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Tensile properties and fracture toughness of heat treated 6082 alloy

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Materials

ABSTRACT

Purpose: The main task of this work was to study the effect of the precipitation hardening on the mechanical properties and fracture toughness of 6082 aluminium alloy.

Design/methodology/approach: The mechanical (R_m and $R_{p0.2}$) and plastic (A,Z) properties of the examined alloy were evaluated by uniaxial tensile test at room temperature. Additionally the artificially aged alloy has been tested in tension in order to determine its fracture toughness. Thus, standard ASTM tests were performed on fatigue precracked compact tension (K_{Ic}) and sharp-notched specimens (R_m^k) in both the longitudinal and transverse orientation with respect to the rolling direction.

Findings: The results show that the microstructure, mechanical properties and fracture toughness changes during artificial aging due to the precipitation strengthening process.

Practical implications: This paper is the part of previous authors' investigations which results in modification of the heat treatment parameters that may lead to the most favorable mechanical properties and fracture toughness of 6082 alloy.

Originality/value: Paper contains a broad spectrum of experimental data including uniaxial tensile test and fracture toughness investigation based on two various technique and as well as a new ideas concerning aging parameters and their effect on the mechanical properties and ductility of the 6082 alloy

Keywords: Metallic alloys; Fracture mechanics, Mechanical properties, Heat tretmeant

1. Introduction

The 6xxx series contain Si and Mg as a main alloying elements. These alloying elements are partly dissolved in the primary α-Al matrix, and partly present in the form of intermetallic phases. A range of different intermetallic phases may form during solidification, depending on alloy composition and solidification condition. Relative volume fraction, chemical composition and morphology of structural constituents exert significant influence on their useful properties [1-4]. Fe is present as an impurity in all commercial alloys [5]. 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 [6,7].

The aluminium alloys of 6xxx group have been studied extensively because of their technological importance and their exceptional increase in strength obtained by precipitation hardening. The precipitation of the metastable precursors of the equilibrium β(Mg_2Si) phase occurs in one or more sequences which are quite complex [8]. The most effective hardening phase for this types of materials is β". In this SEM, TEM microscopy have been utilized to study the effect of the precipitation hardening on the microstructure of aluminium alloy 6082.

Increases in reliability and efficiency of Al alloys require increases in strength and toughness. Hence, tensile test in the presence of sharp notch R_m^k as well as the currently most reliable K_{IC} measurement techniques where used to determine fracture toughness of the heat treated 6082 alloy, on the specimens with various orientations to the rolling direction.

The results show that the microstructure, mechanical properties and fracture toughness are strongly affected by artificial aging due to the precipitation strengthening process. Therefore, the parameters (time and aging temperature) of precipitation strengthening process that may lead to the most favorable mechanical properties of 6082 alloys were determined.

2. Material and experimental

The investigation has been carried out on the commercial 6082 aluminum alloy. The chemical composition of the alloy is: 1.2%Si, 0.78%Mg, 0.5%Mn, 0.33%Fe, 0.14%Cr, 0.08%Cu, 0.05%Zn, Al bal. Heat treated alloy at 575°C for 4 h was subjected to artificial aging at: 130°C for 72 h, 160°C for 50 h, 190°C for 42 h and at 220°C for 48 h.

T6 heat treated samples were strained by tensile deformation at a constant rate, in according to standard PN-EN 10002 [9,10] at room temperature. The hardness was measured with Brinell tester. To evaluate tensile strength in the presence of a sharp notch R_m^k standard-sized specimens containing a sharp notch were used [10]. The tensile and precracked compact tension specimens for evaluation of K_{Ic} were cut from the 6082 alloys plates in longitudinal transverse L-T and transverse longitudinal T-L orientation with respect to the rolling direction according to ASTM's standards [11,12]. Post-failure observation of the fracture surfaces of the failed C(T) specimens were made in the scanning electron microscope (SEM).

3. Results and discussion

The strength (R_m and $R_{p0.2}$) and plastic (A) properties of 6082 alloy after artificial aging were determined (Table 1).

Table 1.
Mechanical properties of 6082 alloy after T6 heat treatment (solutionizing temperature 575°C)

Aging temperature, °C	Aging time, h	Mechanical properties			
		$R_{p0.2}$, MPa	R_m, MPa	A, %	Z, %
130	4	245	376	20	28,9
	10	286	402	19	26,8
	20	313	411	18	23,8
	70	350	422	18	27,2
160	2,5	250	380	20	28
	6	320	418	19	27,5
	20	362	431	18	25
	50	380	440	16,5	23,3
190	1,5	273	381	20	32,3
	2,5	323	410	18	33,5
	6	390	441	17,4	38
	30	383	418	13,4	42
220	1	385	397	13,5	40,3
	5	351	368	12,3	43,7
	30	255	297	14,5	52,6

As can be seen in Fig. 1, the $R_{p0.2}$ and R_m of the alloy aged at 130°C increase with increasing aging time, with almost no elongation changes. The yield strength increases continuously with time, however a significant increase in mechanical properties was achieved during aging for up to 20 h. Further heating causes a steady increase in the yield strength of the material. The increment of the alloy strength similarly to the observed increment in hardness can be treated as the effects of initial formation of GP zones followed by precipitation of metastable particles of β'' and β' phases.

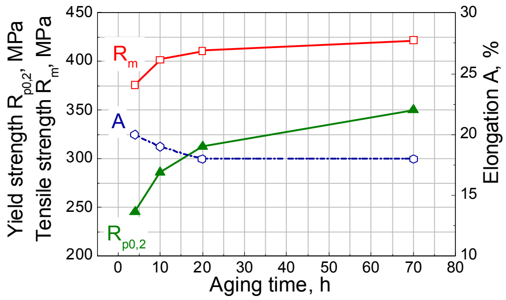

Fig. 1. Effect of time on tensile and yield strength of 6082 Al-alloy aged at 130°C

The curves of R_m, $R_{p0.2}$ and A obtained at aging at higher temperature (190°C) are shown in Fig. 2. These results confirm those obtained earlier. After heat treatment for the first few hours yield strength and tensile strength increases rapidly.

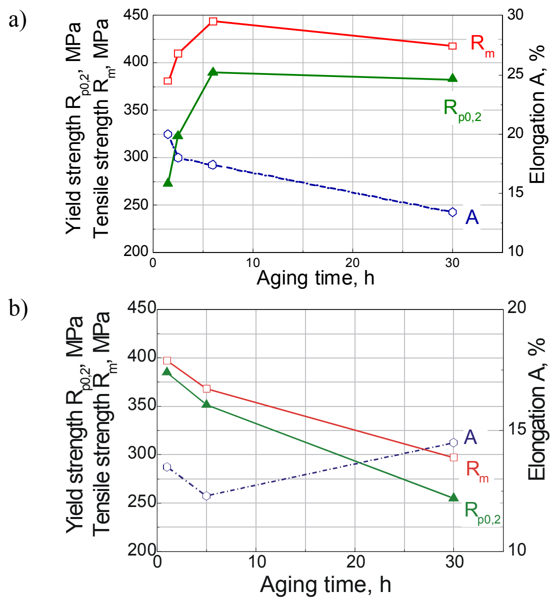

Fig. 2. Effect of time on tensile and yield strength of 6082 alloy aged at: a) 190 and b) 220°C

The growing trend of strength continues and it reaches R_m=440MPa after aging for 6 hours. Further extension of aging time results in insignificant variations of R_m and $R_{p0.2}$ values (Fig. 2a). However in case of higher temperature of aging - 190°C the

maximum of the strength properties is achieved after shorter time of exposing the alloy to an elevated temperature. On the other hand it was found that the aging temperature has a considerable stronger effect on elongation of investigated alloy. Elongation results obtained for the alloy aged at 130°C (Fig. 1) changes with aging time irrelevantly, it can be noticed that there is a greater reduction of plastic properties with the time when the alloy was aged at 190°C (Fig. 2a). There can be noted (see Fig. 2b, sample aged at 220°C) roughly linear drop of both $R_{p0.2}$ and R_m with time. However, elongation increases with increasing time. Initially a minimal deterioration of elongation value was observed but at higher aging time up 5 hours the elongation increase steadily.
The experimental results related to cracking sensitivity of the examined alloy show that its tensile strength in the presence of sharp notch depends mostly on the heat treatment conditions and orientation of the cleavage plane to the rolling direction. The result have shown that the highest R^k_m is achieved for the sample with longitudinal transverse L-T orientation subjected to artificial aging at 190°C (Fig. 3).

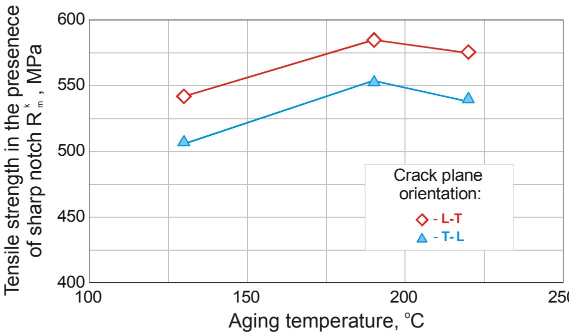

Fig. 3. The effect of aging time on tensile strength in the presence of sharp notch R^k_m of 6082 alloy

Crack resistance K_Q and critical fracture toughness factor K_{Ic} of the examined alloy depend on its respond to the precipitation hardening treatment (Table 3).

Table 2.
Average values of K_{Ic} of examined 6082 alloy ($K_Q = K_{Ic}$)

Aging process	Fracture plane orientation	K_{Ic} MPa·m$^{1/2}$
130°C/17 h	L-T	41,0
130°C/70 h	T-L	33,1
	L-T	38,52
160°C/10 h	L-T	40,5
190°C/4,5 h	T-L	37,0
	L-T	43,34
190°C/6 h	L-T	34,5
220°C/1 h	T-L	34,0
	L-T	38,5
220°C/4,5 h	L-T	36,3
220°C/10 h	L-T	38,0
220°C/17 h	L-T	36,0

The obtained results allow us to conclude that the crack resistance of the alloy is strongly influenced by the condition of heat treatment – aging time and temperature. Analysis of the data obtained by static tensile tests revealed that the 6082 alloy had nearly the same mechanical properties after aging at various temperatures for the same time. After tension of the compact fatigue prenotched samples it was found that the samples of 6082 alloy exposed to aging process at various temperature, but for the same period of time (e.g. 130°C and 220°C - point 1(17 h) and 5(32 h); 160°C and 220°C – point 2(10 h), Fig. 4) even if they are characterized by practically the same yield stress value, they showed differences in their crack resistance, what resulted in different values of the critical stress intensity factor K_{Ic} (Table 3).

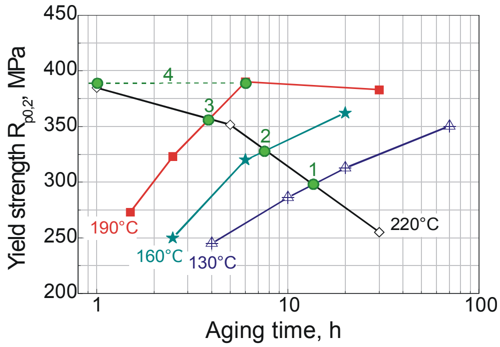

Fig. 4. The effect of the temperature and aging time on yield stress of 6082 alloy

Table 3.
The effect of the temperature and aging time on the mechanical properties of 6082 and 6005 alloy

Points in the Fig. 4	Aging process	Mechanical properties	
		$R_{p0.2}$, MPa	K_{Ic} MPa·m$^{1/2}$
1	130°C/17h	298	41,0
	220°C/17h		36,0
2	160°C/10h	327	40,5
	220°C/10h		38,0
3	190°C/4,5h	357	37,0
	220°C/4,5h		36,0
4	220°C/1h	380	34,5
	190°C/6h		34,0

The samples of 6082 alloy aged at lower temperature - 130°C and 160°C have much higher crack resistance compared to the samples aged for the same period of time at 220°C (Fig. 5 - point 1 and 2, Table 3). Only in the case of shorter aging time- 1h at 220°C and 6 h at 190°C similar values of K_{Ic} parameters were obtained (Fig. 5- point 4, Table 3). Prolongation of aging time at the highest temperature of 220°C results in overaging indicated by a significant drop in K_{Ic} values. 6082 alloy is underaged when undergoing heat treatment at lower temperature (130°C, 160°C) for 10 and 17 hours – what results in the higher value of K_{Ic} (Fig. 5- points 1,2,3,4, Table 3).

Analysis of the literature [1] and experimental data confirmed that in the materials consisting second-phase particles, voids firstly heterogenically nucleates at precipitates of the intermetallic phases. Decohesion process takes place first of all around the non-metallic inclusions and second-phase particles, that is around sites of the interface matrix-particle. Volume fraction of the intermetallic phases in 6082 alloy amount V_V =5,4%, thus the number of potential sites for void nucleation and their growth is considerable. This leads to decrease of crack resistance of 6082 alloy.

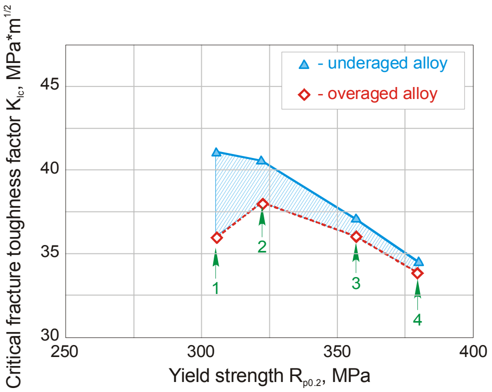

Fig. 5. The influence of yield strength $R_{p0.2}$ on the critical stress intensity factor K_{Ic} of the examined alloy – 6082

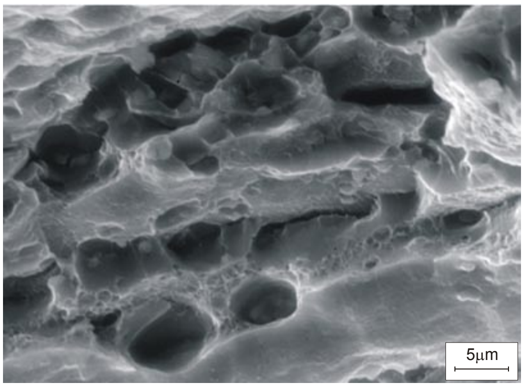

Fig. 6. Large dimples around hard intermetallic $\alpha(Al_8Fe_2Si)$ and $\beta(Al_5FeSi)$ precipitates and smaller around dispersive hardening β-Mg_2Si and α-Al(FeMn)Si precipitates

Crack resistance of 6082 alloy – similarly to the tensile strength in the presence of sharp notch R^k_m, is anisotropic property - depends on fatigue-cracking plane orientation to the rolling direction. The values of K_{Ic} parameter are higher for the samples with the crack plane perpendicular to the direction of greatest plastic deformation – L-T.

Metallographic and fractografic observation of the microstructure and the fracture of the aged samples of 6082 alloy with the highest tensile stress in the presence of sharp notch (Fig. 6) confirmed that fracture usually initiates within void clusters as a result of a sequence of void nucleation, void growth, and void coalescence.

4. Conclusions

1. The initial increase in the strength properties, is due to initial precipitation of GP zones and then formation of very fine needle-shaped particles of metastable phases - β'' and β' in under-aged and peak-aged conditions. Decrease in mechanical properties has occurred because of coalescence of β'' and β' phases.
2. 6082 alloy aged at 190°C for 6 hours exhibits the best combination of performance properties including strength with good fracture toughness.
3. Fracture toughness of 6082 alloy essentially depends on aging conditions as well as orientation of cleavage surface. The highest R^k_m=585 MPa and K_{Ic}=43,34 MPa·m$^{1/2}$ were achieved for the specimens with L-T orientation and aged at 190°C for 6 hours.
4. Observation of microstructure and fracture surface of the failed specimens showed that cracking of the examined alloy begin by nucleation and growth of voids.

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