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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 alloy. 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°C 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 hours 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.

Keywords: 6xxx series Al alloys; Heat treatment; Microstructure

1. INTRODUCTION

The 6xxx-group contains magnesium and silicon as major addition elements. These multiphase alloys belong to the group of commercial aluminum alloys, in which relative volume, chemical composition and morphology of structural constituents exert significant influence on their useful properties. 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. The exact composition of the alloy and the casting condition will directly influence the selection and volume fraction of intermetallic phases. During casting of 6xxx aluminium alloys a wide variety of Fe-containg intermetallics such as Al-Fe, Al-Fe-Si and Al-Fe-Mn-Si phases are formed between the aluminium dendrites. Type of these phases depends mainly on the cooling rate and the Fe to Si ratio in the alloy. These intermetallic phases have different unit cell structures, morphologies, stabilities and physical and mechanical properties. 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 interconnected plate-like β-Al_5FeSi intermetallics into more rounded discrete α_c-$Al_{12}(FeMn)_3Si$ particles and the dissolution of β-Mg_2Si particles. Transformation of β-Al_5FeSi to α_c-$Al_{12}(FeMn)_3Si$ intermetallics is important because it improves the ductility of the material. Dissolution of β-Mg_2Si is also important since it will give maximum age hardening potential for the extruded product. The precipitation of the metastable precursors of the equilibrium β(Mg_2Si) phase occurs in one or more sequences which are quite complex. The precipitation sequence for 6XXX alloys, which is generally accepted in the literature, is:

SSSS ⇨ atomic clusters ⇨ GP zones ⇨ β"⇨ β'⇨ β (stable);
where: SSSS-super saturated solid solution

Some autors 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 vs 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.

Table 1.
Chemical composition of the investigated alloys, %wt.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Others	Al
6005	0.60	0.21	0.12	0.15	0.54	0.028	0.01	0.15	bal
6082	1.2	0.33	0.08	0.50	0.78	0.14	0.05	0.15	bal

3. RESULTS AND DISCUSION

In the interdendritic spaces of α-Al solid solution of the studied alloys in as-cast state one can see the precipitates of the intermetallic 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 Mg_2Si.

During hot extrusion forging process 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 takes place.

It is likely that during homogenization of the 6082 alloy after different modes of cooling at temperature 570°C, the transformation β-AlFeSi phase in more spheroidal α-Al(FeMn)Si phase may occur. It is supposed that the very fine dispersed precipitates shown in Figures 3 a-c are particles of β-Mg_2Si phase. The dissolved particles of β-Mg_2Si 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. The time of homogenization was not particularly affecting the hardness of the cooled samples.

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, an increase in mechanical proprieties. 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 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 MPa to 170 MPa for 6082 alloy and from 120 MPa to 155 MPa for 6005 alloy (Table 2).

Table 2.
Mechanical properties of 6082 and 6005

	6005 alloy		**6082 alloy**	
Mechanical properties	As cast alloy	Wrought alloy	As cast alloy	Wrought alloy
R_m, MPa	120	155	130	170
$R_{p0.2}$, MPa	60	65	60	72
A, %	17	21	25	25
HB	40	50	50	58

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 alloys are similar to that of 6005 alloys. The hardness of the alloys increases rapidly in the initial phase of ageing - after 3 hours. During following 20 hours 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 equations has been used:

$$\mathrm{H\hat{B}} = \mathrm{A} + \mathrm{B}\ln t \qquad (1)$$

Parameters derived from the equation were presented in the tables 3 and 4.

Table 3.
Parameters derived from the equation (1) and hardness HB of 6082 alloy

Solution heat treatment temperature, ^{o}C	A	B	R	$\mathrm{H\hat{B}}$
515	55.882	3.499	0.976	72.6
525	57.185	3.857	0.996	75.7
535	59.945	3.470	0.996	76.6
545	65.829	3.648	0.991	83.3
555	65.628	4.229	0.996	85.9
565	66.578	4.792	0.995	89.5

Table 4.
Parameters derived from the equation (1) and hardness HB of 6005 alloy

Solution heat treatment temperature, ^{o}C	A	B	R	$\mathrm{H\hat{B}}$
520	44.706	3.030	0.982	59.214
530	44.073	2.924	0.970	58.072
540	43.615	2.732	0.989	59.474
550	44.481	2.935	0.983	58.534
560	44.449	2.878	0.984	58.228
570	44.184	3.092	0.991	58.989

The values of regression coefficient B (tables 3 and 4) evaluated from the equation 1 give information about the ageing kinetics of examined alloys. Table 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 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 value of regression coefficient B of the 6082 alloy increases with increasing of the heat treatment temperature in accordance with the following equation:

$$\overline{\mathrm{B}} = 0.126\exp(0.0063T); \qquad \mathrm{R}=0.865 \tag{2}$$

i.e. the higher solution heat treatment temperature the hardening process started earliest and proceeded fastest. 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 hours, 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 in accordance with the equation:

$$\mathrm{H}\hat{\mathrm{B}} = 0.34T - 107.32; \qquad \mathrm{R}=0.985 \tag{3}$$

High value of the linear correlation coefficient R (equation 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 does not depend on the heat treatment conditions. 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.

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 β-Mg_2Si 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.

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 drown from this work:

1. The hardness of the investigated 6082 alloy was generally more sensitive to cooling conditions then 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 Rm then those in the as-cast state.
3. It was shown that the β-Mg_2Si phase precipitates readily during cooling after homogenization. The amount and distribution of β particles depend on the cooling variant. Very fine dispersed precipitates of β-Mg_2Si 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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