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Effects of cryogenic cooling on surface layer characteristics produced by hard turning

W. Grzesik [a], K. Żak [a,*], M. Prażmowski [a], B. Storch [b], T. Pałka [b]

[a] Department of Manufacturing Engineering and Production Automation, Opole University of Technology, P.O. Box 321, 45-271 Opole, Poland

[b] Department of Monitoring Processes, Koszalin University of Technology, ul. Racławicka 15-17, 76-620 Koszalin, Poland

* Corresponding e-mail address: k.zak@po.opole.pl

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ABSTRACT

Purpose: The purpose of this research is to test the applicability of cryogenic hard machining for improving surface integrity produced in turning operations on parts made of high-strength, low alloy 41Cr4 steel with hardness of 57±2 HRC. The aim of the research is to quantify the surface roughness and the mechanical properties of the sublayer produced under practical working conditions.

Design/methodology/approach: The objectives were achieved by the characterization of machined surfaces using 2D and 3D scanning techniques. The surface profile and surface topographies were characterized and compared for optimal machining conditions. Moreover, microhardness beneath the surface was measured using a hardness tester with a Berkovich indenter. The microstucture of the sublayer was examined using SEM/EDS technique.

Findings: This investigation confirms that hard machining allows producing surfaces with acceptable surface roughness and, in some cases, with attractive service properties. The main conclusion is that cryogenic hard cutting operations can partly eliminate grinding operations in cases when white layer is not produced.

Research limitations/implications: The basic limitations concern the measurement of residual stresses and microstructural alterations including phase analysis. Another important problem is to optimize the surface integrity including surface roughness and sublayer properties.

Practical implications: One practical outcome is selecting the machining conditions which guarantee the demanded surface finish together with bearing properties. Moreover, they should be selected in terms of desired microhardness distribution.

Originality/value: Original value of the paper is the presentation of the effects of cryogenic pre-cooling of the workpiece in hard turning operations. Experiments were performed under the conditions combining low surface roughness with attractive service properties. This knowledge can support the design of technological processes of hard steel parts.

Keywords: Hard turning; Cryogenic cooling; Surface integrity

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Machining of hardened materials, mainly steels, is one of the leading removal method of producing parts in many technologically top-level manufacturing branches [1] such as automotive, bearing, hydraulic and die and mold making sectors. However, in many cases this technology is not capable of replacing grinding operations predominantly due to lower surface finish and problems with dimensional accuracy [2,3]. In consequence, hard turned surfaces are finished with special abrasive operations, such as finishing grinding, superfinishing, belt grinding and honing or mass finishing [4,5]. Relatively new trend emerging recently in the industry is to improve the machinability of hard steel materials using special tooling with liquid nitrogen (LN2) supplying. In general, the LN2 is allowed to evaporate near the cutting edge of insulated tools, it promotes the dissipation of heat, which would otherwise soften tools and accelerate wear. In other words, cryogenic cooling is an environmentally friendly new approach for desirable control of cutting temperature. Cryogenic cooling can be performed in several ways including cryogenic pre-cooling of the workpiece, indirect cryogenic cooling and direct cryogenic jet cooling by special micro-nozzles [6].

Sustainable cryogenic machining [7,8] is extensively applied for machining advanced engineering materials such as structural ceramics, titanium alloys, HRSA's [9] to reduce the cutting temperature, tool wear and process stability, to improve chip breakability [10] and dimensional accuracy [11] and also for machining hardened steels to eliminate structural alterations, especially white layer formation [12-14]. Investigations of tool wear, surface finish and cutting forces in cryogenic machining have been attempted by researchers several decades ago, but recently interest have been renewed in these topics [13]. This innovative hybrid machining technique was also examined in this study from the technological and material point of view taking into consideration microstucture alterations in the subsurface layer.

2. Experimental details

2.1. Workpiece material, tooling and machining conditions

Hard machining trials (Figs. 1a and 1b) were performed on the specimens made of 41Cr4 (AISI 5140) steel with Rockwell's hardness of 57±1 HRC. Low content CBN tools containing about 60% CBN, grade CB7015 by Sandvik Coromant, were used. They were carried out dry and with cryogenic pre-cooling of the specimen using special cooling chamber with liquid nitrogen (LN2) and transportation of the frozen workpiece from the chamber on the lathe as shown in Fig. 2. Hard turning conditions were as follows: cutting speed of 150 m/min, variable feed rate of 0.075 (HT1/CHT1), 0.1 (HT2/CHT2) and 0.125 (HT3/CHT3) mm/rev, depth of cut of 0.15 mm/rev. Specification of dry and cryogenic hard turning operations is given in Table 1. Both hard turning processes were performed on a conventional lathe (Fig. 2) and a CNC turning center, Okuma Genos L200E-M.

Table 1.
Specifications of hard turning operations performed

Dry HT		Cryogenic HT	
Feed rate mm/rev	Code	Feed rate mm/rev	Code
0.075	HT1	0.075	CHT1
0.10	HT2	0.10	CHT2
0.125	HT3	0.125	CHT3

a) b)

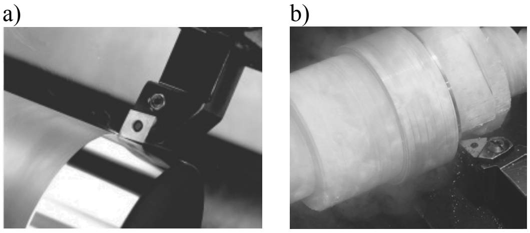


Fig. 1. Dry (a) and cryogenic (b) hard turning

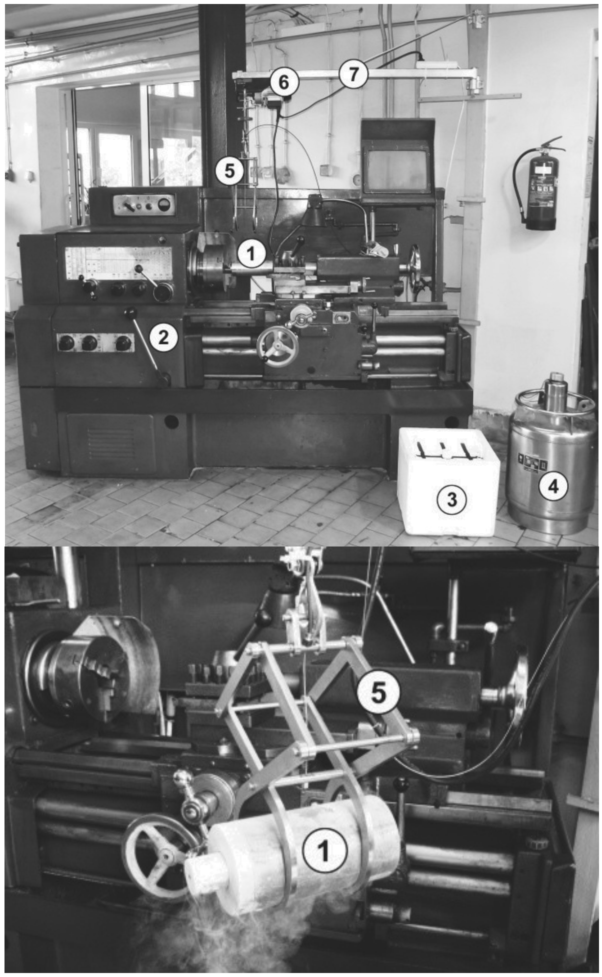


Fig. 2. Setup for cryogenic machining: 1-frozen workpiece, 2-lathe, 3-cooling chamber, 4- liquid nitrogen resevuar, 5- gripping device , 6-rope elevator, 7-rotating arm

2.2. Surface and subsurface characterizations

Surface profiles/ topographies were recorded and 2D and 3D roughness parameters were estimated on the scanned areas of 2.4 mm×2.4 mm by means of a TOPO-01P profilometer with a diamond stylus radius of 2 μm (Fig. 3).

Micro-hardness (μHV) of the machined and 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. A hardness variation within subsurface layer of about 100 μm thickness was determined. In order to avoid interference of indentations and increase the measuring accuracy ($h_i=l_i\times sin\alpha$), the measurements were performed on the oblique sections, inclined at about 3° to the outer surface (see Fig. 10). Based on the micro-hardness data the strain-hardening rates related to the maximum values of microhardness in the subsurface layer were computed.

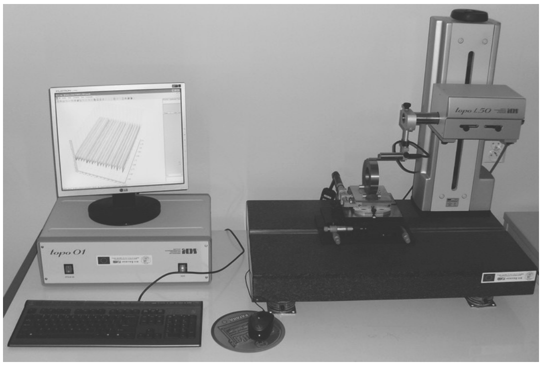


Fig. 3. 3D profilometer, model TOPO 01P

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.

3. Experimental results and discussion

3.1. Geometrical features of turned surfaces

In general, the hard turned surfaces have specific geometrical features depending on the initial state of the workpiece. In particular, cryogenic pre-cooling of the workpiece changes the mechanical properties and results in the generation conditions of both the surface and subsurface layer. Two sets of surface roughness parameters obtained for dry and cryogenic HT operations are specified in Tables 1 and 2 respectively.

Figure 4 presents the obtained values of the Ra parameter with different feeds. First, dry hard operations cause that Ra parameter diminishes but this effect is more pronounced for the lowest feed rate of 0.075 mm/rev applied. The minimum value of Ra=0.27 μm was obtained for variant HT1. The second observation is that the Rz parameter and fractions of Rp and Rv components within the total height Rz depend not only on the feed value but the process variant. As can be seen in Fig. 5 the values of Rz parameter obtained for hard turning of cryogenically pre-cooled workpieces are about 50-100% higher than for equivalent dry HT operations.

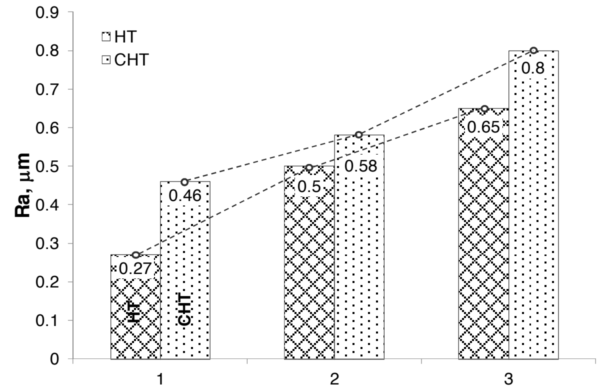


Fig. 4. Comparison of Ra roughness parameters for hard turned surfaces: 1 - f=0.075 mm/rev, 2 - f=0.1 mm/rev, 3 - f=0.125 mm/rev

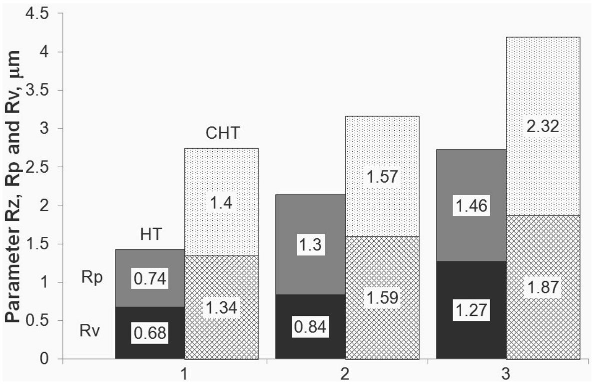
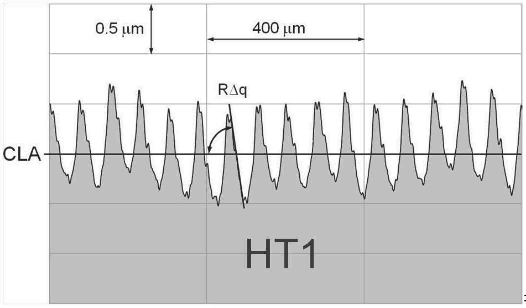


Fig. 5. Comparison of Rz roughness parameters for hard turned surfaces: 1 - f=0.075 mm/rev, 2 - f=0.1 mm/rev, 3 - f=0.125 mm/rev

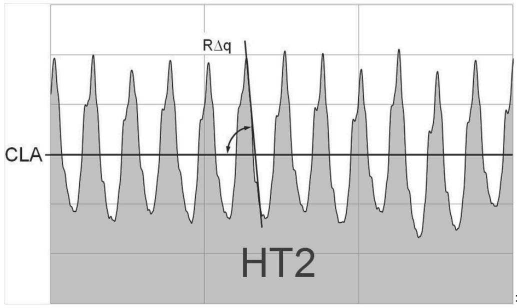
As can be seen in Fig. 6 dry hard turning produced surface profiles with regular tool nose traces, for which the Rsm parameters are almost equal to the feed value, with very small slopes RΔq, generally not greater than 2°. Oppositely, cryogenic HT produced profiles with higher peaks disturbed by the side flow effect, as it was documented in Ref. [15]. This effect results from increased hardness and strength as well as coarser microstructure of the freezing workpiece [6]. As a result, the regularity of the profile is disturbed visibly for the lowest feed rate employed. In addition, small lateral material flows can also be observed on surface topography presented in Fig. 7b.

Fig. 7 confirms that CBN hard turning produces profiles with unsatisfactory bearing properties. As depicted in Fig. 7 they are linear or degressive as produced mainly by dry hard operations (cases B and C. The differences in the bearing properties of surface profiles produced can be visibly represented in Rku-Rsk diagram shown in Fig. 8. It can be seen in Fig. 8 that only after cryogenic hard turning with the smallest feed (case CHT1) surface profile with negative skewness is produced.

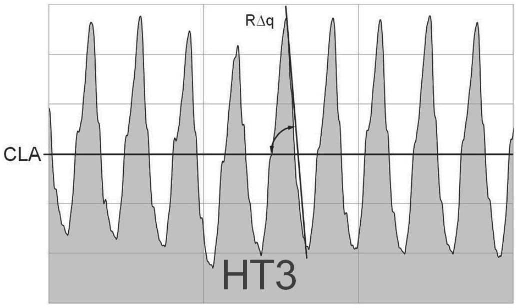
a1) Rz=1.42 µm, RΔq=1.72°, RSm=76.83 µm



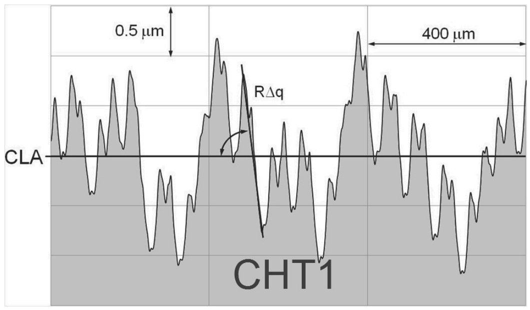
a2) Rz=2.14 µm, RΔq=2.29°, RSm=110.38 µm



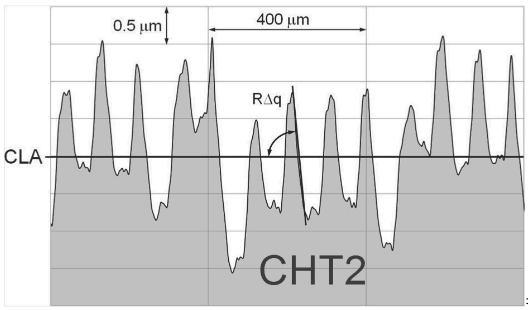
a3) Rz=2.73 µm, RΔq=2.59°, RSm=124.50 µm



b1) Rz=2.73 µm, RΔq=2.29°, RSm=86.90 µm



b2) Rz=3.17 µm, RΔq=2.29°, RSm=95.67 µm



b3) Rz=4.19 µm, RΔq=2.89°, RSm=125.00µm

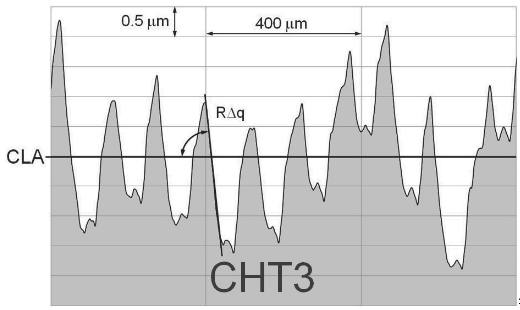
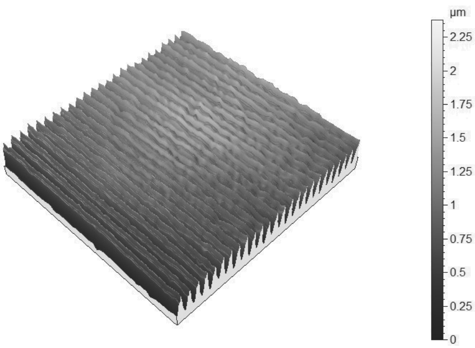


Fig. 6. Examples of surface profiles produced in dry (a1, a2) and cryogenic (b1, b2) hard turning with variable feed rates

a) HT2



b) CHT2

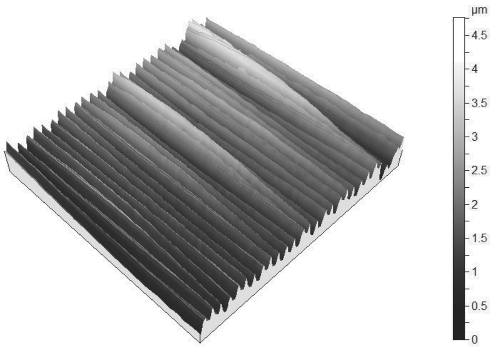


Fig. 7. Surface topographies produced in dry (a) and cryogenic (b) hard turning

Table 2.
Roughness parameters for dry HT

Operation/ Roughness parametr	HT1	HT2	HT3
Rp	0.74	1.30	1.46
Rv	0.68	0.84	1.27
Rz	1.42	2.14	2.73
Ra	0.27	0.50	0.65
Rq	0.32	0.55	0.75
Rsk [-]	0.28	0.32	0.26
Rku [-]	2.00	1.74	1.81
RΔq	0.03	0.04	0.05
RSm	76.83	100.38	124.50
Rk	0.80	1.16	1.72
Rvk	0.14	0.06	0.14
Rpk	0.26	0.59	0.85
Mr1 [%]	20.67	33.67	24.77
Mr2 [%]	96.52	99.02	98.52

Table 3.
Roughness parameters for cryogenic HT

Operation/ Roughness parametr	CHT1	CHT2	CHT3
Rp	1.40	1.57	2.32
Rv	1.34	1.59	1.87
Rz	2.73	3.17	4.19
Ra	0.46	0.58	0.80
Rq	0.56	0.70	0.95
Rsk [-]	-0.22	0.13	0.16
Rku [-]	2.43	2.20	2.31
RΔq	0.04	0.05	0.05
RSm	86.90	95.67	125.00
Rk	1.51	2.06	2.65
Rvk	0.49	0.50	0.54
Rpk	0.36	0.42	0.85
Mr1 [%]	6.20	10.12	7.78
Mr2 [%]	86.73	96.30	91.26

It should be noted that the values of the reduced peak height Rpk are, in general, comparable for HT and CHT operations, but for feed of 0.075 mm/rev lower Rpk was determined for dry turned surfaces, i.e. 0.26 μm versus 0.36 μm.

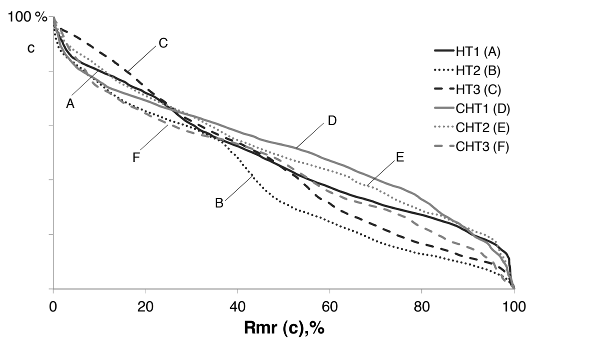


Fig. 8. Material ratio curves for dry (HT) and cryogenic (CHT) hard turning operations with variable feed rates

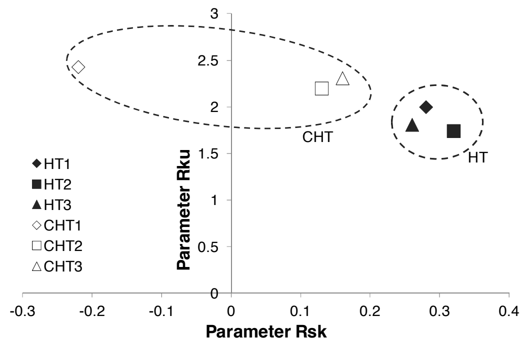


Fig. 9. Kurtosis vs skewness map for a range of hard turning operations

It should be noted in Fig. 9 that correspondingly for curve D negative values of the skewness were determined, respectively Rsk= -0.22. Two characteristic area with different pairs of Rku and Rsk parameters can be distinguished. It suggest that surfaces with sharp irregularities produced by dry hard turning have better locking properties. Otherwise, surface profiles generated by dry and cryogenic turning are characterized by kurtosis near 2 which means that the profiles are congregated at the extremes (they are described as platykurtic).

Worse bearing properties of surfaces generated by cryogenic hard turning can also be related to lower values of upper material ratio Mr1. For the three feed rates used they are equal to: 6.20% vs. 20.67%, 10.12% vs. 33.67% and 7.78% vs. 24.77%.

3.2. Microhardness and thermal effects

Distribution of microhardness in the subsurface layer at the distance of 100 μm from the surface depends on the variant of cryogenically assisted process, as exemplarily shown in Fig. 10. Dry hard turning causes that maximum microhardness is localized close to the surface whereas for cryogenic cooling the trend is to shift this point beneath the surface (12-15 μm). As a result, after dry hard turning maximum microhardness HV0.05 measured directly underneath the generated surface was about 830 MPa. After cryogenic hard turning (CHT2) white layer is not produced and in consequence microhardness in the zone adjacent to the surface is about 740 MPa.

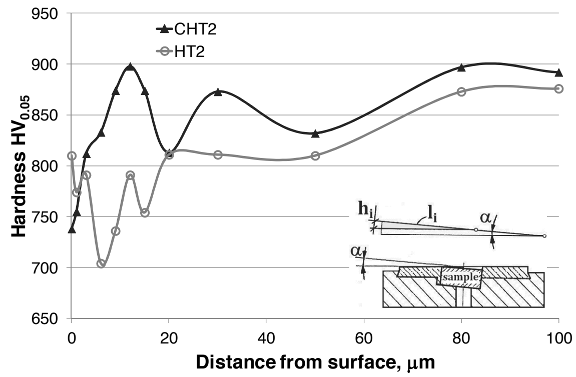


Fig. 10. Microhardness distributions for hard turning (HT and CHT) operations. Feed rate: f=0.1 mm/rev

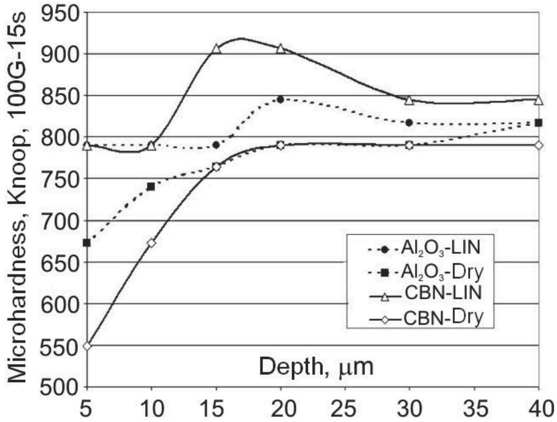


Fig. 11. Knoop microhardness profile as a function of depth under machined surface. Workpiece-AISI 52100 steel, 60 HRC [16]

The microhardness alterations under machined surface resulting from the impact of liquid nitrogen (LIN) are shown in Fig. 11. As shown in Fig. 11, this effect depends on the cutting tool applied. In the case of dry hard turning microhardness at the machined surface decreases due to the thermal softening effect but more distinctly for low-content CBN tools. On the other hand, cryogenic cooling causes that microhardness at a depth of 10 μm does not change and is equal to about 780 HK. In addition, Fig. 12 illustrates the influence of cryogenic cooling on the residual stress profile and its magnitude. In this case, the RS profile is changed for machining with ceramic tools for which practically unstressed surface layer is produced. Both conventional and cryogenic turning with CBN tools produced small compressive stresses in the radial direction at the machined surface.

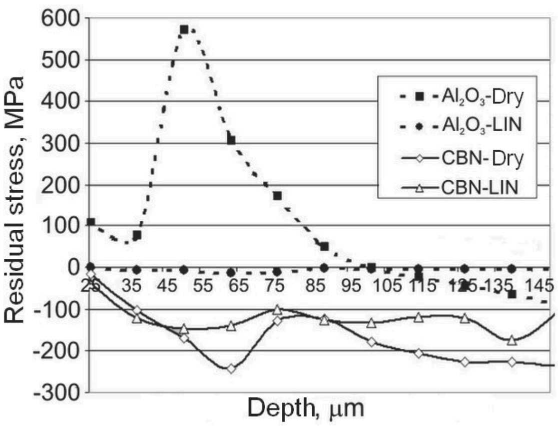
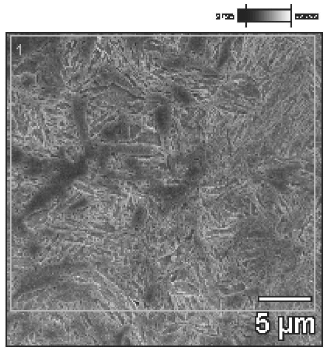


Fig. 12. Residual stress as a function of depth under machined surface. Workpiece-AISI 52100 steel, 60 HRC [16]

3.3. Microstructural alterations of the surface layer

As mentioned above, quantitative microstructural analysis was performed using SEM/BSE technique with additional phase content measurements using EDS technique. The second technique allows to determine the chemical composition of the surface layer and identify the structural effects due to intensive heating and cryogenic cooling. Samples, which were mounted in conductive resin, were prepared by mechanical grinding, diamond polishing and electropolishing. Fig. 13 shows an exemplary BSE image of the bulk material before burnishing with characteristic microstructure consisting of untempered martensite.



#
#
#
Image name: HT2
Accelerating voltage: 15.0 kV
Magnification: 4000×
Microstructure: untempered martensite#

Fig. 13. BSE image showing microstructure for 41Cr4 steel core after quenching

Figs. 14 and 15 show BSE microphotographs of surface layer (SL) produced by dry (Fig. 14) and cryogenic (Fig. 15) hard turning operations. It should be noted that the width of surface layer coincides well with microhardness distribution presented in Fig. 10. The BSE images confirm that LIN pre-cooling of the workpiece causes that the white layer (WL) is not produced, whereas for dry HT it penetrates about 3 μm below the machined surface, as shown in Fig. 14. On the other hand LIN machining produced a significantly coarser structure with submicron dispersive carbides. In particular, in this case easily noticed severely deformed surface layer (DSL) of about 7 μm thickness is observed. This image also shows martensite structure with the grain boundaries of retained austenite.

No evidence of a chemically modified surface layer was observed within the subsurface layer as documented by relevant EDS spectra presented in Fig. 16. The contents of alloying elements correspond to data provided by steel manufacturers and metallurgists.

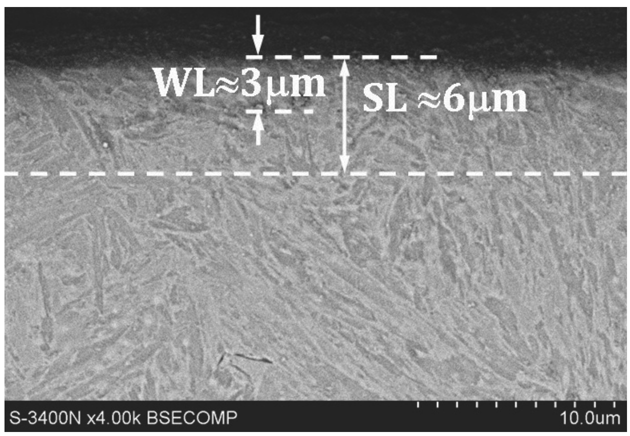


Fig. 14. Microstructure of the surface layer after dry hard machining (HT2). Magnification × 4000

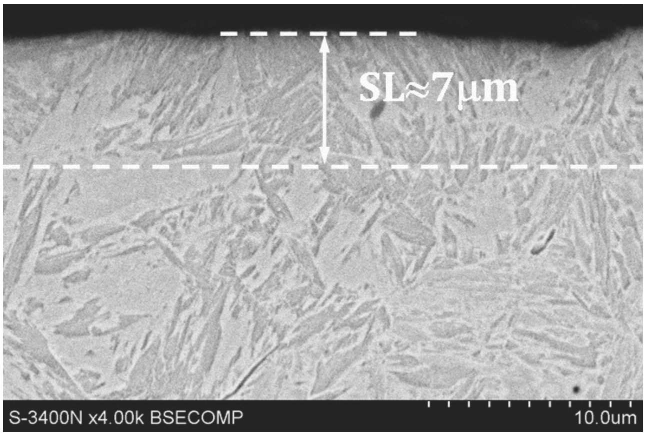
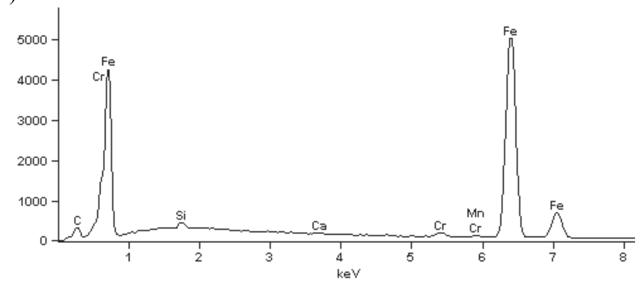


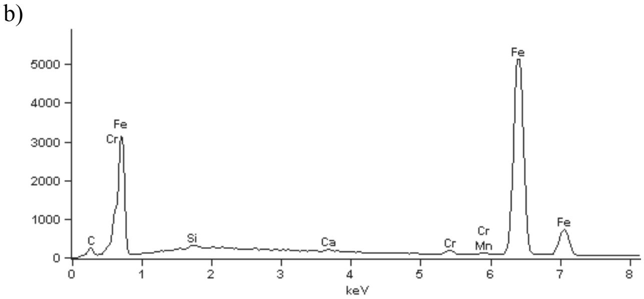
Fig. 15. Microstructures of the surface layer after cryogenic hard machining (CHT2). Magnification × 4000

a)



wt%/at%: Si-1.0/1.9, Cr-1.0/1.0, Mn-0.8/0.8, Fe-96.8/95.4

b)



wt%/at%: Si-0.6/1.1, Cr-1.0/1.1, Mn-0.6/0.6, Fe-97.6/96.8

Fig. 16. EDS spectra of the surface layer after dry (a)-HT2 and hybrid (b)-CHT2 hard machining

4. Conclusions

The following practical findings were explored in this study.

Cryogenic pre-cooling of the workpiece results in substantial modifications of both surface and surface layer.

Dry hard turning produced surface profiles with regular tool nose traces and lower surface roughness. The minimum value of Ra=0.27 μm (correspondingly Rz=1.42 μm) was obtained for the feed rate of 0.075 mm/rev. For cryogenic process its value increased to 0.46 μm (Rz=2.73 μm).

Surfaces produced by cryogenic hard turning are distinctly flattened causing better bearing properties, correspondingly to lower positive or negative values of Rsk parameter. On the other hand surfaces generated by dry hard turning consist of very sharp irregularities and Rsk is always positive in the range of 0.3.

Subsurface layers produced by cryogenic hard turning are white layer free. This effect corresponds to lower microhardness readings of 730 $HV_{0.05}$ near the surface. In contrast, for dry hard turning measured microhardness value is about 820 $HV_{0.05}$

SEM examinations of the SL revealed the presence of martensite structure with the grain boundaries of retained austenite. On the other hand, cryogenic hard machining produced a significantly coarser structure with submicron dispersive carbides.

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