

EFFECT OF SEVERE AIR-BLAST SHOT PEENING ON THE WEAR CHARACTERISTICS OF CP TITANIUM

VPLIV INTENZIVNEGA POVRŠINSKEGA KOVANJA S PESKANJEM Z ZRAKOM NA OBRABNE LASTNOSTI CP-TITANA

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In this study, air-blast shot peening was applied to analyze the wear characteristics of CP titanium (Grade II). The specimens were exposed to different plastic-deformation rates via different severe shot-peening conditions in order to determine the wear behaviour of CP titanium. A free-ball micro-abrasion test was performed on the specimens shot peened with different Almen intensities. Nanohardness measurements were also performed to investigate the work-hardened layer – the coarse-grained-structure transition zone. Light microscopy and scanning electron microscopy (SEM) were used to analyze both the wear tracks and the severely deformed layer. As a result, the plastically deformed layer thickness reaches approximately 100 µm beneath the surface. Moreover, the hardness and wear durability after severe shot peening is increased.

Keywords: air-blast shot peening, wear, nanoindentation, plastic deformation, ultra-fine-grain durability

V tej študiji je bilo uporabljeno peskanje z zrakom za študij lastnosti pri obrabi CP-titana (Grade II). Vzorci so bili izpostavljeni različnim stopnjam deformacije v različnih razmerah peskanja, da bi ugotovili vedenje CP-titana pri obrabi. Izvršen je bil abrazijski preizkus z mikrokroglicami na vzorcih po peskanju z različno Almen-intenziteto. Izvršene so bile meritve nanotrdote za preiskavo utrjenega sloja in grobozrnate strukture prehodne cone. Za analizo sledov obrabe in močno deformiranih slojev sta bili uporabljeni svetlobna in vrstična elektronska mikroskopija (SEM). Debelina plastično deformiranega sloja doseže globino okrog 100 µm pod površino. Trdota in odpornost proti obrabi se po močnem peskanju povečata.

Ključne besede: hladno kovanje površine s peskanjem z zrakom, obraba, nanootisek, plastična deformacija, odpornost ultra drobnih zrn

1 INTRODUCTION

Surface treatments are generally applied to metallic materials, particularly machine parts before service conditions to increase service life and efficiency.¹ Mechanical properties such as wear, fatigue, fretting fatigue and corrosion are influenced by surface treatments.^{2,3} To analyze these mechanical and physical effects on the surface-treated materials, nanoindentation, scratch, hardness and thermal tests are performed.⁴⁻⁹ Surface treatments are investigated within the branch of mechanical and thermal surface treatments. Mechanical surface treatments cover a wide variety of processes and shot peening, laser peening, deep drawing, burnishing, sand blasting, brush cleaning are given as example processes.^{10,11} Nitriding, carburising, nitrocarburising, plasma nitriding and boriding processes are beneath the thermal-surface treatments.¹²

Shot peening has been widely used as a mechanical surface treatment to improve the fatigue resistance of critical machine parts.¹³ Also, the shot-peening effect on the oxidation, corrosion and fretting-fatigue properties of materials has been studied.¹³⁻¹⁵

Oxidation and the above mentioned properties are also important for coatings and other surface treatments.^{16,17}

With respect to enhancing the mechanical properties without altering the chemical compositions of materials, severe plastic deformations attract a lot of attention.¹⁸ Severe plastic deformation, just as ECAP (equal-channel angular pressing), HPT (high-pressure torsion) or ARB (accumulative roll bonding) is performed to increase mechanical properties by decreasing the grain size of the whole bulk materials.^{18,19} Nevertheless, these methods are applied restrictedly due to the high-pressure requirements. Shot peening may be more influential if performed as a severe plastic deformation.¹⁹ It applies a high plastic deformation only to the material surfaces made of a wide variety of materials due to the easiness of the application.^{13,20} By raising the conditions of the conventional shot peening, severe shot peening which applies a very high plastic deformation to a material surface was conceived.²⁰ In recent years, studies depicted that severe shot peening made positive contributions to the increased wear characteristics, creating fine-grained-surface bulk materials.²¹ Severe shot peening is applied in the ways of high-energy shot peening, ultrasonic shot peening, etc.²²⁻²⁴ Most of the severe-plastic-deformation studies show a highly deformed layer with ultra-fine grains that has superior mechanical properties in comparison with the interior parts.²⁵ From this point of view, obtaining a highly deformed surface with better properties is a way of improving the wear properties of metallic mate-

rials.^{26–28} Several techniques are used for determining the wear behaviour of materials.²⁹ Micro-abrasion is one of these test techniques due to its simplicity with respect to the abrasive-wear behaviour of materials.³⁰

In this study, attention is focused on the mechanical properties and the wear characteristics of the bulk CP titanium materials with severely deformed surfaces. The specimens are subjected to a free-ball micro-abrasion test subsequent to a severe shot-peening process. The distinction between the severe shot-peened and as-received titanium specimens are performed via mechanical and physical investigations.

2 EXPERIMENTAL STUDIES

Commercially pure titanium (Grade II) material with the dimensions of 20 mm × 20 mm × 8 mm was machined and a normalizing heat treatment was performed to release the machining and manufacturing effects. The surfaces of the specimens were ground with 200, 400, 800 and 1200 grade emery papers and then mechanically polished with 6 μm and 1 μm pastes. The specimens were subjected to the air-blast severe shot peening with different Almen intensities (Table 1). In addition, the air pressures were (750, 800 and 870) kPa for 31A, 35A and 9C, respectively. The Almen intensities were selected due to the high-plastic-deformation exposure.²⁰ The intensities were 31A, 35A and 9C. The C Almen strip is used as the highest plastic deformation in comparison to the A and N strips.³¹

Table 1: Severe-shot-peening conditions for CP-titanium (Grade II) specimens

Tabela 1: Razmere pri močnem peskanju vzorca CP-titan (Grade II)

Specimen No.	Almen intensity	Shot type	Shot size	Coverage (%)
1	31A	SAE-J2175	S230	200
2	35A	SAE-J2175	S230	200
3	9C	SAE-J2175	S230	200

The specimens were etched with a 3 % Nital solution following the severe shot-peening process. Afterwards light and SEM (Vega Tescan) microstructure images were obtained on the cross-sections and the peened surfaces. A Schimadzu DUH-W201S ultra-micro-hardness tester was used to determine the hardness alteration from the surface to the interior. The experimental load applied was 50 mN and the duration was 10 s.

The fixed-ball micro-abrasion test method was used for determining the wear performance of the shot-peened surfaces with different Almen intensities. The diameter, the material and the hardness of the ball were 25.4 mm, AISI 52100 steel and 65 Rc, respectively. The wear volume was calculated using Equation (1):³²

$$V \approx \frac{\pi b^4}{64R} \text{ for } b \ll R \quad (1)$$

where V is the volume of the material removed by wear, b is the diameter of the wear crater, and R is the radius of the ball.

The fixed-ball micro-abrasion tests were performed on the peened surfaces of the CP-titanium (Grade II) specimens for 2 min, at 120 r/min, under the normal loads of (0.5, 1 and 1.5) N to determine the wear-volume loss on the peened-specimen surfaces. 800-mesh SiC particles were used as the abrasive and distilled water including 25 % SiC particles was used as the abrasive solution.

3 RESULTS AND DISCUSSION

The specimens peened with the 31A, 35A and 9C Almen intensities are shown in Figure 1. The images show the cross-sections of the peened specimens. A severe plastic deformation with a severe shot-peening

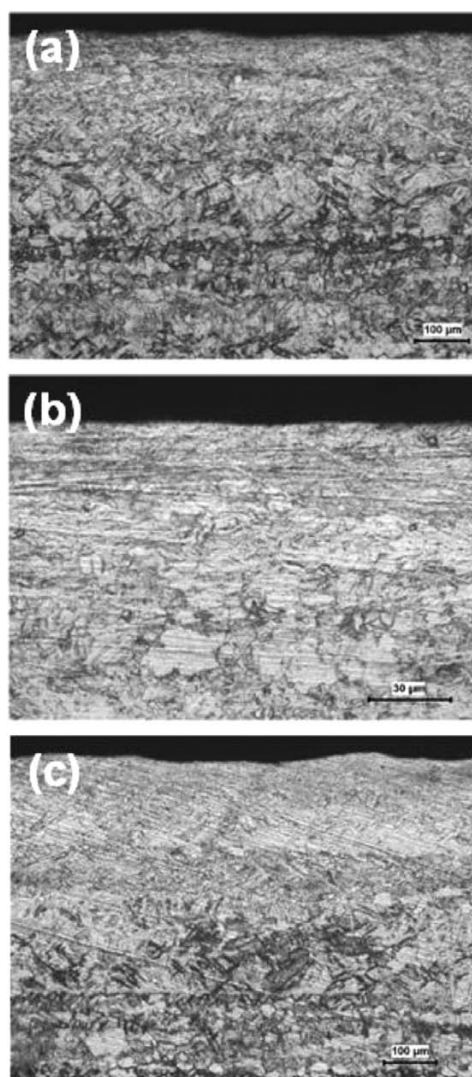


Figure 1: Light-microscope images of severely shot-peened titanium specimens peened with: a) 31A, b) 35A, c) 9C Almen intensities

Slika 1: Mikrostruktura močno peskanega vzorca iz titana z različno Almen-intenziteto: a) 31A, b) 35A, c) 9C

exposure just below the surface is observed. Approximately 100 μm beneath the surface, grain boundaries become dense and lose their homogeneity and visibility. With the increasing Almen intensity, especially at the intensity of 9C, a very dense, severely deformed surface can be noticed; it is separated from the interior structure because fine grains appear due to a high plastic deformation. Also, shot tracks and waves on the surface peened with 9C are denser compared with 31A and 35A. In the literature the reported surface roughness also increases with the increasing plastic deformation.²⁰

The severely deformed structure of the surface was investigated using a SEM analysis (**Figure 2**). In line with the studies made before, the images of the spe-

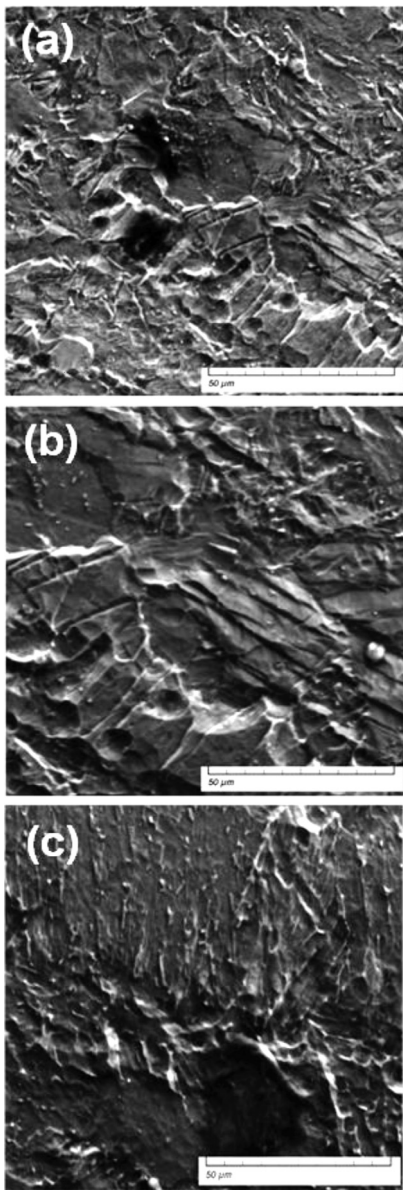


Figure 2: SEM images of severely shot-peened titanium specimens peened with: a) 31A, b) 35A, c) 9C Almen intensities

Slika 2: SEM-posnetki močno peskanega vzorca iz titana z različno Almen-intenziteto: a) 31A, b) 35A, c) 9C

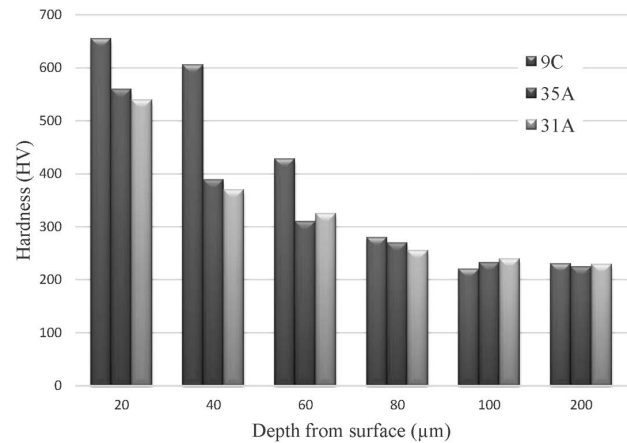


Figure 3: Hardness variation versus depth according to the Almen intensities

Slika 3: Spreminjanje trdote z globino glede na različno Almen-intenziteto

cimens peened with 31A, 35A and 9C show that a high plastic deformation ruined the homogenous microstructure and created quite a dense and heterogenous ultra-fine-grained structure.^{22,33–35} Although the magnifications are high, the grain boundaries cannot be seen. Due to a dislocation-density increase and piling up around the grains, the boundaries are invisible just like reported in^{36,37}.

Nanohardness measurements were performed to determine the effect of the plastic deformation on the surface and the effect release to the interior. **Figure 3** depicts the hardness variation from the surface to the bulk interior. As seen on the figure, after approximately 150 μm a large part of the plastic-deformation impact was released, being very similar to the ones presented in^{21,38}. The hardness increase is the highest on the surfaces of the specimens. Nevertheless, for the specimen peened with the 9C Almen intensity, the hardness decrease does not occur as abruptly as in the cases of 31A and 35A. As seen from **Figure 1**, an ultra-fine-grain, highly deformed layer provides a higher and more stabilized hardness down to 50 μm .

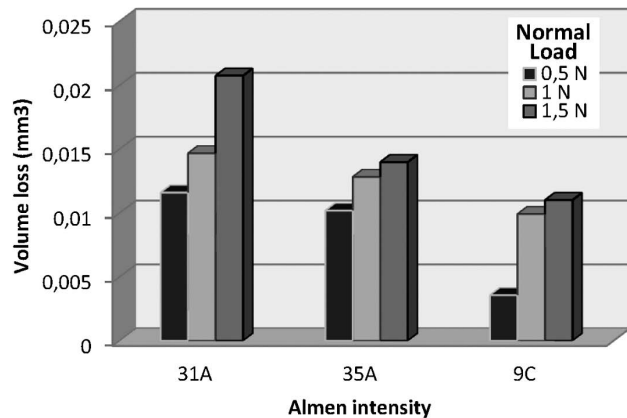


Figure 4: Volume loss versus Almen intensity for the normal load

Slika 4: Izguba volumna v odvisnosti od Almen-intenzitete pri normalni obremenitvi

The volume loss is evaluated on the basis of the crater dimensions from the light and SEM images. The mathematical approach taken from the literature was used in this study.²¹ The volume loss decreases with the increasing Almen intensity. The Almen intensity causes an exposure to a severe plastic deformation, increasing the hardness of the contact surfaces of the materials. The hardness increase induces a reduction in the wear-volume loss.

Figure 4 shows the graphs indicating the volume loss of the specimens, subjected to the wear process using the 800-mesh SiC abrasives under the (0.5, 1 and 1.5) N loads and shot peened at different Almen intensities. As seen in **Figure 4**, the volume loss of the specimens increased in parallel with the increasing load. This is due to the fact that the force applied on the particles, stuck between the subsurface and the ball, increases resulting in a higher shear force with a deeper plunge of the abrasive particles into the specimen.

The lowest volume losses are observed on the specimen shot peened at the 9C Almen intensity, followed by the specimens shot-peened with the 35A and 31A Almen intensities, respectively. This can be primarily attributed to the surface hardness of the specimens. It would be appropriate to correlate the surface hardness of a specimen with the plastic deformation occurring on the surface area of the specimen depending on the increasing Almen intensity, since the stresses generated on the surface result in an increased dislocation density, hence, an increased hardness in this area of the specimen. Additionally, the density of the compressive stresses generated in this area varies depending on the Almen intensity and has a positive effect on the wear resistance.

Figure 5 shows a SEM image of a crater formed as a result of the micro-abrasion wear test made on a specimen that was shot-peened at the 9C Almen intensity. The wear tracks, obtained as a result of the tests carried out in compliance with the ASTM G77 standard using different Almen values, exhibited a circular geometry as expected.

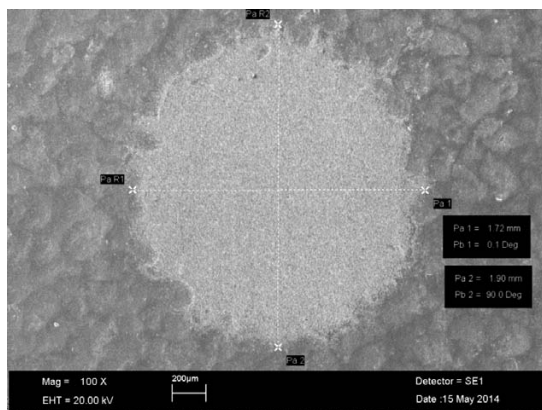


Figure 5: SEM image of a wear crater obtained on the titanium alloy shot peened with the 9C Almen intensity

Slika 5: SEM-posnetek kraterja na titanovi zlitini, peskani z 9C Almen-intenziteto

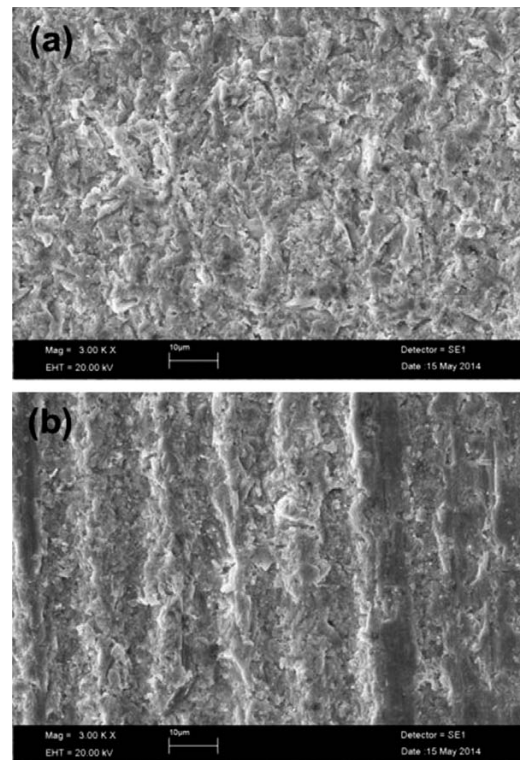


Figure 6: SEM images of the worn surfaces obtained with the 31A Almen intensity at the normal loads of: a) 0.5 N and b) 1.5 N

Slika 6: SEM-posnetka obrabljene površine, obdelane z Almen-intenziteto 31A pri obtežbi: a) 0,5 N in b) 1,5 N

Figures 6a and **6b** show the wear-surface images of the specimens subjected to the micro-scale abrasion process under the loads of 0.5 N and 1.5 N and shot-peened at the 31A Almen intensity. A three-body wear-abrasion mechanism was encountered on the specimens that were subjected to the wear process under 0.5 N. This is due to the rolling abrasion of the abrasive particles on the surface. A two-body abrasion-wear mechanism, thereby, a groove formation was observed on the specimens, subjected to the wear process under 1.5 N. This is a consequence of the plunging of the abrasive SiC particles into the ball surface with the increasing load, which results in a cut-off titanium alloy.

The wear-surface images of the specimens shot peened at the 35A Almen intensity under the 0.5 N and 1.5 N loads are given in **Figures 7a** and **7b**. Here, the wear mechanisms occurring at the 31A Almen intensity are observed as well; however, the groove depths, obtained under the load of 1.5 N, happened to be lower due to a higher material hardness.

The wear-surface images of the specimens shot peened at the 9C Almen intensity are shown in **Figure 8**. The wear mechanism obtained under the 1.5 N load differs from that of the other two specimens. The plunging of the abrasive particles into the material surface was obstructed due to an increased surface hardness and a three-body abrasion mechanism was observed due to the rolling of these particles.

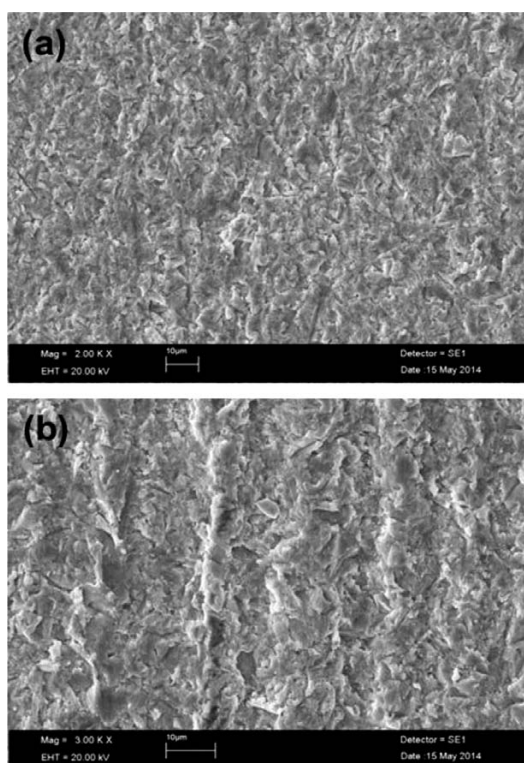


Figure 7: SEM images of the worn surfaces obtained with the 35A Almen intensity at the normal loads of: a) 0.5 N and b) 1.5 N

Slika 7: SEM-posnetka obrabljene površine, obdelane z Almen-intenziteto 35A pri obtežbi: a) 0,5 N in b) 1,5 N

4 CONCLUSIONS

In this study, commercially pure titanium (Grade II) specimens were subjected to severe air-blast shot peening with different Almen intensities. Different Almen intensities exposed the specimen surfaces to different plastic-deformation rates. Severe plastic-deformation rates caused a microstructural and mechanical behaviour alteration. With the increasing Almen intensity a finer and deeper grain structure occurred and this structure become more complex. However, according to the SEM images, although the magnifications were so high, the grain boundaries cannot be seen and the structure has a very dense layer and a plastically deformed surface. The hardness variation is also compatible with the optical and SEM images. With the decreasing Almen intensity the hardness was reduced and after approximately 100 µm a large part of the plastic deformation was released. The wear-volume loss was reduced with the increasing Almen intensity. The highest wear resistance was obtained with the specimens shot peened at the 9C Almen intensity, followed by the 35A and 31A Almen intensities. On the specimens shot peened at the 9C Almen intensity a three-body abrasion-wear mechanism was observed at all normal loads. However, on the specimens shot peened at the 35A and 31A Almen intensities, three-body abrasion was observed at the low load

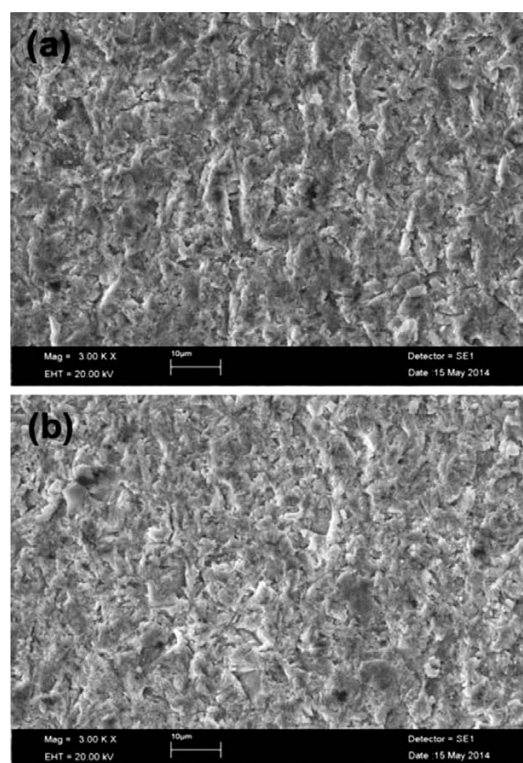


Figure 8: SEM images of the worn surfaces obtained with the 9C Almen intensity at the normal loads of: a) 0.5 N and b) 1.5 N

Slika 8: SEM-posnetka obrabljene površine, obdelane z Almen-intenziteto 9C pri obtežbi: a) 0,5 N in b) 1,5 N

(0.5 N) and two-body abrasion was observed at the high load (1.5 N). These results show that the Almen intensity and, thereby, the surface hardness are the key parameters for the control of the wear behaviour of a Ti alloy.

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