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Research Article

CUTTING TOOLS FLANK WEAR AND PRODUCTIVITY INVESTIGATION IN STRAIGHT TURNING OF X38CrMoV5-1 (50 HRC)

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ABSTRACT
The purpose of this work is to investigate flank wear and productivity of cutting tools in machining X38CrMoV5-1 treated at 50 HRC. This steel is intended for hot work and free from tungsten on CrMoV basis. It is employed for the manufacture of moulds, module matrices of door for car and helicopter rotor blades. The tests of straight turning were carried out under dry conditions using the following tools: uncoated carbide (H13A), coated carbide (GC3015), mixed ceramic (CC650), whisker ceramic (CC670), uncoated cermets (CT5015) and coated cermets (GC1525). Experimental results enable us to study the influence of chip machining length on flank wear *VB* of these tools for two different cutting regimes. The results indicate that mixed ceramic (Al_2O_3+TiC) is more efficient than other grades used in terms of wear resistance and productivity. Consequently, it is the most powerful.

***Key Words**: Straight Turning, X38CrMoV5-1, Chip Length, Flank Wear, Productivity, RSM*

Nomenclature

a_p	Depth of cut, mm
f	Feed rate, mm/rev
HRC	Rockwell hardness
L_c	Chip machining length, m
R^2	Coefficient of determination
t	Machining time, min
VB	Flank wear, mm
Vc	Cutting speed, m/min
α	Relief angle, degree
γ	Rake angle, degree
λ	Inclination angle, degree
χ	Major cutting edge angle, degree

INTRODUCTION
Flank wear is an important criterion for machinability assessment of a material. It occurs during machining operations and becomes a common limitation to tool life, productivity and part quality. It influences machining system stability. For these reasons, it was a topic of industrial and academic interest in the manufacturing sector for many years. A great deal of research was carried out to solve the flank wear problem. Researchers studied how to detect, identify, avoid, prevent, control and reduce this important technological parameter. Nowadays, authors still refer to flank wear as a limiting factor, one of the most important machining challenges and, of course, an aspect to be improved. The advantages of studing flank wear are obvious from the negative effects avoided: poor surface quality, unacceptable

inaccuracy, reduced material removal rate, increased costs in terms of time, materials and energy. The term Machinability refers to the ease with which a metal can be machined to an acceptable surface finish. Machinability of a material provides an indication of its adaptability to be manufactured by a machining process. Therefore to manufacture components economically, engineers are challenged to find ways to improve the machinability of a material without harming its performance. In general, in modern industry, the goal is to manufacture low cost, high quality products in a short time. Flexible and automated manufacturing systems are being employed in several of applications starting from a small workshop to a big aerospace company. The machinability of hardened steel was evaluated by measurements of tool wear, cutting forces and surface finish of the work piece. In hard turning, flank wear has been found to be influenced by a number of factors such as cutting speed, machining time, workpiece hardness, etc (Quintana and Ciurana 2011; Mandal *et al.*, 2011; Ozel *et al.*, 2007; Fnides *et al.*, 2008; Fnides *et al.*, 2011; Fnides *et al.*, 2008; Paulo Davim and Figueira 2007; Fnides *et al.*, 2009; Aouici *et al.*, 2010).

Machinability of a material is generally defined in terms of three factors: forces/power consumption, tool wear and surface finish. Thus, a material with good machinability is the one requiring low power consumption, with low tool wear and producing a good surface finish and integrity (Kalpakjian and Schmid Steven 2003).

Horng *et al.*, (2008) presented a model to evaluate the machinability of Hadfield steel by applying RSM and Analysis of Variance (ANOVA) techniques.

An attempt was made to analyze the important wear mechanisms like abrasive wear, adhesive wear and diffusion wear of ceramic cutting tool materials (Senthil Kumar *et al.*, 2003).

Kaye *et al.*, (1995) used Response Surface Methodology in predicting tool flank wear using spindle speed change. A unique model was developed which predicts tool flank wear, based on the spindle speed change.

Flank wear of the alumina-based ceramic cutting tool was indirectly monitored in response to systematic changes in the turning tests using AISI 4340 and 52100 hardened steels and the cutting speeds of 142, 181, and 264 m/min. A comparative analysis of the experimental results showed that the interaction effect elucidated 82% of variation in flank wear. There appeared to be a high correlation (r=0.929) between flank wear values measured in mm and V. This study shows that real-time monitoring of flank wear in the ceramic cutting tool presents a high potential as well as an effective approach for finding optimal cutting speeds for turning operations, and thus, increasing the performance of cutting tools. Further research is needed to explore concurrent quantification multiple factors influencing wear behavior of the cutting tools in order for the use of optical sensor systems to be successfully employed in industrial applications (Cakan 2010).

RSM was applied to develop mathematical model of flank wear in order to investigate the influence of machining parameters during finish turning of AISIH11 hardened steel with a TiC-coated, mixed ceramic tool. Numerical optimization in RSM and the desirability function approach were used to obtain optimum values for machining parameters. The experimental study has led to the following conclusions. TiC-coated-mixed ceramic tools could be employed as an effective and economic alternative to costly PCBN cutting tools in hard turning of tool steels, owing to reasonably good performance within the range of parameters selected in this study. The RSM technique is an effective tool for investigating the influence of various machining parameters on response factors, i.e. flank wear. Feed rate, depth of cut, and workpiece hardness were found to influence flank wear significantly. The optimized machining conditions for minimizing tool wear are in the region of: cutting speed, 100 m/min; feed rate, 0.08 mm/rev; depth of cut, 0.11 mm; and workpiece hardness, 52 HRC; with estimated flank wear of 66.4 µm. The percentage error between the predicted and experimental values of the response factors during the confirmation experiments is within 5 per cent. Tool wear resulted from the combined action of mechanical and chemical wear. The tool appears to be worn out by abrasion, notch wear, and chipping of the tool surface as a result of rubbing and impingement of hard particles in the workpiece material and adhesion wear at high temperatures (Dureja *et al.*, 2009).

Aouici *et al.,* (2011) investigated the flank wear in hard turning of AISI H11 with CBN tool. They found that the flank wear is influenced principally by the cutting time, cutting speed and the interaction effect of cutting speed/cutting time with a contribution of 51.47%, 32.35% and 10.52%, respectively.
Choudhury & El-Baradie (1998) found that Response Surface Methodology coupled with the factorial design of experiments was a useful technique for tool life prediction. A relatively smaller number of designed experiments are required to generate much useful information that could be used to develop the predicting equation for tool life. Rapid developments in ceramics have introduced ceramic- ceramic composites for many engineering application.
The aim of the present study is, thus, to investigate flank wear and productivity of cutting tools on X38CrMoV5-1 hardened steel. Machining tests were carried out under dry conditions with the following tools: H13A, GC3015, CT5015, GC1525, CC650 and CC670. The model predicting equation for flank wear *VB* of mixed ceramic CC650 was developed. To calculate constants and coefficients of this model, the software's Minitab 15 and Design-Expert 8 characterized by analysis of variance (ANOVA), multiple linear regression and response surface methodology (RSM) were exploited.
In order to achieve this, statistical analysis of the experimental results will have to be processed using the analysis of variance (ANOVA). This latter is a computational technique that enables the estimation of the relative contributions of each of the control factors to the overall measured response. In this work, the parameters will be used to develop mathematical model using multiple linear regression and response surface methodology (RSM). RSM is a collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response (Fnides *et al.,* 2012; Bartarya & Choudhury 2012; Gupta *et al.,* 2012; Kadirgama *et al.,* 2011; Suresh *et al.,* 2012; Mokšin 2011; Om *et al.,* 2012).

MATERIALS AND METHODS

The material used for the experiments is grade X38CrMoV5-1, hot work steel which is popularly used in hot form pressing. It is employed for the manufacture of the module matrices of door for car, helicopter rotor blades, the shells, the moulds and inserts of high pressure die casting strongly requested with high lifespan. Its chemical composition is given in Table 1.

Table 1: Chemical composition of grade X38CrMoV5-1

Composition	(wt. %)
C	0.35
Cr	5.26
Mo	1.19
V	0.5
Si	1.01
Mn	0.32
S	0.002
P	0.016
Other components	1.042
Fe	90.31

The workpiece is of 300 mm length and 75 mm in diameter. It is hardened to 50 HRC. Its hardness was measured by a digital durometer DM2D. The lathe used for machining operations is TOS TRENCIN; model SN40C, spindle power 6.6 KW. The cutting inserts used are uncoated carbide H13A, coated carbide GC3015, uncoated cermets CT5015, coated cermets GC1525, reinforced ceramic CC670 and mixed ceramic CC650. These inserts are removable, of square form with eight cutting edges. Their characteristics are shown in table 2.

Table 2: Characteristics of used inserts

Cutting materials	Designation	Chemical composition
Uncoated Carbide H13A	SNMG120408-MR	Tungsten carbide
Uncoated cermets CT5015	SNMG120408-QF	Carbide with titane basis
Coated Carbide GC3015	SNMA120408-KR	Coating CVD TiCN-Al_2O_3- and TiN
Coated cermets GC1525	SNMG120408-PF	Coating PVD TiCN and TiN
Mixed ceramic CC 650	SNGA120408 T 010 20	Al_2O_3 (70%) + TiC (30%)
Reinforced ceramic CC670	SNGN120408 T 010 20	Al_2O_3 (75%) + SiC (25%)

The toolholders adapted are of designation CSBNR2525M12 and PSBNR2525M12 with geometry of the active part characterized by the following angles: χ = 75°; α = 6°; γ = -6°; λ = -6°. An optical microscope model Hund (W-AD) was adapted to measure flank wear of different tools.

RESULTS AND DISCUSSION

Effects of Chip Machining Length on Flank Wear VB

The tests of long duration of straight turning on grade AISI H11 steel treated at 50 HRC were carried. The purpose of these operations is to determine the wear curves as a function of chip machining length and therefore we determine the tool life and the productivity of various cutting tools used.

Figure 1 shows the evolution of flank wear *VB* versus chip machining length at f = 0.08 mm/rev, a_p = 0.15 mm and V_c = 120 m/min.

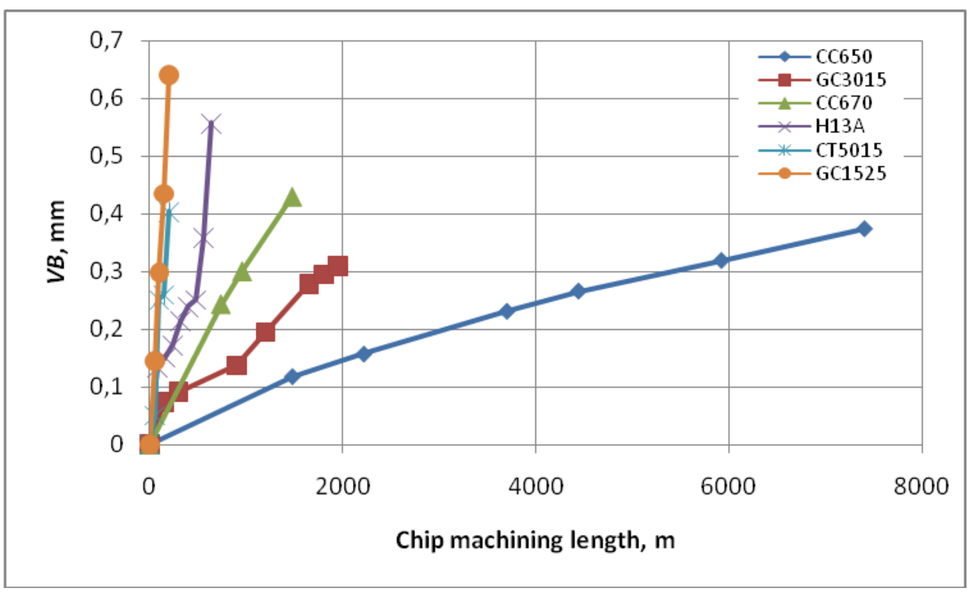

Figure 1: *VB* of cutting tools vs. chip machining length

The following cutting tools: mixed ceramic Al_2O_3 + TiC (CC650) and reinforced ceramic Al_2O_3 + SiC (CC670), uncoated carbide H13A, coated carbide GC3015, uncoated cermets CT5015 and coated cermets GC1525 were used.

Research Article

According to the curve of mixed ceramic Al_2O_3 + TiC (CC650) and for a chip machining length of 1480 m, the flank wear *VB* of this insert reaches a value of 0.118 mm. At the end of machining (when L_c = 7400 m), the flank wear becomes 0.374 mm. This change represents an increase of 217%. The tool life of this insert is 49 minutes.

A first operation of turning by the inset CC670 leads to a value of wear *VB* of 0.243 mm. This latter exceeds its allowable value and reaches 0.429 mm for the second operation of machining. By examining the shape of this curve, the tool life of this insert is only 8 minutes. In these cutting conditions, the tool life of whisker ceramic does not exceed the rate of 17% of that of the mixed ceramic.

For machining done by the uncoated cermets CT5015, its wear *VB* is 0.404 mm which means that the edge of this tool is severely damaged. Its tool life is less than 1.5 minutes.

The flank wear of the coated cermets GC1525 exceeds its allowable value and reaches 0.460 mm. According to its curve, its tool life is 1 minute.

The first machining test done by the coated carbide GC3015 generates a flank wear of 0.074 mm. For a chip machining length of 1950 m, its wear *VB* is 0.309 mm which defines the lifespan of 16 minutes of this tool.

At this chip machining length of 240 m, the flank wear of uncoated carbide H13A is 0.172 mm. Its *VB* exceeds the allowable value and reaches 0.358 mm for a chip machining length of 560 m. Tool life of H13A is 4.5 minutes.

These three cutting tools (mixed ceramic CC650, reinforced ceramic CC670 and coated carbide GC3015) were more resistant than other tools in terms of wear. For this reason, they were selected to study the effect of chip machining length on their flank wear *VB* for this new cutting regime (f = 0.08 mm/rev, a_p = 0.15 mm and V_c = 90 m/min). Figure 2 illustrates the evolution of flank wear *VB* for these three selected tools.

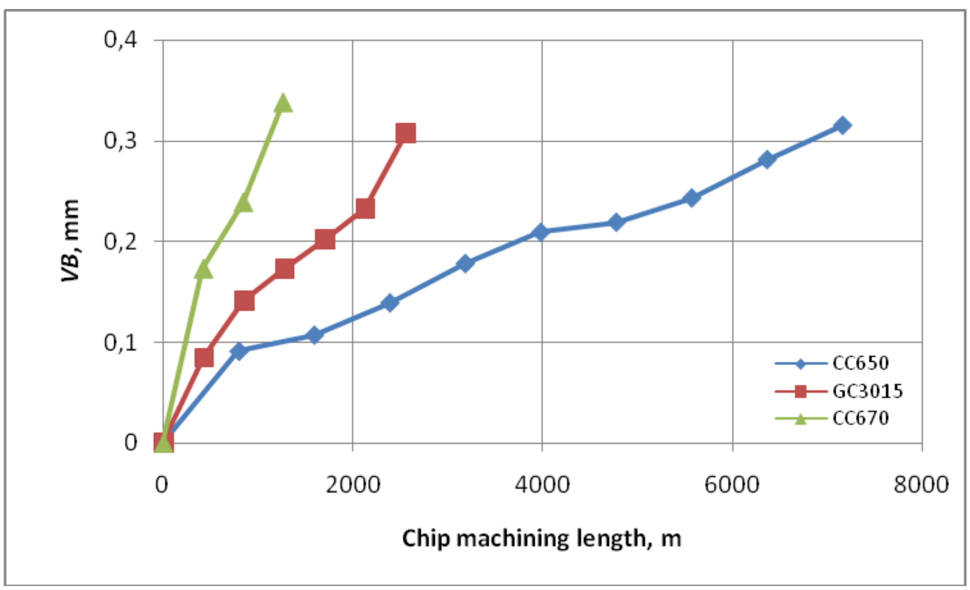

Figure 2: *VB* of Selected Cutting Tools vs. Chip Machining Length

According to the curve of mixed ceramic Al_2O_3 + TiC (CC650) and for a chip machining length of 795 m, the flank wear *VB* of this insert reaches a value of 0.091 mm. After nine operations of machining (when L_c = 7155 m), the flank wear becomes 0.315 mm. This change represents an increase of 246%. The tool life of this insert is 79 minutes.

A first operation of turning by the inset CC670 leads to a value of wear *VB* of 0.173 mm. This latter exceeds its allowable value and reaches 0.338 mm for a chip machining length of 1260 m. By examining the shape of this curve, the tool life of this insert is only 12 minutes. In these cutting conditions, the tool life of whisker ceramic does not exceed the rate of 15.1% of that of the mixed ceramic.

For a chip machining length of 427.5 m, flank wear *VB* of GC3015 is 0.085 mm. This latter becomes 0.308 mm for a chip machining length of 2565 m. The tool life of this insert is 28.5 minutes.

For these two different cutting conditions, mixed ceramic Al_2O_3 + TiC (CC650) was more efficient than other cutting tools in terms of wear resistance.

Productivity of Cutting Tools

Figures 3 and 4 illustrate the productivity in terms of volume chip carved of each cutting tool for these two different cutting regimes (f = 0.08 mm/rev, a_p = 0.15 mm and V_c = 120 m/min) and (f = 0.08 mm/rev, a_p = 0.15 mm and V_c = 90 m/min), respectively.

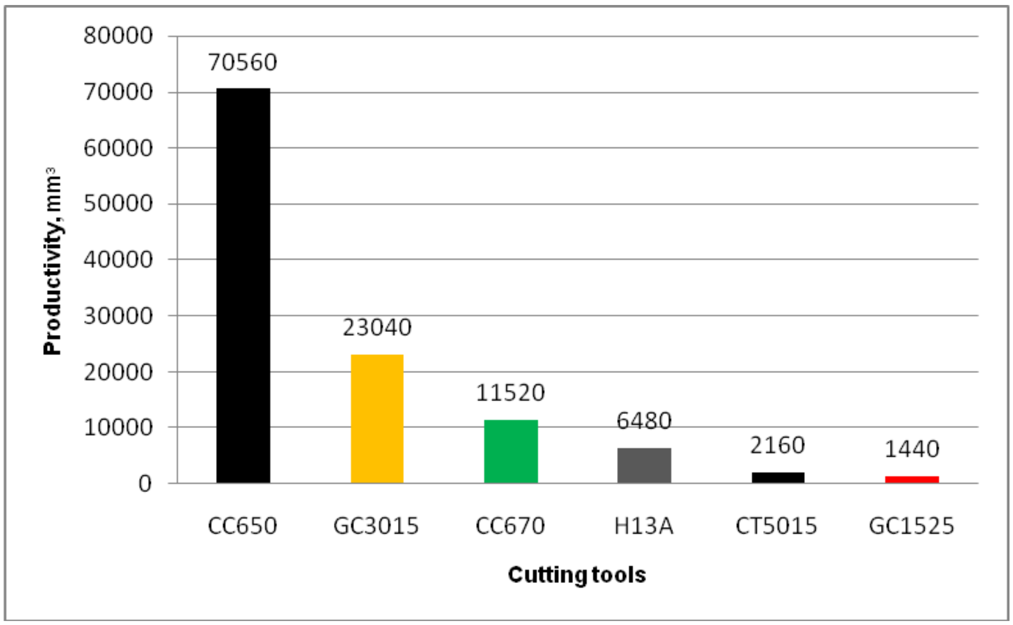

Figure 3: Productivity of cutting tools in terms of volume chip carved

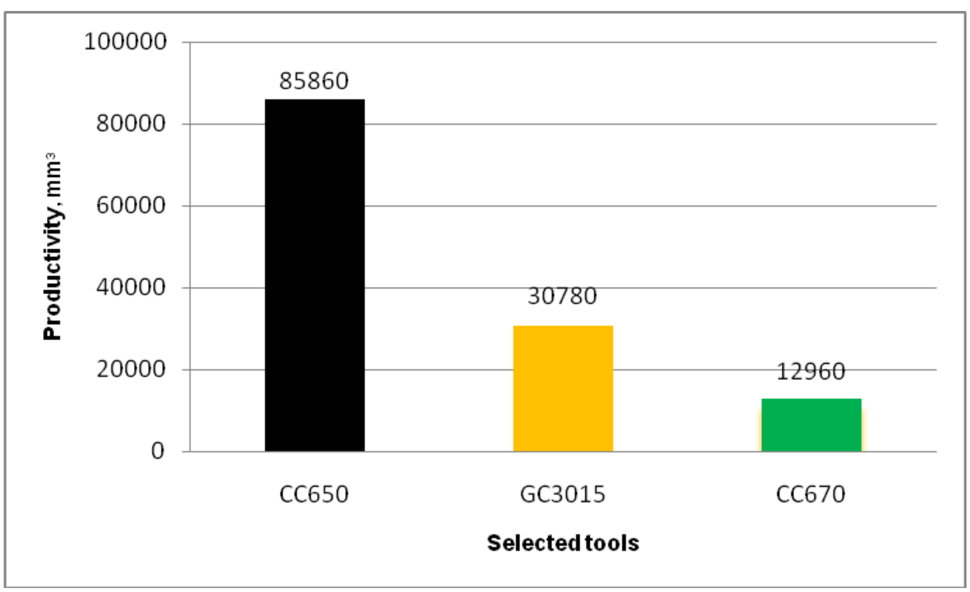

Figure 4: Productivity of seleced tools in terms of volume chip carved

Research Article

The productivity in terms of volume chip carved of composite ceramic Al_2O_3 + SiC (CC670), uncoated cermets CT5015, coated cermets GC1525, coated carbide GC3015 and uncoated carbide H13A are respectively (11520; 2160; 1440; 23040 and 6480) mm^3. These values represent (16.33; 3.06; 2.04; 9.18 and 32.65) % of that of mixed ceramic Al_2O_3 + TiC (CC650).
The productivity in terms of volume chip carved of these selected tools, i.e. mixed ceramic Al_2O_3 + TiC (CC650), composite ceramic Al_2O_3 + SiC (CC670) and coated carbide GC3015 are respectively (85860; 12960 and 30780) mm^3. These two latter values represent (15.1and 35.85) % of that of mixed ceramic Al_2O_3 + TiC (CC650).
These results prove that the mixed ceramic Al_2O_3 + TiC is more efficient than other grades used in terms of productivity.

ANOVA FOR FLANK WEAR *VB* OF CC650

Mixed ceramic Al_2O_3 + TiC were more efficient than other cutting tools in terms of wear resistance and productivity. This is why we felt it necessary to further study the behavior of this nuance in terms of flank wear *VB*. Table 3 presents the results of CC650 flank wear for various combinations of cutting regime elements (feed rate, machining time and cutting speed). Based on 2^3 factorial designs, a total of 8 tests were carried out. The range of each parameter is set at two different levels, namely low and high.
The results of analysis of variance (ANOVA) for flank wear *VB* of CC650 are shown in Table 4. This table also shows the degrees of freedom (DF), sum of squares (SS), mean squares (MS), F-values (F-VAL.) and the percentage contribution (Contr. %) of each factor and different interactions.
It is clear from the results of ANOVA that machining time affects flank wear *VB* in a considerable way. Its contribution is 56.15%.
The second factor influencing *VB* is cutting speed. Its contribution is 37.27%. As for feed rate, its effect is less important and its contribution is 0.96%. The interactions $V_c \times t$ and $f \times t$ are significant. Respectively, their contributions are (2.98 and 1.34) %. The interaction $V_c \times f$ is not significant. Its contribution is 0.11%.

Table 3: Flank wears *VB* of CC650 tool vs. various combinations of cutting regime elements

Tests N^0	*f*, mm/rev	*t*, min	V_c, m/min	*VB*, mm
1	0.08	12	120	0.110
2	0.08	24	120	0.190
3	0.16	12	120	0.118
4	0.16	24	120	0.20
5	0.08	12	180	0.182
6	0.08	24	180	0.28
7	0.16	12	180	0.169
8	0.16	24	180	0.33

Table 4: ANOVA for flank wear *VB* of CC650

Source	DF	SS	MS	F-VAL.	Contr. %
V_c	1	0.0147061	0.0147061	31.62	37.27
f	1	0.0003781	0.0003781	0.81	0.96
t	1	0.0221551	0.0221551	47.63	56.15
$V_c \times f$	1	0.0000451	0.0000451	0.10	0.11
$V_c \times t$	1	0.0011761	0.0011761	2.53	2.98
$f \times t$	1	0.0005281	0.0005281	1.14	1.34
Error	1	0.0004651	0.0004651		1.18
Total	7	0.0394539			100

Figures 5 and 6 respectively show 3D surface plot for flank wear *VB* of CC650 and ggraphs of the main cutting variables effects on *VB* as functions of different cutting regime parameters, namely machining time *t*, cutting speed V_c and feed rate *f*.

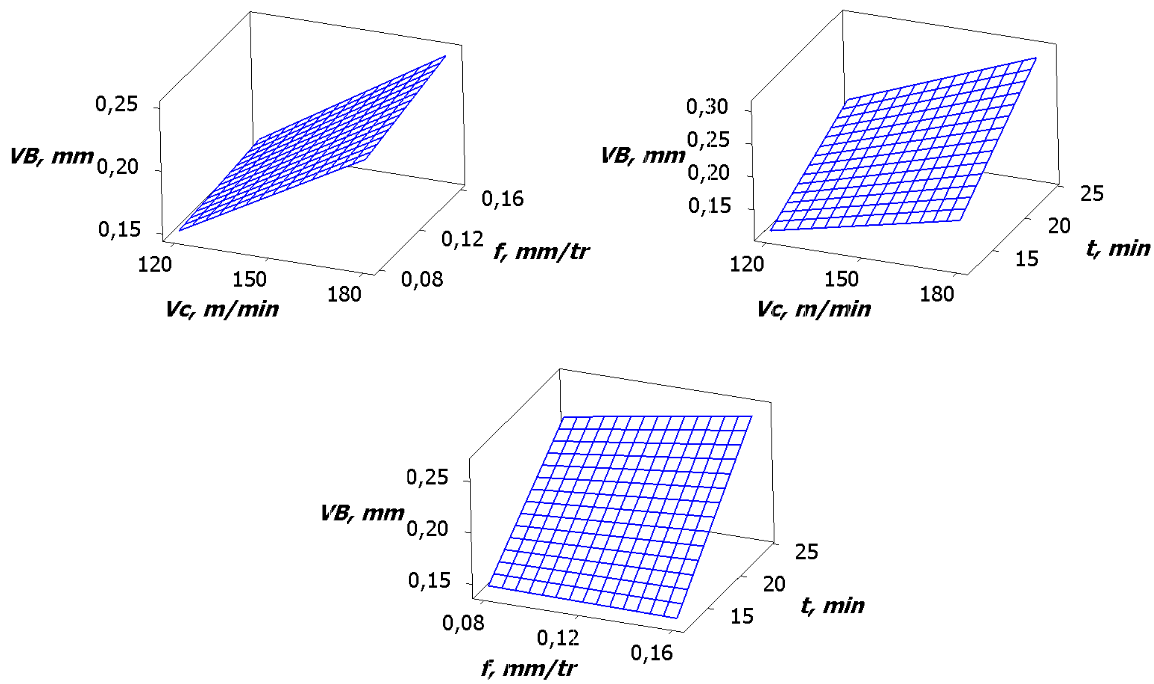

Figure 5: 3D Surface plot for *VB* of CC650 vs. various combinations of cutting regime parameters

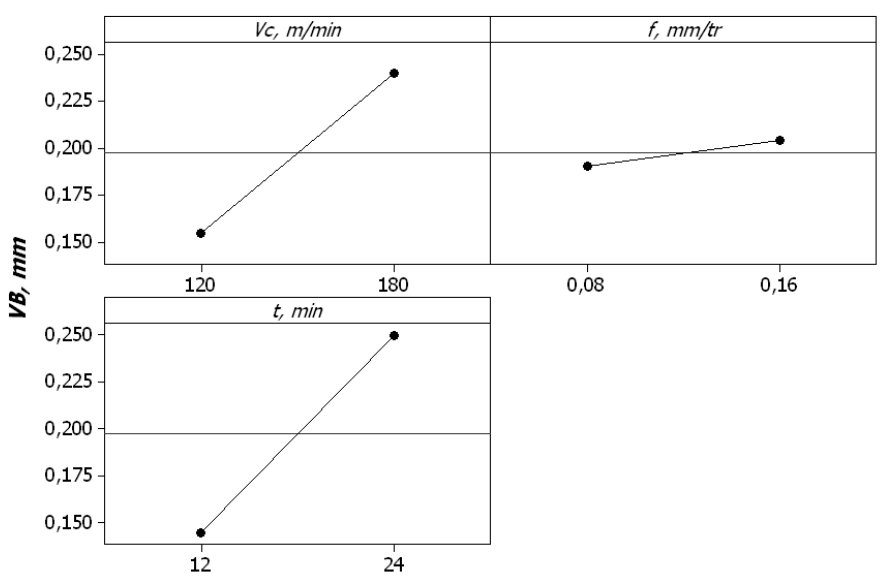

Figure 6: Graphs of the main cutting variables effects on *VB* of CC650

Mathematical model of *VB* is given by equation (1). Its coefficient of correlation R^2 is 91.7%.

$$VB=0.095125-0.000021V_c-0.734375f-0.005396t+0.001979V_c\times f+0.000067V_c\times t+0.033854f\times t \quad (1)$$

To calculate the values of constants and the coefficient of determination R^2 of this mathematical model, we used the software's Minitab 15 and Design-Expert 8 characterized by analysis of variance (ANOVA), multiple linear regression and response surface methodology (RSM).

CONCLUSION

The tests of straight turning carried out on grade X38CrMoV5-1 steel treated at 50 HRC enabled us to study the influence of the chip machining length on flank wear of different cutting tools used and to determinate the productivity of each tool in terms of volume chip carved. The following conclusions were drawn from this investigation.

For this cutting regime (V_c = 120m/min, a_p = 0.15 mm et f = 0.08 mm/rev), the productivity in terms of volume chip carved of the uncoated cermets CT5015, the coated cermets GC1525, the uncoated carbide H13A, the reinforced ceramic CC670, the coated carbide GC3015 and the mixed ceramic CC650 are (2160; 1440; 6480; 11520; 23040 and 70560) mm^3, respectively.

The productivity of these three selected tools (mixed ceramic CC650, reinforced ceramic CC670 and coated carbide GC3015) for these cutting conditions (f = 0.08 mm/rev, a_p = 0.15 mm and V_c = 90 m/min) are (85860; 12960 and 30780) mm^3, respectively.

Machining time seems to influence flank wear *VB* of CC650 more significantly than cutting speed and feed rate.

Mathematical model deduced defined the degree of influence of each cutting regime element, i.e. machining time t, cutting speed V_c and feed rate f on flank wear *VB* of the mixed ceramic CC650.

This study confirms that in dry straight turning of this steel and for the cutting coditions tested, the mixed ceramic is the most powerful tool in terms of wear resistance and productivity.

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