Surface integrity of hardened steel parts in hybrid machining operations

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ABSTRACT

Purpose: Purpose of this paper is the investigation of surface integrity generated in hard turning and subsequent finish abrasive machining. The primary reason for undertaking this problem was insufficient magnitude of compressive residual stresses after hard turning which determines the fatigue resistance of highly loaded transmission parts.

Design/methodology/approach: Methodology employed uses 2D and 3D description of the surface roughness/surface microstereometry and the X-ray diffraction method for measurements of residual stresses. The main scope of this research program is to record the relevant changes of surface layer features resulting from the application of finish abrasive passes.

Findings: Findings can be distinguished into two groups. First, finish belt grinding produces the residual stresses with the maximum value of –1000 MPa, which is satisfactory for improving fatigue life. Second, the bearing properties improve due to displaying negative values of the skew.

Research limitations/implications: Research limitations deal with the identification range of 3D roughness parameters and the lack of modern equipment for robust measurements of residual stresses. Future research should be focused on the stronger correlation between technological and exploitation properties of the surfaces produced by hard and abrasive technologies. However, it needs more detailed inputs from automotive industry.

Practical implications: Practical implications are related to the automotive industry, especially to manufacturers of such transmission elements as synchronizing cones/planes on gear wheels. The sequences of new hybrid machining processes are partly verified in terms of industry needs (machining conditions, machine tools, special equipment, cutting and abrasive tools).

Originality/value: Originality of this industry–oriented contribution is based on the aggregating hard cutting and abrasive machining processes. The practical value of the paper is that it proposes a very beneficial machining process for highly loaded hardened parts.

Keywords: Machining; Hybrid process; Surface roughness; Residual stress

1. Introduction

Hard turning (HT) of steel workpieces harder than 60 HRC with mixed ceramic and PCBN cutting tools can be essentially performed as rough, precision, and high precision operation when the Rz parameter is less than 1 µm [1,2]. Precision finishing of hardened steel components using superhard cutting tools offers manufacturers an attractive alternative to traditional grinding. In particular, it can often cut manufacturing costs, decrease production time, and improve overall product quality [1-4].

According to many industry reports, hard machining (HM), sometimes termed as hard part machining (HPM), covers both turning and milling, generally semi-finishing and finishing, operations. Gears and axles, and bearing components are typically
transferred parts, while milling is preferable in the die and mold industry [4].

Many previous investigations of surface finish in HT operations with mixed ceramic and low content CBN (CBN-L) tools documented only achievable values of the Ra parameter about 0.2-0.3 µm under optimal cutting conditions [5,6]. First, complex multi-parameter 2D and 3D analysis of the surface finish after hard turning has been done by Klocke et al. [1] and Grzesik and Wanat [7]. One of the fundamental findings of this research is that hard turning and grinding produce different surfaces related to the form of profile and topography structure. In particular, surfaces with negative skewness (Rsk<0), which indicates better bearing properties, can be obtained in hard turning.

Despite many advantages of HT technology, the resulting surface integrity on high performance materials is often not sufficient for strong demands dealing with fatigue life or pitting resistance. In these aspects the following limitations of single-point hard turning can be distinguished, namely [1,8-12]:

- low magnitudes of compressive residual stresses, the process-induced white layer which can lead to substantial variations in component service performance, and dimension, geometric form and surface roughness errors resulting from tool wear.

In conventional grinding-based technology, superior surface quality and fatigue strength of gears, bearing rings, crankshafts, camshafts, etc. is usually obtained by microfinishing, superfinishing or honing. When using hard turning, special abrasive finishing processes such as CBN grinding and belt grinding are proposed for machining synchronizing cones/planes on gearwheels [8,13]. As reported [8,13], additional belt grinding allows generating higher compressive tangential residual stresses localized at the distance of a few microns from the surface, and removing partly or completely white layer.

So far, surface finish after hybrid processes have not been studied. Therefore, the paper deeply investigates surface finish on the hardened bearing steel parts produced by hard turning operations, and that resulting from additional abrasive operations.

2. Experimental program

2.1. Machine tools and machining conditions

In this study, CBN turning was carried out on an ultra-precision facing lathe with special construction features, such as granite body, the thermally controlled, direct tool clamping on the table, and the chuck and jaws with improving rigidity and accuracy. A CNC lathe was equipped with Siemens 840D control system in order to reduce the displacement down to 0.1 µm. The triangular 60% CBN (Sandvik’s 7020 grade) inserts were used in these hard turning tests, named as HT1. The cutting edges of each tip were prepared to produce a chamfer with 0.1 mm width, –20° inclination angle, and the honing radius of 0.05 mm. Cutting parameters used were:

- cutting speed \( v_c = 100 \) m/min, feed rate \( f = 0.1 \) mm/rev, and depth of cut \( a_p = 0.3 \) mm. For comparison, hard turning operations (HT2) with mixed ceramic (Sandvik’s CC650 grade) tools [7,14,15] were carried out on a precision conventional lathe. In this case cutting speed \( v_c = 115 \) m/min, feed rate \( f = 0.1 \) mm/rev, and depth of cut \( a_p = 0.3 \) mm.

In the first variant, belt grinding operations with 30µm (BG1) and 9 µm (BG2) grains were performed after PCBN turning (HT1) on a special device mounted on the lathe during 9 sec under MQL conditions [8]. The process conditions were as follows:

- rotation speed of the workpiece of 900 rev/min, belt feed of 0.6 mm/s, 2 bars pressure between the workpiece and the belt, axial oscillation of 12 Hz and 1 (±0.5) mm in amplitude.

In the second variant, the turned surfaces (HT2) were abrasively finished with 29µm grain stones (reference 99A320N10V) using coolant containing 85% kerosene and 15% machine oil. During superfinishing (SF) the oscillation frequency of 680 osc/min; applied force of 40N and amplitude of 3.5 mm were kept.

2.2. Measurements of surface roughness

A set of the 2D and 3D roughness parameter measurements was carried out by means of a TOPO 01P profilometer with a diamond stylus radius of 2 µm [7,14]. The scanned areas of 4x0.8 mm and 1.25x1.25 mm were selected. Cut-off length was set to 0.8 mm (the evaluation length was equal to \( l_p = 4.8 \) mm) and 0.25 mm (corresponding \( l_p = 1.5 \) mm) according to ISO 4288, and the ISO 2CR filter was selected. In summary, selected height (Ra,Rz,Rp,Rq,Rsk), profile height distribution (Rsk,Rku,Rmr(c)) and profile topography were measured. Correspondingly, in order to reflect the specific properties of the surfaces generated, amplitude distribution functions (ADFs), bearing area curves (BACs), surface topographies, and contour maps for the four surface types selected were determined.

2.3. Measurements of residual stresses

The residual stresses were measured using an X-ray diffractometer. It was a Philips X’Pert MRD system with a horizontal, high-resolution Ω-20 goniometry [16]. The biaxial residual stress with tangential (σt1) and axial (σt2) components was considered as shown in Fig. 1.

![Fig. 1. Scheme of residual stress resolution in the specimen](image-url)

This apparatus was operated at 40 kV tension, 40 mA current (1.8 kW) using CrKa radiation (λ=2.2897Å) and Bragg-Bretano configuration. The Ψ tilts were achieved with Ω-goniometry, tilting in the diffraction plane. Residual stresses were measured at the surface and at different depths by successive etching ultra-thin stressed layers up to 200 µm. The RIM (X-ray Integral Method)
was used to calculate residual stress depth profiles with accuracy of ±60 MPa.

3. Experimental results and discussion

3.1. Height and spacing roughness parameters

In this section, the changes of the selected roughness parameters SRa, SRz, SRp, SRv, Rsm and R∆q, resulting from single hard turning operations and additional finishing abrasive processes, were successively illustrated in Figures 2 and 3.

Figure 2 shows that both hard turning processes (bars 1 and 3) generate surfaces with average values of SRa (Ra) parameters about 0.35(0.3) and 0.45(0.4) µm respectively. On the other hand, belt grinding (2) and honing (4) reduce them to the values of 0.02 (0.02) and 0.35(0.3) µm.

The SRz (SL peak to valley height) and its two components SRp (maximum peak height) and SRv (maximum valley height) are shown in Figure 3. This diagram clearly depicts that the partition of SRp and SRv components in the total profile height changes distinctly depending on the process variant applied.

![Fig. 2. Comparison of Ra and SRa parameters for HT1 (1), HT1+BG1,2 (2), HT2 (3) and HT2+SF (4) operations](image)

For example, profiles produced by HT2 operations (3) contain lower peaks and deeper valleys, whereas those obtained in PCBN turning (HT1) have higher peaks and lower valleys. In particular, the final application of 9 µm belt grinding causes the ratio of SRp (0.15 µm) to SRv (0.30 µm) to be equal 0.5 (after previous turning it is about 1.5). After honing (4), the SRz parameter decreases to 0.3 µm but the ratio of SRp/SRv increases from 0.7 to about 1.

The average spacing parameter RSm decreases substantially after both belt grinding operations, from 62.5 µm down to 20.5 µm for the operations with finer grains. In contrast, honing operations reduce the peak spacing recorded after HT with ceramic tools about 20% (79.5 µm vs. 62.5 µm). Moreover, both finish abrasive processes cause the R∆q decreases and oscillates slightly about 4°.

3.2. 3D visualizations of surfaces

Typical topographies of the scanned machined surfaces are shown in Figures 4 and 5. For these examples the 3D roughness parameters were the same as reported in Section 3.1.

![Fig. 4. Isometric view of surface machined with CBN tools- HT1; SRa=0.35µm](image)

By analogy to the surface profiles, corresponding topographies produced by CBN (Figure 4) include visible regular sharp peaks. In contrast, the modified surface presented in Figure 5 contains randomly distributed extremely small irregularities of SRz=0.45µm.

![Fig. 5. Isometric view of surface after CBN turning and finish belt grinding (HT1+BG1,2), SRa=0.02 µm](image)

3.3. Profile height distribution parameters

Figure 6 compares the relevant changes in the shapes of bearing curves. In all cases, the BACs have typical degressive-progressive character. For example, belt grinding causes that the
same values of Rmr(20) parameter are progressively recorded for depths c=62% (2) and 70% (3), whereas for CBN turning c=38% (1). Similar effect can be obtained after honing, for which c increases from 54% (4) to 64% (5). Moreover, finishing abrasive processes lead to negative values of skew (about -0.2 for BG and – 0.5 for SF), which improve bearing properties of the surfaces.

3.4. Residual stress distribution

Figure 7 presents exemplary distributions of the tangential residual stresses $\sigma_{1t}$ determined in the sublayer generated in CBN hard turning and belt grinding operations. It is clear from Figure 7 that the belt grinding results in higher compressive residual stresses at the surface, similar to case-hardened steel [8,13].

4. Summary

Finish abrasive passes result in changing both height and spacing roughness parameters. The ratios of SRp to SRv are equal to 0.5 (belt grinding) and 1 (super-finishing).

It is observed that an elastic belt modifies both valleys and peaks of the surface, whereas a rigid abrasive stone changes the configuration of the peaks above the CLA.

Hard turned surfaces, treated additionally by abrasives display negative values of skewness. This effect is basically observed for PCBN turning and following belt grinding.

Belt grinding generates compressive residual stresses at the machined surface in comparison to CBN turning. The changes of residual stresses are localized in a very thin sublayer of $\sim 5 \mu m$.

References