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HARD TURNING OF COLD WORK TOOL STEEL WITH CBN TOOLS

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S u m m a r y

The paper presents example of hard turning application, comparison with grinding technology and results of hard turning researches on cold work tool steel with cubic boron nitride tools. The influence of cutting conditions and material hardness on cutting forces and surface roughness are presented.

Keywords: hard turning, CBN, tool steel, cutting forces, surface roughness

Obróbka stali narzędziowej do pracy na zimno w stanie twardym narzedziami z CBN

S t r e s z c z e n i e

W pracy podano przykład aplikacyjny toczenia stali w stanie twardym w celu porównania ze szlifowaniem ściernicowym. Wykonano badania w zakresie toczenia zahartowanej stali narzędziowej do pracy na zimno narzędziami wykonanymi z regularnego azotku boru. Przedstawiono wpływ parametrów skrawania oraz twardości materiału na chropowatość powierzchni i składowe całkowitej siły skrawania.

Słowa kluczowe: toczenie w stanie twardym, CBN, stal narzędziowa, siły skrawania, chropowatość powierzchni

1. Introduction

Hard machining is the cutting process of metal parts with the hardness of above 45 HRC with the cutting tool of geometrically defined cutting edges. At present, hard machining is a finishing or semi-finishing machining process with accuracy similar to grinding. Hard machining includes: hard turning, hard milling and hard drilling. The most popular is hard turning, which is an alternative for grinding of axisymmetric parts.

The hard turned work pieces are made of various hardened alloy steels (bearing steels, carburized steels, cold- and hot work tool steels, high speed steels), superalloys, hardened cast irons, sintered carbides and metal-ceramic composites.

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Hard machining 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, cubic boron nitrides (CBN). Diamond is a tool material which is not suitable for machining ferrous materials due to diffusion wear of the tool, especially intensive at elevated cutting temperatures. Polycrystalline cubic boron nitride is characterized by extraordinary hardness at elevated temperatures and compressive strength with good fracture toughness.

The researchers have been working on many aspects of hard turning and have already presented their own recommendations. Fundamentally the process is a high speed, low feed and low depth of cut finishing or semi-finishing process. The cutting speed, as reported in various works, is in the range 100-250 m/min [1-5]. Some of researchers have reported on stability problems with higher speeds [4]. Usually feed rate belongs to the range 0.05-0.15 mm/rev and depth of cut is not bigger than 0.2 mm [2, 3, 5, 6]. Some of researchers [1] have reported on the depth of cut 1 mm. A correctly conducted hard turning process can deliver the surface finish of Ra 0.4-0.8 μm and roundness ±2-3 μm. Although machining of some materials such as Inconel, Hastelloy and other difficult-to-cut materials is included in the category of hard turning [7], it is not correct as their hardness is much lower than 45 HRC. The reason is the mechanism of chip formation. The requirements of machining are distinctly different [8-11].

2. Comparison of hard turning and grinding

The graph in Fig. 1 presents two different ways of hardened material machining such as shaft, bush or disc. On the left side of the figure, there is an example of conventional machining process and on the right side – a proposal of optimized process. The optimized process, including hard machining, is shorter and enables to avoid some operations because of the higher rate of material removal. It helps to reduce the production time, the number of machine tools and the number of processes. Machining in soft and hardened state can be done on the same machine tool and additional grinding machine is not required.

In the process of hard turning approximately 80-90% of heat is eliminated while getting rid of chips. Tool materials are so durable that coolant is not necessary. In some cases, cold air, minimum volume of oil or minimum quantity of lubrication can be applied. Coolant should be directly applied to machining zone, not to a machined material.

The chart in Fig. 2 shows cost estimation of grinding and hard turning process of the same components for different volume of production.

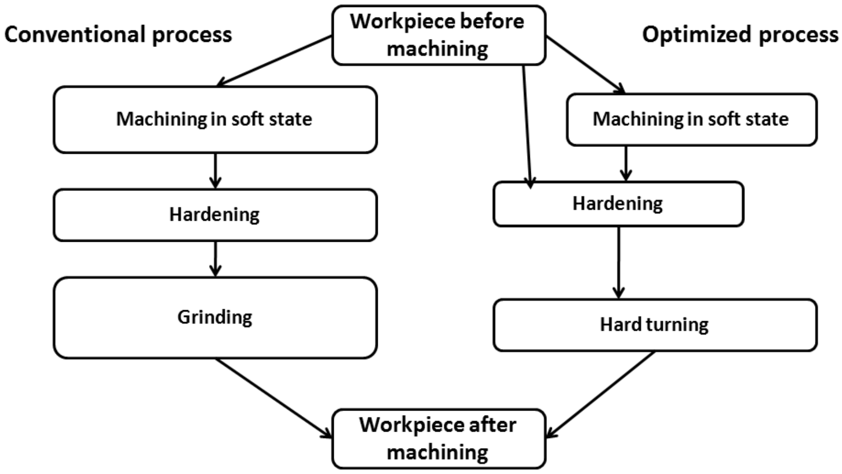


Fig. 1. Conventional and optimized machining process

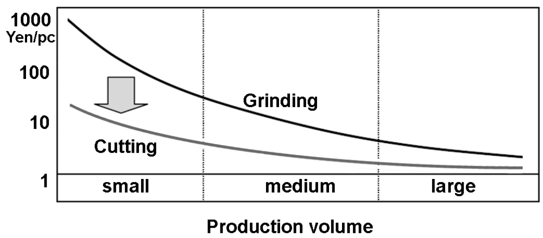


Fig. 2. Costs estimation of hard turning and grinding – by Sumitomo

Table 1. Comparison of grinding and hard turning

Grinding	**+ Better, - Worse**	**Hard turning**
-	Lower energy consumption	+
-	Investments in machine	+
-	Multiple machining operations in one set-up, tool change time, complex contour	+
+	Macro- and micro geometry of machined surface layer	+
+	Physical properties of the machined surface layer	+
-	Ecological aspects of the process	+
-	Operator's safety	+

Table 1 presents some advantages of hard turning in comparison with grinding. As we can notice, energy consumption is much lower for hard turning because of lower range of cutting speed and heat energy generated in the shear zone, higher rates of metal removal. Usually, grinding machines and equipment are more expensive. Multiple machining operations in one set-up are more flexible in case of turning. Tool change time is much shorter and complex contour can be performed. Macro-, micro-geometry and physical properties of the surface can be similar and depend on the machined part and system stiffness (machine tool, chuck, work piece and tool). Better quality and efficiency can be obtained through the connection of hard turning with high precision grinding

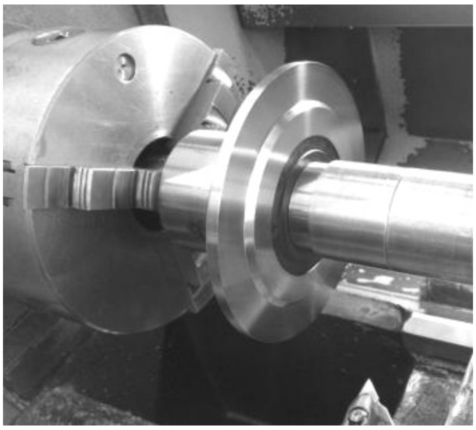


Fig. 3. Turning of part made of hardened cold work tool steel. Application: roller of roll forming machine

Fig. 4. Application of hard turning: punch made of cold work tool steel (X165CrV12, 62 HRC)

processes. Ecology of machining process is much better for hard turning because metal chips can be easy recycled, coolant is not required or cold air can be used. Lathes are safer than grinding machines for the operator of machine tools because some damages of grinding wheel are more dangerous than damages of cutting tool [12, 13].

Figure 3 presents the machining process of hardened roller made of cold work tool steel. The roller is a component of the roll forming machines used for production of metal profiles. Figure 4 presents a punch, also made of cold work tool steel (62 HRC).

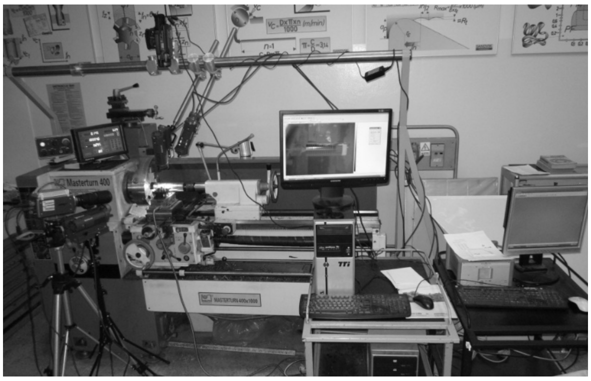
3. Researches on hard turning

3.1. Work piece, tool and equipment

For the purpose of research a test stand was built on the basis of the precision lathe, (Fig. 5-6). Measuring equipment contains:

- hardness tester Rockwell HR150A,
- dynamometer Kistler, amplifier with the DynoWare software,

a)



b)

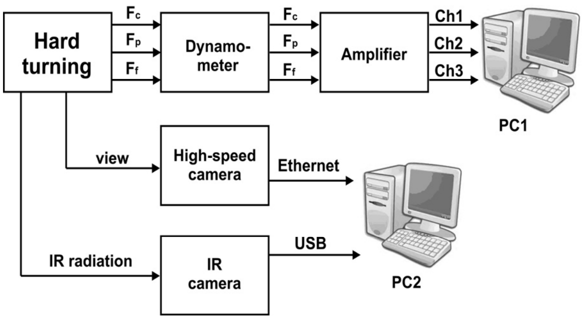
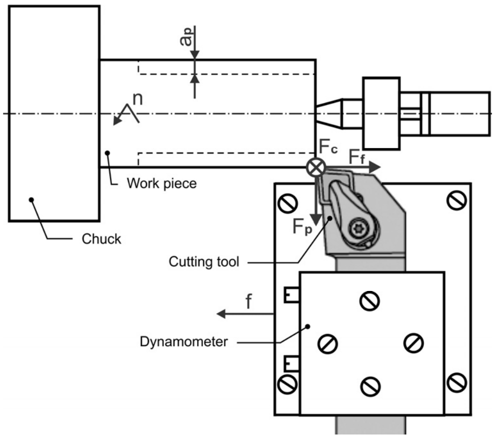


Fig. 5. The research station (a) and the scheme of equipment (b)

a)



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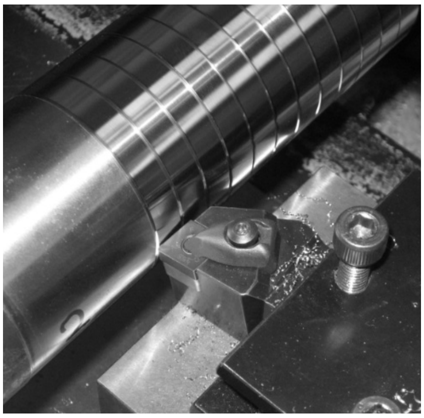

Fig. 6. Kinematic scheme (a) and photography of work piece and tool (b)

- profilometer Surftest SJ-201P Mitutoyo, profilometer Intra Taylor-Hobson,
- IR camera FLIR with the Thermacam Researcher software,
- high-speed camera Phantom with software and cold light system Dedocool.

3.2. Results of researches

For each of three shafts (hardness 56.5 HRC; 58.5 HRC and 62 HRC) made of hardened cold work tool steel (X165CrV12) 11 experiments (and several additional attempts) were carried out according to Hartley investigation plan, Table 2.

During cutting experiments two different inserts made of CBN, produced by WNT company, were used. Chemical composition of steel is given in

Table 3. Some results are presented below. Parameters of the surface roughness obtained after hard turning are as follow: $Ra \in (0.25\text{-}0.89)$ μm; $Rz \in$ $\in (1.44\text{-}4.1)$ μm; $Rq \in (0.3\text{-}1.02)$ μm. The lowest values of surface roughness have been obtained for the lowest feed rate, according to the relation:

$$Rz_t = f^2/(8 \cdot r_\varepsilon) \tag{1}$$

The theoretical equation (1) means that the highest value of roughness should be obtained for the highest value of feed. But lower value of surface roughness in some cases has been achieved for feed 0.134 mm/rev not for 1.53 mm/rev.

Table 2. Plan of experiments (Hartley plan)

No. of experiment	**Case**	**Cutting speed v_c m/min**	**Feed rate f mm/rev**	**Depth of cut a_p mm**
1	10	120	0.105	0.5
2	3	96.9	0.077	0.42
3	4	143	0.134	0.42
4	7	120	0.058	0.3
5	11	120	0.105	0.3
6	8	120	0.153	0.3
7	5	80	0.105	0.3
8	6	160	0.105	0.3
9	1	143	0.077	0.18
10	2	96.9	0.134	0.18
11	9	120	0.105	0.1

High-speed camera was used to record movies with 2400 frames/s, Fig. 7-8. Thermograms and IR movies were recorded with 24 frames/s, Fig. 9.

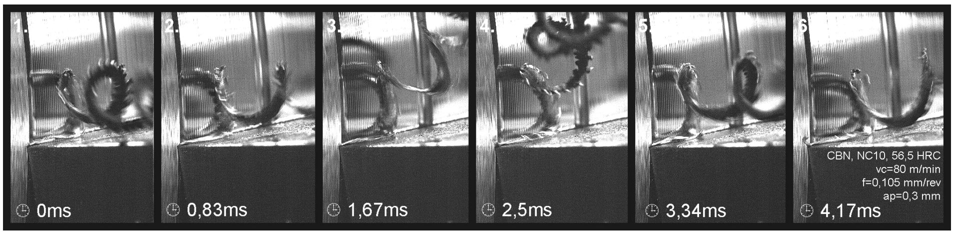

Fig. 7. The sequence of chip formation based on images from the high-speed camera during turning of hardened cold work tool steel (X165CrV12) with the CBN tool (56.5 HRC, $v_c = 80$ m/min, $f = 0.105$ mm/rev, $a_p = 0.3$ mm)

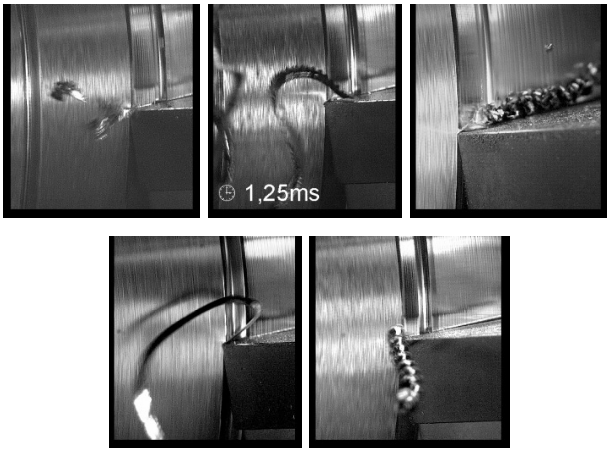

Fig. 8. Examples of different steel chip formation during hard turning of cold work tool steel (X165CrV12)

a) b)

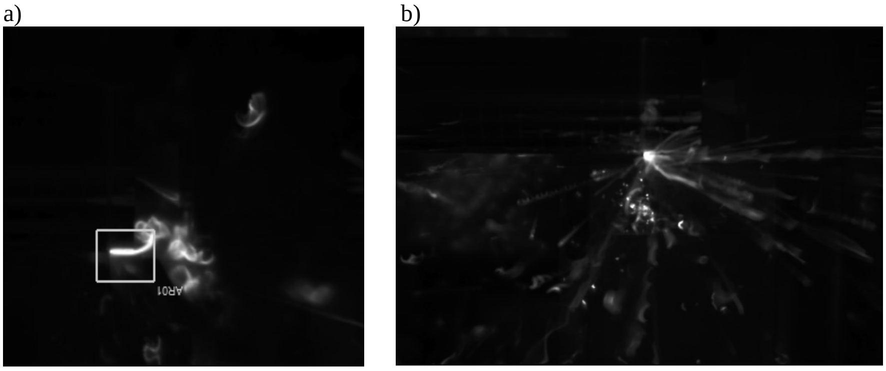

Fig. 9. Cutting of hardened cold work tool steel (X165CrV12, 62 HRC) with the CBN tool: a) thermogram of experiment no. 1: v_c = 120 m/min, f = 0.105 mm/rev, a_p = 0.5 mm, b) thermogram of experiment no. 3: v_c = 143 m/min, f = 0.134 mm/rev, a_p = 0.42 mm. Light color represents hot metal chips

Usually in turning operation it is convenient to consider three components of the total tool force as shown in Fig. 6: the main cutting force component F_c, the feed (axial) component F_f and the passive (radial) component F_p. There is difference between hard turning and classic turning, considering cutting force components values. Usually values of the traditional cutting force components increase gradually in the following order:

$$F_c > F_p > F_f \tag{2}$$

whereas for hard turning, the highest component is F_p, which means [14, 15]:

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

The results presented in Fig. 10-12 are consistent with the relationship (3). Measured values of the cutting force components were in the range: $F_c \in$ (60-240) N, $F_p \in$ (110-285) N, $F_f \in$ (25-160) N. Calculated volumetric metal removal rate, acc. to equation (4), belongs to the range: $Q \in$ (1.26-8.05) cm^3/min:

$$Q = a_p \cdot f \cdot v_c \tag{4}$$

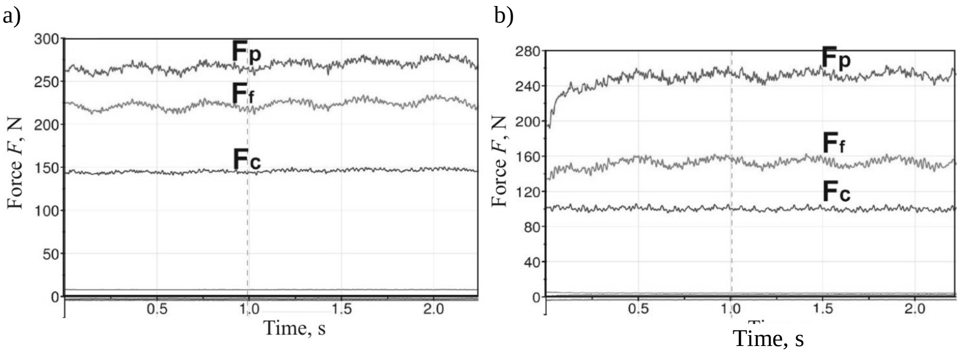

Fig. 10. Example of measured components of the total cutting force for hardened shaft (62 HRC): a) v_c = 143 m/min, f = 0.134 mm/rev, a_p = 0.42 mm, b) v_c = 160 m/min, f = 0.105 mm/rev, a_p = 0.3 mm

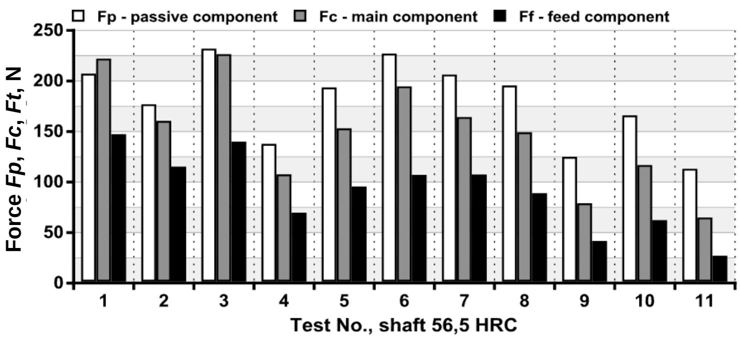

Fig. 11. Comparison between components of the total cutting force in turning of hardened cold work tool steel (X165CrV12) with the CBN tool (56.5 HRC)

Hardness of the work piece materials affects the passive force component *Fp* and the roughness result *Ra*. When the hardness of the work piece material is higher, the obtained passive force component *Fp* and roughness decreases (Fig. 13-14).

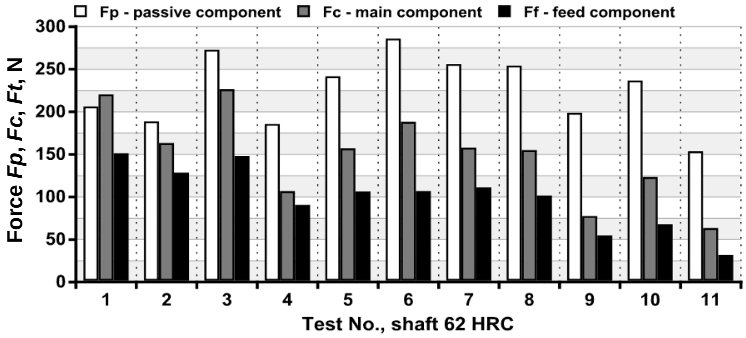

Fig. 12. Comparison between components of the total cutting force in turning of hardened cold work tool steel (X165CrV12) with the CBN tool (62 HRC)

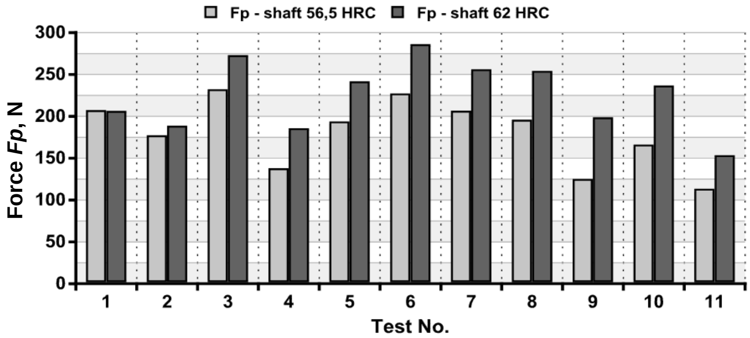

Fig. 13. Effect of hardness on value of passive force component F_P during turning of hardened work piece material made of cold work tool steel (X165CrV12, 56.5 and 62 HRC)

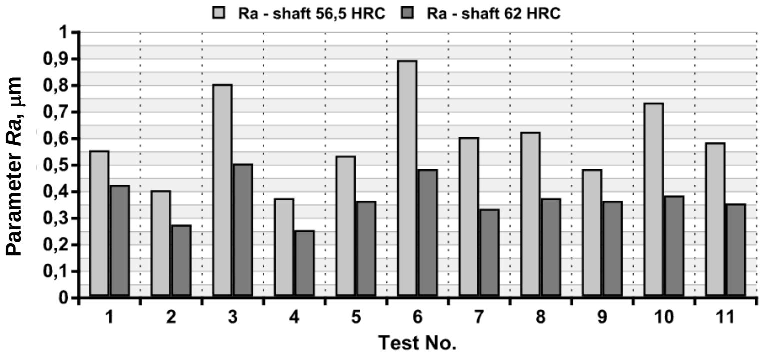

Fig. 14. Effect of hardness on the surface roughness *Ra* after hard turning of cold work tool steel (X165CrV12, 56.5 and 62 HRC)

Cutting speed vc and depth of cut have smaller influence on the surface roughness *Ra* than feed rate f as discussed by Pytlak [16]. Results of experiments are presented in Fig. 15.

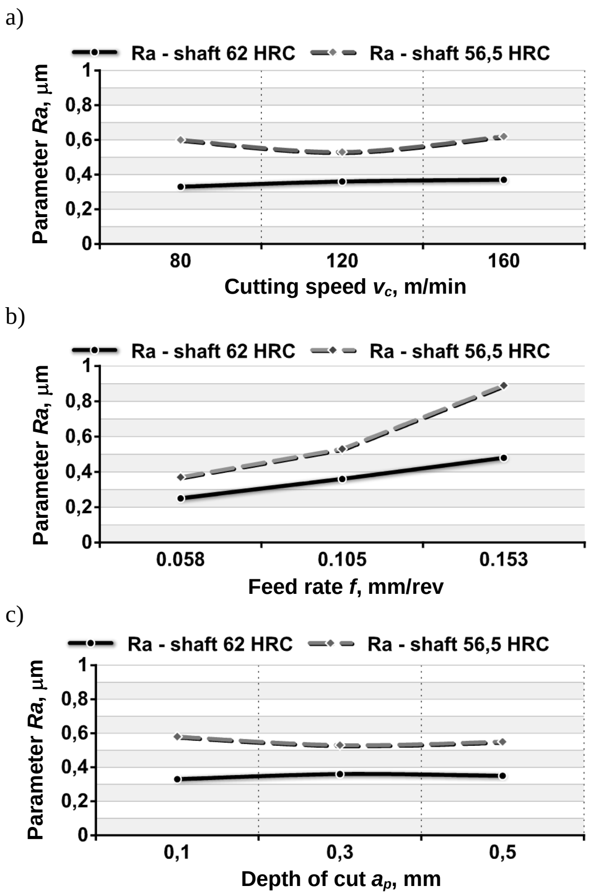

Fig. 15. Dependence between surface roughness and: a) cutting speed (f = 0.105 mm/rev, a_p = 0.3 mm), b) feed rate (v_c = 120 m/min, a_p = 0.3 mm), c) depth of cut (v_c = 120 m/min, f = 0.105 mm/rev); Hardness 56.5 and 62 HRC

Table 3. Chemical composition of cold work tool steel X165CrV12 and X210Cr12

Steel	Chemical composition, %							
	C	Cr	Mn	Si	Ni, Cu	Mo, W	V	P, S
X165CrV12	1.5-1.8	11-13	0.15-0.45	0.15-0.4	<0.35	<0.2	<0.15	<0.03
X210Cr12	1.8-2.1							

3.3. Application of hard turning

After the analysis of literature and hard cutting applications an example part made of cold work tool steel (Fig. 16) was chosen for machining. Its machining, in case of grinding, is expensive when considering shape. Fig. 16 presents also some microscope photos of the machined surfaces in different places. Machining included roughing, profiling and finishing turning of spherical surface, contoured (radial) groove and thread turning (API 60°). The component is made of hardened cold work tool steel X210Cr12 of the hardness 56 HRC, diameter about 90 mm and length 200 mm. During machining different types of the CBN tools (produced by Sandvik Coromant) and cutting parameters for each operations were used (Table 4.) Selected material X210Cr12 is often used for production of hardened tools like punches and rollers (Fig. 3-4). Typical range of hardness after hardening is 55-62 HRC.

Table 4. Turning operations, cutting parameters

Surface	Turning operations	Cutting parameters
-	Roughing - straight turning, d = 90 mm	v_c = 140 m/min, f = 0.2 mm/rev, a_p = 0.5 mm
-	Facing	v_c = 120 m/min, f = 0.15 mm/rev, a_p = 0.5mm
1,2	Roughing of sphere surface	v_c = 95 m/min, f = 0.2 mm/rev, a_p = 0.4 mm
3	Roughing of radial groove	v_c = 80 m/min, f = 0.1 mm/rev, a_p = 0.2 mm
1,2,3	Profiling of sphere and radial groove	v_c = 80 m/min, f = 0.1 mm/rev
1,2,3	Finishing of sphere and radial groove	v_c = 100 m/min, f = 0.07 mm/rev
4	Threading (10x) , pitch = 1.5 mm	v_c = 110 m/min, f = 1.5 mm/rev

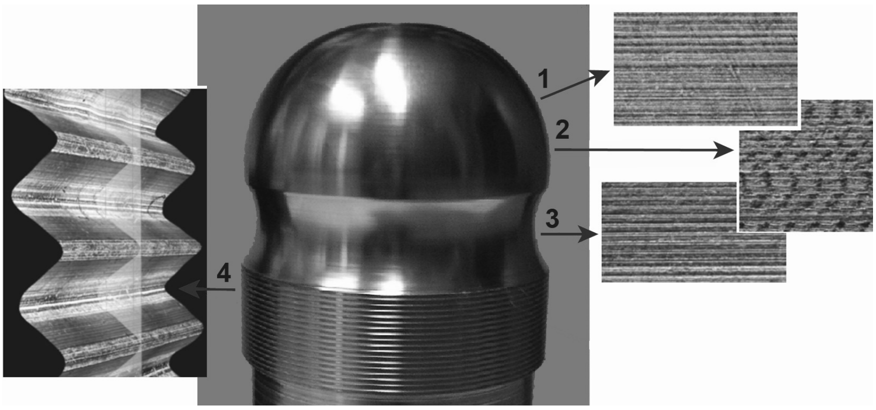

Fig. 16. Part made of hardened cold work tool steel

4. Conclusion

The main advantages of hard turning in comparison with grinding process include: shorter production process, higher metal removal rate, easy cutting of complex contours, high flexibility. Multiple operations can be performed in just one set up. Accuracy and quality are comparable to grinding. Machining of soft and hardened work pieces can be done on the same machine tool at lower energy consumption. Hard machining is environmentally friendly, because metal chips are easy to recycle, coolant is not required or cold air is applicable, instead.

The limitations and disadvantages of hard machining are not usually presented in commercial and promotional materials and in research papers: sometimes tool cost per machined part is significantly higher in hard machining in comparison to grinding. The best solution for hard turning is small ratio of length-to-diameter. Usually special rigid machine tools are required to achieve the good results. Machine rigidity strongly influences on part accuracy.

Better efficiency and economical aspects of hard turning can be obtained through the better quality of machined surface, greater accuracy of machined work piece, longer tool life and cutting edge stability. The success of hard turning depends on the whole machine system including: dynamic stiffness of machine tools and stiffness of work piece, right selection of tool material, tool geometry and cutting conditions, wear of cutting edge and stiffness of cutting tools, method of chip removal and cooling system.

Hard machining gives economical and qualitative benefits. At present some research is being conducted in the field of hard machining technology in laboratories of universities and by cutting tools producers. The goals of this research are costs reduction during machining, revision of both machining performance and quality. It should be noted that hard machining is not intended to exclude completely the grinding process in the machine parts manufacturing. This technology, despite many skeptical opinions is an alternative solution to improve significantly the economics of the machining process, increase productivity and shorten production time.

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