Influence of heat treatment on the microstructure and mechanical properties of 6005 and 6082 aluminium alloys

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Abstract

The main task of this work was to study the influence of the cooling conditions after homogenization of the 6082 aluminium alloys. The effect of the solution heat treatment temperature on the mechanism and ageing kinetics of the two commercial wrought aluminum alloys 6005 and 6082 was also analyzed. The alloys were heat treated—T4 with a wide range of solution heat treatment temperature from 510 to 580 °C and then natural ageing in the room temperature. Then, Brinell hardness measurements were conducted on both alloys in order to examine the influence of ageing time on the precipitation hardening behavior. The microstructure changes of the aluminium alloys following ageing for 120 h has been investigated by metallographic and transmission electron microscopy (TEM). The minor objective of the present study was to determine how extrusion processing affected the microstructure and mechanical properties of both aluminium alloys. For this purpose tensile tests were performed.

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1. Introduction

The 6xxx-group contains magnesium and silicon as major addition elements. These multiphase alloys belong to the group of commercial aluminium alloys, in which relative volume, chemical composition and morphology of structural constituents exert significant influence on their useful properties [1–5]. In the technical aluminium alloys besides the intentional additions, transition metals such as Fe and Mn are always present. Even not large amount of these impurities causes the formation of a new phase component [5]. The exact composition of the alloy and the casting condition will directly influence the selection and volume fraction of intermetallic phases [4]. During casting of 6xxx aluminium alloys a wide variety of Fe-containing intermetallics such as Al–Fe, Al–Fe–Si and Al–Fe–Mn–Si phases are formed between the aluminium dendrites [1–6]. Type of these phases depends mainly on the cooling rate and the Fe to Si ratio in the alloy [1]. These intermetallic phases have different unit cell structures, morphologies, stabilities and physical and mechanical properties [6]. As-cast billets require a homogenization treatment to make the material suitable for hot extrusion. During this homogenization treatment several processes take place such as the transformation of interconnected plate-like β–AlFeSi intermetallics into more rounded discrete α_{5}Al_{15}(Fe,Mn)_{3}Si particles and the dissolution of β–Mg_{2}Si particles [7]. Transformation of β–AlFeSi to α_{5}Al_{15}(Fe,Mn)_{3}Si intermetallics is important because it improves the ductility of the material. Dissolution of β–Mg_{2}Si is also important since it will give maximum age hardening potential for the extruded product [1,3,7]. The precipitation of the metastable precursors of the equilibrium β–(Mg_{2}Si) phase occurs in one or more sequences, which are quite complex. The precipitation sequence for 6xxx alloys, which is generally accepted in the literatures [8–12], is:

SSSS → atomic clusters → GP zones → β'' → β'

where SSSS is the super saturated solid solution. Some authors [10] consider the GP zones as GP1 zones while the β'' is called a GP2 zone. The most effective hardening phase for this types of materials is β''. However, the
details of changes in hardness versus annealing time and the
dependence on the storage time at room temperature (RT) are
not fully understood.

2. Material and experimental

The investigation has been carried out on the commercial
aluminum alloy – appointed in accordance with the standard
PN-EN 573-3 – 6005 and 6082. The chemical composition of
the alloys is indicated in Table 1. The conditions of produc-
tion of the alloy were as follows: an ingot was first heated up
to temperature 500 °C and subsequently subjected to the ex-
trusion forging process to obtain profiles with cross-section
of a 40 mm × 100 mm.

The temperature of profile going out of press was about
550 °C, the cooling on exit side of the press was not applied.

2.1. Metallographic investigations

The metallographic investigations of 6005 and 6082 al-
loy were performed on the as-cast samples, after extrusion
forging process, and after natural ageing. The evolution of
the microstructure of samples subjected to different cooling
modes after homogenization treatment (water, oil, air and
slow cooling, in the furnace) and after ageing process has
been investigated. Microstructure of characteristic states of
examined alloy was observed using an optical microscope
– Nikon 300 and Neophot 2 on polished sections etched in
Keller solution (0.5% HF in 50 ml H2O) and transmission
electron microscopy (TEM) – Tesla BS-540.

2.2. Heat treatment

The temperature of homogenization treatment of 6082 al-
loy was determined on the basis of literature data and calori-
metric investigations. The samples were preheated in an in-
duction furnace to a temperature 570 °C, held for 4 and 6 h
and subsequently cooled using different cooling procedures,
including a quench in water and oil, air or slow furnace cool-
ing. Additionally, water-cooled samples were subjected to T4
heat treatment (natural ageing after solution treatment). The
influence of solution heat treatment temperature on the mech-
anism and kinetics of ageing of the 6005 and 6082 alloys is
investigated. The alloys were heat treated, with a wide range
of solution heat treatment temperature from 510 to 580 °C
and then natural ageing in the room temperature to 120 h. In
order to do the analytical of influence of time on the kinetics of
ageing the Brinell hardness was measured.

Table 1
Chemical composition of the investigated alloys (wt.%)  

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Others</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>6005</td>
<td>0.60</td>
<td>0.21</td>
<td>0.12</td>
<td>0.15</td>
<td>0.54</td>
<td>0.028</td>
<td>0.03</td>
<td>0.15</td>
<td>Bal</td>
</tr>
<tr>
<td>6082</td>
<td>1.2</td>
<td>0.33</td>
<td>0.06</td>
<td>0.50</td>
<td>0.78</td>
<td>0.14</td>
<td>0.05</td>
<td>0.15</td>
<td>Bal</td>
</tr>
</tbody>
</table>

2.3. Determination of mechanical properties

For determination of mechanical properties of the exam-
ined alloys, the samples were deformed in static tensile test in
an Instron TTF-1115 servohydraulic universal tester at a con-
stant rate, according to standard PN-EN 10002-1:2004. The
hardness was measured with Brinell tester under 49.03 N load
for 10 s. The tensile tests and hardness measurements were
performed on the as-cast samples and hot-extruded samples.
The hardness was also measured on the samples after ho-
mogenization treatment followed by water, oil, air and slow
furnace cooling and during ageing process.

3. Results and discussion

The microstructure of the studied alloys in as-cast state is
given in Fig. 1a and b. In the interdendritic spaces of α-Al
solid solution one can see the precipitates of the intermetal-
lic phases. The revealed particles of the intermetallic phases
were formed during casting of the alloy. The typical as-cast
structure of examined alloys consisted of a mixture of β-
AlFeSi and α-AlFeMnSi intermetallic phases distributed at
cell boundaries, connected sometimes with coarse Mg2Si.
The microstructure of the alloy after hot extrusion forging process is given in Fig. 2 a and b. During hot working of ingots, particles of intermetallic phases arrange in positions parallel to direction of plastic deformation (along plastic flow direction of processed material), which allows for the formation of the band structure. As a result, the reduction of size of larger particles may take place.

Microstructures of the 6082 alloy after different modes of cooling after homogenization are shown in Fig. 3 a–c. It is likely that during homogenization of the alloy at temperature 570 °C, the transformation β-AlFeSi phase in more spheroidal α-Al(FeMn)Si phase may occur [13]. It is supposed that the very fine dispersed precipitates shown in Fig. 3a–c are particles of β-Mg2Si phase. The dissolved particles of β-Mg2Si phase precipitates during slow cooling after homogenization [3]. The process of natural ageing in alloy 6082 began almost instantaneously after solution heat treatment. Due to that it is not possible to observe the actual state of microstructure directly after quick cooling (in water or oil).

After homogenization treatment followed by different variants of cooling the hardness of 6082 alloy was measured. The results show the considerable influence of the cooling rate after homogenizing treatment on hardness of the alloy. The highest value of hardness was obtained in the sample followed by cooling in water, however the lowest hardness was observed for the sample cooled from the homogenization temperature in the furnace (Fig. 3c). The time of homogenization was not particularly affecting the hardness of the cooled samples (Fig. 4).

The accumulation of lattice defects in the material during hot extrusion forging process exerts a considerable influence on structure formation. As a result the strain hardening of the alloy takes place and, in consequence, increases the mechanical properties. In order to compare mechanical properties of the alloy after extrusion forging process with the ones in as-cast state, the static tensile tests were performed. To confirm statistically the course of stress-strain curves, 10
Fig. 4. Influence of different variants of cooling and of the time of homogenization on the hardness of the investigated 6082 alloy.

Table 2

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>6005 alloy</th>
<th>6082 alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-cast alloy</td>
<td>Wrought alloy</td>
<td>As-cast alloy</td>
</tr>
<tr>
<td>$R_m$ (MPa)</td>
<td>120</td>
<td>155</td>
</tr>
<tr>
<td>$R_p0.2$ (MPa)</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>A (%)</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>HB</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

Separate tensile tests were done. The mechanical properties of the samples after tensile tests are shown in Table 2. One can see that, the mechanical properties of the wrought alloys are higher by about 40 MPa compared to the ones in the as-cast state: the resistance $R_m$ has grown up from the value 130 to 170 MPa for 6082 alloy and from 120 to 155 MPa for 6005 alloy (Table 2).

During natural ageing of examined alloys of 6082 and 6005 the increase of hardness was observed. The ageing characteristics illustrating the changes of the hardness during ageing process of 6082 alloy are similar to that of 6005 alloy. Fig. 5 shows typical ageing curve observed for both materials after different solution heat treatment conditions. Curve in Fig. 5 shows that the hardness of the alloys increases rapidly in the initial phase of ageing, after 3 h. During following 20 h of ageing, further but insignificant increase of the hardness was observed.

In order to make precise analysis of the ageing kinetics of 6005 and 6082 alloys the following equation has been used:

$$HB = A + B \ln t$$

(1)

Table 3

<table>
<thead>
<tr>
<th>Solution heat treatment temperature ($^\circ$C)</th>
<th>A</th>
<th>B</th>
<th>R</th>
<th>HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>515</td>
<td>55.882</td>
<td>3.499</td>
<td>0.976</td>
<td>72.6</td>
</tr>
<tr>
<td>525</td>
<td>57.185</td>
<td>3.857</td>
<td>0.996</td>
<td>75.7</td>
</tr>
<tr>
<td>535</td>
<td>59.945</td>
<td>3.470</td>
<td>0.996</td>
<td>76.6</td>
</tr>
<tr>
<td>545</td>
<td>65.829</td>
<td>3.648</td>
<td>0.991</td>
<td>83.3</td>
</tr>
<tr>
<td>555</td>
<td>65.628</td>
<td>4.229</td>
<td>0.996</td>
<td>85.9</td>
</tr>
<tr>
<td>565</td>
<td>66.578</td>
<td>4.792</td>
<td>0.995</td>
<td>89.5</td>
</tr>
</tbody>
</table>

Parameters derived from Eq. (1) and hardness HB of 6082 alloy

The values of regression coefficient B (Tables 3 and 4) evaluated from Eq. (1) give information about the ageing kinetics of examined alloys. Tables 3 and 4 clearly demonstrates that with regard to the 6082 alloy the ageing rate itself depends on the solution heat treatment temperature as opposed to the 6005 alloy: i.e. the higher solution heat treatment temperature, the higher B regression coefficient. The hardness of the 6082 alloy increase with increasing heat treatment temperature, however solutioning temperature practically does not affect the hardness of the 6005 alloy.

High values of the correlation coefficient R of the 6082 alloy are evidence for strong hardness dependence on the solution heat treatment condition (temperature), nevertheless for the 6005 alloy this correlation is insignificant. The effect of the solution heat treatment condition on the hardening rate of examined alloys in form of a regression coefficient B-solutioning temperature relation illustrates Fig. 6a, 6005 alloy and Fig. 6b, 6082 alloy.

The value of regression coefficient B of the 6082 alloy increases with increasing of the heat treatment temperature in accordance with the following equation:

$$B = 0.126 \exp(0.0063T), \quad R = 0.865$$

(2)

i.e. the higher solution heat treatment temperature the hardening process started earlier and proceeded fastest. As shown in Fig. 6a, the kinetics of ageing of 6005 alloy does not depend on the solution heat treatment temperature.

The hardness HB of the examined alloys changes similarly. During natural ageing of the 6082 alloy for 120 h, the hardness increases with rising of the solutioning temperature. It has been found that the hardness is well correlated with the solution heat treatment temperature; relationship of both parameters demonstrates a linear character and changes

Table 4

<table>
<thead>
<tr>
<th>Solution heat treatment temperature ($^\circ$C)</th>
<th>A</th>
<th>B</th>
<th>R</th>
<th>HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>520</td>
<td>44.706</td>
<td>3.030</td>
<td>0.982</td>
<td>59.214</td>
</tr>
<tr>
<td>530</td>
<td>44.073</td>
<td>2.924</td>
<td>0.970</td>
<td>58.072</td>
</tr>
<tr>
<td>540</td>
<td>43.615</td>
<td>2.732</td>
<td>0.989</td>
<td>59.474</td>
</tr>
<tr>
<td>550</td>
<td>44.481</td>
<td>2.935</td>
<td>0.983</td>
<td>58.534</td>
</tr>
<tr>
<td>560</td>
<td>44.449</td>
<td>2.878</td>
<td>0.984</td>
<td>58.228</td>
</tr>
<tr>
<td>570</td>
<td>44.184</td>
<td>3.092</td>
<td>0.991</td>
<td>58.989</td>
</tr>
</tbody>
</table>
in accordance with the equation:
\[ HB = 0.34T - 107.32, \quad R = 0.985 \]  

High value of the linear correlation coefficient \( R \) (Eq. (3)) is evidence for strong dependence of the solution heat treatment temperature on the hardness HB of the 6082 alloy.

The hardness of the 6005 alloy the same as the ageing kinetic (Fig. 6a) does not depend on the heat treatment conditions (Fig. 7a).

The lack of influence of the different treatment temperature on both the hardening velocity and the hardness of the 6005 alloy might be caused by smaller content of Mg, Si and Mn compared with (the content of these elements in) the 6082 alloy. It can be seen (Fig. 7b) that the hardness of 6082 alloy increases with growing of the solutioning temperature. This is due to the fact that the amount of Mg and Si in a supersaturated solution, which are essential to forming the hardening particles of \( \beta - \text{Mg}_2\text{Si} \) phase precipitated during ageing process, increases along with rising of the heat treatment temperature. The number of GP zones and strengthening phases, which are responsible for hardening of the alloys, increases with increasing of alloying components content (Fig. 8a and b).

The total content of alloy forming components in the 6082 alloy come to 3.23% and it is approximately twice as much as their content in the 6005 alloy (1.808%).

Hence, it can be concluded that the volume fraction of the strengthening phases in the 6005 alloy is lower which give explanation for the lack of hardening effects during natural ageing process.

4. Conclusions

The following conclusions are drawn from this work:
1. The hardness of the investigated 6082 alloy was generally more sensitive to cooling conditions than to the time of homogenization. The highest hardness was obtained in the samples cooled in water.

2. It was found that the samples after extrusion forging process show higher $R_m$ than those in the as-cast state.

3. It was shown that the $\beta$-Mg$_2$Si phase precipitates readily during cooling after homogenization. The amount and distribution of $\beta$ particles depend on the cooling variant. Very fine dispersed precipitates of $\beta$-Mg$_2$Si phase were observed in the microstructure of samples cooled in air.

4. The ageing kinetics and hardness of the investigated 6005 alloy was not generally dependent on solution heat treatment temperature.

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References