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COMPARISON OF SURFACE TEXTURES PRODUCED BY FINISH CUTTING, ABRASIVE AND BURNISHING OPERATIONS IN TERMS OF THEIR FUNCTIONAL PROPERTIES

The purpose of this research is to asses the functionality of surfaces produced by CBN hard turning, ball burnishing and superfinishing for improving the surface finish of parts made of high-strength, low alloy 41Cr4 steel with a hardness of about 57 HRC. Machined surfaces were characterized using 3D scanning techniques. A set of 3D roughness parameters and real 3D surface topographies produced by the above-mentioned machining operations were estimated and determined. This investigation confirms that sequential processes based on initial CBN hard turning allows producing surfaces with better service properties. The main conclusion is that this sequential technology can partly eliminate grinding operations when hard machining is not enough to produce the desired surface finish.

1. INTRODUCTION

The surface functionality becomes more important for engineering surfaces due to high demands of components produced in precision manufacturing industry. The traditional view for which a surface had to be smooth enough to perform a function, and if it is not, it either had to be reworked or rejected, is not true. Therefore, precision machining of the component surfaces must be conducted with close attention on their functionality rather than using dimension tolerances and 2D surface roughness as in conventional machining operations [1],[2]. The characterization of surface functionality should be integrated with the functional performance of the components. The continuous development of 3D surface roughness parameters allows engineers to inspect and characterize the surfaces in a compressive manner [3],[4]. In 3D surface metrology it is possible to understand how part surfaces behave when encountering their counterparts and fulfilling their various functions. The fundamental technological problem is to relate the surface functionality to process performance, as shown in Fig. 1.

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Machining of hardened materials, mainly steels, is one of the leading removal method of producing parts in such manufacturing branches as automotive, bearing, hydraulic and die and mold making sectors [5],[6]. However, this technology has several drawbacks in comparison to grinding operations including lower surface finish and unsatisfactory dimensional accuracy [6].

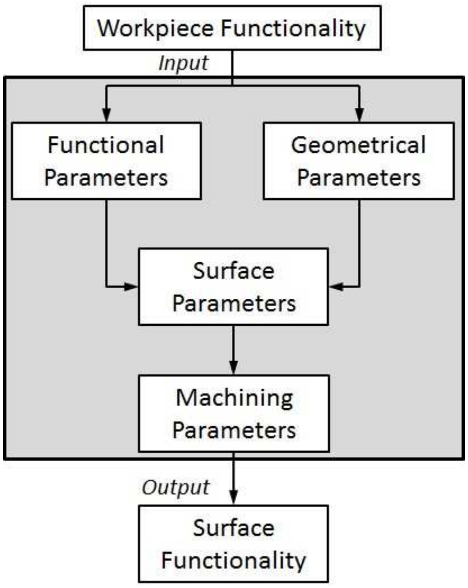


Fig. 1. Relationship between surface functionality and process parameters [2]

Tab. 1. Possible links between functional performance and roughness parameters [16]

Function	Amplitude	Spatial	Hybrid	Functional
Bearings	▲	▲	■	▲
Seals	▲	■	▲	▲
Friction	▲	▲	▲	▲
Joint Stiffness	▲	■	■	▲
Slideways	▲	▲	■	▲
Electrical/Thermal Contacts	▲	▲	▲	▲
Wear	▲	▲	▲	▲
Galling	▲	●	▲	▲
Bonding & Adhesion	▲	●	■	▲
Painting & Plating	▲	■	■	▲
Forming & Drawing	▲	▲	■	▲
Fatigue	▲		●	▲
Stress & Fracture	▲		■	▲
Reflectivity	▲	■	▲	▲
Hygiene	▲		■	▲

▲ = Much evidence ■ = Some evidence ● = Little or circumstantial evidence

Relatively new trends emerging recently in industry is to improve surface finish of hard steel materials using burnishing [8-12]. In particular, burnishing improves surface finish by deforming surface asperities and removing scratches, tool marks and pits, improves the mechanical properties (tensile strength) of surfaces and induces surface compressive residual stresses on the machined parts. The improved surface finish combined with a hardened and smoother surface resulting from strain-hardening improves fatigue strength, the wear and corrosion resistance [3]. In general, the reduction of the surface roughness by the burnishing process ranges, generally, between 40% and 90% [12]. In addition, compressive stresses are directly related to an increase in fatigue life. Moreover, better bearing properties of the burnished surfaces cause both wear resistance and contact load-carrying capacity to increase. Table 1 shows the relationships between various functional performance categories and four classes of 3D roughness parameters. However, the table does not show scale, magnitude, repeatability or variability. On the other hand, it is evident that the significant importance has both amplitude and functional parameters (they are refer to the first and fourth columns). In particular, friction and wear of machined surfaces depend on all roughness parameters.

In this study the focus was made on the correlations between 3D surface texture produced by sequential machining operations including dry hard turning, ball burnishing and superfinishing operations and service properties of the machined surfaces.

2. EXPERIMENTAL DETAILS

2.1. CHARACTERIZATION OF MACHINING OPERATIONS

Machining operations involved in this investigation were performed using conditions shown in Table 2. Schemes of the three machining operations are presented in Fig. 2. Hard machining trials (Fig. 2a) were performed on the specimens made of 41Cr4 (AISI 5140) steel with Rockwell's hardness of 57±1HRC using CBN tools, grade CB7015 by Sandvik Coromant. Hard turning (HT) conditions were as follows: cutting speed of 150m/min, feed rate of 0.1mm/rev, depth of cut of 0.15mm.

Tab. 2. Specifications of HT, BB and SF operations

Dry hard turning		Ball burnishing		Superfinishing	
Feed rate f_t, mm/rev	Code	Feed rate f_b, mm/rev	Code	Feed rate f_{sf}, mm/rev	Code
0.10	HT	0.075	B	0.10	SF

Ball burnishing (BB) was performed using a special burnishing tool with controlled spring-based pressure system to generate the desired load, equipped with Si_3N_4 ceramic ball of 12mm diameter, as shown in Fig. 2b. The burnishing head was mounted in the turret of a CNC turning centre and the burnishing operation was integrated with the CNC program for CBN turning. Burnishing conditions were as follows: burnishing speed of 25m/min, burnishing feed f_b of 0.075mm/rev and the tool correction of 0.25mm in the CNC control system, constant load about 600N. Both hard turning (HT) and ball burnishing (BB) operations were performed on a CNC turning centre, Okuma Genos L200E-M. The superfinishing (Fig. 2c) was performed on a precision lathe using a special superfinishing head with its own power supply. Superfinishing conditions were as follows: v_c=26m/min, f=0.1mm/rev and t≈45min. The oscillation frequency was equal to 680 cycles/min. Honing stone reference was 99A320N10V.

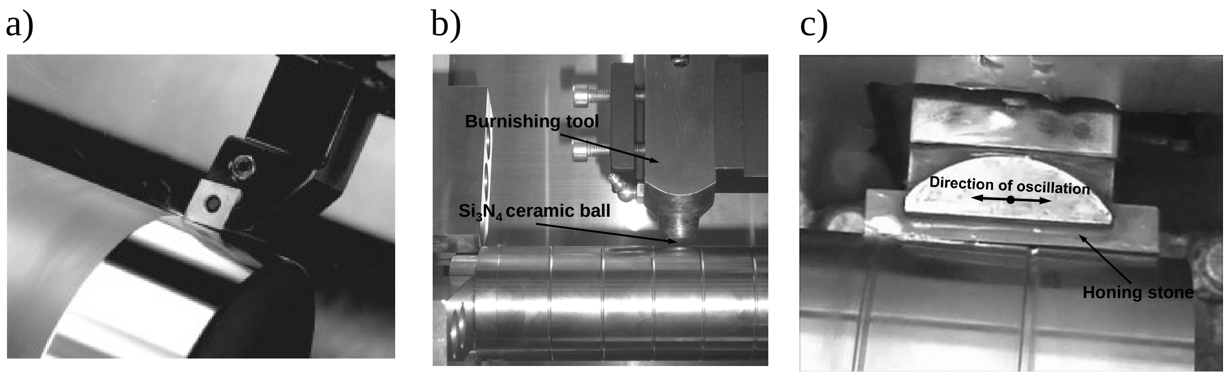


Fig. 2. Three machining operations used in the technological sequences tested in this study: a) hard turning, b) ball burnishing, c) superfinishing

2.2. MEASUREMENTS OF 3D SURFACE ROUGHNESS

Rings of about 40 mm in width were used to reduce the specimen mass which is necessary to measure 3D surface roughness on a 3D profilometer. Surface profiles/ topographies were recorded and 3D roughness parameters were estimated on the scanned areas of 2.4mm×2.4mm by means of a TOPO-01P profilometer with a diamond stylus radius of 2µm. The 3D visualization of machined surfaces was performed using the Digital Surf Mountains® Map package.

Nowadays, 3D roughness parameters are normalized by ISO 25178 and EUR 1517EN because surface topography generated by precision machining is critical for surface functionality and component performance. ISO 25178 [13] is the first international standard taking into account the specification and measurement of 3D surface texture. In particular, the standard defines 3D surface texture parameters which are written with the capital letter S (or V) followed by a suffix of one or two small letters. They are: height parameters, spatial parameters, hybrid parameters, functions and related parameters and parameters related to segmentation (when the surface is segmented into motifs).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. GEOMETRICAL CHARACTERIZATION OF MACHINED SURFACES

In general, hard turned surfaces have specific geometrical features with very sharp, regularly distributed asperities. On the other hand, ball burnishing of the hardened workpiece flattens the surface and changes the mechanical properties of both the surface and subsurface layer. Moreover, superfinishing gives the surface a different texture and lays and minimizes the heights of asperities. Figures 3-9 presents integrally the geometrical state of the surfaces produced by hard turning and two sequential processes.

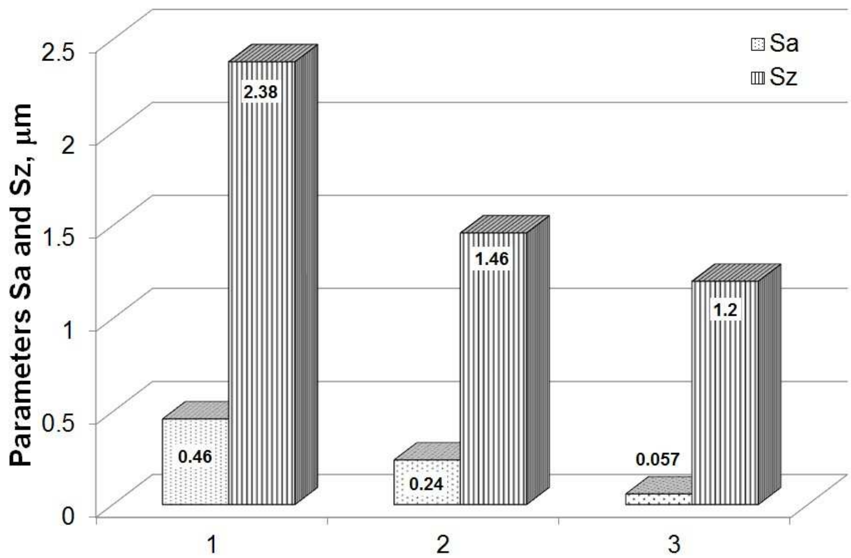


Fig. 3. Comparison of Sa and Sz roughness parameters for HT (1) HT+B (2) and HT+SF (3) sequences

Figure 3 presents the obtained values of the Sa and Sz parameters for the three machining cases. First, dry hard operation with a feed rate of 0.1 mm/rev results in the Sa parameter to be 0.46µm. In addition, such surface roughness was found to be optimal for subsequent burnishing operations [8],[9]. The second observation is that the Sa parameter decreases due to burnishing action to about 0.2µm, which is in precision machining range. This means that the ratio of Rat/Rab is equal to approximately 2µm. Moreover, superfinishing produces a very smooth surface with Sa equal to 0.06. As can be seen in Fig. 3 the values of Sz obtained after ball burnishing are about 50% lower than for initial dry HT operations. After superfinishing the maximum peaks are removed and Sz is about 1.2µm.

Fig. 4 shows representative topographies generated by hard turning and sequential processes using two different scales. In order to magnify the individual asperities a small area of 350µm $\times$ 350µm was cut from a larger area of 1.2mm $\times$ 1.0mm.

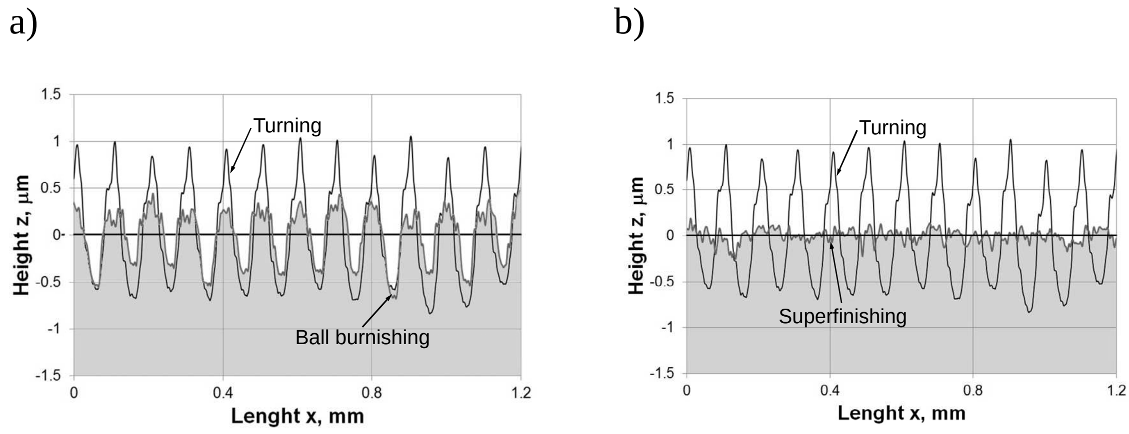
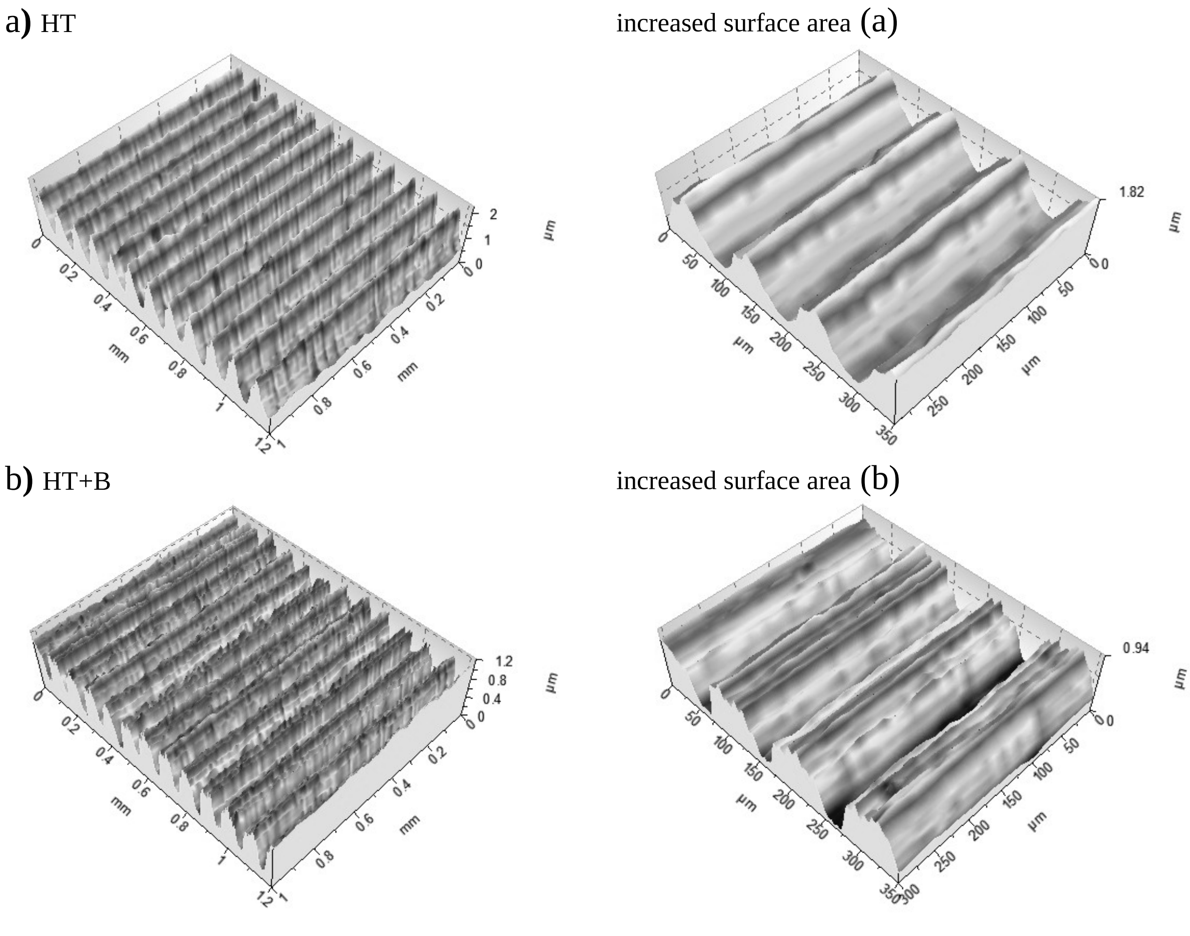


Fig. 4. Examples of surface profiles produced in sequential machining operations: a) HT+BB, b) HT+SF

It can be observed that burnishing causes the irregularities to become smoother without local micro-peaks and lateral flashes visibly increase. On the other hand, superfinishing induced crossing lays and irregularities are visibly flattened. All images show surfaces consisting of well-defined peaks and valleys but their stereometrical features are substantially different.



c) HT+SF increased surface area (c)

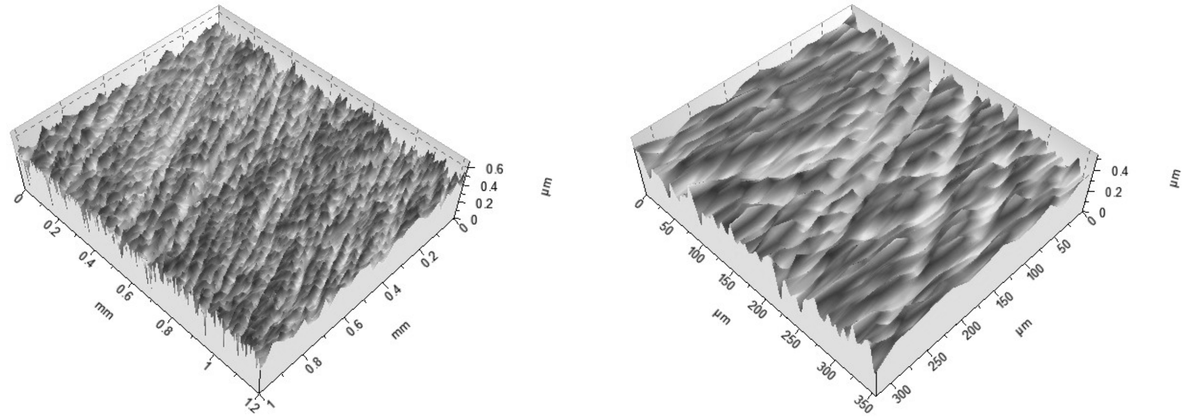


Fig. 5. Surface textures produced in dry hard turning (a), burnishing (b) and superfinishing (c) operations

It was found that dry hard turning produced surface profiles with very sharp and regular tool nose traces, for which the Rsm parameters are almost equal to the feed value, with very small slopes Sdq = 0.0375. On the other hand, BB and SF operations produced surfaces with lower blunted peaks, with Sdq= 0.0285 and 0.0193 respectively. The burnishing effect results partly from both plastic deformation and spalling (brittle fracture) of the hard micro-regularities, as in Fig. 4a. As a result, the regularity of the profile is disturbed visibly, especially for the highest feed rate f_b employed. The finishing effect of superfinishing is caused by abrasive action of small ceramic grids.

The bearing properties of machined surfaces can be differentiated by means of the distribution of Sk, Spk and Svk parameters as shown in Fig. 6 and the values of skewness Ssk as shown in Fig. 9. Fig. 6a confirms that CBN hard turning produces profiles with unsatisfactory bearing properties.

As depicted in Fig. 6a the BAC are linear-degressive type with very high Spk value (Fig. 7). On the other hand, as shown in Figs. 5b and 6, burnishing generates surfaces with very high Svk value. In contrast, superfinishing produces surfaces with both minimum Spk and Svk values. It should be noted that the reduced peak height implies distinctly shorter running-in periods during part service and higher Svk leads to better fluid retention when matting surfaces are lubricated.

Correspondingly to the bearing curves shown in Fig. 7 positive or negative values of the skewness were determined, namely Ssk= 0.14, -0.53 and -1.03 (Fig. 8). These Ssk values suggest that surface profiles generated by sequential CBN turning and ball burnishing processes have better bearing properties. Otherwise, surfaces with sharp irregularities produced by dry hard turning have better locking properties. In addition, kurtosis Sku near 2 obtained after burnishing means that the profiles are congregated at the extremes (they are described in tribology as platykurtic).

Hard turning generated worse bearing properties of surfaces when compared to those obtained after ball burnishing and superfinishing; this may be due to lower values of upper material ratio Sr1. For the three machining cases used they are equal to: 21.4% (HT), 3.43% (HT+BB) and 7.31% (HT+SF), as depicted in Fig. 6.

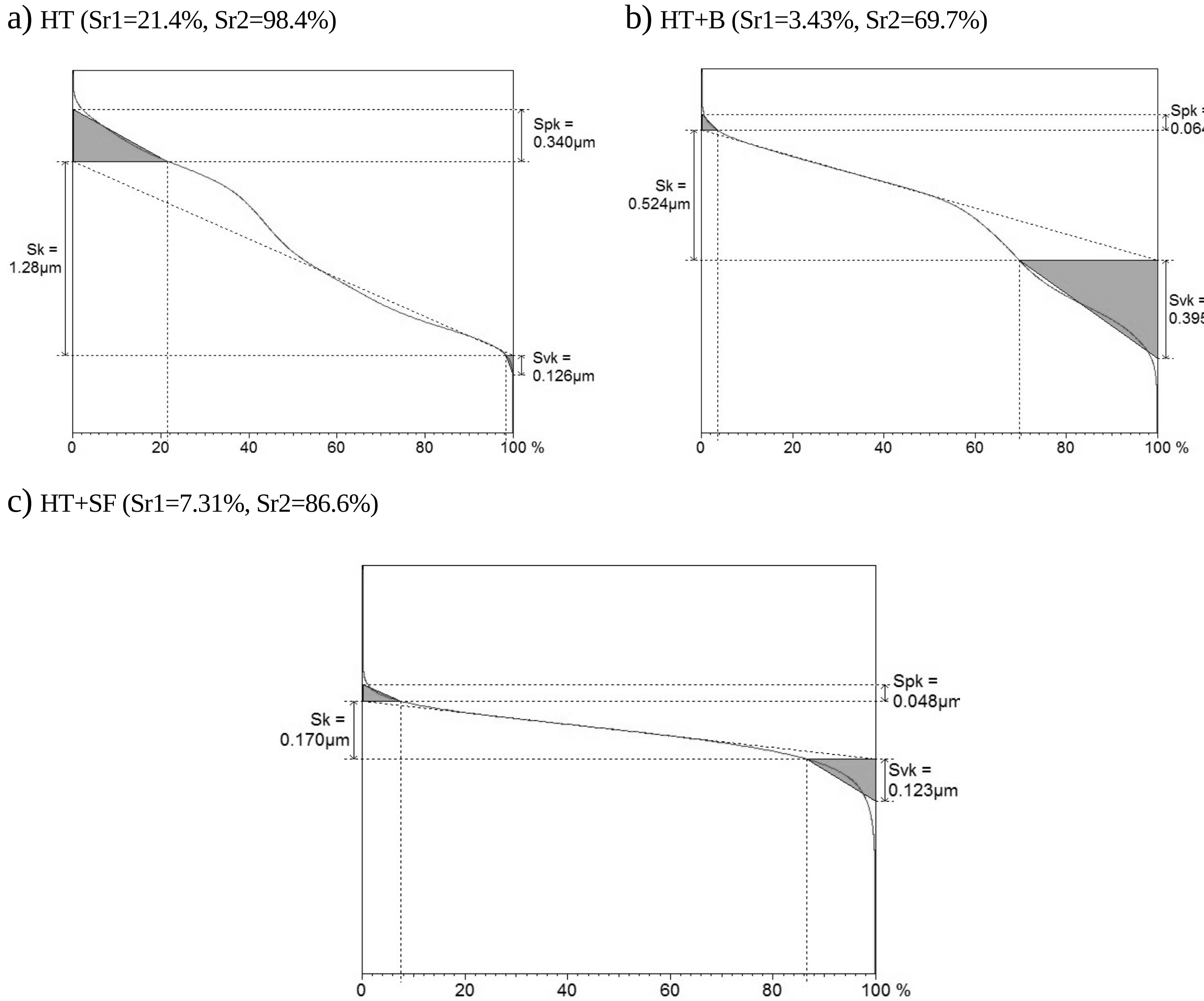


Fig. 6. Bearing curves produced in dry hard turning (a), burnishing (b) and superfinishing (c) operations

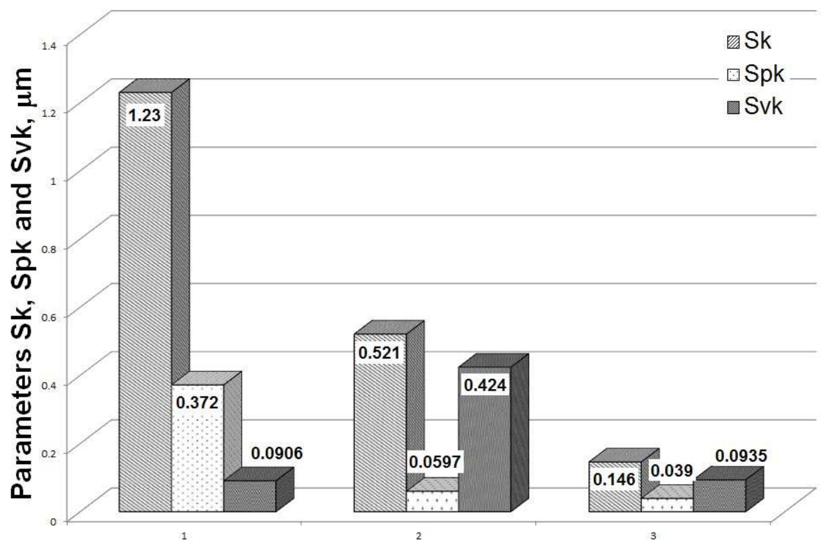


Fig. 7. Distribution of Sk, Spk and Svk parameters for hard turned, burnished and superfinished surfaces.
1-HT; 2-HT+B; 3-HT+SF

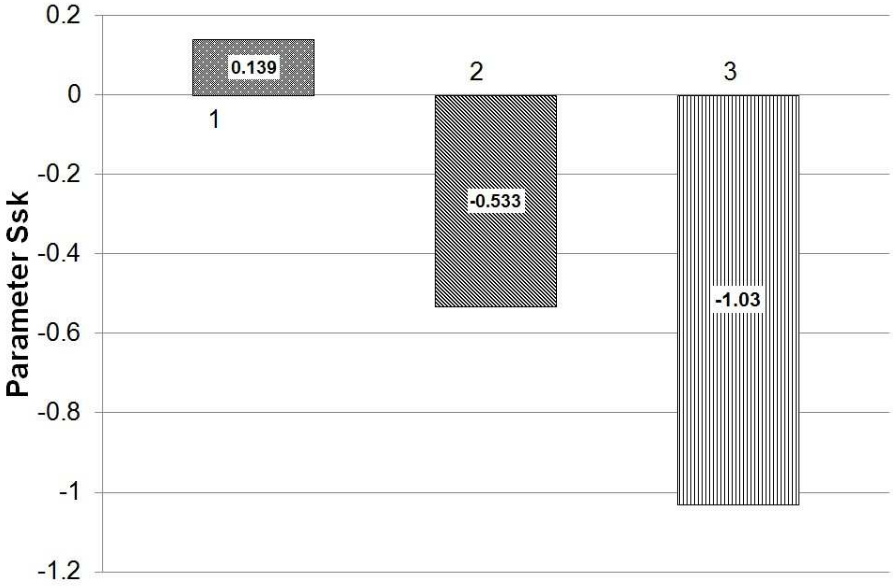


Fig. 8. Values of skewness Ssk for hard turning and burnishing operations.
1-HT; 2-HT+B; 3-HT+SF

3.2. FUNCTIONAL CHARACTERIZATION OF SURFACE TEXTURES

Capturing functionally relevant characteristics of surface topography is a challenging task, especially for a new machining technology. Obviously, 2D parameters are insufficient to represent satisfactorily the surface performance. Typically, it can be assessed in terms of topographic measurements aggregated over the complete surface generated.

3.2.1. AREA HYBRID PARAMETERS

In general, the values of 3D (area) height and amplitude parameters are close to their 2D equivalents. In addition, two area hybrid parameters appear including the developed interfacial area (Sdr) and the mean summit curvature (Ssc). Stout and Blunt [14] quote curvatures for typical machined surfaces in the range 0.004 to 0.03μm^{-1}.

The values of the Ssc parameter are equal to about 0.005 μm^{-1}, 0.008 μm^{-1} and 0.007 μm^{-1} for turned, burnished and superfinished 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%, 0.0407 % and 0.0186% for turned, burnished and superfinished surfaces). Its higher values for the turned surface result from the fact that it contains high peaks and deep valleys (see Figs. 4 and 6). In comparison, the Lpr parameter of most engineered surfaces is typically less than 1.01 [3]. In both the surfaces analysed, Sdr is also less than 1%.

3.2.2. AREA SPATIAL (TEXTURE) PARAMETERS

ISO 25178 (also the B14) parameter set includes four spatial, termed also "*texture*", 3D parameters. These are the density of summits (Sds), the texture aspect ratio (Str), the texture direction (Std) and the fastest decay correlation length (Sal). According to the data obtained, the surfaces generated by hard turning and subsequently modified 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-0.022 vs. 0.021mm for turned and burnished surfaces). For surfaces produced by HT+SF sequential operations these parameters are: Str=0.128 (anisotropic-isotropic surface), Std=112^0 (crossing lays), Sal=0.0117mm (dominated short wavelength components in the frequency spectrum).

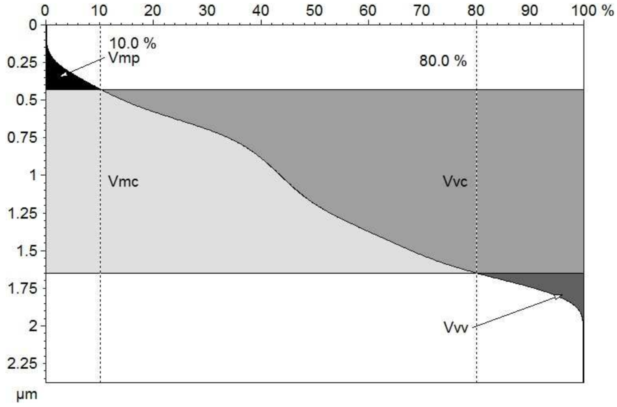
Concerning the Sds parameter, the rule is that the higher the number the asperities, the larger will be the real area of contact. In this comparison, the greater number of summits recorded for burnished surfaces (1793 *vs*. 581 1/mm^2) documents their better bearing properties, as also depicted in Fig. 5. Moreover for surfaces produced by superfinishing Sds= 3421 1/mm^2 which indicates exceptionally good bearing properties. It is reported [15] 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 0.0254mm/rev is equal to Sds=3996pks/mm^2. This difference results from the number of tool traces generated at very small (0.0254mm/rev) and higher (0.1mm/rev) feeds employed.

3.2.3. AREA HEIGHT DISTRIBUTION PARAMETERS

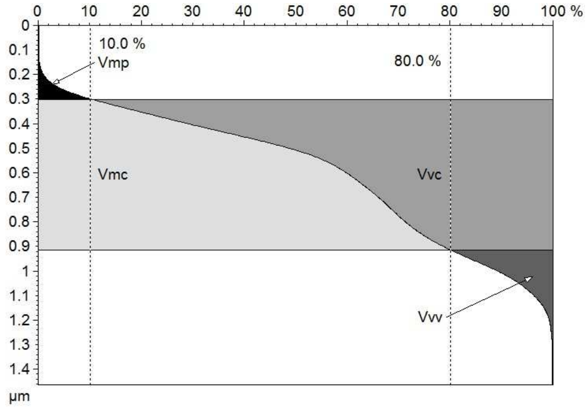
The next group of functional parameters characterizes bearing and oil retention properties. The first three parameters: the surface bearing index (Sbi), the core fluid retention index (Sci) and the valley fluid retention index (Svi) are grouped as the "*index*" family of functional parameters. The Sbi parameter is analogous to the 2D parameter Rpk, hence smaller value Sbi=1.04 for burnished surface and Sbi=0.195 after superfinishing indicate 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. Moreover, a larger value of Svi= 0.0825 for the burnished and Svi=0.158 for superfinished surface indicate good fluid retention ability in the valley zone. For a Gaussian surface, the Svi value is approximately 0.11.

The next three parameters: the material volume of the surface (Sm orVm), the core void volume (Sc or Vvc) and the valley void volume (Sv or Vvv) 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 meanings. Their distributions and values obtained for HT and (HT+BB) and (HT+SF) operations are presented in Fig. 9.

a) HT ($Vmp=0.0108 ml/m^2$, $Vvc=0.679 ml/m^2$, $Vmc=0.547 ml/m^2$, $Vvv=0.0212 ml/m^2$)



b) HT+B ($Vmp=0.0044 ml/m^2$, $Vvc=0.285 ml/m^2$, $Vmc=0.331 ml/m^2$, $Vvv=0.0225 ml/m^2$)



c) HT+SF ($Vmp=0.00256 ml/m^2$, $Vvc=0.0756 ml/m^2$, $Vmc=0.0622 ml/m^2$, $Vvv=0.0119 ml/m^2$)

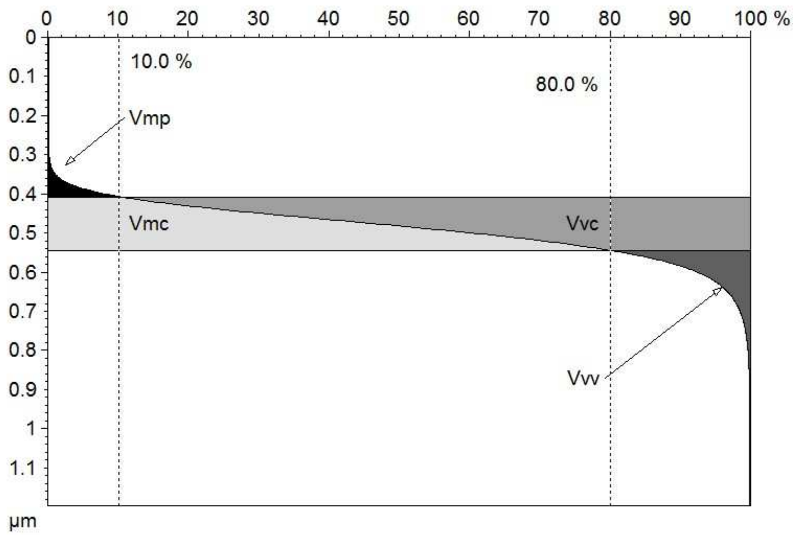


Fig. 9. Volume functional parameters for hard turning, burnishing and superfinishing operations: a) HT, b) HT+B, c) HT+SF

3D bearing ratio parameters include 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% and 100 % determined for burnished and superfinished 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 0.305µm, but for highly peaked turned surface the Smr=43.5% was obtained at the height of 0.69µm. For superfinishing Smr= 100% corresponds with the height of 0.085µm.

4. CONCLUSIONS

The following conclusions can be drawn from this study:

1. Ball burnishing of the hard workpiece results in substantial modifications of surfaces and their functionality.
2. Dry hard turning produced initial surface profiles with regular tool nose traces and surface roughness with the Ra=0.5μm which was reduced to about 0.2μm by ball burnishing and to about 0.06μm by superfinishing (Sz about 1μm m typical for precision machining).
3. Surfaces produced by sequential (HT+BB) and (HT+SF) machining process are distinctly flattened causing better bearing properties, correspondingly to negative values of Ssk=-0.5 and -1.0 respectively.
4. 3D bearing ratio parameters confirms again good bearing properties of burnished and superfinished surfaces in comparison to hard turned surfaces. Moreover, this fact and better wear resistance is supported by greater number of summits (Sds parameter) recorded for burnished and superfinished surfaces.
5. Analysis of Sci and Svi texture parameters reveals good fluid retention in the core area for turned surface as well as good fluid retention ability in the valley zone for both burnished and superfinshed surfaces.

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Nomenclature

Sa - arithmetic mean deviation	Sr1 - upper material ratio
Sz - ten point height of the surface	Sr2 - lower material ratio
Sku - kurtosis	Sal - auto-correlation length
Ssk - skewness	Sbi - bearing index
Sk – kernel roughness depth (roughness depth of the core)	Sci - core fluid retention index
Spk – reduced peak height (roughness depth of the peaks)	Sv - maximum pit height
Svk - reduced valley depth (roughness depth of the valleys)	Svi - valley fluid retention index
Sdq - root-mean-square slope of the surface	Smc - inverse areal material ratio
Ssc - arithmetic mean summit curvature of the surface	Smr - areal material ratio
Sdr - developed interfacial area ratio	Vm - material volume
Sds - density of summits	Vvc - core void volume of the scale limited surface
Str - texture aspect ratio	Vvv - pit void volume of the scale limited surface
Std - texture direction	