EXPERIMENTAL INVESTIGATION ON TURNING OF CASE-HARDENED 21NiCrMo2 CEMENTATION STEEL

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Abstract: *This article presents investigations on the variation of cutting forces, surface quality and chip shapes obtained in the HPM (Hard Part Machining) process, when turning a case hardened 21NiCrMo2 (AISI 8620/ SAE 8620) cementation alloy steel with 3 different hardness values and 3 types of insert materials. This study can be helpful for a better prediction of tool life and surface quality in machining planning.*

Keywords: *cutting force, turning, hardness, roughness, chip form*

1. Introduction

The machining of hard materials with sharped-edge tools is a strongly investigated research topic, known in the scientific literature as Hard Machining (HM) or Hard Part Machining (HPM) and is defined as the cutting process of materials with hardness between 45-75 HRC [Huang'2005]. In recent years, the number of studies of HPM processes have increased. Many of these articles present studies of the influence of the cutting parameters [Yallese'2009, Lima'2005], cutting environment [Varadarajan'2002, Mia'2017], workpiece material [Ebrahimi'2009], tool material [Sales'2009] etc on the cutting forces, tool wear, surface quality and other output parameters. Ebrahimi et al. [Hebrews '2009], studied the behavior of three different materials with different material hardness and showed that with the increase of the cutting speed regardless of the hardness of the material, the forces have similar decreasing tendencies. At the same time, by increasing the feed rate, regardless of the hardness of the material, the cutting forces increase. These trends were also observed by Lima et al. in a study [Lima'2005], published in 2005. The results obtained by Lima also showed that regardless of the hardness of the material, by increasing the cutting speed the cutting forces decrease, and by increasing the feed rate and depth of cut, the forces increase considerably. The tests were carried out on different materials with large differences between the material hardness (42 and 50 HRC, respectively). Another problem investigated in these studies was the surface quality from a geometric point of view, and it was concluded that the roughness improves as the cutting speed increases and it decreases as the feed rate increases. The material of the tool's cutting part, the literature suggests that the most reliable are the cubic boron nitride (PcBN) inserts [Lahiff'2007]. A series of studies exposing the chip morphology have been published, most of them investigating the machinability of hard materials [Surreddi'2013, Youcef'2020] and it has been shown that regardless of the values chosen for cutting parameters, the chips obtained by hard cutting expose a sawtooth shape.

The aim of the paper was to carry out an experimental investigation on HPM cutting and establish the influence of 21NiCrMo2 cementation alloy steel hardness, the tool insert material and cutting parameters on cutting forces, roughness of machined surfaces and chip shape.

2. Experimental setup

The study of the influences mentioned above was performed with a experimental chain with the configuration shown in Figure 1.

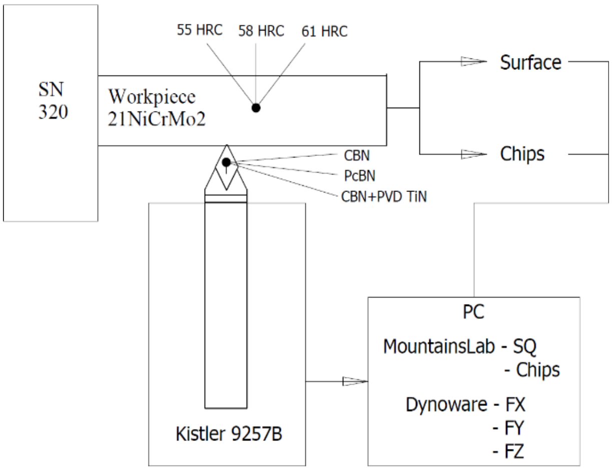


Figure 1: *Testing chain.*

The tests were carried out on a plant lathe type SN 320x750, three 21NiCrMo2 cementation alloy steel workparts with the geometry and dimensions shown in figure 2 were machined. These parts were exposed to different quenching treatments and three different values for material hardness were obtained - 55 HRC, 58 HRC and 61 HRC respectively.

As tool insert materials three types of inserts with similar geometry were used -CBN, PcBN and CBN with PVD TiN coating. The inserts were fixed on a tool holder type PSSN of 20x20x125 mm, with the cutting geometry presented in table 1.

Tabel 1. *Cutting tool geometry*

Cutting tool geometry			
Rake angle, γ [°]	Clearance angle, α [°]	Cutting edge angle, k [°]	Inclination angle, λ [°]
-10	10	50	10

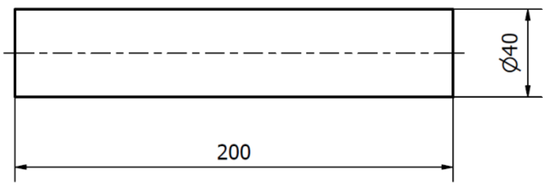
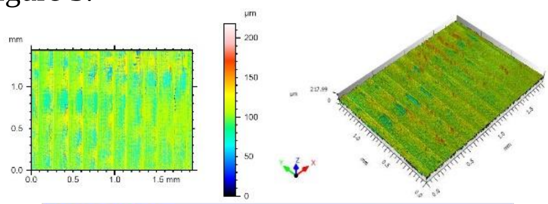


Figure 2: *Test part.*

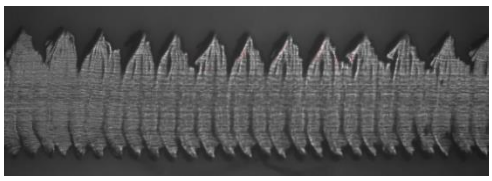
During the cutting tests, the tool was mounted on a specialized dynamometer produced by Kistler type 9257B and the values of the cutting force components were determined. The Mahr CWM100 interferometer and confocal microscope was used to study the topography of the machined surfaces and allowed the determination of the values of the parameters that characterize the geometric microtopography, according to ISO 25178, figure 3.



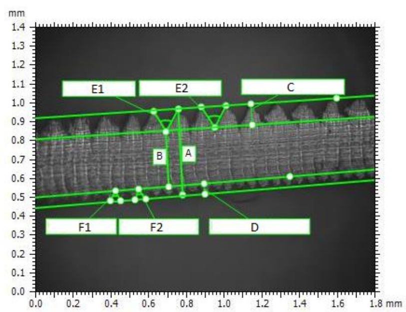
ISO 25178			
Height Parameters			
Sq	31.468	µm	Root-mean-square height
Ssk	-0.24064		Skewness
Sku	2.6391		Kurtosis
Sp	129.31	µm	Maximum peak height
Sv	108.72	µm	Maximum pit height
Sz	238.03	µm	Maximum height
Sa	25.874	µm	Arithmetic mean height
Functional Parameters			
Smr	0.00044057	%	Areal material ratio
Smc	39.634	µm	Inverse areal material ratio

Figure 3: *Tests specimen surface analysis.*

The Mahr CWM100 microscope was also used to perform analyzes on the shape and dimensions of the chips generated during the cutting tests, figure 4.a. The estimation of the chip dimensions and their shapes were analyzed on Mountainslab 7 software installed on the microscope PC, figure 4.b.



a.



b.

Figure 4: *Machining tests resulted chips.*

The machining tests were performed according to a Taguchi DOE experiment array [Ionescu'2004], type L9, designed for 4 input factors with three levels of variation (part material hardness, tool insert material, cutting speed and feed), according to table 2.

Tabel 2. *Taguchi L9 array*

No.	Hardness of the part material, HRC	Tool material	Vc [m/min]	f [mm/rev]
1	55	CBN	125.6	0.10
2	55	PcBN	157.0	0.18
3	55	CBN + PVD TiN	200.9	0.28
4	58	CBN	157.0	0.28
5	58	PcBN	200.9	0.10
6	58	CBN + PVD TiN	125.6	0.18
7	61	CBN	200.9	0.18
8	61	PcBN	125.6	0.28
9	61	CBN + PVD TiN	157.0	0.10

3. Experimental results and discussions

In order to assess the degree of confidence in the results obtained according to the methodology presented above, the experimental tests were repeated three times. The results obtained are given in tables 3, 4, 5.

Tabel 3. *Taguchi L9 array - results for Fx*

Nr.	Material hardness HRC	Tool material	Vc, [m/min]	f, [mm/rev]	Fx 1, [N]	Fx 2, [N]	Fx 3, [N]
1	55	CBN	125.6	0.10	19.3	28.0	27.2
2	55	PcBN	157.0	0.18	20.2	38.4	25.2
3	55	CBN + PVD TiN	200.9	0.28	23.6	31.1	20.9
4	58	CBN	157.0	0.28	15.9	22.0	17.3
5	58	PcBN	200.9	0.10	40.9	40.8	42.5
6	58	CBN + PVD TiN	125.6	0.18	48.2	48.7	50.6
7	61	CBN	200.9	0.18	44.2	45.4	46.0
8	61	PcBN	125.6	0.28	42.8	41.8	35.3
9	61	CBN + PVD TiN	157.0	0.10	38.3	38.3	46.9

Tabel 4. *Taguchi L9 array - results for Fy*

Nr.	Material hardness HRC	Tool material	Vc, [m/min]	f, [mm/rev]	Fy 1, [N]	Fy 2, [N]	Fy 3, [N]
1	55	CBN	125.6	0.10	90.8	92.6	89.1
2	55	PcBN	157.0	0.18	100.7	134.4	112.4
3	55	CBN + PVD TiN	200.9	0.28	162.2	190.9	155.0
4	58	CBN	157.0	0.28	115.3	120.7	127.4
5	58	PcBN	200.9	0.10	124.3	122.1	127.1
6	58	CBN + PVD TiN	125.6	0.18	182.8	180.0	170.9
7	61	CBN	200.9	0.18	174.6	177.9	179.9
8	61	PcBN	125.6	0.28	166.1	173.2	153.4
9	61	CBN + PVD TiN	157.0	0.10	143.3	143.2	159.7

Tabel 5. *Taguchi L9 array- results for Fz*

Nr.	Material hardness HRC	Tool material	Vc, [m/min]	f, [mm/rev]	Fz 1, [N]	Fz 2, [N]	Fz 3, [N]
1	55	CBN	125.6	0.10	26.0	26.6	25.5
2	55	PcBN	157.0	0.18	30.8	45.8	35.9
3	55	CBN + PVD TiN	200.9	0.28	42.0	50.9	39.5
4	58	CBN	157.0	0.28	34.4	42.5	36.9
5	58	PcBN	200.9	0.10	36.9	36.8	36.4
6	58	CBN + PVD TiN	125.6	0.18	55.6	53.6	55.8
7	61	CBN	200.9	0.18	55.1	56.1	55.8
8	61	PcBN	125.6	0.28	64.0	62.3	58.2
9	61	CBN + PVD TiN	157.0	0.10	34.0	33.4	41.7

The values of the main effects of the factors considered and the linearized mathematical model were determined with the Minitab software. The expressions of the regression functions for each case have the forms according to the relations: (1), (2) and (3).

$$\boldsymbol{Y\_(F\_x) = 32,06 + [26,01\ 36,30\ \ 42,11]\ \ [HRC] + [29,48\ 36,43\ 38,51]\ \ [Tool] + [37,98\ 29,18\ 37,26]\ \ [Vc] + [35,80\ 40,77\ \ 27,85]\ \ [F]} \quad (1)$$

$$\boldsymbol{Y\_(F\_y) = 140,01 + [125,3\ 141,2\ \ 163,5]\ \ [HRC] + [129,8\ 134,9\ 165,3]\ \ [Tool] + [144,3\ 128,6\ 157,1]\ \ [Vc] + [121,4\ 157,1\ \ 151,6]\ \ [F]} \quad (2)$$

$$Y\_(F\_z) = 42,09 + [35,90 \; 43,20 \; 51,19] \; [HRC] + [39,88 \; 45,24 \; 45,17] \; [Tool] + [47,52 \; 37,27 \; 45,50] \; [Vc] + [33,02 \; 49,4 \; 47,87] \; [F] \qquad (3)$$

The graphical representation of the main effects of each of the input factors considered in this study are presented in the figures 5÷7.

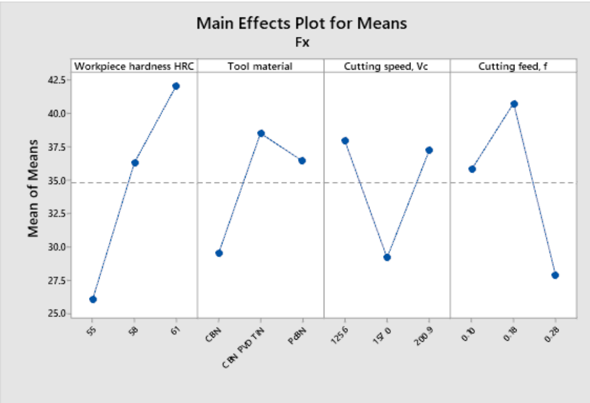


Figure 5: *Main effects for the force component Fx.*

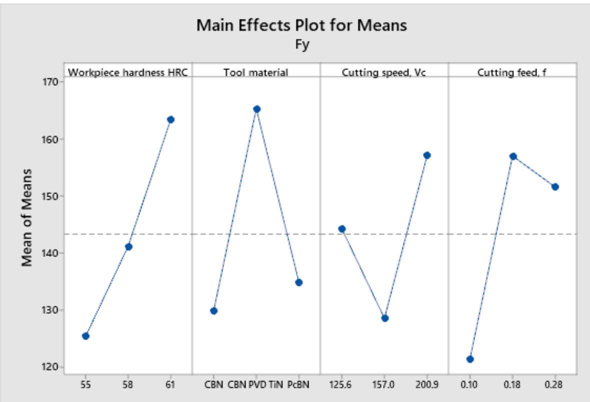


Figure 6: *Main effects for the force component Fy.*

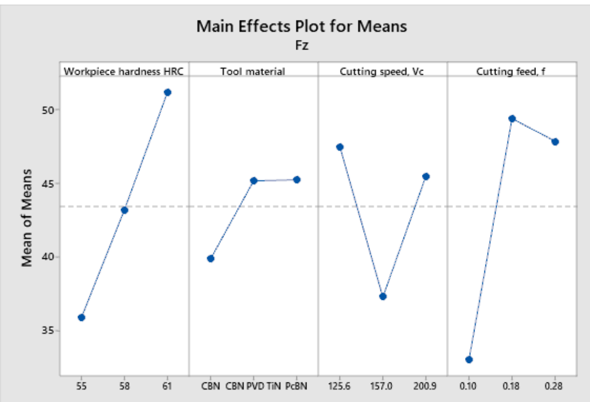


Figure 7: *Main effects for the force component Fz.*

The experimental results obtained show that the values of the cutting force components increase with the increase of the part material hardness and of the cutting feed.

The material of the cutting tool inserts, CBN, PcBN and CBN + PVD TiN, exposed a significant influence on the cutting force components Fx, Fy, and Fz. An increase in the values of the three cutting force components was observed when cutting was performed with PCBN inserts. This can be explained by the coefficients of friction on the chip tool contact interfaces. The increase of the cutting speed values caused a decrease of the cutting force components for the cutting speeds ranging from 120 to 160 m/min, explainable and in agreement with other similar results presented in the scientific literature, and an average increase of about 35 ÷ 40% for higher speed range (160 ÷ 210m/min).

The roughness of the machined surfaces with the cutting conditions established in the Taguchi experimental array was also investigated (see table 6). The main effects plots of the input factors are presented in figure 8.

Tabel 6. *Taguchi L9 array*

Nr.	Material hardness HRC	Tool material	Vc, [m/min]	f, [mm/rev]	Sq, [µm] 1	Sq, [µm] 2	Sq, [µm] 3
1	55	CBN	125.6	0.10	24.74	24.80	25.50
2	55	PcBN	157.0	0.18	27.00	28.93	28.60
3	55	CBN + PVD TiN	200.9	0.28	31.47	34.34	33.30
4	58	CBN	157.0	0.28	28.43	26.35	27.09
5	58	PcBN	200.9	0.10	24.52	25.10	26.66
6	58	CBN + PVD TiN	125.6	0.18	29.71	29.99	29.98
7	61	CBN	200.9	0.18	25.42	27.45	25.41
8	61	PcBN	125.6	0.28	33.43	36.89	35.13
9	61	CBN + PVD TiN	157.0	0.10	23.69	24.51	20.94

By analyzing the variation curves from the main effect plots of the input factors on the surface roughness parameter Sq, we could observe that the hardness of the material has a minor influence. The root mean square height-Sq is a surface texture parameter that represents the root mean square value of ordinate values within the definition area.

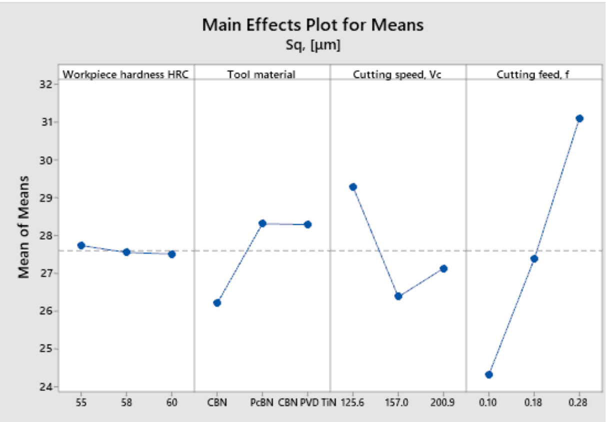


Figure 8: *Main effects for Sq.*

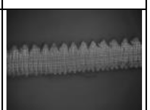
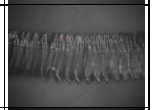
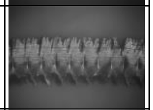
The CBN tool insert influences in a higher percentage the values of the Sq parameter, compared to the other two insert materials used.

The effect of the cutting speed on the root mean square height is shown in figure 8, which shows a tendency to improve the roughness for values in the range of 150 ÷ 160 m/min.

The cutting feed has the most consistent influence on the surface parameter Sq causing an increase of the roughness investigated parameter by about 30%, for the range of the cutting feed investigated (0.1 ÷ 0.22 mm/rev).

The chips obtained in the cutting tests carried out by the Taguchi L9 experimental array are shown in Table 7.

Table 7. Resulted chips – tool-chip contact surface view

Nr.	Material hardness HRC	Tool material	Vc, [m/min]	f, [mm/rev]	Chips
1	55	CBN	125.6	0.10	
2	55	PcBN	157.0	0.18	
3	55	CBN + PVD TiN	200.9	0.28	
4	58	CBN	125.6	0.28	
5	58	PcBN	157.0	0.10	
6	58	CBN + PVD TiN	200.9	0.18	
7	61	CBN	125.6	0.18	
8	61	PcBN	157.0	0.28	
9	61	CBN + PVD TiN	200.9	0.10	

The image captures analyzed with Mountainslab specialized software expose the the representative shape of the chips, highlighting their structure and geometric shape (front-back). The following conclusions could be drawn:

- the geometry of the chips is similar to the geometries indicated by the scientific literature from the field;
- the sides of the chips exposed saw teeth shape of different sizes and pitch (figure 9, details 1 and 2);
- detail 2 correspond to the area adjacent to the machined surface and detail 1 corresponds to the free surface;
- one tooth in detail 1 corresponds to approximately two teeth in detail 2;

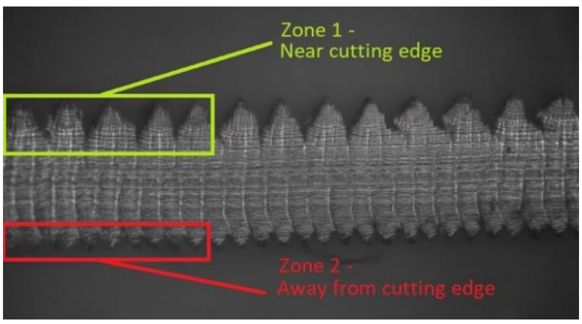


Figure 9: *Back of the chip.*

- the sliding planes have different lengths for the two edges of the chip, the higher values corresponded to the details 2- the area adjacent to the machined surface.

- in some experimental tests, the analysis according to the color of the chips reveals a high thermal load (det 6).

Assuming that the loading on the edge is uniform over the entire length of contact with the chip, then the above findings could be explained by the "end effect" in the extreme areas corresponding to the edges of the chip, which differently influences the stress evolution until reaching the level of the plastic deformation forces from which the material flows and the chip formation begins.

4. Conclusions

The paper addressed the method of turning with cutting tools applied to the cutting of quenched cementation steels.

A number of experiments were carried out within a Taguchi experimental array and some results were obtained, mainly in accordance with other results highlighted by the specific scientific literature. The conclusions formulated regarding the influences of the input factors considered on the cutting force components and surface texture parameter Sq depended on the nature and mechanical characteristics of the tool and part material interference and the cutting parameters (cutting speed and feed). The experimental data showed that there is a decrease in cutting forces levels for the parts with lower material hardness and that the values of the cutting force components strongly depends on the nature of the tool insert material. A decrease of the cutting force components values could be observed with the increase of the cutting speed and cutting feed values.

The lacy shape of the chip with different geometry on the two edges, is specific to the machining of hard materials when the ductile-brittle transition tilts in favor of fragility. The difference between the geometries of the two edges of the detached chip was explained by the influence of the "end effect".

Acknowledgments

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