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INCREASE IN FATIGUE LIFE DURING CYCLIC TORSION OF 6060 T6 AND T64 ALUMINIUM ALLOY SAMPLES AFTER VIBRATORY SHOT PEENING

The paper analyses the influence of strengthening treatment by vibratory shot peening on the fatigue life of samples made of 6060 aluminium alloy. Samples made of material in the T6 and T64 conditions were selected for the analyses. The analysed materials were strengthened using vibratory shot peening for 1 and 10 minutes. Vibration strengthening showed that fatigue life was increased in all cases. For aluminium in the T6 condition, the increase in durability increases with the extension of the strengthening process, and for aluminium in the T64 condition, a short strengthening process results in a significant increase in fatigue life, while further strengthening not only does not improve durability but even worsens it. The fatigue crack surfaces in the analysed cases were also observed and compared. Origin, fatigue cracking zone, and instantaneous zone have been distinguished. This analysis showed that T6/T64 machining and strengthening by 1/10 minute vibratory shot peening have different effects on the fatigue life and the structure of fatigue fractures. It has been shown that the strong strengthening of the plastic aluminium alloy in the T64 condition causes the formation of something like a structural notch on the material's surface.

Keywords: Aluminium alloys; surface strengthening by vibratory shot peening; cyclic torsion fatigue; fracture structure

1. Introduction

Machine elements are often subjectedto variable loads during operation. As a result of operational loads, including cyclic loading of elements, damage occurs, most often in the form of cracks, which can spread, causing failure or even a catastrophe. There are various methods to increase fatigue life by appropriate treatment [1,2]. These treatments include: roller burnishing, ballizing, coining, mandrelizing, split or solid sleeve cold expansion, bushing cold expansion, applied expansion and others. Burnishing (B) and shot peening (SP) are among the processing methods that increase the fatigue strength of machine elements. Typical components requiring high fatigue strength, treated with shot peening and ball burnishing include gears [3], fan blades [4] and ship shafts [5]. It is known that changes in the stereometric properties of the surface layer, hardening of the surface layer, and compressive residual stresses resulting from ball burnishingor shot peening affect the fatigue strength [6]. The wide use of vibratory shot peening was noticed, among others, in [7], where, based on [8], it was shown that the fatigue life for cyclic bending after such treatment can increase by up to 1900%, i.e. as much as 19 times.

The paper [9] showed that the residual stress state resulting from low plasticity burnishing (LPB) of samples from the Al 7075-T6 alloy increases fatigue life by 20% to 70%. Aviles et al. [10] proved that the fatigue limit for DIN 34CrNiMo6 alloy steel samples was 52% higher after low-plasticity burnishing compared to samples after machining and mirror-polishing. Slide burnishing of shafts made of X19NiCrMo4 increases fatigue strength by 28.5% compared to unburnished samples [11]. Research [5] showed that elements with burnished surfaces have a 30% higher fatigue strength in a seawater environment than ground elements. The introduction of ultrasound into the burnishing process (Ultrasonic assisted (UA) burnishing process was used) resulted in an increase in the fatigue life of elements made of the Al 7075-T6 alloy by 32% compared to conventional burnishing [12]. Using sliding burnishing, optimal machining conditions the 2024-T3 aluminium alloy increase the fatigue limit to 250 MPa, considering the maximum high-cycle fatigue (HCF) performance criterion [13]. However, in work [14], a 116% increase in the fatigue life of samples from the AA-7075-T6 aluminium alloy was obtained after the roller burnishing process. The significant increase in fatigue life should be explained by the limited propagation of fatigue cracks, which results from reduced

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surface roughness, high hardening by work hardening and the induction of compressive residual stresses in the surface layer.

Shot peening technology also positively affects the fatigue life of treated components. Using shot peening for DIN 34CrNiMo6 steel samples after tempering and hardening increased the fatigue limit by 21.8% compared to the value obtained after polishing [15]. Also, the fatigue strength of the self-piercing riveting joint of AA5052-H32 aluminium alloy sheets increases by 9.2% after using SP [16]. After shot peening, a slightly greater fatigue limit (13%) was obtained with rotary bending SX single crystal alloy [17]. However, the paper [18] noted that the re-shot peening process has a greater impact on the low-cycle fatigue performance. Bycomparison, severe shot peening has a greater impact on the high-cycle fatigue performance of AISI 1050 steel. Ferreira et al. [19], however, noticed that the use of shot peening elements of different dimensions and made of different materials during shot peening does not result in a significant improvement in the fatigue life of samples made of Al 7475-T7351 aluminium alloy subjected to three-point bending (3 PB). Beneficial changes in fatigue life can only be noticed when using small glass beads. In the case of fatigue life, the values determined in the tensile test are higher than in unprocessed samples [19]. For AA 6005-T6 aluminium alloy samples subjected to rotational bending tests at room temperature, it was also possible to improve the fatigue strength by shot peening in relation to the value after grinding [20]. More favourable fatigue properties were obtained by shot peening for severe conditions (the source of the crack was moved below the surface).

Vibratory shot peening (VSP) is one of the varieties of shot peening (SP). During VSP, the workpieces are mounted in the working chamber along with peening elements that affect the workpiece through the vibrations of the chamber. During vibratory shot peening, the entire surface is treated simultaneously. This technology allows the processing of rotating and non-rotating objects with complex shapes, both larger and smaller. The advantagesof vibratory shot peening include the possibility of obtaining a lower surface roughness compared to shot peening [21], which limits the formation of microcracks on the treated surface, as well as inducing compressive residual stresses that penetrate deeper than those generated by SP [21]. Tribological properties are also improved [22]. The favourable properties of the surface layer after VSP, primarily the state of residual stresses, allow for improved fatigue performance [23,24]. The results from the work [25] showed that using vibration finishing after shot peening increased the fatigue limit both at room and elevated temperatures. Favourable changes, over 3.5 times increase in fatigue life in relation to ground samples, were obtained after vibratory and rotational shot peening of elements made of C45 steel [26].

As a result of the strengthening treatment, significant compressive stress is created under the material's surface. For the 2618-T61 aluminum alloy, the additional compressive stress reaches approximately 400 MPa [27]. As a result, such compressive stress increases fatigue life. The beneficial effect of compressive residual stresses was also confirmed in [28]. The authors of [28] noticed that the compressive stress field and grain refinement delay crack initiation and partially slow down crack propagation in the first stage of fatigue damage of AW 7075 aluminum alloy components subjected to shot peening. For metals, in the case of additional tensile stress, the fatigue life decreases, as shown in many works, such as one of the latest works on the research of aluminum alloy 2618A-T61 [29]. In the case of cyclic torsion, the influence of the average value on the torsion is smaller. The situation is different in the case of additional compressive stress. Here, fewer fatigue tests have been performed, and the situation is not fully resolved. However, fatigue strength certainly increases to some extent. Of course, it should be remembered that under very high stress, destruction occurs by compression. In the case of cyclic torsion, there is no additional negative value of shear stress. However, we can talk about additional compressive value for cyclic torsion. Here, additional compression causes a slight increase in fatigue life. However, in this case, such a comparison can be found only in one work, as presented in detail by Sines [30].

All methods proposed in the literature for increasing fatigue life by surface treatment include introducing additional compressive stress, positively affecting fatigue life. The cyclic torsion of layers with higher fatigue strength may be relatively small due to the significant stress gradient in the case of twisting. Since aluminum alloys are relatively soft, reinforcement by shot peening is a relatively simple technological procedure.The literature review shows that it is possible to increase the fatigue strength of machine elements thanks to ball burnishingand shot peening. Objects made of aluminium alloys are also processed in this way. However, no studies have been found in the literature that show the influence of vibratory shot peening on the fatigue life of elements made of this material. Additionally, increasing strength through strengthening treatments is generally used for elements subjected to loads in the form of cyclic tension-compression. This work analyzed the effect of vibratory shot peening for cyclic torsion loading. As a result, the impact of creating additional subsurface compressive stress on cyclic torsion is analyzed, which is an unknown phenomenon in the fatigue process. Therefore, it seems justified to undertake such work. The research aimed to assess the influence of vibratory shot peening parameters of elements made of 6060 aluminium alloy in T6 and T64 conditions on the fatigue life after cyclic torsion.

2. Experimental research

2.1. Material

The popular aluminium alloy 6060, commonly used in producing various structures, was used for the tests. Other designations of this material are PA38, AlMgSi, AlMgSi0.5, 3.3206. Apart from aluminium, this aluminium alloy contains alloy components, mainly Mg (0.35-0.60)% and Si (0.30-0.60)%.

TABLE 1 presents the chemical composition of the tested AA6060 aluminum alloy based on the normative documentation and the manufacturer's profile certificates. Additionally, an

TABLE 1

Chemical composition of aluminum alloy 6060

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Other
EN 573-1:2004		**0.30÷0.60**	**0.10÷0.30**	**<0.10**	**<0.10**	**0.35÷0.60**	**<0.05**	**<0.15**	**<0.10**	**The rest**	**<0.05**
T6	Certyfication	0.63	0.22	0.15	0.17	0.45	0.01	0.01	0.02	The rest	0.01
	Measurement	0.41	0.21	0.03	0.05	0.50	0.001	0.04	0.02	98.99	0.04
T64	Certification	0.45	0.21	0.02	0.05	0.39	0.00	0.01	0.01	The rest	0.01
	Measurement	0.38	0.19	<0.002	0.02	0.41	<0.002	<0.005	0.02	98.92	0.03

independent chemical composition analysis was performed using the MiniLab 300 spark discharge optical emission spectrometer manufactured by the Italian company Analytical Instruments Group. Five measurements (burns) were performed for each of the analyzed samples, and the values presented in the tables are the arithmetic mean of the obtained results. The analysis of the obtained chemical composition indicates compliance with the normative requirements for the AA6060 alloy. Only in the case of the sample in the T6 condition was a slightly increased content of Cu and Si elements noted by the manufacturer's certificate. However, the measurements we carried out did not confirm this deviation.

This material is used, for example, to produce window and door frames installed in trains. An example profile used in the train structure is shown in Fig. 1, while Fig. 2 shows a window frame made of the aluminium alloy tested in this work. For the tests and analyses, the 6060 aluminum alloy was selected because this alloy in two conditions (T6 and T64) is most often used for the production of windows and doors installed in trains. The selection of the condition depends on whether the profiles are later subjected to strong plastic processing by bending or not. All methods proposed in the literature for increasing fatigue life by surface treatment includeintroducing additional compressive stress, which positively affects fatigue life. The cyclic twisting of layers with higher fatigue strength may be relatively small due to the significant stress gradient in the case of twisting. Sincealuminum alloys are relatively soft, reinforcement by shot peening is a straightforward technological procedure. The material for experimental research and analysis was obtained directly from the trainprofiles. It was used to producediabolo specimensrequiredfor fatigue tests on a test stand for proportional cyclic bending with torsion, as described in detail, among others, in [31]. The work [32] presents the fatigue tests of an aluminium alloy in the T6 and T64 states. The T6 treatment involves solution heat treatment followed by artificial aging, resulting in maximum strength and hardness. The T64 treatment also includes solution heat treatment at the same temperature, but the artificial aging is performed at a lower temperature, between the aging conditions for T6 and T61. This adjustment allows for improved formability while maintaining good strength, offering a better balance between strength and ductility than T6.As a result, we obtain a material that is easily plasticised but has lower strength than the material in the T6 state, obtained through artificial aging after solution heat treatment. **T6 treatment involves Solution Heat Treatment at a temperature of 530-550°C for 1-2 hours.**

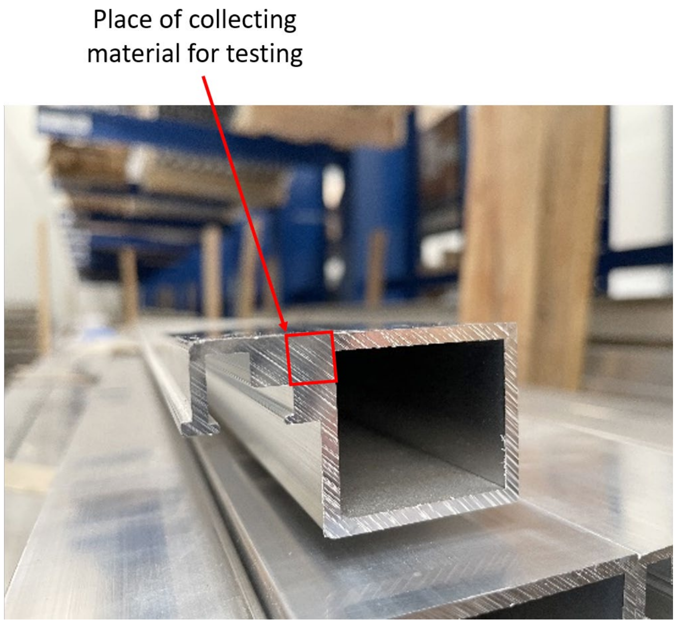

Fig. 1. An example profile made of aluminium alloy

Fig. 2. The window frame is made of tested aluminium alloy

Heat treatment in the T6 condition for the AA6060 aluminum alloy involves a two-stage process. In the first stage, Solution Heat Treatment is carried out, consisting of heating the charge to a temperature of 530-550°C and soaking for 1-2 hours. Then, rapid cooling in water is carried out to retain the alloying elements (mainly Mg and Si) in a supersaturated state before they can precipitate from the solid solution. In the second stage, Artificial Aging is used at a temperature of 160-180°C for about 6 hours. The purpose of this process is the controlled precipitation of fine particles of the Mg_2Si phase, which leads to a significant increase in the hardness and mechanical strength of the alloy.

In the case of T64 heat treatment, the first stage – solution annealing – is carried out in a similar way to the T6 state. The second stage of T64 treatment consists of a two-stage aging process: initially, Natural Aging is carried out for at least 24 hours, which allows the structure of the supersaturated solution to fully develop. Then, artificial ageing is applied in Artificial Underaging conditions at a temperature of 155-175°C for 1-3 hours. The aim is to limit the precipitation of the Mg_2Si phase, which allows for increased plasticity of the material at the cost of slightly reduced mechanical strength.

The tests carried out included cyclic torsion. After cutting in accordance with the desired dimensions and surface roughness, the samples tested in this work were not subjected to any additional processing.

2.2. Surface treatment by vibratory shot peening

The vibratory shot peening (VSP) process was performed on a mechanical-kinematic vibrator with a working chamber. Diabolo samples with a diameter of $d = 10$ mm made of AW-6060 aluminium alloy in T6 and T64 condition were attached to the bottom of the working chamber. The working chamber was filled with steel balls – the so-called 'batch'. The input was 1/3 of the height of the working chamber. Shot peening balls with a diameter of $d_k = 6$ mm made of 100Cr6 bearing steel were used for vibratory shot peening. The following technological parameters of vibratory shot peening were used:

– vibration frequency $v = 2100$ 1/min,
– vibration amplitude $a = 5$ mm,
– vibratory shot peening time $t = 1$ min and $t = 10$ min.

Fig. 3 shows a view of the workstation, the working chamber, and the technological parameter vibratory shot peening.

2.3. Fatigue tests

Samples after vibratory shot peening were subjected to fatigue tests. The cyclic torsion test was selected as the fatigue test for analysis. In this case, the possibility of initiating fatigue cracking is located around the entire circumference of the critical cross-section, i.e. in the largest narrowing of the sample. The shear stress amplitude from torsion was chosen to select the load level. TABLE 2 summarises the results of cyclic torsion tests for samples in both states – T6 and T64.

TABLE 2

Results of fatigue tests of aluminium alloy 6060 – T6 and T64 – torsion

Aluminium alloy 6060 – T6		**Aluminium alloy 6060 – T64**	
τ_a, **MPa**	N_f, **cycles**	τ_a, **MPa**	N_f, **cycles**
122	98274	61	2000000
102	275813	122	8474
112	124454	92	487900
92	275617	82	668644
92	1349027	71	11004386
112	227693	102	15140
97	728827	112	3700
107	260929	82	562587
87	1740012	92	68884
117	24122	102	66960
127	40889	112	19109
132	31439	122	6201
143	19874		
82	1295223		
153	10560		
148	17413		

Based on the ASTM standard [33], Basquinfatigue characteristics were determined for cyclic torsion, respectively T6 treatment,

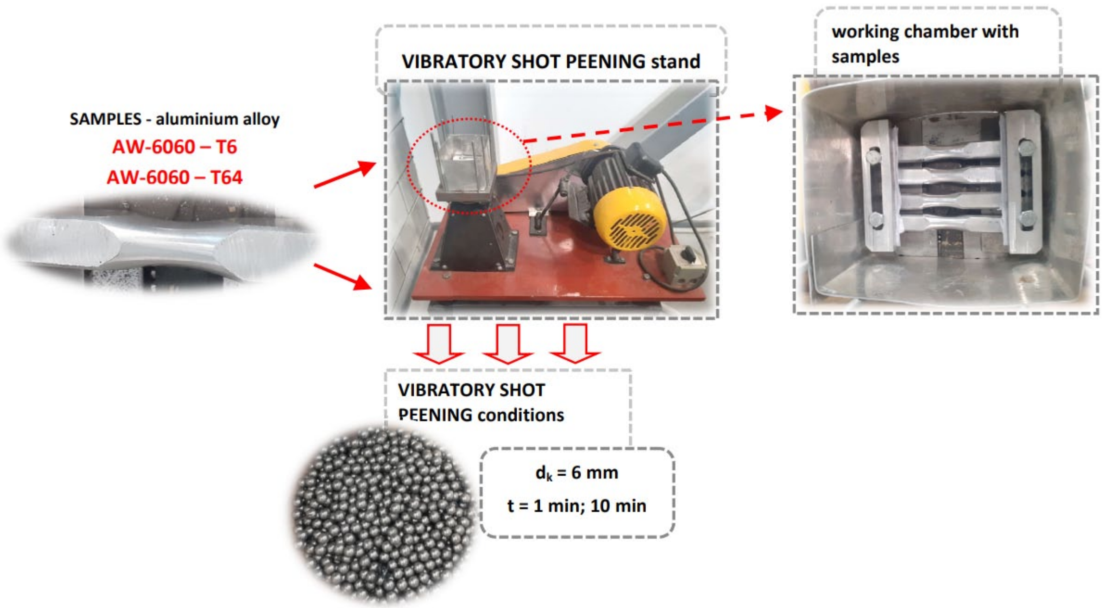

Fig. 3. Vibration shot peenedamplification process

$$\tau_a = 440.21(2N_f)^{-0.109} \quad (1)$$

and T64 treatment

$$\tau_a = 243.42(2N_f)^{-0.078} \quad (2)$$

Characteristics (1) and (2) are taken from earlier paper [32].

In the experimental studies, the given amplitude τ_a for the T6 and T64 conditions was taken from fatigue characteristics (1) and (2), respectively, for the life of 100,000 cycles without strengthening treatment. These amplitudes are different for the different T6 and T64 conditions.

3. Research results and their analysis

TABLE 3 shows the results of the fatigue life of samples made of 6060 aluminium alloy in the T6 condition with the expected fatigue life of 100,000 cycles according to characteristic (1) with a torque amplitude of 22.37 N·m, which corresponds to the stress amplitude τ_a = 116.37 MPa, for variousconditions of vibratory shot peening. As observed, strengthening the samples' surface significantly influenced the material's fatigue life. Just 1 minute of vibratory shot peening improved the fatigue life of the material by 2.2 times. In turn, treatment lasting 10 minutes increased the average number of cycles to failure by almost 5 times. It can be concluded from this that 1 minute of strengthening the material improved its fatigue strength significantly, and further surface treatment improved the material properties, but not to such a significant extent. The mean fatigue life values are given as geometric due to the logarithmic nature of the fatigue phenomenon.

TABLE 3

The fatigue life of samples made of 6060-T6 aluminium alloy at torsion amplitude 22.37 N·m

Sample number	Surface treatment	Number of cycles to failure, N_f	The mean value of the number of cycles to failure, N_f
E1	—	104100	
E2	—	51800	
E3	—	48500	86861
E4	—	137000	
E5	—	138000	
A1	1 minute	281200	
A2	1 minute	180900	220552
A3	1minute	210900	
B1	10 minutes	475151	
B2	10 minutes	295700	479741
B3	10 minutes	785845	

Figs. 4-6 show representative fractures of samples of 6060 aluminium alloy in the T6 condition, successively without any surface strengthening and aftervibratory shot peening lasting 1 minute and 10 minutes.

Fig. 4, showing the fracture of a sample made of the 6060-T6 aluminium alloy without strengthening treatment and subjected to cyclic torsion, is a classic example of fatigue fracture. There is a distinct fatigue zone (where slow fracture occurs) and an instantaneous zone, also called an overload zone (where fast fracture occurs). The origin of the fatigue crack initiated within the fatigue zone is also visible. The progression marks, alsocalled beach marks, appear as a result of subsequent cycles and can also be observed. Their visibility with the naked eye is characteristic of aluminium alloys.

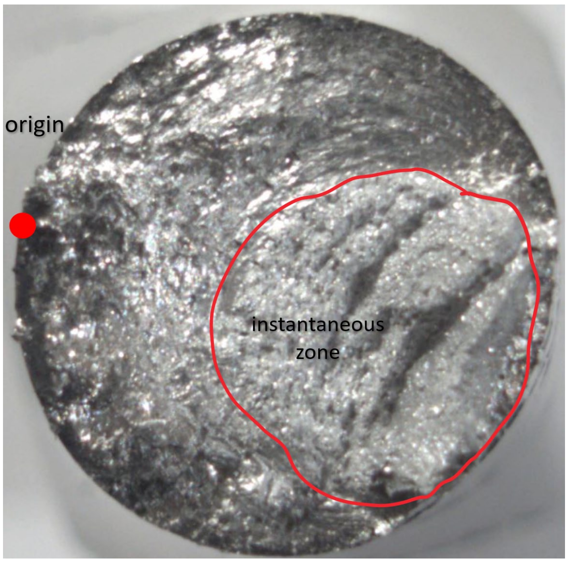

Fig. 4. Fracture of a sample made of 6060-T6 aluminium alloy without strengthening treatment and subjected to cyclic torsion (sample E1)

Fig. 5, showing the fracture of a sample made of 6060-T6 aluminium alloy after vibratory shot peening for 1 minute and subjected to cyclic torsion, reveals the fracture surface very similar to thatof the unprocessed sample. It shows instantaneous zone, fatigue zone, and single origin, as well as visible progres-

Fig. 5. Fracture of a sample made of 6060-T6 aluminium alloy after vibratory shot peening for 1 minute and subjected to cyclic torsion (sample A3)

sion marks. However, a significant difference was noticed – in addition, plastic deformation of the sample occurred near the fracture zone. In contrast to Fig. 4, an ideal circular cross-section is not observed, but a locally flattened one, resulting from plastic elongation in this area.

Another surface, presented in Fig. 6, is the fracture of a sample made of the 6060-T6 aluminium alloy after vibratory shot peening for 10 minutes and subjected to cyclic torsion. Unlike the unprocessed and shot peened sample for 1 minute, not one but two origins can be distinguished here. In this way, two fatigue zones can be distinguished; on one side, they are separated by a breakdown zone, and on the other, a ratchet mark is observed. The occurrence of more than one origin is usually associated with the occurrence of high stress or high-stress concentrations. Because, regardless of the peening time, the torsion with which the samples were loaded was constant, it can be assumed that local high-stress concentrations occurred in this case. At the same time, based on the shape and surface of the fracture, it was observed that the origin described as origin 1 was probably the primary origin.

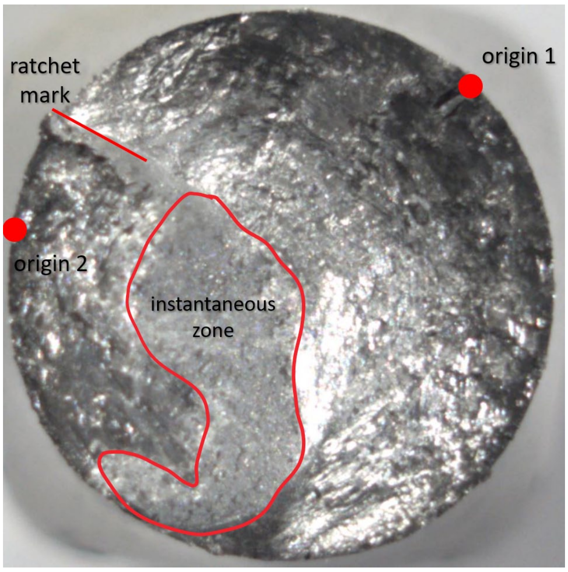

Fig. 6. Fracture of a sample made of 6060-T6 aluminium alloy after vibratory shot peening for 10 minutes and subjected to cyclic torsion (sample B3)

The second type of material tested was also 6060 aluminium alloy, but this time in T64 condition. TABLE 4 shows the results of the fatigue life of samples made of aluminium alloy 6060-T64 with a torsion amplitude of 22.37 N·m, corresponding to the amplitude of τ_a = 93.95 MPa. The load amplitudes in this case, as for the T6 condition, correspond to a durability of 100,000 cycles according to the fatigue characteristics (2). As in the case of the previous group of samples, there were also unprocessed samples, and vibration peened for 1 minute and 10 minutes. In the case of peening lasting 1 minute, the fatigue life increased more than 8 times. In turn, in the case of 10-minute vibratory peening, the average fatigue life was only less than 2.5 times higher than that of unprocessed samples. This means that although 1 minute of treatment improved the fatigue life significantly, subsequent minutes of surface treatment did not continue this effect and even worsened the result. Figs. 7-9 show representative fractures corresponding to subsequent samples with different degrees of surface processing.

TABLE 4

The fatigue life of samples made of 6060-T64 aluminium alloy at torsion amplitude 22.37 N·m

Sample number	Surface treatment	Number of cycles to failure, N_f	The mean value of the number of cycles to failure, N_f
F1	—	42230	
F2	—	19900	
F3	—	271200	107807
F4	—	228200	
F5	—	280000	
C1	1 minute	1179477	
C2	1 minute	973100	836184
C3	1minute	509400	
D1	10 minutes	240400	
D2	10 minutes	611500	248113
D3	10 minutes	103900	

Fig. 7 shows the fracture of a sample made of 6060-T64 aluminium alloy without surface treatment and subjected to cyclic torsion. Unlike the analogous sample for the T6 aluminium alloy, two origins can be distinguished. However, between these origins, there was not a ratchet mark but a height difference, because 2 fatigue fractures occurred in two planes.

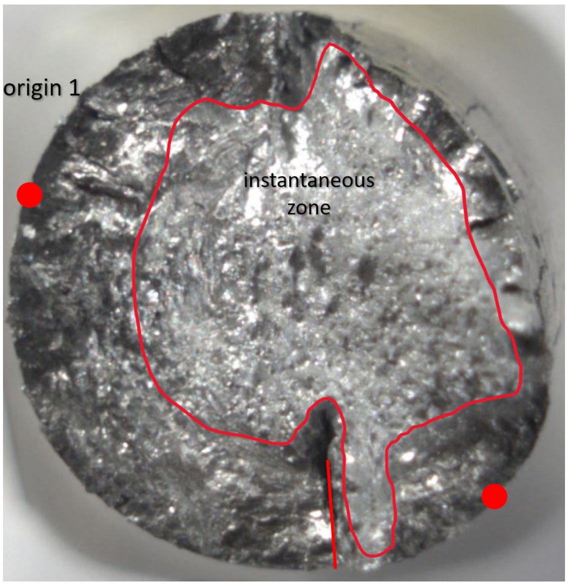

Fig. 7. Fracture of a sample made of 6060-T64 aluminium alloy without cyclic torsion treatment (sample F3)

Fig. 8 shows the fracture of a 6060-T64 aluminium alloy sample after 1 minute of vibratory shot peening and subjected to cyclic torsion, and is analogous to Fig. 5, which shows the fracture of a sample in the T6 condition, processed in the same way. In this case, the fracture surface also exhibits fatigue zones, instantaneous zones, a single origin, visible progression marks, and local plastic elongation at the instantaneous zone.

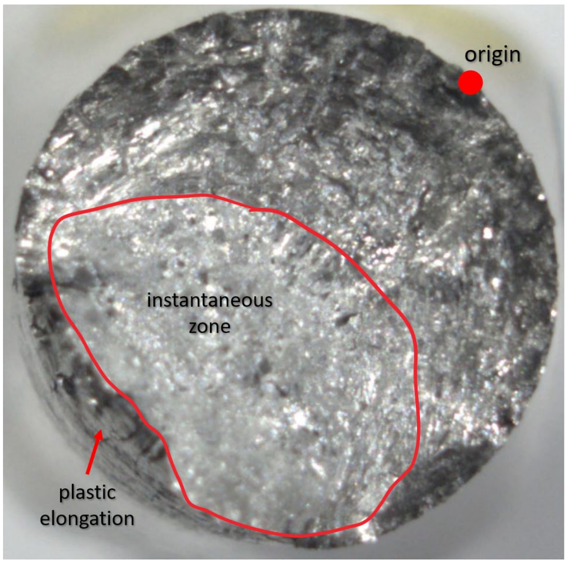

Fig. 8. Fracture of a sample made of 6060-T64 aluminium alloy after vibratory shot peening for 1 minute and subjected to cyclic torsion (sample C3)

Fig. 9 shows three different fractures of a sample made of aluminium alloy 6060-T64 after vibratory shot peening for 10 minutes and subjected to cyclic torsion. Part a) shows a fracture in which there is a single origin and local plastic elongation – similar to the shot peening time of 1 minute. In turn, part b) is a case in which the fracture zone was located in the very centre of the sample. At the same time, many origins can be distinguished on its periphery, and each of the fatigue zones that initiated these origins is separated from the neighbouring one by a ratchet mark. This fracture indicates the occurrence of many stress concentrations. It is even difficult to identify which origin was the primary origin. Similar fractures occur for samples with notches, which can be interpreted here as a situation in which the surface is strengthened, but the unreinforced part inside the sample structure behaves like a notch. Also noteworthy is the fracture of the sample shown in part c). It is possible to distinguish the main fatigue fracture (the upper part of the sample), along with a single origin (described as origin 1), an instantaneous zone, and, similarly to part b), multiple origins indicating local stress concentration.

From the data analysis, it can be seen that the vibratory shot peening of samples made of aluminium alloy, after prior rotation in the T6 and T64 temper, increases the fatigue life.

ANOVA showed that for the 6060-T6 aluminum alloy tests (TABLE 3), considering three different groups and the logarithmic scale of durability, the F value was 13.81, yielding a p-value of 0.0025. This indicates significant differences between the groups with a probability of less than 5%. Conversely, a similar analysis for the 6060-T64 aluminum alloy tests (TABLE 4) gave an F value of 3.93, resulting in a p-value of 0.06447. These calculations indicate no significant difference between the groups at a 5% probability. However, at a more lenient probability of

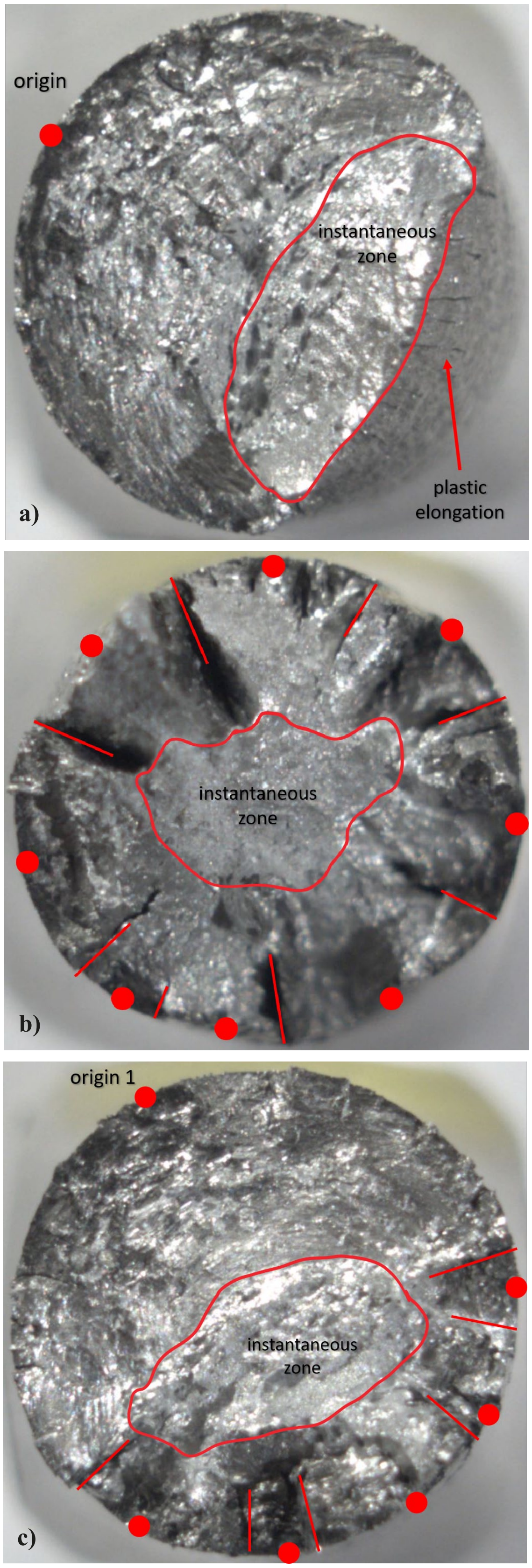

Fig. 9. Fracture of a sample made of 6060-T64 aluminium alloy after vibratory shot peening for 10 minutes and subjected to cyclic torsion (samples: a) D1 b) D3 c) D2)

7.5% (often used in fatigue analysis, for example, in the study of welded joints), differences between the groups can be observed.

In Fig. 10 the nominal fatigue characteristics for the T64 and T6 states are summarized along with the experimental points after the strengthening treatment. The marked Basquin fatigue characteristics are in accordance with equations (1) and (2).

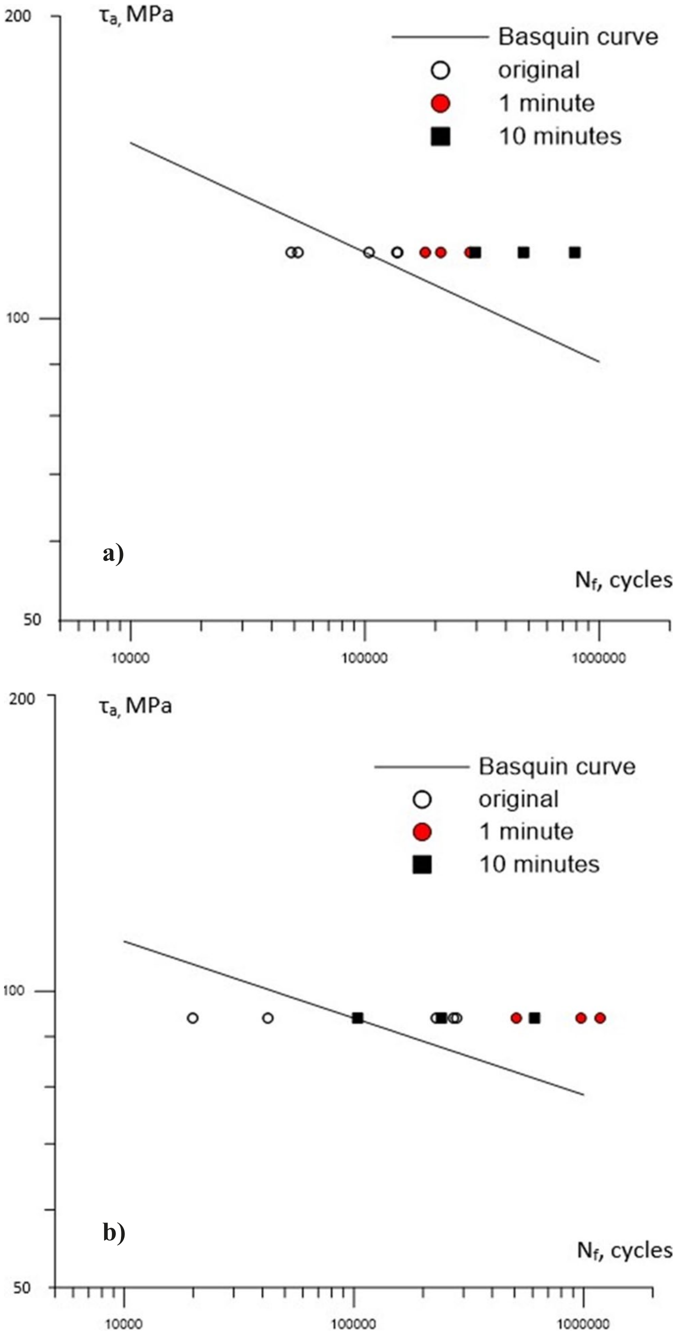

Fig. 10. Summary of nominal fatigue characteristics for cyclic torsion along with experimental points when strengthened by vibratory shot peening: a) T6, b) T64

After determining the average fatigue lives for individual tests (without treatment, 1 minute and 10 minutes) and 'nominal' (calculated based on the fatigue characteristics – marked in Fig. 11 with a full symbol), for the T6 and T64 states, they were determined, respectively, according to formulas (1) and (2), shear stress equivalent amplitudes, as shown in Fig. 11. From the analysis of the figure, it can be seen that, in terms of fatigue life, there is a decrease in the equivalent amplitude that is favourable for the 1-minute treatment, followed by a further decrease for the T6 condition and an increase for the T64 condition for 10 minutes. The increase for the T64 condition does not ultimately exceed the nominal shear stress amplitude.

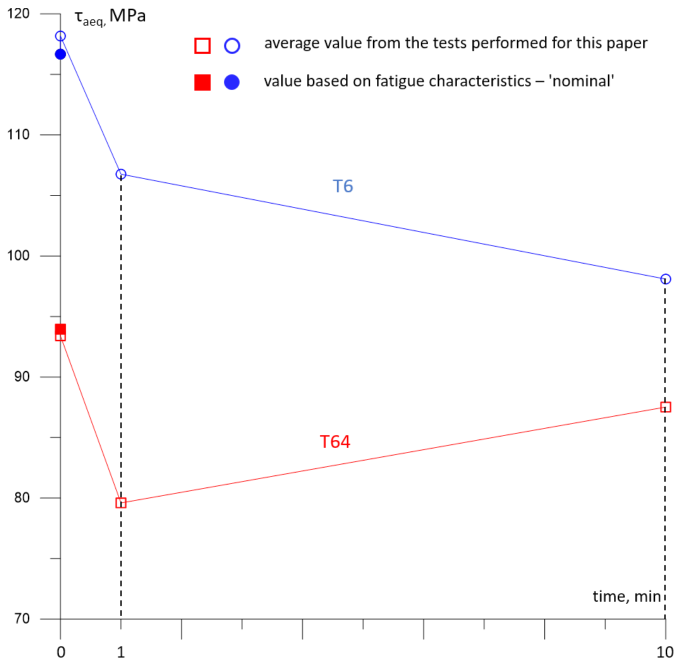

Fig. 11. Summary of equivalent shear stress amplitudes for states T6 and T64 for unprocessed samples and after 1 and 10 minutes of processing

Various phenomena occur during the process of surface strengthening by vibratory shot peening. Among other things, there is a change in surface hardness and roughness. Micro-hardness measurements were performed using SIOM semi-automatic microhardness tester. Hardness measurements were made on the circumference of the sample 4 times every 90 and carried out with a load of 200 g. As a result, the hardnesses corresponding to individual samples were determined and summarized for the T6 and T64 states, respectively, in Fig. 12a and 13a. However, Fig. 12b and 12c show the average values for individual types of starting samples Ei, Fi, after 1 minute Ai, Ci, and after 10 minutes Bi, Di. Analyzing the measurement results, it can be noticed that individual measurements are characterized by similar, slight scatters of approximately 5%. From the analysis of the obtained microhardnesses, it can be concluded that in the case of the T6 state, the hardnesses are always higher than for the plastic material in the T64 state. These are microhardnesses of 95.60 and 73.64 for the initial state, respectively. However, the peening process itself slightly increases the hardness. The highest level is for T6 when shot peening for 1 minute. It is worth noting here that there is a slight decrease in microhardness with the same peening time for steel T64. At the same time, as shown in Fig. 10b, the greatest increase in durability was achieved through the shot peening process.

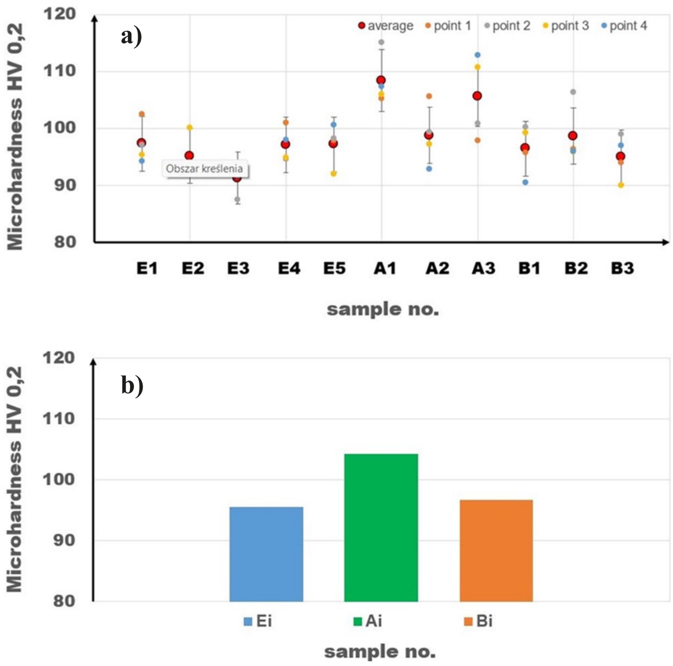

Fig. 12. Summary of $HV_{0.2}$ microhardness for samples made of 6060-T6 aluminum alloy: a) individual samples, b) average values of samples without reinforcement after 1 minute and 10 minutes

Fig. 13 presents the relationship between HV hardness and fatigue life. For the states T6 and T64, respectively, this relationship can be written as a linear function (fatigue life in logarithms) as

$$HV_{0.2} = 1.482 \cdot \ln(N_f) + 77.91 \quad (3)$$

$$HV_{0.2} = 7.296 \cdot \ln(N_f) + -22.39 \quad (4)$$

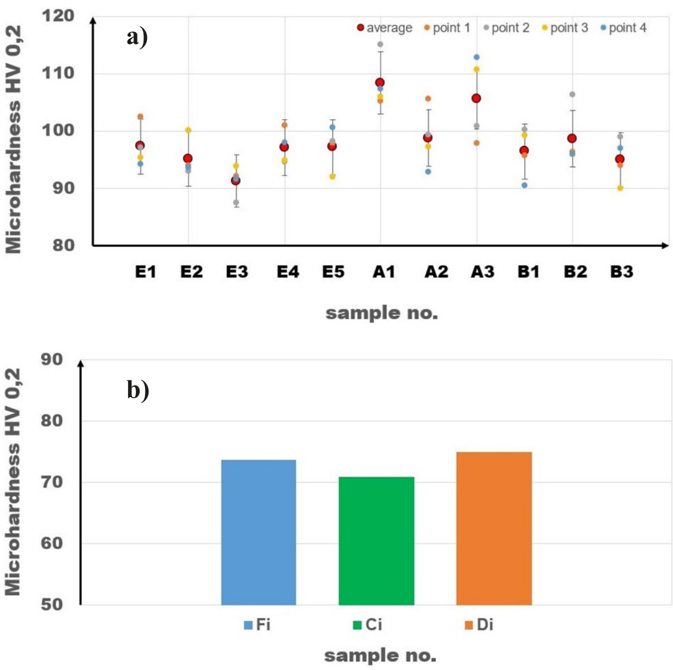

Fig. 13. Summary of $HV_{0.2}$ microhardness for samples made of 6060-T64 aluminum alloy: a) individual samples, b) average values of samples without reinforcement after 1 minute and 10 minutes

The analysis of Fig. 13 and formulas (3) and (4) shows that the higher the hardness, the greater the fatigue life.

In addition to microhardness measurements, roughness measurements were performed. The measurement was performed using the contact method, using the T8000 RC120-400 device from Hommel-Etamic. The length of the elementary section is 0.8 mm, and the measuring section is 4.8 mm. As a result of the roughness measurements, the amplitude (*Ra* – arithmetical mean deviation), height (*Rt* – total height of profile, *Rz* – highest roughness profile height, *Rp* – maximum peak height of profile, and *Rv* – maximum pit height of profile) parameters were determined. The results of these measurements are summarized in TABLE 5. It turns out that T64 thermal treatment always gives higher roughness than T6, with an increase ofapproximately 2-3 times. Moreover, it can be observedthat surface treatment by shot peening increases the roughness parameters to a similar level regardless of the previous thermal treatment T6 and T64. Numerous studies on the influence of roughness on fatigue life (e.g. [34]) show that an increase in roughness reduces fatigue life. Therefore, it canbe assumed that additional surface treatment, e.g., by grinding, would result in a greater increase in fatigue life than indicated by the results of this work presented in TABLES 3 and 4 and Fig. 10.

TABLE 5

Average results of roughness measurements for individual processing states and strengthening time

Treatment	Type of samples	*Ra*, µm	*Rt*, µm	*Rz*, µm	*Rp*, µm	*Rv*, µm
T6	Ei	0.36	1.99	1.25	0.34	0.91
	Ai	0.99	7.82	5.42	2.16	3.26
	Bi	0.95	6.64	5.19	1.97	3.06
T64	Fi	0.50	4.33	3.35	1.11	2.25
	Ci	1.03	7.11	5.13	2.22	2.91
	Di	1.04	7.57	5.17	2.23	2.99

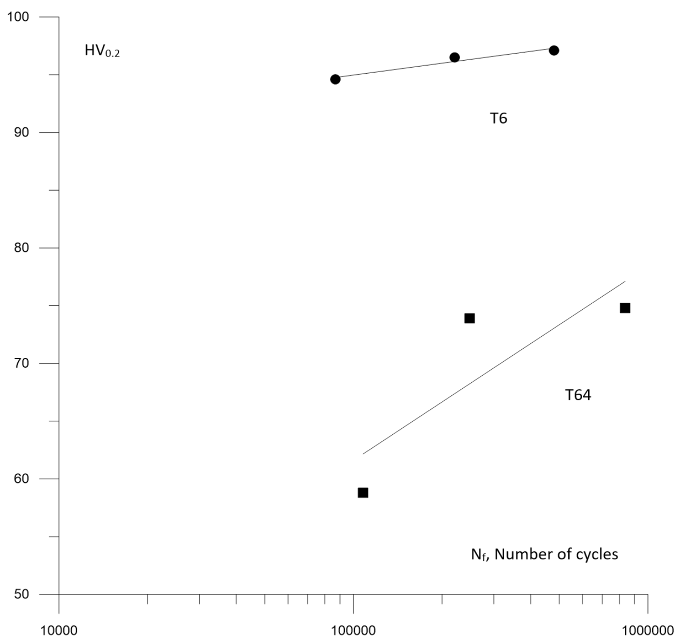

Fig. 14. Relationship between HV0.2 hardness and fatigue life

4. Conclusions

The analysis of fatigue tests after vibratory shot peening showed different effects of strengthening time on samples made of 6060 aluminium alloy in T6 and T64 treatments. In all cases, it was proven that surface strengthening by vibratory shot peening improved the fatigue life of the materials. This is visible in the graphs presented in Fig. 10, where all points reflecting the lifetime of the material after processing are above the Basquin curve. The exact conclusions from the conducted research can be synthesised in several points:

1. For the T6 condition, 1 minute of vibratory shot peening improved the fatigue life of the material by 2.2 times. In turn, treatment lasting 10 minutes increased the average number of cycles to failure by almost 5 times.These effects were observed under the specific vibratory shot peening amplitudes applied in this study and may be representative for similar conditions.
2. For the T64 condition, in the case of vibratory shot peening lasting 1 minute, the fatigue life increased more than 8 times. In turn, in the case of 10-minute vibratory peening, the average fatigue life was only less than 2.5 times higher than that of unprocessed samples.Such results, although encouraging, are currently confirmed only for the specific treatment parameters used in this research.
3. Generally, the structure of fractures for samples in the T6 and T64 conditions without and after strengthening for 1 and 10 minutes is characterised by 1 or 2 origins on the surface. However, in the case of an aluminium alloy in the T64 condition and processed for 10 minutes, the material on the surface was deformed. The surface has the nature of a structural notch with many origins.
4. The values of shear equivalent amplitudes are reduced by applying a surface strengthening treatment with a duration of 1 minute. There is a further decrease for the T6 condition and an increase for the T64 condition in the case of 10 minutes of treatment, but these values do not exceed the nominal shear stress amplitude. Reducing the values of tangent equivalent amplitudes is a beneficial phenomenon from the point of view of fatigue life.However, this tendency has been observed only within the range of amplitudes and durations tested.
5. In the case of the T6 condition, the hardnesses are always higher than for the plastic material in the T64 condition. These are microhardnesses of 95.60 and 73.64 for the initial state, respectively. However, the peening process itself slightly increases the hardness. There is a slight decrease in microhardness at a shot peening time of 1 minute for the T64 condition. At the same time, in this case, the greatest increase in durability was achieved in the shot peening process.
6. After manufacturing components from 6060 aluminum alloys, it is recommended to shot peening these components in order to increase fatigue life.This recommendation is based on experimental results and is particularly justified under conditions similar to those analysed in this study.
7. Based on roughness measurements, specifically the amplitude parameter (*Ra*) and height parameters (*Rt*, *Rz*, *Rp*, and *Rv*), it can be seen that T64 thermal treatment always gives higher roughness than T6. Moreover, surface treatment by shot peening increases the roughness parameters to a similar level regardless of the previous thermal treatments T6 and T64.
8. The relationship between HV hardness and fatigue life can be written as a linear function with the logarithmic fatigue life. The higher the hardness, the higher the fatigue life.This correlation was confirmed for the materials and processing parameters considered in the current research and may also be valid in broader contexts, though further study is needed.

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