qualitative trend of the hardness as a function of ageing time and single contribution of the GP zones, semi-coherent or coherent metastable precipitates and equilibrium precipitates[12]
Slika 19: Kvalitativno gibanje trdote kot funkcije časa staranja in deleža GP zon, polkoherentnih ali koherentnih metastabilnih precipitatov in ravnotežnih precipitatov[12]

phenomenological, description. The observation that, as expected, the maximum in hardness increases when temperature decreases, suggested that the experimental data could be more conveniently described in normalised form (for example as H/H_{max}, where H_{max} is the hardness at the peak ageing). Then, in the present study, an equation in the form:

$$P = T\,(C + \log t) \qquad (2)$$

where C is a constant, t is the ageing time (in minutes) and T is the absolute ageing temperature, was used to obtain a master curve for all the ageing curves. Eqn. 2 is similar in form to the Larson-Miller parameter normally used to extrapolate time to rupture during creep[10]. Interpolation of the experimental data suggested that a good superimposition of the ageing curves produced at 170, 185 and 210 °C is obtained with C=8 (**Figure 17**). Thus, the curve in **Figure 17** can be used to evaluate the hardness variation with ageing time, for temperatures between 170 and 210 °C, once the value of the peak hardness is properly estimated. **Figure 18** provides just this description, since it shows that the peak hardness varies approximately linearly with absolute temperature.

A significant deviation between the curve in **Figure 17** and the experimental points is observed only for the ageing temperature of 160 °C. This difference clearly requires a more detailed analysis of the microstructure (by means of transmission electron microscopy) to be fully explained. Nevertheless, some qualitative considerations on the nature and chemistry of the Al-Mg-Si alloys could give very useful information. The high strength typical of the 6082 alloy, as well as of other materials in the same family, is the result of different types of precipitates. In particular, the precipitation sequence in the Al-Mg-Si alloys passes through the formation of a GP zone in the form of needles along d directions, the formation of β' hexagonal Mg_2Si (semi-coherent rods that probably form from the GP zones[7]), and finally the precipitation of the equilibrium face-centred cubic β (Mg_2Si in the form of platelets). A typical feature of the constitution of these alloys is conventionally used ageing temperature (around 170 °C) is below the GP solvus (i.e. the temperature above which the GP zones are unstable). Thus, the formation of GP zones, that are ordered, solute-rich, clusters of atoms finally dispersed in the matrix (they require movements of atoms over relatively short distances[7]), is a process that significantly influences the ageing treatment. In particular, for a relatively high ageing temperature, as previously seen, the formation of the equilibrium phase is preceded by the formation of GP zones and subsequently by the β' metastable phase. Since the GP zone and semi-coherent phases introduce an elastic distortion in the lattice, their strengthening contribution is relevant, as qualitatively illustrated by **Figure 19**.

If the temperature is too low, it can be supposed that the transformation of the GP zone in the intermediate phase, as well as the β' - β transition, are extremely slow processes. Thus, it can not be excluded that while hardening at high temperature involves the formation of the equilibrium precipitate, at 160 °C the structure is hardened mainly by the presence of the GP zones and/or metastable precipitates. This analysis is fully consistent with the conductivity measurements shown in **Figure 7**. Alloying elements in solid solution are known to depress the conductivity, since they tend to impair the periodicity of the lattice[11]. Artificial ageing at high temperature (for example at 210 °C) is thus accompanied by a marked increase in electrical conductivity. The formation of a GP zone, typical of low-temperature ageing, on the other hand, is accompanied by a low electrical conductivity, since in this case the periodicity of the lattice is also substantially disturbed. The variation in electrical conductivity measured after ageing at 160 °C probably reflects just such phenomena. The hardness after ageing for 500 min at 160 °C, is equivalent to that measured after 50 min at 210 °C; yet, as clearly shown in Figure 7, the electrical conductivity is substantially higher in the latter case. Thus it can be argued that the continuous increase in hardness at 160 °C is the result of the precipitation of GP zones and eventually of semi-coherent precipitates, reflected in a very moderate increase in electrical conductivity. By contrast, ageing at 210 °C results in the precipitation of the equilibrium incoherent phase, accompanied by the marked increase in conductivity.

4.2 Analysis of the thixoformability of the alloy

The above discussion has shown that the 6082 alloy, with a proper heat treatment, can be aged to obtain high values of hardness. Yet, one of the major concerns in the production of sound and defect-free components, is the necessity of avoiding porosity and other similar defects. The analysis of the microstructure of the conrod confirmed the preliminary observations about the general difficulty in thixoforming alloys of the 6XXX family. One of the possible developments to combine the good properties of the 6XXX alloy with an improved quality of the product after thixoforming could involve a variation in the Si content of the alloy[9], moving toward the typical composition of materials more extensively used for thixoforming (for example A357).

Even if it is clear that the chemical composition of the 6082 alloy is not particularly suited for the production of components of complex shape following this technological route, nevertheless the knowledge of the ageing response of these materials is useful for the development of other alloys.

5 CONCLUSIONS

The heat-treatment response and the microstructure of a 6082 alloy produced in the form of bars by thixoforming were investigated. The analysis of the effect of increasing solution- treatment times indicated that a duration over 2h did not give any significant advantages in terms of hardness after ageing. A general relationship between ageing temperature (170-210 °C) and duration was obtained by reporting the hardness as a function of the parameter $P = T(8+\log t)$, where T is the absolute temperature and t the ageing time in min. The hardness data obtained after ageing at 160 °C did not follow the above mentioned relationship; this effect was attributed to a different hardening mechanism (exclusive presence of coherent zones or semi-coherent precipitates at low temperature, precipitation of equilibrium phases at higher temperatures).

The microstructural investigation of a component of relatively complex shape showed the presence of voids and hot-cracks; the hardness was not homogeneous throughout the component, but the heat-treatment response was similar to that observed when testing thixoformed bars.

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6 REFERENCES

[1] G. Chiarmetta: Thixoforming of automotive components, proc. 4th International Conference on semi-solid processing of alloys and Composites, Sheffield, 19-21 June 1996, 204

[2] K. P. Young, Semi-solid forming of alloys and composites, in nature and properties of semi-solid materials, J. A. Sekhar and J. A. Dantzig eds., TMS, 1991, 245

[3] B. Wendinger, Findings and experiences in thixoforming of aluminium alloys, proc. 4th International Conference on semi-solid processing of alloys and composites, Sheffield, 19-21 June 1996, 239

[4] G. Chiarmetta, Thixoforming and weight reduction - Industrial Application of SeSoF, 5th International Conference on processing of semi-solid alloys and composites, 23-25 June 1998, A. K. Bhasin et al. eds., Colorado School of Mines, Golden, Colorado, USA, 1998, 87

[5] G. Hirt, R. Cremer, A. Winkelmann, T. Witulski and M. Zillgen, SSM Forming of usually wrought aluminium alloys, proc. 3rd International Conference on processing of semi-solid alloys and composites,13-15 June 1994, M. Kiuchi Ed., Institute of Industrial Science, University of Tokyo, Japan, 1994, 107

[6] T. Witulski, U. Morjan, I. Niedick and G. Hirt, The thixoformability of aluminium alloys, 5th International Conference on processing of semi-solid alloys and composites, 23-25 June 1998, A. K. Bhasin et al eds., Colorado School of Mines, Golden, Colorado, USA, 1998, 353

[7] I. J. Polmear, Light Alloys: Metallurgy of the light metals, Edward Arnold, London, 1981, 82

[8] H. E. Pitts and H. V. Atkinson, Thixoforming of 6061 Al alloy for automotive components, proc. 5th International Conference on processing of semi-solid alloys and composites, 23-25 June 1998, A. K. Bhasin et al eds., Colorado School of Mines, Golden, Colorado, USA, 1998, 97

[9] EFU GmbH, 3rd Six Month Progress Report, BRITE EURAM Project BE95-1244, October 1997

[10] F. R. Larson and J. Miller, Trans. ASME, 74 (**1952**) 765

[11] Aluminum: Properties and physical metallurgy, J. E. Hatch ed., ASM, 1984, 207

[12] M. Conserva, E. Di Russo, P. Fiorini, Alluminio e nuova metallurgia, 10 (**1970**), 515