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FUNCTIONAL PROPERTIES OF HARDENED STEEL PARTS GENERETED BY TURNING AND BALL BURNISHING OPERATIONS

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Summary

This paper presents the experimental results of the role of ball burnishing in improving of the surface integrity produced in finish hard machining of hardened 41Cr4 steel. The characterization of the surface integrity includes two standardized sets of 2D and 3D roughness parameters, the distributions of microhardness, residual stresses and the microstucture of the sublayer which was examined using SEM/EDS technique. The functional properties of the surface layer were predicted and discussed. This study reveals that ball burnishing performed on hard turned surfaces improves not only surface roughness but also results in better service properties compared with those generated by CBN hard turning.

Keywords: CBN hard turning, ball burnishing, hardened steel, surface integrity, functional properties

Właściwości funkcjonalne elementów maszyn ze stali utwardzonej obrabiane przez toczenie i nagniatanie

Streszczenie

W artykule przedstawiono analizę wyników doświadczalnych dotyczących roli nagniatania tocznego kulką ceramiczną w polepszeniu właściwości warstwy wierzchniej wytworzonej podczas wy-kończeniowego toczenia utwardzonej stali 41Cr4. Charakteryzacja wytworzonej warstwy wierzchniej obejmuje określenie dwóch zbiorów znormalizowanych parametrów chropowatości powierzchni, rozkład wartości twardości naprężeń własnych oraz badania mikrostruktury metodami mikroskopii elektronowej EM/BSE/EDX. Analiza wyników badań pozwala stwierdzić, że nagniatanie kulką po toczeniu na twardo poprawia nie tylko chropowatość powierzchni, ale również polepsza właściwości eksploatacyjne w porównaniu z efektami toczenia narzędziami z CBN.

Słowa kluczowe: toczenie na twardo, nagniatanie kulką, stal utwardzona, właściwości warstwy wierzchniej, właściwości użytkowe

1. Introduction

Machining hardened materials, mainly steels, is one of the leading removal methods of producing parts in such manufacturing branches as automotive, bearing, hydraulic and die and mold making sectors [1]. However, this

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technology has several drawbacks in comparison to grinding operations including lower surface finish, unsatisfactory dimensional accuracy and producing white layer (WL) which is classified as a fault of the machined components [2]. In consequence, hard turned surfaces should be additionally finished using such special abrasive operations as finishing grinding, superfinishing or belt grinding to improve surface finish and remove WL [1, 3]. Now, special roller and sliding burnishing tooling is applied in the industry in order to improve the service properties of parts made of hard steel materials.

Klocke et al. report [4] that the *Ra* parameter after burnishing of bearing steel of 62 HRC hardness using a ceramic ball of 3 mm diameter was reduced from initial Ra_t = 0.3 µm after turning to below Ra_b = 0.17 µm. Moreover, the compressive residual stresses of -1600 MPa were induced into the surface layer. Similarly [5], after burnishing of a hardened steel component (64 HRC) using a ceramic ball of 6.35 mm diameter, the roughness is reduced down to Ra_b = = 0.2 µm and the ratio of Ra_t/Ra_b ranges from 1.4 to 2.4. Burnishing also improves the surface finish of the previously ball-end milled surfaces of dies and moulds using CNC machining centers [6].

This innovative non-removal machining technique was also examined in this study with respect to both surface finish and changes of microhardness and residual stresses in the subsurface layer. It can be reasoned that aggregating hard turning and ball burnishing operations can result in substantial improvement of the quality of hardened parts and, consequently, eliminating grinding operations when hard machining is not enough to produce the desired surface integrity.

In this paper investigations are focused on the correlations between fundamental characteristics of the surface layer produced and corresponding service properties required by highly loaded and wear resistant machine parts.

2. Experimental investigations

2.1. Cutting and burnishing conditions

In this experimental study, the workpiece material was 41Cr4 (AISI 5140) steel with Rockwell's hardness of 57±1 HRC. Hard turning (Fig.1a) was performed using low content CBN tools containing about 60% CBN, grade CB7015 by Sandvik Coromant. The finishing ball burnishing (Fig. 1b) was performed using a special head mounted in the turret in which Si_3N_4 ceramic ball of 12 mm diameter was loaded by the scaled spring. Hard CBN turning and ball burnishing operations were performed using the cutting speed of 150 m/min and 25 m/min respectively. Machining operations performed on a CNC turning center Okuma Genos L200E-M and feed rates used in cutting and burnishing tests are specified in Table 1.

Table 1. Specifications of hard turning and burnishing operations

Dry hard turning (HT)		**Ball burnishing (B)**	
Feed rate f_t, m/rev	Code	Feed rate f_b, mm/rev	Code
0.075	HT1	0.05	B1
0.10	HT2	0.075	B2
0.125	HT3	0.10	B3

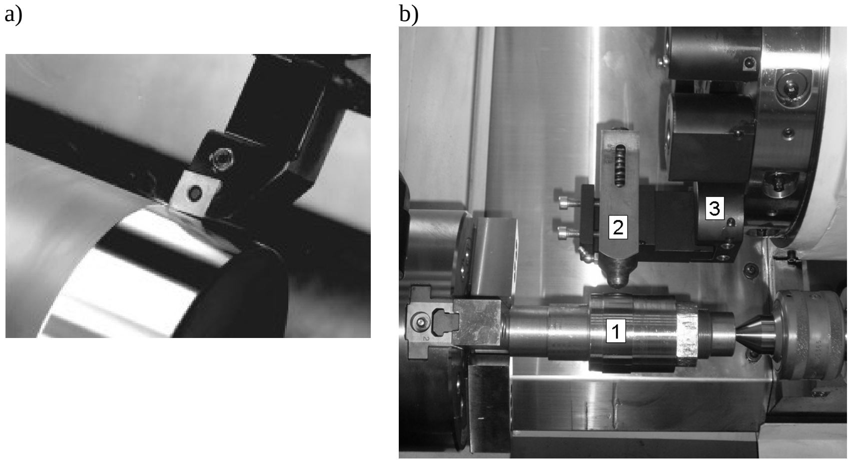

Fig. 1. Performing dry CBN hard turning (a) and ball burnishing (b) operations on a CNC turning center: 1 – workpiece, 2 – burnishing head, 3 – turret

2.2. Measurements of the properties of surface layer

After machining, surface profiles/topographies were recorded and 2D and 3D roughness parameters were determined using a TOPO-01P profilometer with a diamond stylus radius of 2 μm. They were estimated on the scanned areas of 2.4 mm×2.4 mm

Hardness (μHV) of the polished samples across the subsurface was measured using a LECO hardness tester MHT Series 200 with a Berkovich indenter at a load of 50 G, i.e. HV0.05. Based on these data, the hardness distribution at the depth of about 100 μm thickness was determined. Because the changes of microstucture penetrate to several microns, the measurements were performed on the inclined sections, at about 3^0 to the outer surface (see details in Fig. 6), in order to increase the measuring accuracy ($h_i = l_i \times \sin\alpha$).

The microstructure and texture changes induced by burnishing were examined by means of a scanning microscope, model HITACHI S-3400N equipped with X-ray diffraction head EDS, model THEMO NORAN System

Six. Both SEM and BSE images were recorded. The samples were mechanically and chemically polished. The measurements of residual stresses were carried out using XRD technique.

3. Experimental results and discussion

3.1. Surface roughness of turned and burnished surfaces

In general, CBN hard turning produces surfaces with regularly distributed irregularities and their heights depend on the initial hardness of the workpiece and machining conditions used. During ball burnishing, the turned profile is modified and the surface layer is hardened, which results in the generation of higher compressive stresses than those following hard turning operations.

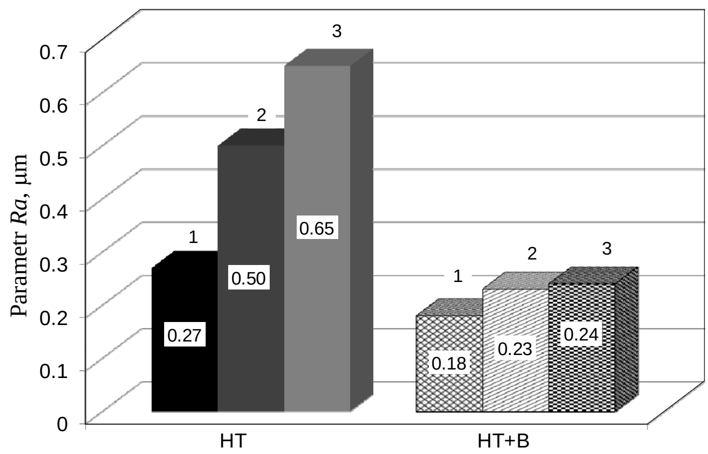

Fig. 2. Comparison of Ra values for hard turned and burnished surfaces.
HT: 1 – HT1, 2 – HT2, 3 – HT3; HT + B: 1 – HT1 + B1, 2 – HT2 + B2, 3 – HT3 + B3

Figure 2 presents the values of the *Ra* parameter obtained after both operations performed with different feeds. First, after dry hard operations the *Ra* parameter changes depending on the feed rate and for the lowest feed rate of 0.075 mm/rev applied the *Ra* = 0.27 μm (variant HT1). Due to burnishing action, the *Ra* parameter decreases visibly and for all process variants its value is about 0.2 μm. However, the ratio of Ra_t/Ra_b depends distinctly on the initial roughness generated in CBN hard machining. Moreover, the values of *Rz* parameter obtained after ball burnishing are about 20-50% lower than for initial dry HT operations. The greatest effects were achieved for initial hard surfaces turned with lower feeds. Exemplarily, Fig. 3a and b show how burnishing reduces the peak heights and changes its shape.

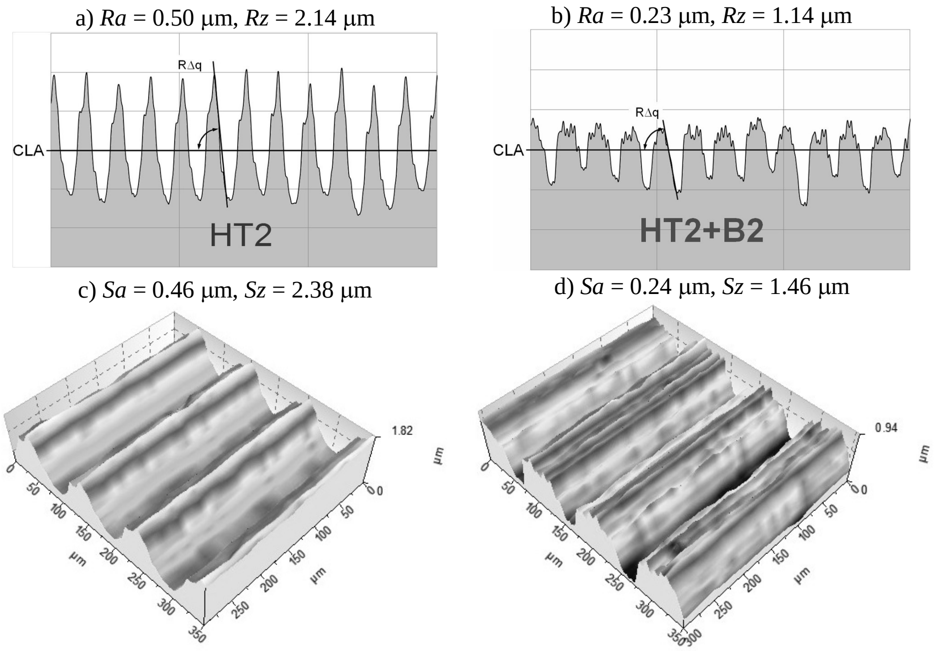

Fig. 3. Examples of surface profiles and topographies produced in dry hard turning (a), (c) and burnishing (b), (d)

As can be seen in Fig. 3a and c, dry hard turning produces surface profiles with very sharp and regular tool nose traces, with very small slopes $R\Delta q$, generally not greater than 2^0. In contrast, burnishing produces profiles with lower blunted peaks, as shown in Fig. 3b and d. This effect results partly from both plastic deformation and spalling (brittle fracture) of the hard micro-regularities.

At present, 3D roughness parameters are described in ISO 25178 and EUR 1517EN standards to underline that surface topography generated by precision machining is critical for surface functionality and component performance. Figs. 3c and d show two representative topographies generated by hard turning and sequential (HT+B) processes respectively. The visualization of machined surfaces was performed using a *Digital Surf*, *Mountains® Map* package. Both images show surfaces consisting of well-defined peaks and valleys but their stereometrical features are different. The measured values of 3D height, amplitude, and area and volume parameters are:

• for CBN hard turning: *Sa* = 0.46 μm, *Sz* = 2.38 μm, *Sq* = 0.509 μm, *Sdq* = 0.0375, *Ssk* = 0.139, *Sku* = 1.60, *Sdr* = 0.0703%, *Ssc* = 4.93 1/mm,

• for ball burnishing: *Sa* = 0.24 μm, *Sz* = 1.46 μm, *Sq* = 0.273 μm, *Sdq* = 0.0285, *Ssk* = –0.533, *Sku* = 2.02, *Sdr* = 0.0407 %, *Ssc* = 7.75 1/mm.

In this set, two area hybrid parameters appear including the developed interfacial area (*Sdr*) and the mean summit curvature (*Ssc*). Stout and Blunt [7] quote curvatures for typical machined surfaces in the range from 0.004 to 0.03 μm^{-1}.

The values of the Ssc parameter are equal to about 0.005 μm^{-1} and 0.008 μm^{-1} for the turned and burnished surfaces respectively. The *Sdr* parameter is the 3D equivalent of the profile length ratio (*Lpr*) and is low for most machined surfaces (accordingly *Sdr* = 0.0703% and 0.0407% for turned and burnished surfaces). Its higher values for the turned surface result from the fact that it contains high peaks and deep valleys (see Fig. 3a). In comparison, the *Lpr* parameter of most engineered surfaces is typically less than 1.01 [7, 8]. In the case of both of the analysed surfaces the *Sdr* is also less than 1%.

Figure 4 shows that sharp profiles produced by CBN hard turning have low bearing properties. As a result, the BAC's are linear or degressive (cases 1, 2 and 2). On the other hand, the material ratio increases progressively after ball burnishing as represented by BAC's # 4, 5 and 6.

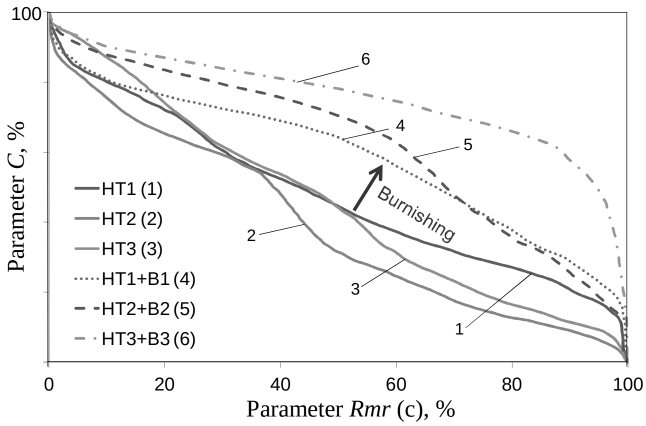

Fig. 4. Material ratio curves for dry hard turning and burnishing operations with variable feeds

The differences in the bearing properties of surface profiles produced can be visibly represented by the *Rku-Rsk* plot shown in Fig. 5. The characteristic effect (Fig. 5) is that hard turning produces surface profiles with positive skewness. The profile with a small value of the reduced peak height *Rpk* was obtained in the HT1 case. In contrast, the burnishing causes the values of the

Rpk to decrease from 0.25-0.85 μm to 0.06-0.10 μm. Such modification of the profile peaks implies distinctly shorter running-in periods during parts' service. Two characteristic areas with different couples of *Rku* and *Rsk* parameters are distinguished in Fig. 5. Correspondingly to curves # 4, 5 and 6 in Fig. 4, negative values of the skewness *Rsk* = –0.51, –0.63 and –1.37 were determined.

These *Rsk* values suggest that surface profiles treated by ball burnishing have better bearing properties. Otherwise, surfaces with sharp irregularities produced by dry hard turning have better locking properties. In addition, kurtosis near 2 means that the profiles are congregated at the extremes (they are described in tribology as platykurtic).

The comparison of bearing properties of surfaces generated by HT and BB can also be performed based on the values of upper material ratio Mr1 (lower Mr1 indicates worse bearing properties). For the three pairs of operations they are equal to: $Mr1^{HT}/Mr1^{BB}$= 20.67% vs. 6.30%, 33.67% vs. 3.98%, and 24.77% vs. 5.54%.

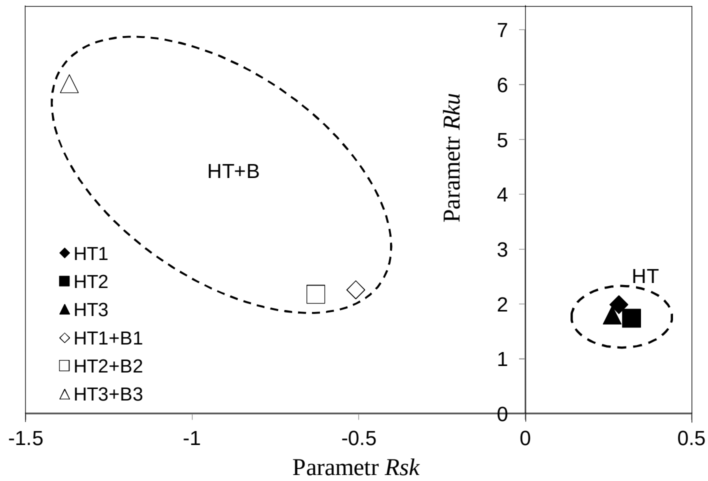

Fig. 5. Kurtosis vs skewness map for a range of hard turning and burnishing operations

In order to characterize satisfactorily the surface performance the ISO 25178 (also the B14) parameter set includes four spatial, also termed "*texture*", 3D parameters. These are the density of summits (*Std*), the texture aspect ratio (*Str*), the texture direction (*Std*) and the fastest decay correlation length (Sal). The values of these parameters are:

• for CBN hard turning: *Sds* = 581 1/mm^2, *Str* = 0.018 mm, *Std* = 89.8^0, *Sal* = 0.022 mm,

• for ball burnishing: *Sds* = 1793 1/mm^2, *Str* = 0.017 mm, *Std* = 90^0, *Sal* = 0.021 mm.

It can be reasoned, based on these data, that the surfaces treated additionally by ball burnishing are highly anisotropic (low values of *Str* parameter) with the dominant lays perpendicular to the measurement direction (*Std* values close or equal to 90^0) and the texture produced is dominated by short wavelength components in the surface topography (small values of *Sal* parameter).

Concerning the *Sds* parameter, the rule is the higher the number the asperities, the larger will be the real area of contact. In the studied case, higher number of summits recorded for burnished surfaces (1793 *vs*. 581 $1/mm^2$) documents their better bearing properties, as also depicted in Fig. 4. Waikar and Guo [9] reported that the number of peaks in a unit of sampling area measured for hard turning of AISI 52100 bearing steel with fresh CBN tools and feed of 0.0254 mm/rev is equal to *Sds* = 3996 pks/mm^2. This difference results from the number of tool traces generated at very small (0.0254/0.01" mm/rev) and higher (0.1 mm/rev) feeds employed.

Next group of functional parameters characterizes bearing and oil retention properties. The first three parameters: the surface bearing index (*Sbi*), the core fluid retention index (*Sci*) and the valley fluid retention index (*Svi*) are grouped as the "*index*" family of functional parameters. The values of these parameters are:

- for CBN hard turning: *Sbi* = 1.56, *Sci* = 1.52, *Svi* = 0.0417, *Sm* (Vm) = = 11 $\mu m^3/mm^2$, *Sc* (Vvc) = 680 $\mu m^3/mm^2$, *Sv* (Vvv) = 21.3 $\mu m^3/mm^2$, *Smr* = = 43.5 %, *Smc* = 0.69 μm,
- for ball burnishing: *Sbi* = 1.04, *Sci* = 1.17, *Svi* = 0.0825, *Sm* (Vm) = = 4.49 $\mu m^3/mm^2$, Sc (Vvc) = 287 $\mu m^3/mm^2$, *Sv* (Vvv) = 22.6 $\mu m^3/mm^2$, *Smr* = = 88.6%, *Smc* = 0.305 μm.

The *Sbi* parameter is analogous to the 2D parameter *Rpk*, hence smaller value *Sbi* = 1.04 for burnished surface indicates lower wear of peaks. For a Gaussian surface, the Sbi value is approximately 0.61. On the other hand, large value of *Sci* = 1.52 suggests good fluid retention for turned surface. For a Gaussian surface, the *Sci* value is approximately 1.56. In addition, larger value of *Svi* = 0.0825 for the burnished surface indicates good fluid retention ability in the valley zone. For a Gaussian surface, the *Svi* value is approximately 0.11. The next three parameters: the *Sm* (material volume of the surface), the core void volume (*Sc*) and the valley void volume (*Sv*) parameters are based on the 3D BAC and termed "*volume*" functional parameters. At first sight, these parameters represent volumes equivalent of the *Sbi*, *Sci* and *Svi* and their interpretations have the same (trends) meanings.

3D bearing ratio parameters includes the areal material ratio (*Smr*) and the inverse areal material ratio (*Smc*). The interpretation of the areal material ratio (*Smr*) is that its higher value indicates better bearing and wear properties. In this aspect, distinctly higher value of *Smr* = 89.2% determined for burnished surfaces confirms again their good bearing properties in comparison to hard turned surfaces for which *Smr* = 43.6%. The inverse areal material ratio (*Smc*) defines the height which gives the specified material ratio *Smr*. Hence, the material ratio *Smr* = 88.6% for the burnished surface was determined at the height of 0.305 μm, but for highly peaked turned surface the *Smr* = 43.5% was obtained at the height of 0.69 μm.

3.2. Hardness distribution

The effect of burnishing of hard turned surfaces also concerns the distribution of hardness in the subsurface layer. Figure 6 shows how hardness is distributed beneath the surface depending on the process variant.

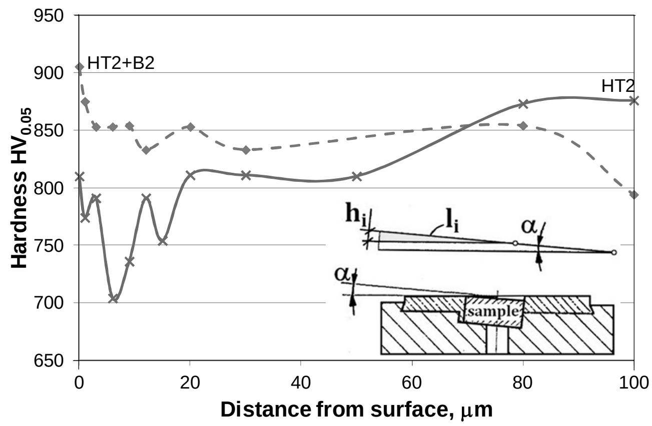

Fig. 6. Hardness distributions for hard turning (HT) and sequential (HT+BB) operations (f_t = 0.1 mm/rev, f_b = 0.075 mm/rev)

Dry hard turning causes that maximum microhardness within the sublayer is localized close to the surface and its maximum value measured directly underneath the generated surface was about $HV_{0.05}$ = 800 MPa. However, the hardness tends to decrease and at the distance of about 7 μm. The minimum value at this point of about 700 MPa. correlates well with the existence of white and dark layers. After one-pass ball burnishing (HT2 + B2), the sublayer is hardened and in consequence microhardness in the zone adjacent to the surface increases to about 900 MPa. Moreover, the dark layer is also deformed to the hardness level of bulk material (850 MPa). Some discrepancies can be also caused by measuring errors and various hardnesses of bulk materials for individual specimens. Taking these fluctuations into account, the average hardness of the bulk material is 800 ±25 MPa.

3.3. Residual stresses in the surface layer

It is well documented that residual stresses induced during machining operations influence fundamental service properties of parts, predominantly its fatigue life. In the case of sequential processes examined it is crucial to highlight how the additional burnishing action modifies the profile and the magnitude of compressive stresses induced by previous CBN hard turning. Figures 7 and 8 show the distributions of tangential and axial residual stresses induced by CBN hard turning and their changes after subsequent ball burnishing with constant pressures at p = 20 and 40 MPa [10]. The residual stresses were determined using the X-ray diffraction (XRD) method.

It can be shown in Fig. 7 and 8 that both components of residual stresses are compressive and their distributions have typical hook shapes. The characteristic feature is that burnishing causes that the maximum stresses are localized substantially deeper than after hard turning, especially when the rolling pressure was kept at p = 40 MPa. The result of the XRD measurements is that the maximum values of the tangential stresses are equal to –400 MPa (1), –900 MPa (2a) and –1300 MPa (2b). Accordingly, the values of the axial component are equal to –700 MPa (1), –850 MPa (2a) and –1600 MPa (2b). This comparison suggests clearly that ball burnishing causes additional cold working of the surface profile and increases the magnitude of compressive stresses produced by previous CBN hard turning.

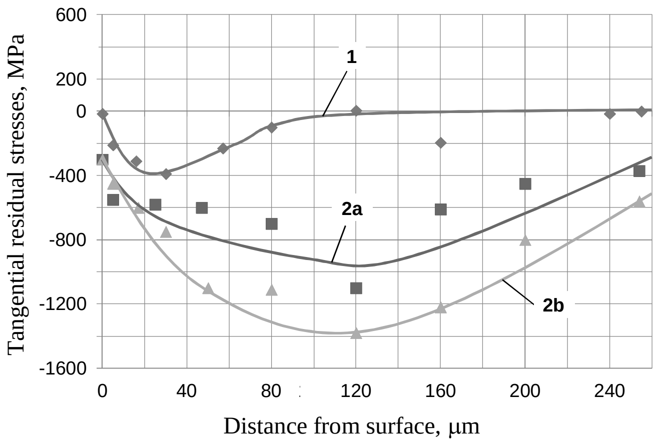

Fig. 7. Distribution of tangential residual stresses for a hard turned and burnished 41Cr4 steel after [4]: 1 – hard turning, 2a – ball burnishing at p = 20 MPa, 2b – ball burnishing at p = 40 MPa

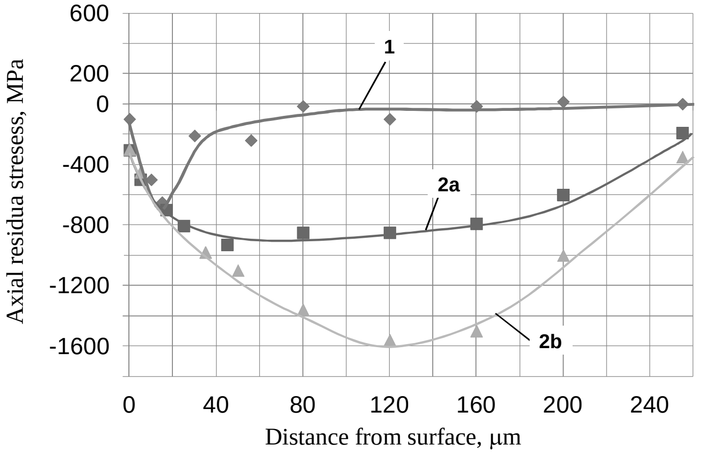

Fig. 8. Distribution of axial residual stresses for a hard turned and burnished 41Cr4 steel after [4]: 1 – hard turning, 2a – ball burnishing at p = 20 MPa, 2b – ball burnishing at p = 40 MPa

3.4. Microstructure of the surface layer

As mentioned above, quantitative microstructural analysis was performed using SEM/BSE/EDS technique [10]. Samples, which were mounted in conductive resin, were prepared by mechanical grinding, diamond polishing and electropolishing. First evidence documented was that the bulk material before burnishing has a characteristic microstructure consisting of untempered martensite.

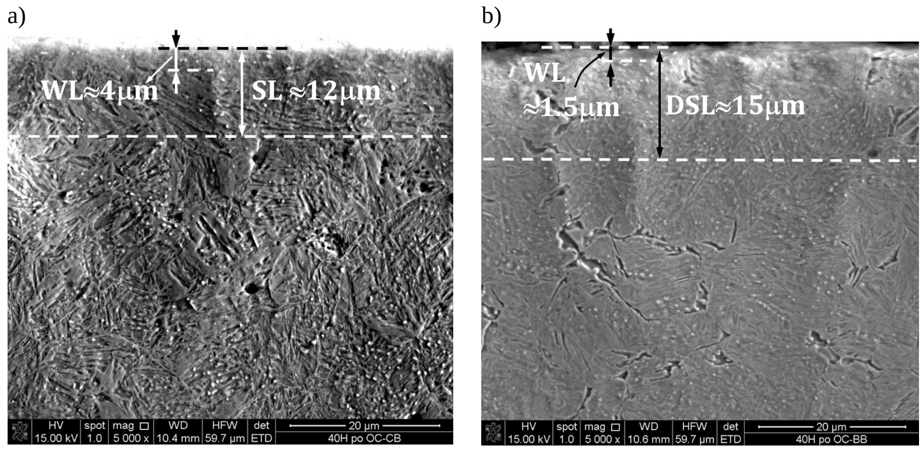

Fig. 9. Microstructures of the surface layer after: a) dry hard machining (HT2), b) sequential hard machining (HT2) and ball burnishing (B2). SE micrographs

Figure 9 shows BSE microphotographs of surface layer (SL) produced by dry hard turning (Fig. 9a) and additional ball burnishing (Fig. 9b) operations. It should be noted that the width of surface layer coincides well with microhardness distribution presented in Fig. 6. The BSE images confirm that ball burnishing causes that the thickness of the white layer (WL) is visibly diminished, from 4 to 1.5 μm due to plastic deformation of profile peaks (Fig. 9b). On the other hand, BB produced a highly deformed structure pronounced by visibly elongated grains with submicron dispersive carbides. In particular, in this case, easily noticed severely deformed surface layer (DSL) of about 15 μm thickness is observed. This image also shows martensite structure with the grain boundaries of retained austenite.

The EDS examination confirms no evidence of a chemically modified surface layer and the contents of main alloying elements (Fe, Si, Cr, Mn) correspond to data provided by steel manufacturers and metallurgists.

4. Conclusions

1. In general, ball burnishing of hard steel parts changes substantially properties of the technological surface layer.

2. Dry hard turning produced surface profiles with sharp regular peaks which are visibly flattened by subsequent ball burnishing. In consequence, surfaces with lower surface roughness, *Ra* parameter below 0.2 μm (*Rz* about 1 μm typical for precision hard machining) can be produced.

3. Surfaces additionally treated by burnishing are distinctly flattened causing better bearing properties characterized by negative values of *Rsk* parameter. In contrast, surfaces generated by dry hard turning consist of very sharp irregularities for which *Rsk* is about 0.3.

4. Burnishing reduces the thickness of the white layer. This effect corresponds to higher microhardness of about 900 $HV_{0.05}$ near the surface whereas dry hard turning measured microhardness value is about 820 $HV_{0.05}$.

5. SEM examinations of the SL revealed the presence of martensite structure with the grain boundaries of retained austenite. On the other hand, sequential (HT + B) machining produced a significantly finer crystalline structure with submicron dispersive carbides.

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