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# Nanostructuring burnishing and subsurface shear instability

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ABSTRACT

Numerical as well as physical modeling of nanostructuring burnishing has been carried out to reveal the limiting values of process parameters, which serve both to provide the appropriate surface quality and positive deformation-induced structural modification of the subsurface layers as well as to avoid shear instability in the subsurface layers of burnished metal. The effects of load, burnishing speed, tool tip material, tool pass number and tribological transfer on the burnished surface roughness have been elucidated by the example of quenched and tempered steels 20X (EN 20Cr4) and 20X13 (EN X20Cr13 or 1.4021). It was shown that overloading results in quasi-viscous flow of the subsurface material, deterioration of the surface and ruining the positive effect of nanostructuring burnishing.

## 1. Introduction

Surface finishing methods and techniques based on plastic deformation of micro-irregularities are well-known and widely used both for improving the surface geometry of machine components and subsurface work-hardening as could be seen from work by Galda et al. (2007). Some of these methods utilize rolling friction (Luca et al., 2005) while other ones are based on sliding. The latter is the subject of the present investigation from the viewpoint of tribology. The tribological aspects of burnishing by natural diamond tool under condition of either smoothing or the work-hardening burnishing has been studied by many researchers. Korzynski (2007) has shown the effect of roughness on the burnishing force. Also Korzynski (2009) studied the effect of the ball burnishing parameters such as force and ball radius on the final roughness. Siemiatkowski and Przybylski (2007) analyzed the burnishing process as a part of multistage manufacturing process.

The emphasis of burnishing is on improving the surface geometry characteristics while the work-hardening is an auxiliary albeit useful effect achieved since the thickness of such a work-hardened layer has never been related to its desired value implied by service conditions. On the other hand, the work-hardening methods involve such severe plastic deformation (SPD) techniques as surface mechanical attrition treatment (SMAT), ultrasonic impact treatment which provide thick work-hardened layers whose thickness might be even excessive for the service conditions given. Also these superficial SPD methods give very rough surface.

In connection with this, it is important to develop a surface finishing method which would allow combining high surface quality and simultaneously improving the wear resistance of the processed component. Solution to this problem lies with understanding the structural modification by severe plastic deformation in sliding.

It has been shown by Tarasov et al. (2013) that combination of normal and shear plastic strain induced in sliding provides severe plastic deformation and fast generation of a nanosize subgrain layer in the subsurface of metals in sliding together with severe deformation in the form of folding Chumaevskii et al. (2014). Such a severe deformation under conditions of friction and deformation heating may lead to shear instability of this layer with respect to shear stress as described Tarasov et al. (2010) and quasi-viscous flow of the plasticized material as reported by Tarasov and Rubtsov (2011). The origin of such a phenomenon is related to changing the deformation mechanism at the real contact areas from shear to grain boundary slipping in nanosize SPD-generated structures. This structurally modified and plasticized material is deformed as a quasi-viscous medium (Tarasov and Rubtsov, 2011) and has very strong adhesion to the counterpart thus causing galling and seizure.

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**Table 1**
Chemical composition of steels.

| Steel | Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ni | Mn | Si | Cu | P | S |
| 20Cr4 | 0.21 | 0.84 | 0.08 | 0.57 | 0.27 | 0.18 | 0.017 | 0.019 |
| X20Cr13 | 0.22 | 13.06 | 0.17 | 0.28 | 0.30 | 0.057 | 0.020 | 0.008 |

It is plain to see that the processed surface's quality may serve as an indicator to notice the shear instability onset which normally has to be avoided when presetting the burnishing process parameters. Another part of the story is that nanosized subgrains generated by sliding in the subsurface provide hardening due to Hall-Petch law and thus may reduce the wear rate of the component processed. So the choice is to generate the optimum thickness nanosize subgrain structure but avoid its instability against shear stress in the subsurface of metals. In other words, we have to determine the optimum values of the main process parameters such as normal load, burnishing speed, number of tool passes, and friction factor. These factors are critical for the process because they determine the internal process parameters such as strain accumulated and heat generated. The maximum allowable burnishing rate is also important since it determines the maximum temperature which structurally modified subsurface layer can sustain until shear instability. We said above that the burnished surface roughness may be a process parameter allowing us to judge on the critical state of shear instability. In addition to this, the stick-slip auto-oscillations are transmitted to the tool under these conditions.

The objective of this work is to establish a relation between nanostucturing burnishing process parameters and specific subsurface material behavior under overloading conditions expressed as the onset of shear instability.

To achieve this we undertake numerical and physical modeling of the nanostructuring burnishing process. In our opinion the subsurface structural modification is determined by the power of the friction process, i.e. the energy delivered to the subsurface per time. From this standpoint we plan to study the effect of loading and sliding speed. However, the subsurface strain is also dependent on the number of tool's passes. Numerical modeling will be devoted to studying the effect of loading on the subsurface structural modification while physical one will take into account also sliding speed and number of passes.

Another important issue is the friction coefficient the value of which determines the shear strain component of burnishing. Its value is greatly dependent on the adhesive interaction and metal transfer between the workpiece and tool and therefore it is also the subject of the present research.

## 2. Setup

### 2.1. Experimental methods and materials

Steel samples have been fabricated of steels 20X (EN 20Cr4) and 20X13 (EN X20Cr13 or 1.4021) (see Table 1) in the shape of 80 mm diameter, 12 mm thickness disks. Steel 20X samples have been carburized by gas to obtain 0.95 wt % concentration of carbon at the 0.1 mm depth below the surface. The final heat treatment was quenching 839 °C in oil and tempering 250 °C for 2 h. The amount of retained austenite was 30 vol%. The hardness of the sample was HRC55.

The X20Cr13 steel samples have been quenched 1050 °C and then tempered either at 150 °C 2 h or at 560 °C for 2 h. The hardness of these samples was HB470 and HB270, respectively.

Before nanostructuring burnishing, the samples have been precision turned by Sandvik WNGA 08048 hard metal cutters at cutting speed $v_c = 80$ m/min and feed rate $f_c = 0.06$ mm/rev for one tool setting block on Multus B300-W turning and milling center. The surface roughness Ra was 0.34 μm and 0.76 μm, respectively.

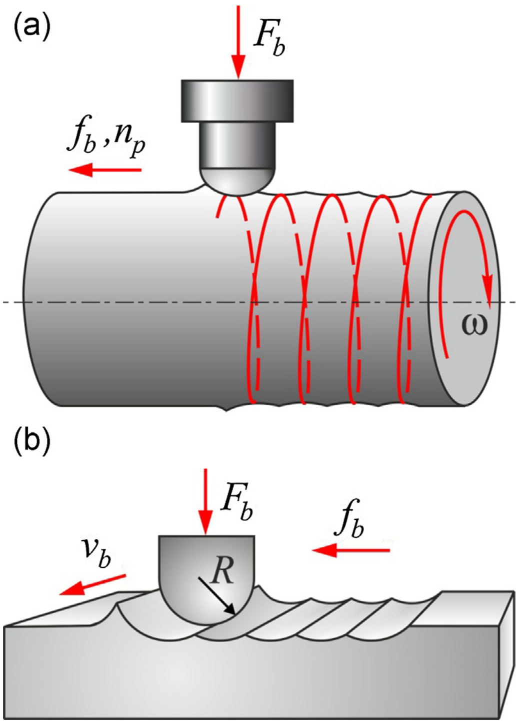

**Fig. 1.** Schematics of the nanostructuring burnishing by half-spherical indenter's tip of radius $R$. $F_b$–normal load; $v_b$–burnishing rate, $f_b$–feed, $n_p$–tool pass number, $\omega$–rotation rate. a–cylindrical workpiece; b–disk workpiece.

The nanostructuring burnishing of the 20Cr4 (HRC55) steel has been carried out using $R = 2$ mm spherical tool of polycrystalline DBN material as schematically shown in Fig. 1 and corresponding friction coefficients were $\mu = 0.34$ and $\mu = 0.13$ for dry sliding conditions and lubrication by Rhenus coolant, respectively. The normal load was 200 N, feed rate $f_b = 0.04$ m/rev. These process parameters served to improve the surface quality characteristics as compared to those obtained after finishing turning. The number of tool passes applied at $v_b = 10$ m/min was four. Synthetic diamond APSM-3 $R = 2$ mm tool has been applied for burnishing the X20Cr13 (HB640) steel samples at $\mu = 0.14$ for dry sliding conditions and lubrication by Rhenus coolant, respectively. The normal load 340 N has been chosen to deliver maximum plastic strain for minimum number of cycles from preliminary experimenting, feed rate $f_b = 0.04$ m/rev. The number of passes were three.

The friction coefficient values have been determined from preliminary testing on a tribological setup as described by Kuznetsov et al. (2014). To determine the friction coefficient we experimentally reproduced the nanostructuring burnishing on tribological reciprocal sliding setup at normal load in the range $F_b = 200–230$ N, mean sliding speed $v = 0.07$ m/s for X20Cr13 steel and $v = 0.035$ m/s for carburized 20Cr4 steel, tool path length 40 and 20 mm, for X20Cr13 and 20Cr4 steels, respectively. The number of double tool passes was 30. The friction force has been measured using a spring ring element with strain gauge transducers glued on it (Fig. 2).

The microstructure of the samples have been examined using transmission and scanning electron microscopes JEOL JEM-2100 and Tescan Mira 3 LMU with autoemission Schottky cathode as well as scanning autoemission electron microscope AURIGA CrossBeam. Surface roughness was determined using optical profilometer Wyko NT-1100.