Friction and wear behavior of shot peened surfaces of 36CrNiMo4 and 36NiCrMo16 alloyed steels under dry and lubricated contact conditions

Slobodan Mitrovic*, Dragan Adamovic, Fatima Zivic, Dragan Dzunic, Marko Pantic

Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, Kragujevac 34000, Serbia

A R T I C L E   I N F O

Article history:
Received 17 June 2013
Received in revised form 13 November 2013
Accepted 13 November 2013
Available online 21 November 2013

Keywords:
Shot peening
Friction
Wear
Sliding

A B S T R A C T

Tribological behavior of two alloyed steels subjected to shot peening was investigated, under dry and lubricated sliding. 36CrNiMo4 and 36NiCrMo16 alloy steels were investigated at block-on-disc sliding testing machine, and three different applied loads (10 N, 30 N, 50 N) and sliding speeds (0.25 m/s, 0.5 m/s, 1 m/s) were observed. Shot peened surfaces were compared to ground ones, from aspects of their micro hardness and friction and wear properties. Microhardness tests were realized for both steel materials, ground and shot peened samples.

Shot peening increased hardness of the near surface layers with approximately 10% increase near the top surface, in comparison to ground surfaces. Both friction and wear properties of the investigated steels showed improvement after shot peening, especially under high loads and speeds for dry sliding and low speeds and high loads for lubricated sliding. For all test conditions, 36NiCrMo16 steel showed better wear resistance and frictional characteristics than 36CrNiMo4 steel. Shot peening produced lowering of the friction coefficient, as well as wear rate, in comparison with ground surfaces, in both dry and lubricated sliding and for both materials. Wear tracks exhibited severe abrasive wear, accompanied with adhesive wear, in all test conditions, but in case of lubricated sliding of shot peened surfaces, at the lowest speed and the highest load, wear tracks showed regions with mild wear also. Important result was significantly lower number of cracks, with smaller sizes within wear tracks of shot peened surfaces, in comparison with ground surfaces.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

General purpose steel is widely available material with good mechanical properties and low cost. However, there are demands to improve certain characteristics in specific applications, such as fatigue strength, fatigue life or wear resistance. Different technologies have been studied, among which surface hardening is widely recognized as a good methodology to increase fatigue and/or wear resistance.

Shot peening is often applied surface modification technology with a goal to increase fatigue resistance and fatigue life, by increasing the surface strength [1–4]. The material surface is exposed to a stream of small ball shots, by using compressed air. Steel balls are usually used in a shot peening process. The repeated impacts greatly changes the surface roughness, increase surface hardness due to refinement of the microstructure at surface and sub-surface regions, and induce compressive residual stresses, resulting in different surface state and mechanical properties of the material [5–7]. Grain refinement is achieved in the thin surface sub-layers, due to repeated impacts by the shot balls. The technology can also be used to increase wear resistance, due to increased surface hardness and mitigation of cracks initiation and development within the surface contact zone. It is inexpensive and reliable industrial surface treatment, belonging to cold working processes. The technique introduces high compressive stresses on the treated surface, and further changes surface roughness and hardness [8,9]. Every shot impact creates a dimple, that is, peak and valley are formed. Micro dimples formed by shot peening influence lower friction [7,10]. After the ball impacts, the surface and a small volume around the dimple are stretched. The surrounding material tends to change this stretched volume to its original shape and impose a compressive stress on it, thus making uniform layer of compressive residual stress on the surface through overlapping dimples [5,8]. Residual stresses on the surface of metallic parts have highly positive influence on its fatigue performance [7]. Compressive residual stresses induced by shot peening into the thin surface layer of the treated material, contribute to the prolonging of its fatigue life, by reducing...
external tensile stresses imposed on the material [11]. However, the influence of surface residual stresses on bulk material wear rate is not sufficiently explored in case of material surface treatments [12], mainly focusing on coatings and a few papers dealing with this topic present rather diverse conclusions. Some results points to negative influence of surface residual compressive stress on wear rate in case of nano scale wear [13] and others indicate that compressive stress decrease wear rate [14]. Alanazi et al. [15] showed that in case of nanocrystalline coatings, wear resistance does not increase linearly with increasing the residual stress. The increase of compressive residual stresses produced wear resistance increase up to a certain stress value, after which its further increase produced rather rapid decrease of wear resistance [15]. Direct influence of the compressive residual stresses produced by shot peening, such as distribution or magnitude, on wear performance, has not been explored so far.

The influence of the shot peening has been mainly studied in relation to fretting [7,16-17], fatigue [3,4] and stress corrosion cracking [18]. Tribological characteristics, especially wear evolution, have been a subject to only a small number of papers with rather different conclusions in relation to wear behavior influenced by shot peening [19-22]. Vaxevanidis et al. [20] observed tribological behavior of two kinds of tool steels with variation of different shot peening parameters (shot size and air-blast pressure). They demonstrated positive effect of shot peening on sliding wear, by reduction of wear rate and friction coefficient [20]. The influence of shot-peening on the wear resistance of steel in the dry rolling/sliding contact wear tests was investigated by Matsui et al. [19]. They performed duplex shot-peening of steel with ceramic balls and the particulate MoS₂ solid lubricant and obtained highly improved wear resistance under a severe loading and sliding condition [19]. However, Zammit et al. [21] studied the wear resistance of austempered ductile iron during sliding and reported that shot peening did not improve wear resistance. They explained it by the fact that in case of this shot-peened material, stress induced austenite to martensite transformation and residual compressive stresses are counteracted. In case of Ti₆Al₄V alloy, shot peening produced no effect on the wear behavior under fretting loading [17]. It is obvious that the influence of the shot peening on the wear and friction behavior firstly depends on the material which is treated. Altogether, compressive residual stresses and typical peening created roughness (peaks and valleys) has generally positive influence on tribological processes [2,17,19], even though the shot peening influence on friction and wear is still largely unexplored.

Material surface defects can be eliminated or mitigated, if the ball size is appropriately selected according to initial surface topography. Also, peaks and valleys originating from shots influence friction and wear process through different mechanisms: from increasing number of contact points between two relatively moving surfaces; mitigating risks from particles detachment due to elastic response of peaks; and collecting wear debris in valleys thus removing them from the direct contact zone [8]. In case of lubricated contact, the surface valleys produced by shot peening act like oil reservoirs (oil pockets). These oil pockets contribute to generation of the hydrodynamic pressure and accordingly separation of materials in contact.

It is a well known fact that the material performance is significantly influenced by its surface finish. On the other hand, it is well documented that initial surface roughness is highly significant for the evolution of the friction and wear process during the contact of two rough surfaces, whereat friction coefficient is lower and wear rate is higher for rough surfaces, generally [16,23,24]. Surface topography can be efficiently controlled by different shot peening parameters. Further investigations of different influences of shot peening process are needed.

This paper investigated the influence of the shot peening on tribological characteristics of two types of general purpose alloyed steels, namely 36CrNiMo4 and 36NiCrMo16 steel. Dry and lubricated sliding by using block-on-disk tribometer, were observed, as well as three different values of normal loads and sliding speeds.

### 2. Materials and methods

#### 2.1. Materials

Two types of steels were used for shot peening and tribological tests afterwards, namely 36CrNiMo4 and 36NiCrMo16 steels. The chemical composition of the observed materials is given in Table 1. Their mechanical characteristics are shown in Table 2, with the following parameters: Rp, yield strength; Rm, tensile strength; A₅, elongation; Z, contraction; KU₃₀₀₀, Charpy impact energy. First, the samples for shot peening were prepared. Prior to the shot peening, the samples were flat polished by using the radial grinding wheel with intensive cooling to prevent heat effects. After the shot peening, samples for tribological tests were prepared using treated and untreated materials. Material of the rotating counter disc in contact with tested steels, during tribological investigations was HS 18-1-1.5 high speed tool steel (Table 1).

#### 2.2. Shot peening

Shot peening of samples was realized at shot peening machine of ES-1580-1 model, PANGBORN, by using steel balls of d = 0.8 mm (S330) diameter and 48–55 HRC hardness. Based on literature recommendations [25,26], and 15 mm thickness of the steel sample, Almen intensity of 16A was selected. Duration of shot peening, necessary to achieve Almen intensity of 16A was determined by Almen test strip. Pressure of 4 bar and shot peening time of 5 min correspond to the selected shot peening intensity of 16A. Surface coverage was P = 1 × 98%. Surface coverage on shot peened sample was investigated by the magnifying glass with 10× magnification. It was confirmed that complete coverage of 98% was achieved. Appearance of the surfaces before and after the shot peening for both tested materials are shown in Fig. 1.

The arithmetic average roughness, Ra was as follows: in case of 36CrNiMo4 steel, Ra = 0.28 μm (ground samples); Ra = 1.81 μm (shot peened samples) and in case of 36NiCrMo16 steel, Ra = 0.62 μm (ground samples); Ra = 1.11 μm (shot peened samples). Surface profiles of ground and shot peened samples are shown in Fig. 2. It is obvious from Fig. 2 that shot peening produced completely changed topography, compared to initial state obtained by polishing. It can be seen that more pronounced change of roughness parameters was obtained in case of 36CrNiMo4 steel.

### Table 1

<table>
<thead>
<tr>
<th>Chemical composition of tested steels and counter disc in tribological investigations (wt%).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>36CrNiMo4</td>
</tr>
<tr>
<td>36NiCrMo16</td>
</tr>
<tr>
<td>HS 18-1-1.5</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Mechanical characteristics of tested steels.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>36CrNiMo4</td>
</tr>
<tr>
<td>36NiCrMo16</td>
</tr>
</tbody>
</table>
2.3. Micro-hardness tests

Microhardness tests according to Knoop at 3 N load, were realized for both steel materials and ground and peened samples. This method enables measurements at very short distances between the imprints and along the depth, close to the surface. Selected load of 3N enabled adequately large imprints. Hardness was measured up to the minimum distance from the surface of 0.02 mm. Hardness was measured on several positions, with adequate distances between each other, in order to avoid the influence of the plastically deformed zone of another hardness test imprint. Hardness values, as a function of the distance from the surface, are shown in Fig. 3. Obtained results correspond to hardness distribution after shot peening presented by other authors [1].

From Fig. 3, it can be clearly seen that shot peening increased hardness of the near surface layers. The micro-hardness (HK) of peened samples has the maximum at the top surface and decreases slightly along the depth, as opposed to ground samples which showed hardness increase along the depth. Shot peened samples exhibited the largest hardness increase within layers close to the top surface, of approximately 10% increase. At the depth of approximately 0.1 mm from the top surface, both treated and untreated samples started to have equal hardness, indicating the approximate depth of shot peening influence in case of observed materials. Interesting fact is that micro-hardness is rather uniform
along these near surface layers, in case of shot peened materials (upper lines in Fig. 3). And in case of ground surfaces, there is a difference of approximately 10% between the micro-hardness values at the top surface and at 0.1 mm from it (lower lines in Fig. 3).

2.4. Tribological tests

Tribological tests were carried out at block-on-disc sliding testing machine (tribometer) with the contact pair geometry in accordance with ASTM G 77. Schematic view of the contact geometry between the block (samples of tested steels) and the disc is shown in Fig. 4. The static test block is loaded against the rotating disc. This provides a nominal line contact Hertzian geometry for the contact pair. More detailed description of the tribometer is available elsewhere [22].

The test blocks were prepared of ground and shot peened 36CrNiMo4 and 36NiCrMo16 steel, with dimensions of 6.35 × 15.75 × 10.16 mm. The cutting of sample blocks from shot peened materials was done by machine saw with intensive cooling in order to avoid changes of the surface layers, due to the high temperature. Disc used in contact with tested samples was made of HS 18–1–1–5 high speed tool steel, with diameter of 35 mm and thickness of 6.35 mm (the same as the width of 6.35 mm at test sample block as shown in Fig. 4). The hardness of the block was 62 HRC and the disc material was selected because it is considerably harder than investigated 36CrNiMo4 and 36NiCrMo16 steels. From Fig. 3, it can be seen that the hardness of the investigated shot peened steels were in the range of 470–480 HK0.3, what corresponds to 469–47.7 HRC. Therefore, all the changes obtained during the tribological tests can be attributed to 36CrNiMo4 and 36NiCrMo16 steels.

The tests were performed under dry and lubricated sliding conditions at three different sliding speeds (0.25 m/s, 0.5 m/s, 1 m/s) and applied loads (10 N, 30 N, 50 N). The duration of the sliding was 10 min for dry sliding and 30 min for lubricated sliding conditions. Each experiment was repeated five times and average values taken. The tests were performed at room temperature. ISO grade VG 46 hydraulic oil was used at lubricated contact. This is a multipurpose lubricant recommended for industrial use at bearings, machine tools, chains and gear boxes, etc. The lubrication is achieved by the following procedure: while rotating, the lower end of the disc is continuously immersed up to 3 mm in 30 mL of lubricant which is positioned below the disc, as shown in Fig. 4, thus providing boundary lubrication of the sliding contact.

During the test, friction coefficient was continuously recorded by the tribometer software and provided in the form of the real time friction coefficient curves. The wear behavior of the block was monitored in terms of the wear track width. Using the wear track width and the geometry of contact pair, the wear volume (expressed in mm³), wear rate (mm³/m), as the wear volume over the sliding distance and specific wear rate, as the wear volume over the sliding distance and applied load (mm³/Nm) were calculated.

3. Results

3.1. Friction

The real time friction coefficient curves for dry and lubricated sliding, at v = 1 m/s and Fₚ = 50 N, for both tested steels, are shown in Fig. 5. It can be seen that shot peening produced lowering of the friction coefficient in both dry and lubricated sliding and for both materials. The friction curves shown in Fig. 5 are in accordance with results of other authors related to the influence of the initial roughness increase on the friction coefficient evolution during the sliding contact [16,19,20,24]. Our results show that the running in period of friction is very short as can be seen on Fig. 5, that is, steady state is reached almost from the very beginning of the sliding. Pronounced oscillation of the friction coefficient curves that can be noticed under the dry sliding is consistent with occurrence of the stick–slip phenomenon, as reported in other studies [24]. On average, oscillation amplitude, in case of dry sliding, was around 0.05 (Fig. 5b and d), while the friction coefficient curve did not exhibit any oscillations in case of lubricated sliding (Fig. 5a and c). Pradeep et al. [24] demonstrated average oscillation amplitude around 0.1, in cases of different surface roughness produced on steel surface, for aluminium pin against steel plate.

Histogram display of the average values of the friction coefficient depending on the contact conditions is given in Fig. 6. It is clearly visible that friction coefficient values were significantly lower under lubricated than under dry sliding.
case of dry sliding, the friction coefficient for peened samples was about 10% lower than for ground ones, whereat in case of lubricated sliding this difference is in the range 20–40%. It can be noticed that larger difference exists for higher sliding speed under lubricated contact, due to the high influence of the generated hydrodynamic pressure in relation to formed peening valleys. In case of dry sliding, friction coefficient linearly increased with sliding speed and load increase. In case of lubricated sliding, the load and speed had the opposite influence on the friction coefficient, namely it slightly increased with load increase and decreased with sliding speed increase. These trends were noticed for both ground and shot peened 36NiCrMo16 and 36NiCrMo16 steels. It can be noticed that 36NiCrMo16 steel has better frictional characteristics in all contact conditions. According to Stribeck curve, and according to the behavior of the friction coefficient with sliding speed increase (slight decrease of the friction coefficient), it can be assumed that the test conditions in our study are in boundary friction domain, what is in consistence with boundary lubrication provided in the tests.

### 3.2. Wear

Values of calculated wear rate as a function of the sliding speed, under dry and lubricated sliding of 36CrNiMo4 and 36NiCrMo16 steels, are shown in Fig. 7. The increase of the sliding speed produced increase of the wear rate, for dry contact and its decrease for lubricated contact, especially pronounced under low load and high sliding speed (Fig. 7a). It should be noted that the vertical axes scales for lubricated and dry sliding in Fig. 7 are approximately $10^3$ times different, indicating significantly lower wear rate in case of lubricated sliding, but it was impossible to present both with the same scales precisely due to this large difference. Histogram display of the wear rate values for all contact conditions is given in Fig. 8. It can be seen that load increase produced linear increase of the wear rate under all contact conditions. Linear trends of wear rates
obtained in our results are consistent with results of other authors related to the influence of the initial roughness increase on the wear process [10,16,20]. Rivolta et al. [10] studied steel surface hardening by gas nitriding in combination with shot peening. They also observed very slight decrease of micro-hardness along the depth up to 1 mm from the top surface, for shot peened samples. They also observed sliding speeds in range of 0.2–1 m/s, corresponding to our range of sliding speeds (0.25–1 m/s) and reported perfectly linear increase of wear volume with sliding speed increase under dry contact [10], as obtained within our investigation. Since their

![Fig. 7. Wear rate as a function of the sliding speed, under dry and lubricated sliding of 36CrNiMo4 and 36NiCrMo16 steels.](image)

![Fig. 8. Histogram display of wear rate dependence of contact parameters.](image)
test conditions are almost identical with our investigations, we can assume that the depth of the residual stresses influence of 200 μm that Rivolta et al. [10] obtained, can also be valid for our study. This is also in consistence with presented micro-hardness diagram in Fig. 2.

Beside wear rates, shown in Figs. 7 and 8, we calculated specific wear factors for all test conditions, in order to determine whether severe or mild wear occurred. Calculated values of specific wear rate were of order of $10^{-5} - 10^{-4} \text{mm}^3/\text{Nm}$(dry sliding) what corresponds to severe wear regime and $10^{-7} - 10^{-6} \text{mm}^3/\text{Nm}$(lubricated sliding), aiming toward mild wear [27]. Under low sliding speed, lubricated contact exhibited values of wear rate near the area of mild wear, but with speed increase it firmly entered severe wear domain, supported also by the appearance of wear tracks given in Figs. 9 and 10, with regions of mild wear throughout the wear tracks.

It is clear from Figs. 7 and 8 that shot peening produced lowering of the wear rate, especially pronounced under high load and sliding speed. The largest difference between peened and ground surfaces was exhibited for dry contact and the highest applied load and speed (50N, 1 m/s). For all test conditions, 36CrNiMo16 steel showed better wear resistance than 36CrNiMo4 steel.

Wear tracks in cases of dry and lubricated sliding, for both tested steels, are given in Figs. 9 and 10. It is clear that abrasive wear was a governing wear mechanism, confirmed by clearly visible parallel scratches and abrasive grooves in direction of sliding. Visual inspection by using optical microscope revealed that there was no visible damage on the disc surface, due to its higher hardness, as predicted. Accordingly, wear of the disc can be assumed as negligible. If appropriate images of shot peened surfaces in Figs. 9 and 10 (right images) are compared, the distinct difference in wear rate levels under dry and lubricated sliding can be clearly noticed. Under dry sliding, even with a shorter sliding time (10 min), surface topography created by the shot peening is all removed, as shown in Fig. 9b and d (end area of the wear track is shown), while in case of lubricated sliding with longer contact time (30 min), shot peening topography is still clearly visible (Fig. 10b and d). This can be seen also if the appearances of surfaces in Fig. 10b and d are compared to Fig. 1b and d.

4. Discussion

Shot peening introduces significant changes of the surface topography of the treated material, which obviously further produce different changes of the material tribological behavior. Schematic view of different aspects related to the shot peening influences is given in Fig. 11. First, number of contact between the asperities of two surfaces in contact is significantly increased in comparison with ground surface (Fig. 11a and b), Friction and wear processes are fundamentally determined by the nature and dynamics of the asperities contact. Another two distinct benefits by the shot peening are: (1) possibility to collect wear debris and third body particles within peening valleys (Fig. 11c) thus preventing their deteriorating influence on the wear resistance and (2) in case of lubricated contact, these valleys provide zones with oil reservoirs (oil pockets) contributing to separation of surfaces in contact due to hydrostatic and hydrodynamic pressure generation within these zones (Fig. 11d).

The basic definition of friction comprises two independent components of friction: adhesion and deformation. Three basic phenomena are related to friction process: (1) creation of interfacial bonds; (2) shear and breaking of the contact materials within and around the contact zone and (3) real contact area. Shot peening generates higher roughness compared to ground surfaces, meaning that it highly increases contact points of asperities, or real contact area between two materials in contact (Fig. 11b). Accordingly, this indicates that higher number of interfacial bonds will be created. Junctions are developed at real contact spots. Formation and breaking of these junctions control the adhesion component of friction. The shearing of the interfacial bonds (or junctions) is developed under the applied tangential force, resulting in the frictional force. According to previous, shot peened surface would need higher force to break higher number of interfacial bonds, if compared to ground surface.

On the other hand, another component contributing to the friction process is deformation of the asperities in contact. The surface asperities in contact can have elastic, plastic or viscoelastic response depending on many influential factors. Hardness is one of the mechanical properties highly influencing deformation modes of the material. Higher hardness usually means more pronounced plastic deformation, but residual stress contributes as well. Axial stress originating from sliding is opposed to residual stress originating from shot peening, thus lowering frictional energy needed for sliding. What is in consistence with diagrams in Fig. 5, indicating the higher influence of the surface compressive residual stress than hardness increase. This means that elastic response of the asperities on the peened material is higher than those at ground surfaces. According to our results related to friction coefficient (Figs. 5 and 6), deformation (or ploughing) component is of the higher influence than adhesion component of the friction, under dry contact.

Under dry sliding, in our tests, load and sliding speed both influenced the increase of the friction coefficient (Fig. 6). This is in accordance with the fact that the load increase promotes formation of new pairs of asperities which contributes to new contact spots and higher real contact area. Higher speed promotes more rapid breaking of the interfacial bonds and higher energy input to the surface, originating from speed generated heat.

If lubrication is observed, the surfaces in contact are separated by the lubricant film and in our test, boundary lubrication regime was applied. This means, that there are certain spots where asperities of the surfaces come into the contact, but in significantly less extent than in the case of dry sliding. With load increase, contact area increases, as in the case of dry contact, due to boundary lubrication regime. And with sliding speed increase, more efficient lubrication is achieved, meaning less asperities contacts, so the friction coefficient slightly decreased with speed increase (Fig. 6). Also, presence of the lubricant in the contact zone prevents the friction heat.

According to Pradeep et al. [24] and considering Bowden–Tabor model [28] for sliding friction, both adhesion and ploughing components govern friction under dry sliding, while lubricated sliding can be characterized only by the ploughing component. Accordingly, the difference between lines in Fig. 5 for dry and lubricated contact represents the adhesive component. It can be seen that this difference is not as large as reported by Pradeep et al. [24], probably due to the boundary lubrication regime in our study. It is obvious that surface roughness control friction process, since it fundamentally influences friction behavior.

From Fig. 5, it can be seen that, in case of dry sliding, friction coefficient curves exhibit certain degree of oscillations. Pradeep et al. [24] attributed these oscillations to the stick–slip effect related to friction process development and adhesive component. They reported that surface roughness did not affect the amplitude of these oscillations significantly, but that they are mainly influenced by the ploughing component of the friction. Stick–slip phenomenon is also usually related to the transfer of materials in contact. In our study, there was no noticeable transfer of steel samples (36CrNiMo4 and 36NiCrMo16 steel) onto the disc. This also points to the absence or significantly less influence of adhesive component of the friction in case of lubricated sliding in our tests, since the friction curves exhibited almost no oscillations then (Fig. 5a and c).
Fridrici et al. [17] showed that the friction coefficient was decreased by the shot peening only at the beginning of the sliding, as long as the asperities generated by it are not worn-off. However, our results did not demonstrate it, indicating the influence of the material subjected to shot peening, since they studied Ti₆Al₄V alloy. In our study, in case of dry sliding, shot peening asperities were all removed during the test, which is confirmed by the appearance of the wear tracks in Fig. 9b and d. And the friction coefficient curves in Fig. 5b and d, exhibited the almost uniform difference if the curves for ground and peened surfaces are compared. It seems that the surface roughness induced by the shot peening is not the only influencing factor in case of our materials (36CrNiMo4 and 36NiCrMo16 steel), pointing probably the influence of the surface compressive residual stresses.

Bartha et al. [12] showed that near-surface compressive residual stress is generated during the wear process influenced by the applied normal load under sliding contact, becoming more compressive in a very short sliding distance, especially in the axial direction.

Fig. 9. Wear tracks in case of dry contact, at 50 N and 1 m/s: 36CrNiMo4 steel, (a) ground, (b) shot peened and 36NiCrMo16 steel, (c) ground, (d) shot peened; (C—crack; P—pitting crack).

Fig. 10. Wear tracks in case of lubricated contact, at 50 N and 1 m/s: 36CrNiMo4 steel, (a) ground, (b) shot peened surface and 36NiCrMo16, (c) ground, (d) shot peened; (P—pitting crack).
direction. They also concluded that during the wear process, plastic zone is formed around the wear track, larger with higher loads, influencing further the wear process. The residual stress originating from ploughing during the wear process, changes with sliding distance, as well as the surface microstructure [12]. If the influence of shot peening induced topography and compressive residual stresses are added, very complex set of parameters govern the wear process. Zhan et al. [2] investigated properties of 304 austenitic steel after shot peening in relation to fatigue and reported that the main beneficial effect of shot peening is introduction of compressive residual stress, because it reduces the effective applied stress during loading. The changed microstructure of the surface layers produces high yield strength of the shot peened steel surfaces [2,21]. In our study, increase of the applied load increased the wear rate, for both dry and lubricated sliding (Figs. 7 and 8). Shot peening significantly lowered wear rate, especially pronounced for dry sliding, under the highest load and speed (1 m/s, 50 N), where the largest difference between ground and shot peened surfaces in relation to wear was exhibited.

Our results showed that cracks occurring during the sliding contact were significantly smaller and shorter in case of shot peened surfaces (Figs. 9 and 10). It is obvious that compressive residual stresses induced by the shot peening had beneficial effect on crack initiation and propagation, as reported also by other authors [2,7,17]. Zhan et al. [2] predicted delayed crack initiation and mitigation of the crack development from the surface. Kritzler et al. [18] reported that stress corrosion cracking (SCC) mainly occurs when a critical state in material is achieved and sufficiently high tensile stress is present. Our results showed no evidence of SCC phenomenon under lubricated conditions. It is well known that initiation of SCC is usually related to surface discontinuities and defects originating from manufacturing processes. It is well known that shot peening efficiently mitigate and eliminate these defects, thus preventing one important source of SCC phenomenon.

Under dry sliding, characteristic surface topography produced by shot peening was removed after some time, unlike lubricated contact where this topography was preserved in large extent. This indicates that the obtained improvement of the wear resistance under dry sliding can probably be attributed to the influence of considerably higher hardness of surface layers in comparison to ground surfaces and existence of the near-surface compressive residual stresses, which lower tensile stresses from sliding and mitigate cracks. Increased hardness produces increased abrasive wear resistance, due to grain size decrease and the volume loss produced by wear follows Archard’s law [29]. This is supported by the appearance of the wear tracks in Fig. 9b and d, where considerably lower number of cracks can be seen and more shallow abrasive grooves and scratches. The function of the characteristic shot peened valleys to entrap loose wear debris and third body particles originating from the wear process (Fig. 11c), is contributing to the process until the destruction of the shot peening topography, that is, this is important factor during the first period of dry wear [7].

Considerably lower wear values of shot peened surfaces as compared to ground ones, for lubricated contact can be attributed to one additional function of the shot peening topography. Namely, for lubricated contact, roughness valleys act like oil reservoirs contributing to the separation of surfaces in contact due to hydrostatic and hydrodynamic pressure generation within these zones (Fig. 11d), supported also by other authors [8,29]. For lubricated contact, increase of sliding produced lowering of the wear rate as shown Figs. 7 and 8. This speed influence can be explained by the higher degree of contact lubrication provided when the disc rotating speed is higher, as per tribometer design (Fig. 4).

Abrasive wear mechanism can be clearly seen on both Figs. 9 and 10. Deep scratches and grooves, together with cracks (denominated C in Fig. 9) originating from detachment of larger pieces of surface material and pitting cracks (denominated P in Fig. 9) are clearly visible in case of dry sliding and lubricated sliding of ground surfaces (Fig. 10a and c). Also, it is clear that 36NiCrMo16 steel showed better wear resistance than 36CrNiMo4 steel, especially for shot peened surfaces. If dry sliding is observed, it is clearly visible that severe abrasive wear, with deep grooves and number of large cracks, indicating also adhesive wear, are dominant in case of 36CrNiMo4 steel (Fig. 9b) in comparison with shallow scratches and pitting cracks in case of 36NiCrMo16 steel (Fig. 9d). In case of lubricated sliding and shot peened surfaces, larger number of valleys is preserved for 36NiCrMo16 steel (Fig. 10d) than for 36CrNiMo4 steel (Fig. 10b), that is, shot peening topography which positively influence wear resistance is more prominent for lubricated sliding of 36NiCrMo16 steel than for 36CrNiMo4 steel. Under lubricated sliding of both shot peened materials, there were hardly any visible cracks on the worn surfaces (Fig. 10b and d).

Another distinct difference between ground and shot peened surfaces is the size of the cracks. In case of ground surfaces, there were many large cracks and delaminated areas within the wear tracks (5a and c and 10a and c), especially under dry sliding (Fig. 9a and c). Shot peened surfaces exhibited small size cracks in case of dry sliding (Fig. 9b and d) and no cracks in case of lubricated sliding (Fig. 10b and d). This supports the fact that shot peening topography prevents tribological third body formation, crack initiation and development, as reported by other authors [2,7,8,12,17,18].

5. Conclusions

Shot peening increased hardness of the near surface layers with approximately 10% increase near the top surface, in comparison to
ground surfaces. The micro-hardness of shot peened samples had the maximum at the top surface and decreased slightly along the depth.

The shot peening showed positive influence on tribological characteristics of investigated 36CrNiMo4 and 36NiCrMo16 steels. For all test conditions, 36NiCrMo16 steel showed better wear resistance and frictional characteristics than 36CrNiMo4 steel. Shot peening produced lowering of the friction coefficient, as well as wear rate, in comparison with ground surfaces, in both dry and lubricated sliding and for both materials.

Friction coefficient curves exhibited pronounced oscillation, under the dry sliding, which probably corresponds to the occurrence of the stick–slip phenomenon. In case of dry sliding, friction coefficient linearly increased with sliding speed and load increase. In case of lubricated sliding, the friction coefficient slightly increased with load increase and decreased with sliding speed increase.

The largest difference, related to wear resistance, between peened and ground surfaces was exhibited for dry contact and the highest applied load and speed (50 N, 1 m/s). In case of lubricated contact, the largest difference was exhibited under the lowest speed and the highest load (50 N, 0.25 m/s). Calculated values of specific wear rate indicated that dry sliding produced severe wear in all regimes and lubricated contact was close to mild wear domain, but mainly in severe wear, as well. Under low sliding speed, lubricated contact exhibited values of the specific wear factor very near the area of mild wear, but with speed increase it firmly entered severe wear domain.

The main wear mechanism was abrasive wear, accompanied with adhesive wear, both in conditions with and without lubrication. Dry sliding resulted in severe abrasive wear with number of delaminated areas and large cracks over the wear track surface. Another distinct difference between ground and shot peened surfaces is the size of the cracks. In case of ground surfaces, there were many large cracks and delaminated areas within the wear tracks, especially under dry sliding. Shot peened surfaces exhibited small size cracks in case of dry sliding and almost no cracks in case of lubricated sliding.

Acknowledgment

The research study was financed by Ministry of Education, Science and Technological Development, Serbia, project no. 35021 and project no. 32036.

References