Research on hardened steel turning with superhard tool material

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Abstract

The paper presents results of research on hardened steel turning with tool made of cubic boron nitride - superhard tool material. Arcitle present comparison of grinding and hard cutting, which is an alternative technology for machining hardened materials. During experiments workpiece made of hardened cold work tool steel was machined in accordance to investigation plan with cubic boron nitride inserts by means of specialised equipment, such as high speed camera, surface and roughness 2D and 3D profilometers, thermal camera, dynamometer, roundness tester and hardness tester. Research is connected with real industrial component application. Mathematical equations of influence cutting parameteres, such as cutting speed, feed rate, depth of cut and hardness on surface roughness and cutting force components are presented.

Keywords

hard cutting, hard turning, hardened steel turning, cbn.

1. Introduction

Hard cutting is a machining process of metal components, made of materials harder than 45 HRC, with geometrically defined cutting edge. Hard cutting, which is known also as hard machining or hard part machining, includes hard drilling, hard turning and hard milling. Usually, hard turning is a finishing or semi-finishing cutting process and it is an alternative for grinding of axisymmetric parts. In some applications grinding and hard turning are combined in order to exploit advantages of both technologies. Nowadays, the hard turned work piece is made of: bearing steel, cold- or hot work tool steel, high speed steel, super alloy or hardened cast iron. Hard cutting requires special tool materials, with high wear-resistant and high hardness at elevated temperatures. The most commonly used as tool materials are: silicon nitrides, sintered carbides, cermets, polycrystalline diamonds, oxide and mixed ceramic and cubic boron nitrides. The last one is characterized by extraordinary hardness at elevated temperatures and compressive strength with good fracture toughness [1-8].

2. Comparison of hard turning and grinding

In the Table 1 there are compared some aspects of both processes of machining hardened materials, grinding and hard turning. Hard turning is characterized by several times lower energy consumption in comparison with grinding and it is easy to adapt multiple machining in just one setup. Because of the limitations of the technology grinding has much lower possibility to machining of complex shape and interrupted cutting. Costs of machine tool and tools depend on the application. Properties of surface layer can be comparable, but there will be differences in tensions of the surface layer, depth of heat influence inside the surface layer, profile and structure. Hard cutting provides good tribological properties of workpiece surface, so wear of a surface layer can be twice lower in comparison with grinded surfaces. Abrasive methods of machining allow to obtain a lower roughness of surface. Ecology of hard cutting is better than grinding because coolants and lubricants are not required or cold air can be applied instead. In case of hard cutting chips can be easily recycled. Some damages of the grinding wheels are more dangerous for the operator than the damages caused by the cutting tools.

Table 1. – *Comparison of hard turning and grinding aspects. Worse: (-), Better: (+), Application-dependent: (+/-).*

Aspect	Hard turning	Grinding
Lower energy consumption	+	-
Multiple machining in one setup	+	-
Machining of complex shape	+	-
Interrupted cutting	+	-
Investments in machine tool, equipment and tools	+/-	+/-
Surface layer properties after machining	+/-	+/-
Ecology	+	-
Operator's safety	+	-
Market and marketing	+	-

3. Research on hard turning process

3.1 Machined material and tool.

The machined workpiece was made of hardened cold work tool steel (X165CrV12, hardness: shaft no. 1: 62HRC, shaft no. 2: 56,5HRC). Shaft has diameter 60mm, each of cylindrical segment has a width of 10mm. Segments of the workpiece were machined in accordance to the investigation plan. The inpus parameters taken: $v_c \in (80\text{-}160)$ *m/min; f* $\in$*(0.058-0.153) mm/rev;* $a_p \in (0.1\text{-}0.5)$ *mm*. Chemical composition of X165CrV12 steel in presented in Table 2.

Fig. 1. *Machined workpiece made of X165CrV12 mounted in the chuck of machine tool.*

Table 2. – *Chemical composition of cold work tool steel X165CrV12*

Chemical composition in %							
C	Cr	Mn	Si	Ni, Cu	Mo, W	V	P, S
1.5-1.8	11-13	0.15-0.45	0.15-0.4	<0.35	<0.2	<0.15	<0.03

The removable cutting inserts CNGA120408 were made of CBN tool material. Tool geometry was described by three angles: χ_r =95°, λ_s= -6°, γ= -6° and tool nose radius r_ε=0.8mm.

3.2 Equipment and research stand.

Fig. 2. *Research stand.*

During the investigation following equipment was used:

- lathe Knuth Masterturn 400/1500 with 7.5 kW,
- hardness tester Rockwell HR150A,
- dynamometer Kistler with amplifier 5070A and the DynoWare software,
- profilometer Surftest SJ-201P Mitutoyo,
- profilometer Intra Taylor-Hobson,with software,
- roundness tester Talyrond 365 Taylor-Hobson with ULTRA software,
- high-speed camera Phantom with software and Dedocool cold light system,
- microscope BRESSER with MikroCamLab software,
- photo camera Sony SLT-A37 with objectiv 18-55mm,
- FLIR thermal camera.

Experiments were carried out on Knuth Masterturn lathe. Hardness tester Rockwell was used to measure the hardness of machined shafts. Dynamometer Kistler was applied to measure cutting force components during during hard turning process, which are schematicaly presented in Fig. 3, feed force (F_f), passive force (F_p) and main force (F_c). Profilometers were used to prepare 2D and 3D profiles of surface layer and to measure surface roughness. Roundness total measurements we carried out on roundness tester Talyrond. High-speed camera and thermal camera were used to observe and record hard turning process. Microscope and photo camera were applied to prepare photographies of metal chips formed during the machining process.

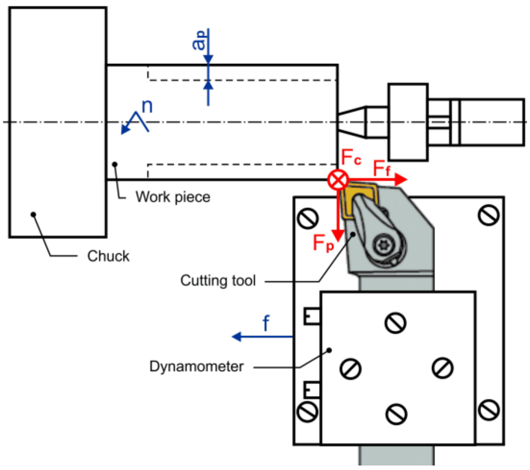


Fig. 3. *Kinematic scheme of turning and cutting force components.*

3.3 Results of research

Each of machined surface profiles were measured by Mitutoyo Surftest SJ-201P and Intra Taylor-Hobson profilometers. The measurements were repeated three times and at three reference lines equally positioned at 120°. The results of measured and modeled values of *Ra* and *Rz DIN* are presented in Table 3.

Table 3. *– Comparative analysis of the measured and modelled values of Ra and Rz_{DIN}.*

Test no.	v_c *[m/min]*	*f [mm/rev]*	a_p *[mm]*	*Ra [µm]*	$Ra_{\_model}$ *[µm]*	Rz_{DIN} *[µm]*	Rz_{DIN_model} *[µm]*
1	120	0.105	0.5	0.417	0.392	2.237	1.964
2	96.9	0.077	0.42	0.273	0.273	1.627	1.432
3	143	0.134	0.42	0.497	0.494	2.553	2.180
4	120	0.058	0.3	0.250	0.255	1.470	1.258
5	120	0.105	0.3	0.357	0.366	1.930	1.699
6	120	0.153	0.3	0.483	0.480	2.410	2.149
7	80	0.105	0.3	0.327	0.338	1.790	1.699
8	160	0.105	0.3	0.367	0.394	2.097	1.699
9	143	0.077	0.18	0.357	0.327	2.147	1.619
10	96.9	0.134	0.18	0.377	0.376	2.177	1.939
11	120	0.105	0.1	0.350	0.341	2.080	1.926

Designated mathematical models of surface roughness, shaft 62HRC:

$$Ra_{\_model} = 0.0007 \cdot v_c - 0.7008 \cdot a_p + 7.8862 \cdot f \cdot a_p + 0.2441 \quad (1)$$

$$Rz_{DIN\_model} = -6.873 \cdot a_p + 31.2573 \cdot f \cdot a_p + 6.1453 \cdot a_p^2 + 2.2234 \quad (2)$$

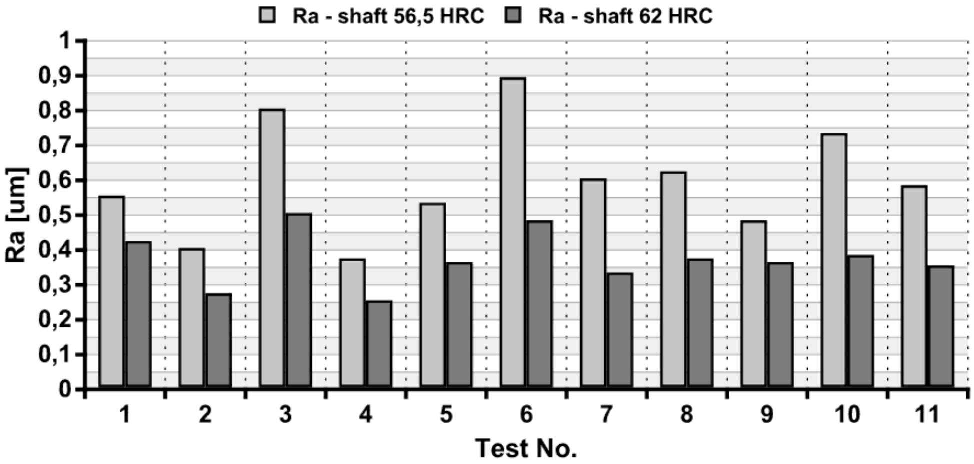


Fig. 4. *Influence of workpiece hardness on surface roughness Ra after hard turning.*

Hardness influences on workpiece surface roughness after hard turning. If hardness of machined workpiece is higher then lower surface roughness will be received.

In the traditional turning cutting force components increase gradually in the following order:

$$F_c > F_p > F_f \tag{3}$$

whereas for hard turning, the highest component is F_p, which means [9]:

$$F_p > F_c > F_f \tag{4}$$

The results of measured and modelled values of the cutting force components are presented in Table 4.

Table 4. *– Comparative analysis of the measured and modelled values of F_p, F_c and F_f.*

Test no.	***v_c [m/min]***	***f [mm/rev]***	***a_p [mm]***	***F_p [N]***	***F_{p_model} [N]***	***F_c [N]***	***F_{c_model} [N]***	***F_f [N]***	***F_{f_model} [N]***
1	120	0.105	0.5	204.710	207.303	218.890	218.602	149.710	150.334
2	96.9	0.077	0.42	187.110	184.812	161.660	162.072	126.760	125.911
3	143	0.134	0.42	271.310	268.622	224.820	225.234	146.550	145.694
4	120	0.058	0.3	184.070	188.328	105.100	104.820	89.120	89.711
5	120	0.105	0.3	240.110	238.252	155.390	154.841	104.830	105.086
6	120	0.153	0.3	284.480	289.237	186.500	186.209	105.260	105.879
7	80	0.105	0.3	254.490	251.676	156.280	156.333	109.660	110.017
8	160	0.105	0.3	252.610	250.747	153.290	153.349	99.790	100.155
9	143	0.077	0.18	197.150	198.098	75.920	76.330	53.010	52.172
10	96.9	0.134	0.18	235.070	235.485	121.690	122.098	66.290	65.458
11	120	0.105	0.1	151.900	150.684	61.770	61.487	30.270	30.874

Designated mathematical models of cutting forces, shaft 62HRC:

$$F_{p\_model} = 2235.1901 \cdot f + 658.7285 \cdot a_p + 0.0081 \cdot v_c^2 - 18.6249 \cdot v_c \cdot f + \\ +3539.9876 \cdot f \cdot a_p - 1481.4661 \cdot a_p^2 - 54.2057 \tag{5}$$

$$F_{c\_model} = -0.3427 \cdot v_c + 1312.2551 \cdot f + 332.6772 \cdot a_p + 1.018 \cdot v_c \cdot a_p + \\ -4324.1731 \cdot f^2 + 1522.9083 \cdot f \cdot a_p - 369.9257 \cdot a_p^2 - 45.277 \tag{6}$$

$$F_{f\_model} = -0.9078 \cdot v_c + 231.6652 \cdot a_p + 3.9359 \cdot v_c \cdot f + 1.2375 \cdot v_c \cdot a_p + \\ -3269.6125 \cdot f^2 + 1292.5435 \cdot f \cdot a_p - 362.0547 \cdot a_p^2 + 78.2976 \tag{7}$$

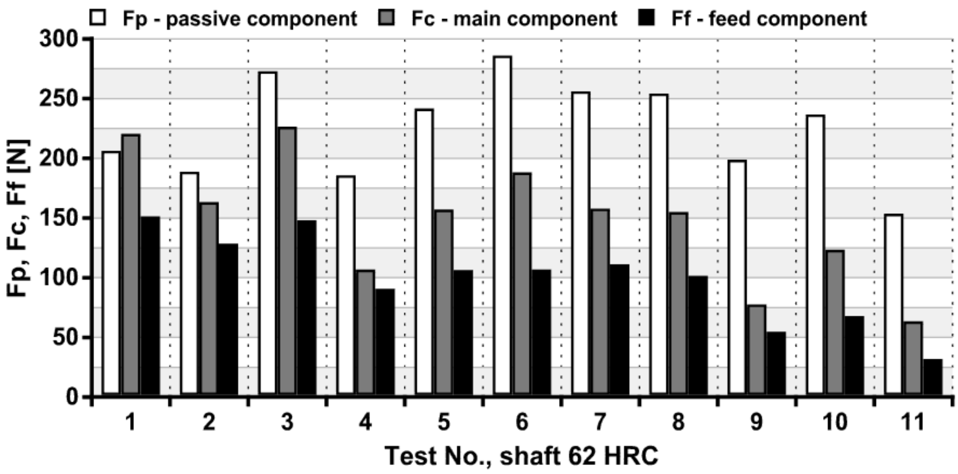
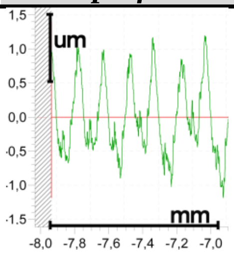
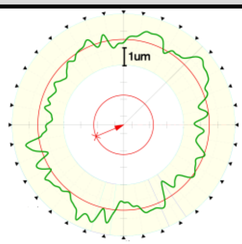
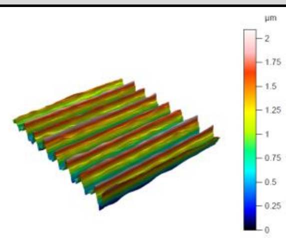


Fig. 5. *Comparison of measured cutting force components during machining of 62HRC cold work tool steel [2].*

During shape deviation measurements radial method was applicable, in three equally spaced planes, by means of Talyrond 365 that is dedicated to measurements of cylindrical surfaces roundness, waviness and roughness. The device measures with the point collection pin system, with an error less than ±0.02 µm in R axis. The results of measurements were analyzed using Ultra Roundness Software V4.1 PL. RONt, RONv and RONp parameters were determined based on the average LSCI element. During analyze of roundness deviations Gaussian filter was chosen, undulations were limited to 50 upr. Results of measurements are presented in Table 5.

Table 5. *–Graphical comparison of feed rate influence on surface during hard turning steel X165CrV12, 62 HRC.*

	Chip formation	***2D roughness profile***	***RONt***	***3D surface profile***
f=0.153 mm/rev				

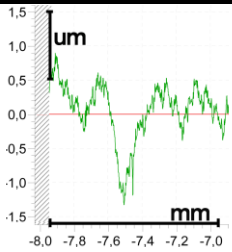
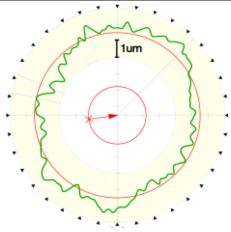
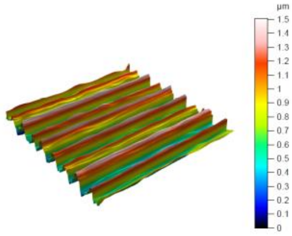
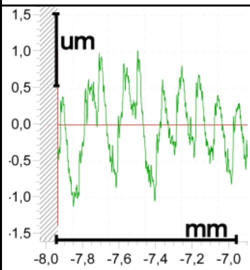
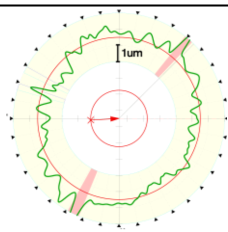
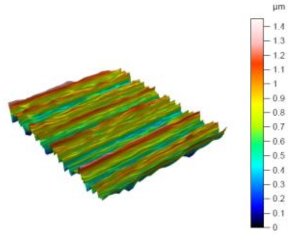
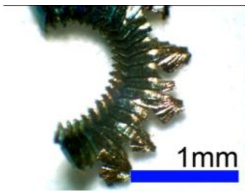
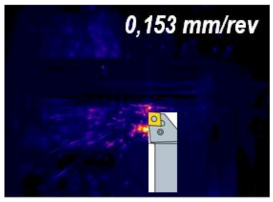
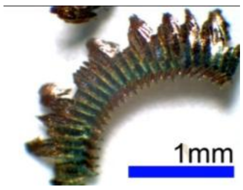
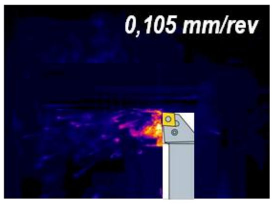
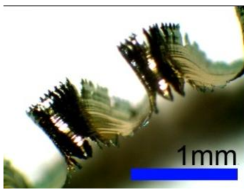
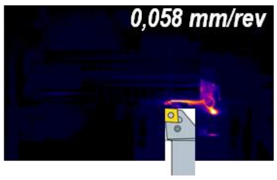
f=0.105 mm/rev				
f=0.058 mm/rev				

Table 6. *– Graphical comparison of feed rate influence on chips and heat fluxes during hard turning steel X165CrV12, 62 HRC.*

	Chip formation	***Microphotography of chip***	***Macrophotography of chip***	***Thermogram***
f=0.153 mm/rev				
f=0.105 mm/rev				
f=0.058 mm/rev				

4. Conclusion

Hard cutting technology is very promising and without any doubt, it will be widely used in many applications where grinding has been the only choice or possibility. Hard cutting has many advantages in comparison with grinding, but still need to investigate the process. Cutting parameters and properties of workpiece material, such as cutting speed, feed rate, depth of cut and hardness, have important influence on the surface layer properties and quality of machined component. These parameters influence on cutting forces, surface roughness, tensions, roundness total, accuracy, etc. Designated mathematical equations help to calculate e.g. approx. values of surface roughness and cutting forces, with good accuracy – $R^2 \in (0.92\text{-}0.97)$. The effective surface layer created in the cutting process is characterized by a set of deviations from the nominal contour, formed as a result of simultaneous impact of cutting parameters, geometry of cutting tool and workpiece material properties. Presented research will be carried out on many levels to better understand the process, to model and to describe the process - by means of mathematical equations in order to help in optimization of the process in real industrial conditions.

Symbols

a_p	depth of cut	(mm)
f	feed rate	(mm/rev)
LSCI	least squares reference circle	-
R^2	coefficient of determination	-
Ra	arithmetic mean roughness	(μm)
Rz_{DIN}	mean value of the single roughness depth *Zi*	(μm)
r_ε	tool nose radius	(mm)
RONt	roundness total; peak to valley roundness deviation	(μm)
upr	undulations per revolution	-
v_c	cutting speed	(m/min)
γ	rake angle	(^{o})
λ_s	inclination angle	(^{o})
χ_r	major cutting edge angle	(^{o})

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