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INVESTIGATION OF SEQUENTIAL CRYOGENIC HARD TURNING AND BALL BURNISHING PROCESSES

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This paper presents a sequential machining process which incorporates CBN hard turning with cryogenic pre-cooling of the workpiece (CHT) and ball burnishing (BB). The main goal of this study was to select machining conditions enhancing the quality of parts machined by hard turning including the surface roughness Ra of about 0,2 μm, good bearing properties and reducing the white layer. Changes of surface roughness, surface texture, microstructure alterations and micro-hardness distribution are discusses.

Key words: cryogenic hard turning, ball burnishing, CBN tool, hardened alloy steel

INTRODUCTION

Modern machining processes need to be more and more effective, less costly, environmental friendly and sustainable. These criteria are often applied to hard and cryogenic machining operations as references. However, hard machining did not replace grinding operations to such extent as expected a few decades ago despite many technological advantages [1]. Relatively new technology which is capable of limiting these technological bottlenecks is sliding or roller burnishing of the hard turned or milled surfaces, using special commercial burnishing tools, for instance hydrostatic heads.

The main advantages provided by burnishing of a bearing steel of 62 HRC hardness were that the Ra parameter was reduced to 0,17 μm and the compressive residual stresses of-1600 MPa were induced into the surface sublayer [2]. The ratio of Ra_t/Ra_b (Ra_t and Ra_b are values Ra roughness parameter after turning and burnishing respectively) ranges from 1,4 to 2,4 [3].

On the other hand, sustainable cryogenic machining is extensively used to eliminate structural alterations, especially white layer formation [4]. This fact inspired authors to investigate deeply the effects of cryogenic treatment of the workpiece before ball burnishing. The preliminary assessment of technological effects resulting from ball burnishing of dry hard turned surfaces was reported by authors [5]. This study is focused on a sequential machining process which aggregates hard machining of cryogenically pre-cooled bearing steel and ball burnishing.

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EXPERIMENTAL STUDIES

Machining conditions

A series of hard machining tests (Figure 1a) were performed using 41Cr4 (AISI 5140) steel with Rockwell's hardness of 57 ± 1 HRC and low content CBN tools containing about 60 % CBN, grade CB 7015 by Sandvik Coromant, respectively. TNGA 160408 S01030 chamfered CBN inserts were used. The workpiece was cryogenically pre-cooled (Figure 1a) in a special chamber with liquid nitrogen (LN2).

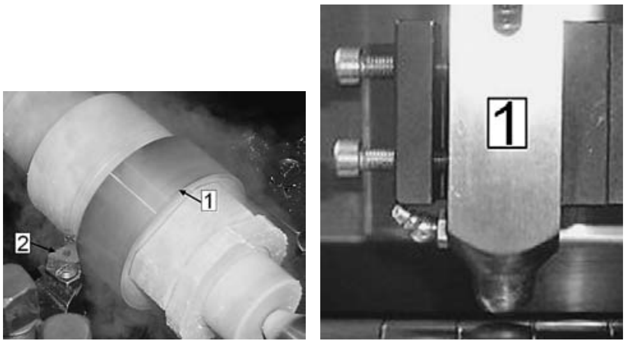
Hard turning conditions were as follows: cutting speed of 150 m/min, three feed rates of 0,075 (CHT1), 0,1 (CHT2) and 0,125 (CHT3) mm/rev, depth of cut of 0,15 mm/rev. As a result, surfaces with different values of the Ra parameter were prepared to be further finished by ball burnishing.

Roller burnishing operations were performed on a CNC turning center, Okuma Genos L200E-M, using special burnishing tool equipped with Si_3N_4 ceramic ball of 12 mm diameter shown in Figure 1b.

The desired load of about 60 N generated by controlled spring-based pressure system was equivalent to the tool correction of 0,25 mm in the CNC control system. Burnishing conditions were selected as follows: burnishing speed of 25 m/min, burnishing feed fb of 0,05 (BB1), 0,075 (BB2) and 0,1 (BB3) mm/rev, which was always lower than turning feed f_t.

Measurements of surface and subsurface characteristics

Surface profiles/topographies were recorded using a TOPO-01P contact profilometer with a diamond stylus radius of 2 μm. After their digitalization, 2D and 3D roughness parameters were estimated on the selected



a) 1-frozen workpiece, 2- cutting tool

b) 1-burnishing head, 2-turret, 3-workpiece

Figure 1 Cryogenic hard turning a) and ball burnishing b) operations

scanned areas of 2,4 mm × 2,4 mm. Micro-hardness $HV_{0,05}$ of the as-machined and polished samples across the subsurface was measured using a LECO Vickers hardness tester MHT Series 200 with a Berkovich indenter. As a result, the strain-hardening rates related to the maximum values of micro-hardness in the subsurface layer were computed.

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. These analyses were performed on mechanically and chemically polished sections.

EXPERIMENTAL RESULTS AND DISCUSSION

Surface roughness and texture

The effects of the ball burnishing of initially turned pre-cooled surfaces are shown successively in Figures 2-6.

Figure 2 presents changes of the values of the Ra and Rz parameters due to burnishing action for different feeds. The index Ra_t / Ra_b decreases from 2,47 to about 1,39 when the feed rate increases. For variant 1 (CHT1 + BB1) the minimum value of Ra = 0,17 μm was obtained. Moreover, cryogenic HT produced profiles with higher peaks disturbed by the side flow effect and burnishing is able to modify turned profiles effectively rather at smaller feeds. This effect results from increased hardness and strength as well as coarser microstructure of the freezing workpiece.

Figure 3 shows percentage changes of Rp and Rv roughness parameters which constitute the entire surface profile (Rz = Rp + Rv). For fine profile produced with the smaller turning and burnishing feeds the changes of Rp and Rv components are quite proportional (67,5 % vs. 52,1 %). On the other hand, burnishing profile with higher Rz parameter results in larger deformations of peaks than the reduction of valleys (Rv).

For instance, for subsequent operation CHT2 + BB2 the peaks were reduced by 28,8 % and the valleys only by 3,8 %. This comparison suggests that peaks are partly

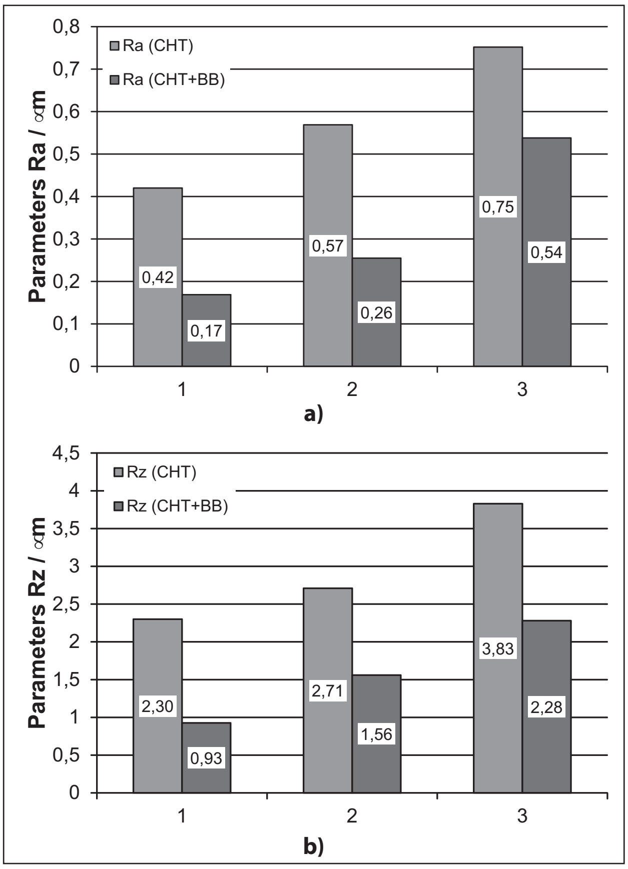


Figure 2 Comparison of Ra and Rz roughness parameters for hard turned and ball burnished surfaces, 1-f_t = 0,075 mm/rev, 2-f_t = 0,1 mm/rev, 3-f_t = 0,125 mm/rev

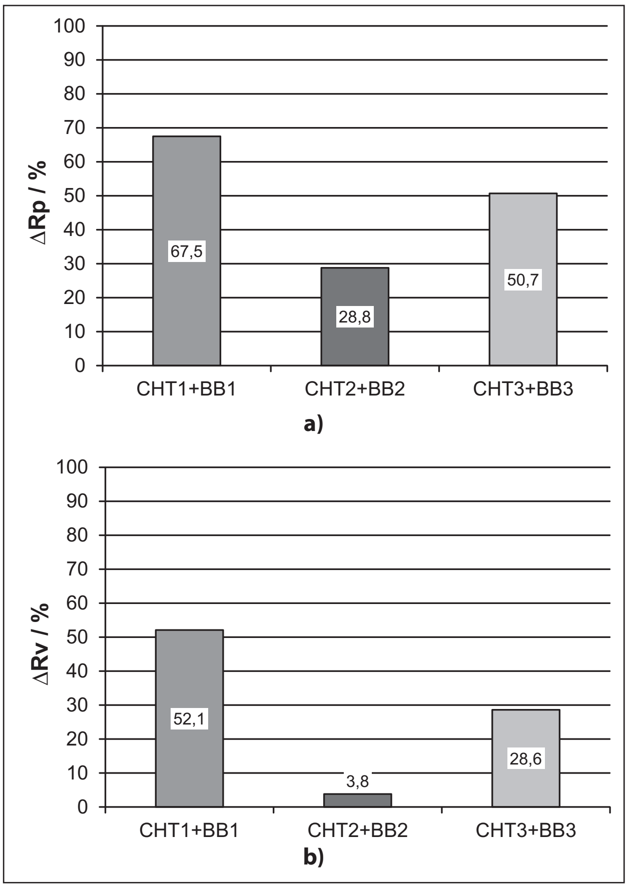
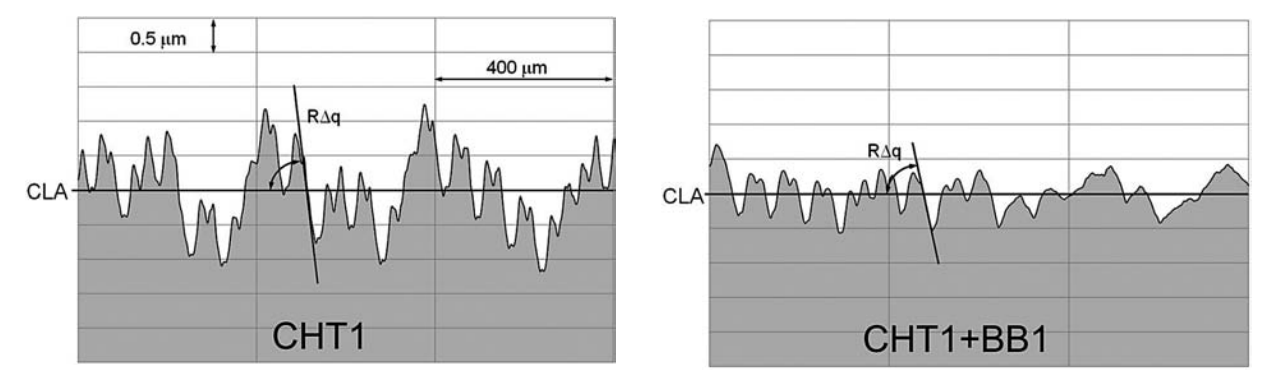
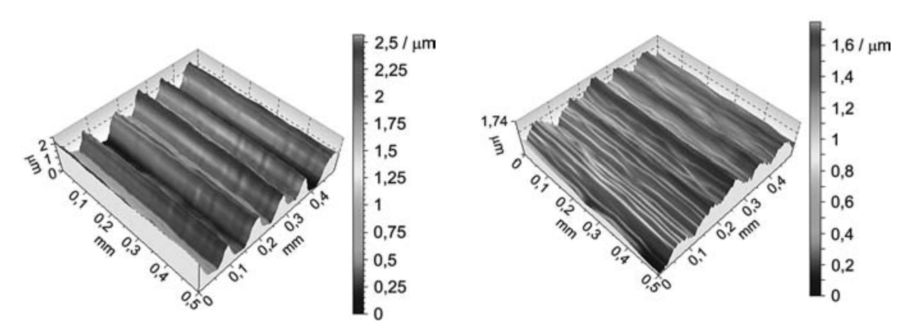


Figure 3 Percentage changes of Rp (a) and Rv (b) components of maximum profile height Rz



a) Rz = 2,30 µm, RΔq = 2,29°, RSm = 92,8 µm **b)** Rz = 0,93 µm, RΔq = 1,15°, RSm = 145 µm

Figure 4 Modifications of surface profile produced in cryogenic (a) hard turning by ball burnishing operations (b)



a) **b)**

Figure 5 Surface topographies produced in cryogenic hard turning (a) and by ball burnishing operations (b)

fractured because plastic deformations of brittle material is substantially limited (only about 29 % as mentioned above). As shown in Figure 4a burnishing produces a plateau-type of the surface profile with the bearing area curve (BAC) shown in Figure 4b. In this case the shape of the amplitude distribution function (ADF) is asymmetric and extremely shifted towards the peaks [6].

Figure 4 presents some zoomed fragments of the surface profiles produced by hard turning and ball burnishing. Cryogenic hard turning produced surface profiles (Figure 5) with non-regular tool nose traces with very small slopes RΔq of 2 - 3°. For the case of CHT1 + BB1, burnishing deforms sharp peaks within Rp height and also changes the Rsm parameter. Moreover, profile slope RΔq decreases by 1,2 - 2,0° depending on the burnishing feed. Otherwise, for higher feeds irregularities are partly spalled and severely deformed, and finally flattened.

Some representative fragments of surface topographies are shown in Figure 5. Because the profile contains asperities with different heights burnishing generates textures containing more or less fragments of uniformly deformed asperities (Figure 5b).

Figure 6 confirms that additional roller burnishing operations enhance bearing properties of hard surfaces depending on the initial cutting parameters.

Burnishing of surfaces generated in cryogenic HT causes that new surfaces profiles with negative skeweness and kurtosis between 2 and 3,5 (Figure 7) are produced.

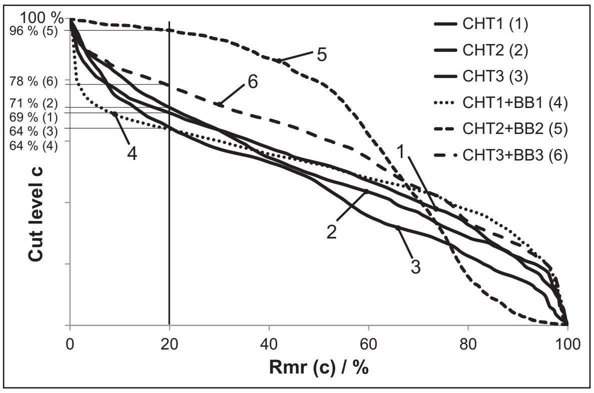


Figure 6 Material ratio curves for hard turning (CHT) and sequential (CHT+BB) operations

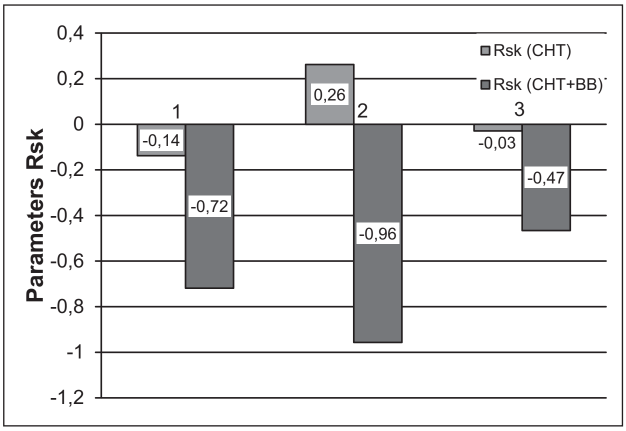
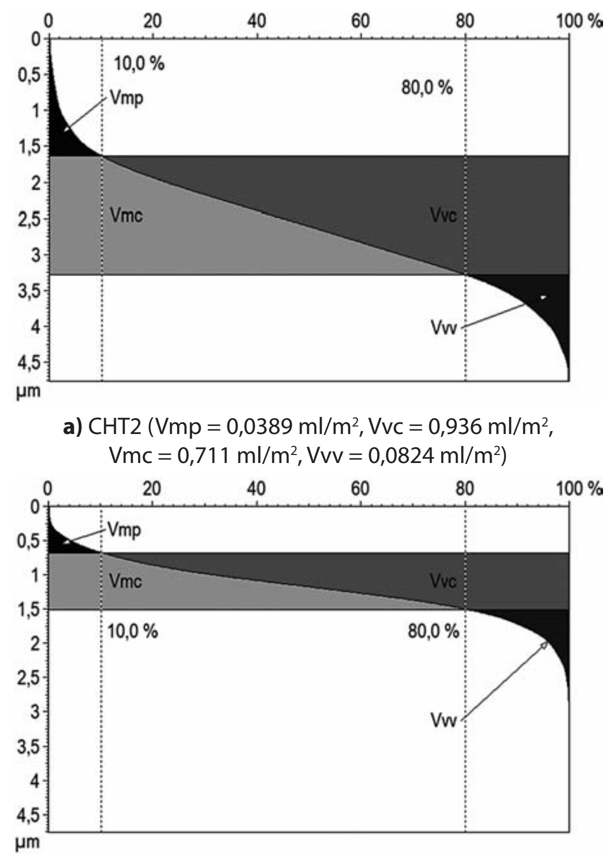


Figure 7 Skewness distributions for a range of sequential operations



a) CHT2 (Vmp = 0,0389 ml/m², Vvc = 0,936 ml/m², Vmc = 0,711 ml/m², Vvv = 0,0824 ml/m²)

b) CHT2 + BB2 (Vmp=0,0169 ml/m², Vvc=0,479 ml/m², Vmc=0,350 ml/m², Vvv=0,0579 ml/m²)

Figure 8 Volume functional parameters for cryogenic hard turning CHT2 (a) and burnishing (b) operations

It should be noted in Figure 7 that correspondingly to bearing curves # 4 - 6 shown in Figure 6 negative values of the skewness Rsk= -0,72, -0,96 and -0,47 were determined respectively. Burnishing causes reducing Rpk from 0,50 to 0,07 μm when (CHT+BB) with the feed ratio of f_t/f_b=0,1/0,075 mm/rev.

Area height distribution parameters

The functional parameters include the surface bearing index (Sbi), the core fluid retention index (Sci) and the valley fluid retention index (Svi).

Smaller value of Sbi=0,578 for turned surface indicates lower wear of peaks. On the other hand, the large value of Sci=1,53 suggests good fluid retention of the turned surface. Moreover, larger value of Svi=0,140 for the burnished surface indicates a good fluid retention ability in the valley zone.

The volume functional parameters, include the core void volume (Vvc) and the valley void volume (Vvv) parameters. Their distributions and values obtained for CHT and BB operations are presented in Figure 8. Bearing ratio parameters include the areal material ratio (Smr) and the inverse areal material ratio (Smc). Distinctly higher value of Smr=31,9 % determined for burnished surfaces re-confirms their good bearing properties in comparison to hard turned surfaces for which Smr=2,0 %.

The inverse areal material ratio (Smc) defines the height which ensures the specified material ratio Smr. In the sequential process its value is reduced from 0,98 μm and to 0,52 μm.

Moreover, the material ratio Sr1 = 10,8 % for the burnished surface was determined at the height of 0,347 μm, but for highly peaked turned surface the Sr1 = 7,49 % was obtained at the height of 0,772 μm. Values of areal parameters are: CHT2: Spk = 0,77 μm, Sk = 2,19 μm, Svk = 0,64 μm; CHT2 + BB2: Spk = 0,35 μm, Sk = 0,97 μm, Svk = 0,56 μm.

Area spatial and hybrid parameters

The burnished surfaces contain distinctly more summits - Sds = 1 996 1/mm² versus 593 1/mm² for turned surfaces. The texture aspect ratio Str is higher for burnished surfaces but its values for both operations less than 0,1 are characteristic for highly anisotropic surfaces [6]. The texture direction Std close to 90° indicates that the dominant surface lay is perpendicular to the measurement direction. The values of Sal parameter (the fastest decay autocorrelation length) obtained suggest that the burnished texture is more dominated by long wavelength unit events whereas the turned texture is dominated by short wavelength feed-marks.

The burnished surfaces contain irregularities with lower slopes Sdq - about 2,60 versus 4,20 for turned surfaces. The values of the average summit curvature Ssc of about 0,007 μm^{-1} agree with those for typical machined surfaces (0,004 - 0,03 μm^{-1}) given in [6].

Micro-hardness distribution and strain-hardening effect

In order to increase the measuring accuracy, the measurements were performed on the sections, inclined at the angle $\alpha \approx 3°$ to the outer surface as shown in Figure 9.

The distribution of micro-hardness in the subsurface layer before and after burnishing is shown in Figure 9b.

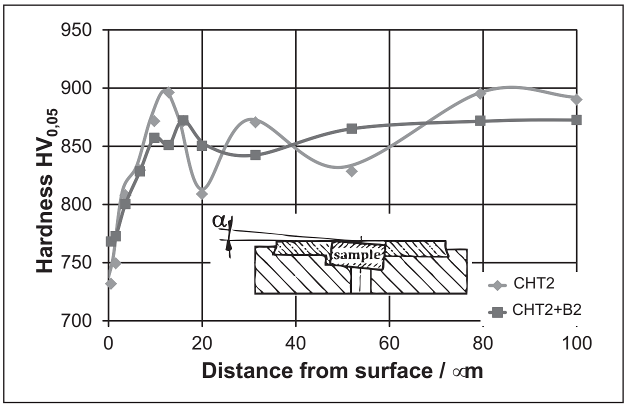
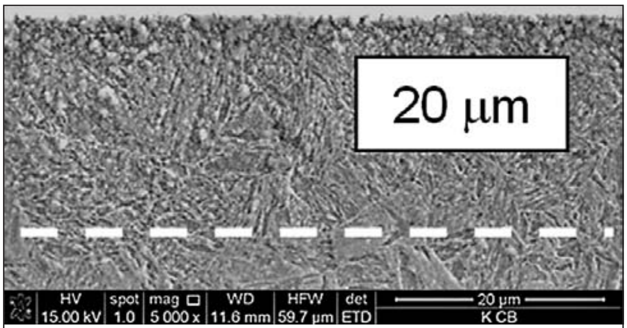
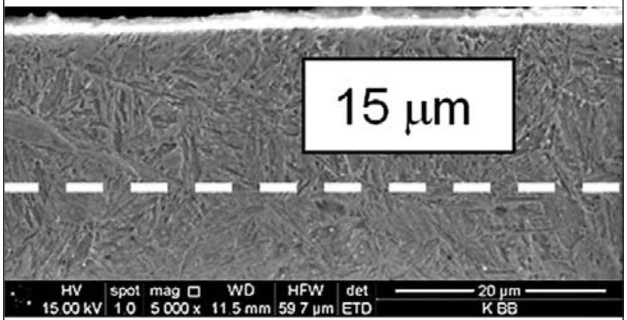


Figure 9 Sample for micro-indentation Vickers tests (a) and micro-hardness distributions (b). Feed ratio: f_t/f_b=0,1 / 0,075 mm/rev



a) cryogenic hard machining CHT2)



b) sequential CHT2 + BB2

Figure 10 Microstructures of the surface layer (SL). Magnification × 5000

Figure 10b shows that for cryogenic cooling the maximum micro-hardness is shifted beneath the surface (12 - 15 µm in depth). As a result, Vickers micro-hardness in the zone adjacent to the surface is about 740 MPa and increases slightly to 775 MPa after burnishing. This fact suggests that after cryogenic hard turning (CHT2) white layer is not produced and superficial effects resulting from ball action dominate.

The strain-hardening coefficients S_h ($S_h = (\mu HV_b - \mu HV_t) / \mu HV_t$) related to the maximum values of $HV_{0,05}$ obtained increases from about 5 % to 10 % depending on the process variant.

Microstructure and chemical composition

In this study, quantitative microstructure analysis was performed using SEM/BSE technique. Figure 10 shows BSE microphotographs of surface layer (SL) produced by cryogenic hard turning (Figure 10a) as well its modifications induced by sequential burnishing (Figure 10b) respectively. The width of SL (max. 20 µm) coincides well with microhardness distribution presented in Figure.

Moreover, the thickness of DSL in Figure 10 agrees, in percentage, with the effects of plastic deformation and reduction of Sz parameter (4,76 µm vs. 2,84 µm) due to burnishing. Again, it confirms the occurrence of brittle fractures of surface peaks.

The BSE images confirm that LIN pre-cooling of the workpiece causes that the white layer (WL) is not produced, whereas for dry HT its width is about 10 µm [5]. On the other hand, LIN machining produced a significantly coarser structure with submicron carbides.

CONCLUSIONS

1) Ball burnishing modifies both surface and subsurface layer. Additionally, cryogenic cooling of the machining zone curbs white layer formation.
2) Turned surfaces are flattened due to burnishing. High quality surfaces with Ra ≈ 0,2 µm, Rz <1 µm and Rpk ≈ 0,1 µm are produced.
3) The surface flattening results in better bearing properties of burnished surfaces. Their functional parameters are visibly favourable.
4) During ball burnishing the surface is slightly strain-hardened but micro-hardness profile remains practically the same.
5) Hardening after ball burnishing is due to the transformation of austenite into martensite.

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Note: G. Forc is responsible for English language, Opole, Poland