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THE EFFECT OF TWO-STAGE AGE HARDENING TREATMENT COMBINED WITH SHOT PEENING ON STRESS DISTRIBUTION IN THE SURFACE LAYER OF 7075 ALUMINUM ALLOY

WPŁYW DWUETAPOWEGO PROCESU STARZENIA POŁĄCZONEGO Z KULOWANIEM NA ROZKŁAD NAPRĘŻEŃ W WARSTWIE WIERZCHNIEJ STOPU ALUMINIUM 7075

The article present the results of the study on the improvement of mechanical properties of the surface layer of 7075 aluminum alloy via two-stage aging combined with shot peening. The experiments proved that thermo-mechanical treatment may significantly improve hardness and stress distribution in the surface layer. Compressive stresses of 226 MPa±5.5 MPa and hardness of 210±2 HV were obtained for selected samples.

Keywords: Aluminum, heat treatment, multi stage, shot peening, residual stress

W ramach niniejszego artykułu przedstawiono wyniki badań dotyczące poprawy właściwości mechanicznych warstwy wierzchniej w stopie aluminium 7075 poprzez kombinacje starzenia dwuetapowego i kulowania. Dowiedziono w ramach prowadzonych badań, że istnieje możliwość znacznego poprawienia twardości oraz rozkładu naprężeń w warstwie wierzchniej stosując obróbkę cieplno-plastyczną. Dla wybranych próbek uzyskiwano naprężenia ściskające na poziomie 226MPa±5,5 MPa oraz twardość rzędu 210±2 HV.

1. Introduction

For a number of years, a trend to lighten the weight of products has dominated global industry. This applies to electronic components used in the production of mobile phones, tablets but also to devices such as tanks and aircraft [1 – 7]. The drive to lighten the weight of vehicles is the sum of a number of different needs. Decreasing fuel consumption (improving fuel economy) and enhancing the maximum range of vehicles are of major importance. It would be most profitable for the arms industry where increased range and maneuverability could be critical. Alloys of lightweight metals such as aluminum, titanium, magnesium or composites based on them are used in order to make products lighter [8 – 11], and of those, aluminum and its alloys have become an especially popular choice in many industries [12 – 17]. Their strength-to-density ratio is their major advantage and therefore they are more and more frequently used in structural components where component weight is very significant. Nevertheless, their mechanical properties in most cases are insufficient to render them a reliable substitute for functional steel components e.g. gearwheels.

To improve mechanical properties of aluminum based alloys, heat treatment parameters are optimized and combinations of thermal and mechanical treatments are used [18 – 24]. The combination of shot peening and two-stage age hardening appears to be very promising as not only does it lead to the hardening of the material and increased strength of the surface layer (due to the presence of core-shell type of phases in the continuous phase of some aluminum alloys) but it also introduces advantageous compressive stresses. Aluminum alloys subject to the combined treatments exhibit mechanical properties similar to those of steel, which significantly expands the range of their applications to include critical structural components as well as subcomponents working under friction conditions e.g. gears in unmanned vehicles. The synergistic effect of shot peening and two-stage age hardening has caused a surge in the number of studies on commercial applications of heat treated aluminum alloys. That is also the reason why the main objective of the foregoing study was to investigate the applicability of 7075 aluminum alloy treated with two-stage thermo-mechanical treatment to lightweight transmission gears. Such transmissions could be used in drones or military robots.

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2. Experimental method

The first part of the experiment involved mechanical treatment of the surface layer of the 7075 aluminum alloy samples (TABLE 1) in order to ensure maximum strengthening of the layer during the two-stage T6I6 or T6I4 aging (Fig. 1). The processes of mechanical treatment coupled with two-stage aging were planned in such a way as to obtain maximum hardness of the surface layer and simultaneously, the highest possible value of compressive stresses induced during the shot peening. This value is a compromise between on the one hand (a) mechanical treatment of the surface layer of the aluminum alloy during which compressive stresses are induced, and on the other hand (b) relaxation that occurs both at the temperature of the first as well as of the second stage of the aging.

TABLE 1

7075 aluminum alloy chemical composition

Content [wt%]						
Zn	Mg	Cr	Si	Mn	Cu	Al.
0,6	0,5	0,23	0,4	0,4	0,6	rest

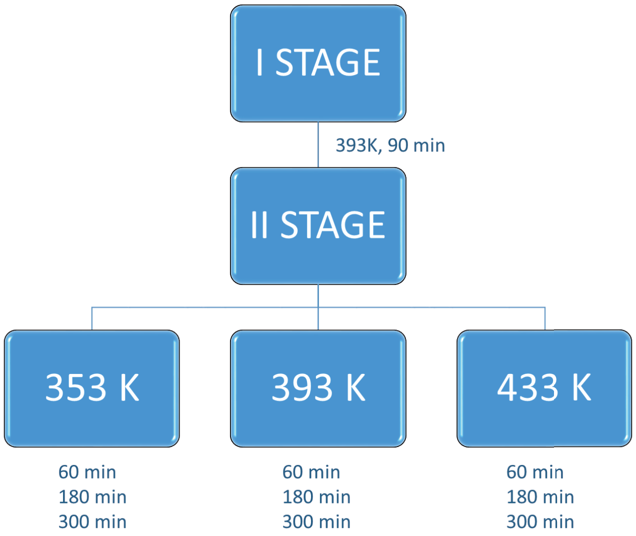

Fig. 1. Two-stage aging of 7075 aluminum alloy

The effect of shot peening on the values of the induced residual stresses and micro hardness distribution in the surface layer (Table 2) was analyzed with regard to the parameters of each of the stages of the T6I6 and T6I4 aging. Thus, the impact of mechanical surface treatment on the kinetics of change in microhardness and residual stresses as a function of the temperature and time of the two-stage aging was investigated first. Next, in order to determine the shot peening induced stress gradient (and its dynamics during the two-stage aging), the samples were subject to surface grinding performed with a 38A60KV grinder at the constant feed speed Vs = 36m/s. The need to eliminate residual stresses introduced in the surface layer in the grinding process required that the following parameters were controlled and analyzed: grinding depth, treated material speed V_w, table axial feed V_{fo}. Three coolants were used:

- Oil mist (aerosol) with propylene glycol MQL/GP [25],
- CA – compressed air,
- D – Dry.

7075 aluminum samples in T0 temper with stress values of 0±15MPa were used to identify the range of parameter values for which actual residual stress values in the surface layer remain unaltered. Based on the test results, the following grinding parameters were determined that do not introduce residual stresses into the surface layer of the sample: a_e =0.02 mm, v_{fo} = 0.5 mm/increment, v_w = 0.2 m/s, coolant – compressed air. Grinding treatment performed to these parameters permits accurate representation of stresses of the shot-peened samples.

TABLE 2

7075 aluminum alloy shot peening parameters

Sample	Shot type	Pressure range, [MPa]	Nozzle distance from sample range, L_d, [mm]
PN-EN 7075-T0	S280	0,4÷0,8	50÷90
	S330		

TABLE 3

7075 aluminum alloy grinding parameters

Grinding depth a_e	Treated material speed v_w	Table axial feed v_{fo}	Cooling medium
0,02mm	0,2m/s	0,5mm/stroke	MQL/GP CA D
0,05mm	0,5m/s	1mm/stroke	

'Alumetal Technik' cast steel shot was used in the tests, fractions S280 (diameter of 0.71mm) and S330 (diameter of 1.0mm), microhardness of 500 HV±40 HV according to ISO 11125-3, and density of 0.7 g/cm^3.

Surface roughness parameters of the shot-peened samples were calculated on the basis of the primary profile of the measured surface. The primary profile was measured with T8000 Hommelwerke profilometer with Turbo Wave 7.35 software in compliance with PN-ISO 4288:1998. The evaluation length l_n of 4 mm consisted of five sampling lengths l_r of 0.8 mm. Measurements were performed at the lowest speed of the stylus probe of 0.05 mm/s and the radius of the stylus tip r_{tip} = 2μm. Residual stress in the strengthened surface layers was examined with the X-ray diffraction technique using the PROTO iXRD diffractometer.

Four measurements, at different locations on the sample surface, were taken for each sample, each measurement at ten x-ray beam incidence angles using both detectors. Residual stress measurements were performed to the following parameters: a chromium anode x-ray tube, $K_{\alpha 1}$ radiation, tube voltage 20kV, tube current 4 mA, Bragg angle 2θ = 156, 31˚ (reflections from the 222 planes), oscillation in beta angle = 3˚, LPA corrections, x-ray beam aperture of 2 mm and a vanadium K-β filter.

The profiles of the obtained diffraction peaks were approximated as a Cauchy function where 100% peak height was assumed. X-ray elastic constants provided in the software database were used: $(1/2)S_2$ = 18.56 E^{-6} [1/MPa] and $-S_1$ = 4.79 E^{-6} [1/MPa].

Zwick hardness tester was used to measure hardness. To ensure the highest accuracy, each measurement was performed five times and the variability of the results was illustrated as error bars.

3. Test results

To determine the effect of the mechanical surface treatment (shot peening) on the kinetics of change in residual stress and microhardness of the surface layer of 7075 aluminum alloy, the samples were pretreated with solution heat treatment in order to achieve a more homogenous structure of the alloy. The annealing was performed in the NeoTherm resistance furnace at the temperature of 773 K for 4 h with subsequent solution heat treatment in water at the temperature of 282 K.

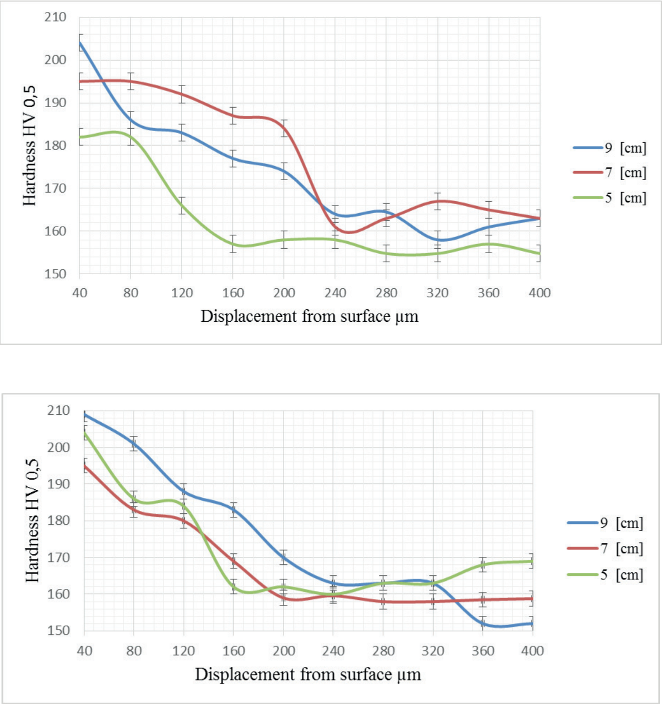

Fig. 2. Microhardness profiles as a function of distance from the surface at constant pressure Pm = 0.6 MPa and variable nozzle distance from the surface (Ld) for shot S280 (a) and S330 (b) respectively

The analysis of the microhardness profile as a function of the distance of the nozzle from the surface of the sample - L_d shows that the highest value of the surface microhardness (210±2 HV 0.05) was obtained for the shot peening treatment where L_d equalled 70 mm regardless of the diameter of the shot used (Fig. 2). However, a comparison of the microhardness profiles achieved for the same values of L_d and process pressure P_m reveals that for the S330 shot the obtained microhardness values were higher than for the S280 shot (Fig. 2).

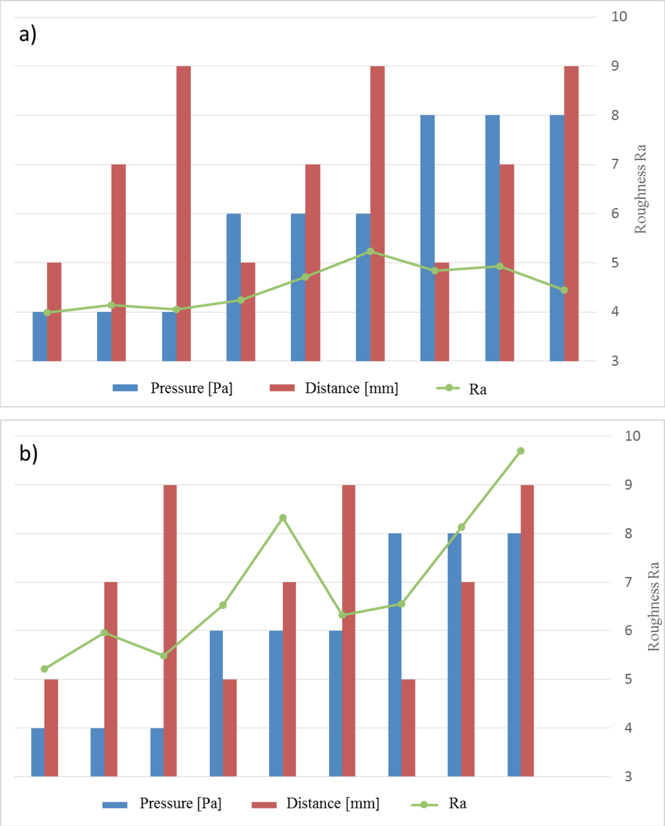

Fig. 3. Changing the value of the roughness as a function of pressure and nozzle distance from the surface for S280 (a) and S330 (b) respectively

Using the shot of the smaller diameter results in higher values of residual stress on the surface of the examined 7075 aluminum alloy. Additionally, within a certain range, the values of the residual stress can be controlled by modifying the distance of the nozzle to the sample surface and the pressure of the shot propelling gas. Furthermore, reduction of the diameter of the shot causes a decrease in the values of the surface roughness R_a of the treated surface (e.g. R_a = 8.32 µm (shot S330) and 4.71 µm (shot S280) respectively, at constant values of P_m = 0.6 and L_d = 70 mm). The highest values of residual stresses in the surface layer were obtained for the S280 shot with the distance of the nozzle from the sample surface L_d = 70 mm regardless of the examined range of the pressure of the process medium. In these cases, the value of residual stress in the surface layers was -230 MPa. The highest residual stress values are observed when the distance of the nozzle from the surface of the sample is 70 mm. It could be attributed to the fact that for distances shorter than 70 mm not only plastic but also elastic impact of the process medium on the sample surface is observed. This phenomenon constrains generation of compressive stresses compared to situations where the distance from the nozzle to the sample is shorter than 70 mm. When, on the other hand, the distance exceeds 70 mm, the energy of the process medium impacting the surface of the sample tends to decrease, which consequently results in reduced plastic deformation (strain) of the surface layer and simultaneously lower values of compressive stresses.

For the sake of comparison, for the S330 shot the stress value of about -170 was recorded for the process parameters

P_m = 0.4 MPa and the distance from the sample surface L_d = 70 mm. This may stem from the relatively lower value of the impact force of individual spheres of the shot on the sample surface due to their greater diameter in comparison to the S280 shot for the same values of the P_m pressure.

Additional analysis of the effect of the type of the process medium on tribological properties confirms that for the shot of smaller diameter the coefficient of friction of the examined sample is 30 % lower compared to the untreated sample surface where μ = 0.50. Obtaining a higher value of the surface microhardness does not reduce the value of the coefficient of friction, which may be attributed to higher surface roughness and lower residual stress.

The next step in the study was to determine the effect of two-stage age hardening on the microhardness profile and residual stresses of the 7075 aluminum alloy samples treated with T6I6 or T6I4 two-stage heat treatment prior to or post the shot peening. To this end, kinetics of changes in residual stresses on the surface of the shot-peened 7075 aluminum alloy samples during the aging treatment was investigated first. The samples were thermo-mechanically treated following one of the three regimes. Each set of the samples was prepared in the following way: annealing at the temperature of 773 K for 4 hours followed by cooling in a furnace. This allowed for the relief of stresses in the entire volume of the sample. The value of stresses in this case was 0 Mps±15 MPa. Next, based on the optimized parameters of two-stage aging [26] which ensure maximum strengthening of the 7075 aluminum alloy substrate, the samples were treated with:

Heat treatment (T6I6 – the first stage of aging at the temperature of 393 K, the second stage at 433 K) followed by mechanical treatment – shot peening, or

1. Mechanical treatment – shot peening, followed by heat treatment (T6I6 or T6I4)
   a. In the first variant, T6I6 aging was performed (the first stage at the temp. of 393 K, the second stage at 433 K),
   b. In the second variant, T6I4 aging was performed (the first stage at the temp. of 393 K, the second stage at 353 K)

Relaxation of compressive stresses is observed during the two-stage age hardening process of the shot-peened samples where the change of the stress values depends on the temperature of the second stage of the aging treatment (Fig. 4). The relaxation is the most intense at the temperature of 433 K, and the least intense at the temperatures within the range of 393 – 393 for the first and the second stage of the aging treatment respectively. Similar dependency is also observed for the microhardness of the tested samples in which case microhardness values increase most dynamically during the aging at the temperature of 433 K (second stage), but remain nearly constant during the thermal treatment at 353 K. However, when the second stage of aging is performed at the temperature of 393 K, the values of microhardness reach their maximum – close to 200±2 HV 0.1. For comparison sake, the maximum value of residual stresses in the surface layer of the tested samples heat treated with T6I6 (I stage – 3939 K, II stage – 433K) and subsequently shot-peened was -226 MPa±5.5 MPa. The microhardness peaked at almost 210±2 HV 0.1.

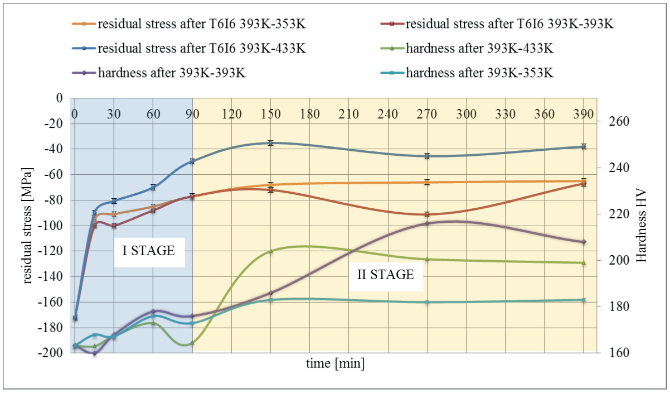

Fig. 4. 7075 aluminum alloy surface residual stress and hardness kinetics after shot peening and subsequent two-stage aging T6I4 or T6I6

The analysis of the microhardness distribution of the shot-peened and T6I6 treated samples for the preset temperature range (I stage – 393 K, II stage – 433 K) did not reveal significant differences in the microhardness of the plastically deformed (strained) surface layer and the core. Most probably, for this temperature range, recrystallization processes in the surface layer played a major role, which led directly to the achievement of similar microhardness values of the surface layer and the core of the examined alloy. Stress relaxation in the tested layer yields additional support to such claim. A number of studies have been conducted on this account in which the temperature of the second stage of aging was lowered to the range of 353 K – 298 K. The highest surface microhardness values were recorded for the temperature of 353 K for the second stage of the aging treatment where after 5 hours of exposure time the microhardness value reached 195±2 HV 0.1 (Fig. 5). This shows that aging treatment of shot-peened samples can be performed without the relaxation of residual stresses and with simultaneous achievement of the maximum value of the surface microhardness of ≈ 200 HV 0.1.

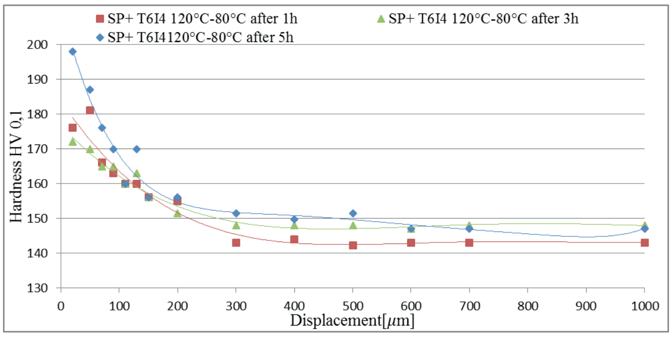

Fig. 5. Microhardness distribution after shot peening and subsequent two-stage aging T6I4

In the further part of the study, two samples were selected for stress gradient measurements. The samples were treated with (in this order):

- Two-stage aging: I stage at 393 K for 1.5 hours and II stage at 393 K for 3 hours, followed by shot peening,
- Shot peening followed by two-stage aging, I stage at 393 K for 1.5 hours and II stage at 353 for 5 hours.

The analysis of the stress gradient measurements clearly shows that high compressive stresses have been introduced at significant depth, which could have been caused by the combination of the thermal and mechanical treatments. In the case of traditional shot peening beneficial compressive stresses are induced at the depth of 0.2 mm. Because the tested samples were additionally heat treated their stresses remained high deep into the material. According to the literature, it is possible to obtain sub-surface stress peaks of 350 MPa, yet it also depends on the type of shot and other process parameters that are subject of further study.

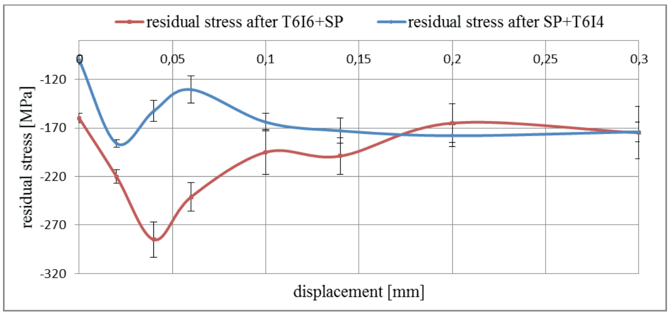

Fig. 6. Stress gradient comparison in 7075 aluminum alloy surface after: (a) T6I6 + shot peening, and (b) shot peening + T6I6, respectively

2. Conclusions

The analysis of the stress gradient reveals that relatively high compressive stresses (about -170 MPa) were introduced at the depth of about 0.15 mm. This fact is a result of the combination of thermal and surface mechanical treatments. The residual stress distribution as a function of the distance from the surface (depth) (Fig. 6) is consistent with the results of tests presented in the literature on the subject [26–28]. The differences in the residual stress values obtained in the foregoing study result from the sequence of the treatments applied. Higher values of stresses in the surface layer were observed when shot peening preceded the two-stage age hardening treatment. Consequently, the stresses induced during the mechanical surface treatment were relieved during the aging processes. It needs to be pointed out however that at the depth exceeding 1.15 mm the stresses remained at nearly the same level for both samples. Furthermore, it bears emphasizing that the stresses in the entire investigated range have a negative value (they are a result of strengthening phase formation in the continuous phase), which is desirable if enhancement of contact fatigue is considered.

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