Experimental robust optimal machining of hardened AISI 420 stainless steel with $Al_2O_3 + TiCN$ mixed ceramic tool

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Abstract: The high hardness and wear resistance levels of Alumina (Al_2O_3)-based ceramics make them excellent choices for incorporation into cutting tools that can be used to machine hardened steels. However, their poor fracture behaviour usually leads to catastrophic failures when they are used in these machining tasks. Thus, there is a need for an investigation that probes the effect of cutting parameters on the machining of hardened steels with Al_2O_3-based ceramic cutting tools and isolates a set of optimal values of cutting parameters. This paper is such a study. An experimental study that is guided by Taguchi's techniques is performed to analyse the effects of three cutting parameters: cutting speed; feed rate; and depth of cut on two performance measures, flank wear and surface roughness. The robust optimal cutting parameters for each performance measure are reported.

Keywords: metal cutting, hardened steels, experimental design, Taguchi techniques, analysis of variance, robust optimization

1 INTRODUCTION

The major improvements that have occurred in cutting tools over the last two decades mean that materials can now be machined in their hardened state. This process has many advantages including reduction in machining costs, reduction in lead time, reduction in the number of required machine tools, improved surface integrity, reduced requirements for finishing operations, and elimination of part distortion caused by post-cutting heat treatments [**1**, **2**]. Alumina (Al_2O_3)-based ceramics are highly suitable for incorporation into tools to be used in the machining of hardened steels because of their high hot hardness, wear resistance, and chemical inertness [**3**, **4**]. Unfortunately, Al_2O_3-based tools have a high degree of brittleness, which usually leads to a short tool life due to excessive chipping or fracture especially when machining hardened materials. In order to improve their toughness levels Al_2O_3-based ceramic cutting tools are reinforced with a wide range of other ceramics including TiC, TiN, ZrO_2, (W,Ti)C, Ti(C, N), SiC_p, SiC_w, and TiB_2 [**5–8**]. These additions result in improved toughness levels of Al_2O_3-based tools but they are still much lower than those of other tools such as cemented carbides. As a result, the possibility of sudden failures when machining hardened materials with Al_2O_3-based ceramics is very high [**9**]. Thus, there is considerable interest in the exploration of the

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effect of cutting parameters in the machining of hardened steels in order to find their optimal values and increase the efficiency of the machining operation. While Al_2O_3-based ceramic cutting tools are widely used in the machining of hardened steels [**10–13**] there is very little information in the literature about their use to machine hardened stainless steels. This paper aims to address this deficiency in that it considers the milling of an AISI 420 stainless steel, quenched and tempered to 48 HRC, with an $Al_2O_3 + TiCN$ mixed ceramic tool. Typical applications of AISI 420 stainless steels include cutlery, knife blades, surgical instruments, and shear blades. The cutting parameters of interest are the cutting speed (V_c), feed rate (f), and depth of cut (a_p). The flank wear and surface roughness are minimized using an approach based on an experimental design obtained using Taguchi's techniques.

Experimental design (ED) is a method of planning, conducting, analysing, and interpreting experiments to draw conclusions in an efficient, effective, and economic manner [**14**]. Even though ED methods have been extensively studied by statisticians since the early 1920s, they have attracted only limited attention from engineers due to their perceived complexity. In comparison, the experimental techniques developed by Taguchi [**15**] are easy and straightforward to implement by practitioners with a limited knowledge of statistics and they have been extensively adopted by the engineering and scientific community [**16**]. For example, they are routinely used in engineering design to determine optimum values of parameters of interest for maximum performance with minimum variation [**15–17**]. They have also been applied to the problem of process optimization in materials processing, see, for example, the work reported in [**18–27**]. Of particular relevance to the proposed study in this paper are the studies on the isolation of the optimal combination of cutting parameters for metals discussed in [**23–27**].

2 EXPERIMENTAL PROCEDURE

The objective of this study is to investigate the effects of cutting parameters on tool wear and surface roughness, and to select the optimal values of cutting parameters for maximum performance with minimum variation. The cutting parameters of interest are the cutting speed, feed rate, and depth of cut. The investigated work material was AISI 420 stainless steel with dimensions 300 × 250 × 50 mm. This material was hardened and tempered to 48 HRC. The chemical composition of the investigated sample is given in Table 1.

Table 1 Chemical composition (wt%) of AISI 420 stainless steel

C	Cr	Mn	Si	P	S	Fe
0.2	13.0	0.9	0.8	0.04	0.03	Balance

Table 2 Levels for cutting parameters

	Cutting speed, V_c (m/min)	Depth of cut, a_p (mm)	Feed rate, f (mm/rev)
1	50	0.05	0.05
2	100	0.10	0.10

The milling tests were conducted on a Mazak VTC-20B vertical machining centre. The cutting tool was a TiN-coated $Al_2O_3 + TiCN$ mixed ceramic with a designation of RNGN120700. The inserts were screw-clamped to an end-milling tool holder which had the provision to hold two inserts. However, only one insert was used in the milling tests. The combination of the insert and the tool holder resulted in a -6° axial rake angle, -6° radial rake angle, and an 11° clearance angle.

Two levels were specified for each cutting parameter and they are listed in Table 2. The parameter levels were chosen so as to be within the intervals recommended by the manufacturer of the cutting tool. Three cutting parameters at two levels led to a total of $2^3 = 8$ designs for testing. At each test, the same amount of metal volume (50 cm^3) was removed from the workpiece. Flank wear was measured with a Scherr Tumico 98/0001 toolmakers microscope at 50× magnification with a 0.01 mm precision. The instrument has a solid cast iron stand and a column capable of making tilting helical angular movement and it uses a monocular eyepiece with an optical angle vernier. The maximum wear depth (VB_{max}) on the flank wear bandwidth was taken as the wear measure. Surface roughness was measured using a Mahr Perthometer M1 with a cut-off length of 0.8 mm, a traversal length of 5.6 mm, and a measuring range of up to 150 μm. In order to reduce uncertainty the reported R_a values are the average of three separate measurements.

3 PLANNING AND CONDUCTING THE EXPERIMENTS

Since two levels were specified for each of the three factors, Taguchi's orthogonal array L8 design of experiment (DOE) approach was used to guide the experiments. Tool wear and surface roughness results obtained from milling experiments conducted in

Table 3 Flank wear and surface roughness measurements at the experimental designs (there are eight different designs, for which the experiments are repeated three times)

Design	V_c (m/min)	a_p (mm)	f (mm/rev)	VB_{max}	R_{a1}	R_{a2}	R_{a3}
1	50	0.05	0.05	0.515	0.992	0.571	0.365
	50	0.05	0.05	0.171	0.047	0.352	0.698
	50	0.05	0.05	0.235	0.204	0.146	0.129
2	50	0.05	0.1	0.683	1.436	1.196	2.402
	50	0.05	0.1	0.318	0.806	0.469	1.481
	50	0.05	0.1	0.084	0.097	0.135	0.122
3	50	0.1	0.05	0.142	0.199	0.194	0.334
	50	0.1	0.05	0.185	0.312	0.619	0.373
	50	0.1	0.05	0.199	0.129	0.27	0.951
4	50	0.1	0.1	0.182	0.194	0.426	0.192
	50	0.1	0.1	0.105	0.121	0.082	0.111
	50	0.1	0.1	0.179	0.13	0.135	0.088
5	100	0.05	0.05	0.344	0.28	0.246	0.295
	100	0.05	0.05	0.539	0.344	0.218	0.193
	100	0.05	0.05	1.132	0.26	1.463	0.592
6	100	0.05	0.1	0.212	0.355	0.15	0.443
	100	0.05	0.1	0.779	0.308	0.569	0.987
	100	0.05	0.1	0.796	0.411	0.526	0.232
7	100	0.1	0.05	0.716	0.176	0.357	0.619
	100	0.1	0.05	1.33	0.122	0.394	0.234
	100	0.1	0.05	0.945	0.47	0.149	1.679
8	100	0.1	0.1	0.929	0.207	0.942	0.694
	100	0.1	0.1	1.095	0.135	0.457	0.836
	100	0.1	0.1	1.116	0.248	0.25	0.716

accordance with this DOE are listed in Table 3. In order to make reliable statistical analyses, three tests were performed for each set of design parameters, resulting in a total of 24 tests. The advantages of the replication of the tests are twofold: first, it allows uncertainty analysis of tool wear and surface roughness; and second, it allows outliers to be removed from the data set. Note also that the surface roughness values were measured three times (R_{a1}, R_{a2}, and R_{a3} in Table 3).

It should be noted that performing a scanning electron microscope (SEM) analysis of the coatings and their wear conditions would have been very valuable. However, the institution of the first and second authors did not have an SEM facility at the time of the study, however, SEM analysis is planned for future studies.

4 ANALYSIS OF EXPERIMENTAL RESULTS

Analysis of variance (ANOVA) was used to identify the effects of cutting parameters on the flank wear and surface roughness. To remove the effect of uncertainty in the measurements, the median values of the measurements were computed over each design. For the surface roughness, the median value of R_{a1}, R_{a2}, and R_{a3} is used. The obtained results are provided in Table 4 and these results were used in the ANOVA studies.

Table 4 Refined flank wear and surface roughness measurements

Design	V_c (m/min)	a_p (mm)	f (mm/rev)	VB_{max}	R_a
1	50	0.05	0.05	0.235	0.352
2	50	0.05	0.1	0.318	0.806
3	50	0.1	0.05	0.185	0.27
4	50	0.1	0.1	0.179	0.13
5	100	0.05	0.05	0.539	0.28
6	100	0.05	0.1	0.779	0.411
7	100	0.1	0.05	0.945	0.357
8	100	0.1	0.1	1.095	0.457

Table 5 ANOVA table for the flank wear VB_{max}

Source	Degrees of freedom	Sum of squares	F	p-value	Per cent contribution (%)
V_c	1	0.744 81	5958 481	0.0003	80.3
a_p	1	0.035 51	284 089	0.0012	3.8
f	1	0.027 26	218 089	0.0014	2.9
$V_c \times a_p$	1	0.103 74	829 921	0.0007	11.2
$V_c \times f$	1	0.012 25	97 969	0.002	1.3
$a_p \times f$	1	0.004 01	32 041	0.0036	0.4
Error	1	0			0.0
Total	7	0.927 57			100.0

4.1 Analysis of flank wear, VB_{max}

Table 5 shows the ANOVA results for flank wear. The main terms are listed in the first three rows, followed by the three interaction terms and an error term. Note that the error term in an ANOVA table represents the contribution of the terms that are not included in the table. In Table 5, the error term represents the triple interaction term $V_c \times a_p \times f$. The analysis was performed for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95 per cent. The number of degrees of freedom of each source, the sum of squares due to each source, the F-statistics, and the p-values of each source are provided in Table 5. The p-value determines whether or not the result is statistically significant. It is common practice to state that a result is statistically significant, if the p-value is less than 0.05 or 0.10. Table 5 shows that the results for all the terms are statistically significant. The last column of Table 5 shows that the cutting speed V_c is the most important parameter for the flank wear VB_{max}. The contribution of V_c to the total variation is around 80 per cent. It can be seen that the second-most-important term is the cutting speed and feed rate interaction term, with an around 11 per cent contribution to the total variation. Therefore, it is worth presenting main-factor plots as well as the interaction plots.

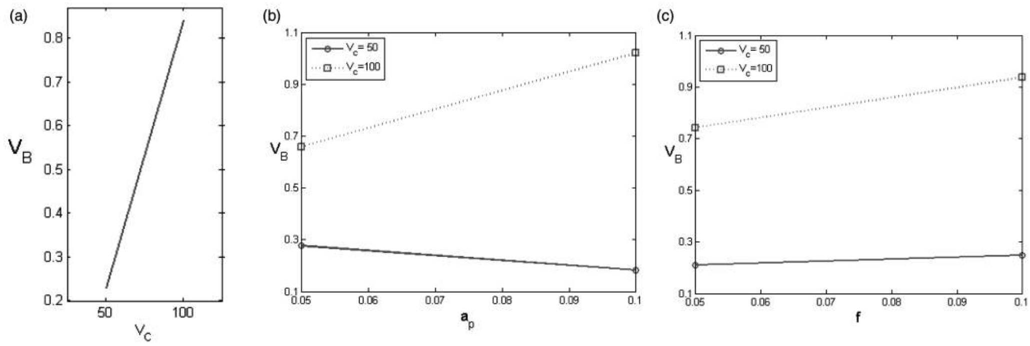

Fig. 1 Main factor and interaction plots for the flank wear VB_{max} (a) V_c main factor, (b) V_c and a_p interaction, and (c) V_c and f interaction

The main factor and interaction plots for the flank wear are provided in Figs 1(a) to (c). For main factor analysis, only V_c is used since the other main effects can be neglected. For interaction analysis the V_c and a_p interaction is the most important interaction, however, the V_c and f interaction is also provided for completeness. Figure 1(a) shows that the flank wear reduces with a reduction in the cutting speed. For small flank wear, the cutting speed must be adjusted to 50 m/min. When the cutting speed is adjusted to 50 m/min, the depth of cut needs to be increased for smaller flank wear as seen from Fig. 1(b). This finding may appear to be counterintuitive at first, but there is an explanation. Recall that the amount of material removed from the sample is constant during machining. When the depth of cut is $a_p = 0.05$ mm, the cutting operation takes two times as long as the case of $a_p = 0.10$ mm, thus the accumulative flank wear is larger when the depth of cut is smaller. However, when the cutting speed is increased, the total amount of flank wear is greater when the depth of cut is increased. This means that the accumulative flank wear with $a_p = 0.05$ mm is smaller than the flank wear with $a_p = 0.10$ mm. At high cutting speeds, cutting tools are exposed to high temperatures. This is advantageous for brittle tool materials because they become softer and more ductile with increased resistance to fracture and cutting edge chipping. As a result, they behave more, though not exactly, like hard metals such as high-speed steels at high temperatures. Therefore, at higher cutting speeds, cutting force fluctuations at low depth of cut values become less significant compared to the case of lower cutting speeds. Consequently, less wear is observed when the combination of high cutting speed and low depth of cut is used. Thus, instead of cutting force fluctuations, depth of cut becomes more significant at high cutting speeds as the cutting tool edge is exposed to high cutting forces at a high depth of cut, resulting in enhanced gradual wear of the cutting tool edge. Finally, Fig.1(c) shows that as the feed rate increases, the flank wear increases, as expected. It is seen that when the cutting speed is higher, the effect of feed rate on tool wear becomes more pronounced. This is expected because a higher cutting speed means a higher speed of the machine tool spindle and consequently faster linear movement of the cutting tool on the workpiece and higher cutting forces.

In summary, for small flank wear, the cutting parameters should be adjusted to $V_c = 50$ m/min, $a_p = 0.1$ mm, and $f = 0.05$ mm/rev.

Table 6 ANOVA table for the surface roughness R_a

Source	Degrees of freedom	Sum of squares	F	p-value	Per cent contribution (%)
V_c	1	0.000 35	0.01	0.9402	0.1
a_p	1	0.050 40	1.27	0.4618	18.4
f	1	0.037 13	0.94	0.5103	13.5
$V_c \times a_p$	1	0.097 02	2.45	0.362	35.4
$V_c \times f$	1	0.000 86	0.02	0.9068	0.3
$a_p \times f$	1	0.048 83	1.23	0.4668	17.8
Error	1	0.039 62			14.4
Total	7	0.274 21			100.0

4.2 Analysis of surface roughness, R_a

Table 6 shows the ANOVA data for the surface roughness. The analysis was performed at a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95 per cent. The fifth column of Table 6 shows that the results for all the terms are statistically insignificant. This is due to the large variability in the surface roughness measurements. The last column of Table 6 shows for the surface roughness that the depth of cut is the most important parameter amongst the main terms, while its interaction with cutting speed is the most important term overall. It is interesting to note that the cutting speed was the most important parameter for the flank wear whereas

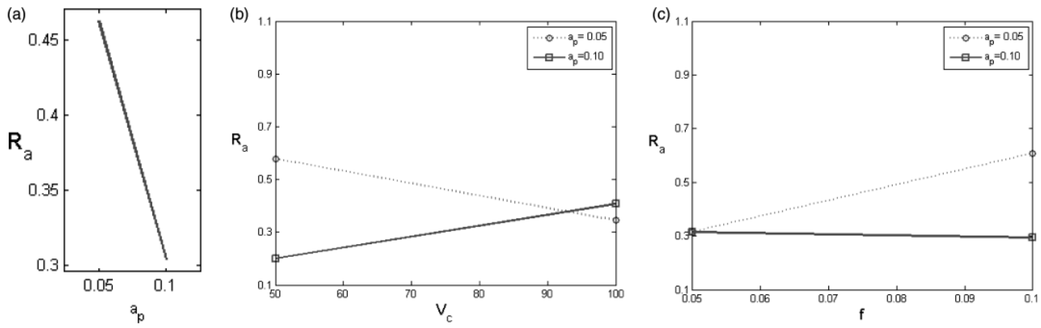

Fig. 2 Main factor and interaction plots for the surface roughness R_a (a) a_p main factor, (b) a_p and V_c interaction, and (c) a_p and f interaction

it is the least important parameter for surface roughness. The contributions of interaction terms to the total variation are generally larger than the contribution of the main terms.

The variation with the two most influential factors, the depth of cut a_p and the cutting speed V_c, were used in the main factor analysis whereas the interaction of a_p with f and V_c were investigated in the interaction analysis. The main factor plots and interaction plots are presented in Figs 2(a) to (c). The main factor analysis shows that the surface roughness reduces with an increase in the depth of cut. This finding may also be surprising at first; however, a similar explanation as in the case of flank wear can be used to explain this behaviour. Recall that the amount of material removed from the sample is constant during machining. When the depth of cut is a_p= 0.05 mm, the cutting operation takes two times longer as for the case of a_p = 0.10 mm, therefore the flank wear is larger, and the surface roughness increases. When the depth of cut is adjusted to 0.10 mm, the cutting speed needs to be reduced to decrease the surface roughness as seen from Fig. 2(c). It is interesting to note that when the depth of cut is adjusted to 0.05 mm, the cutting speed needs to be increased to decrease the surface roughness. Figure 2(c) shows that when the depth of cut is small, the feed rate should be reduced to decrease the surface roughness. On the other hand, when the depth of cut is large, the feed rate becomes ineffective. The observed insensitivity of the surface roughness to the feed rate may be the result of large uncertainties in the surface roughness measurements. That is, the change of surface roughness due to the change of feed rate from 0.05 to 0.1 mm/rev is small compared to the uncertainty in the surface roughness measurements.

4.3 Robust choice of optimal cutting parameters

As noted earlier, experimental design techniques were used to determine the optimum values of the parameters of interest for maximum performance with minimum variation. In this section, the optimal values of the cutting parameters are sought for minimum flank wear and minimum surface roughness. In addition, the minimum variation of the flank wear and the surface roughness are sought. Table 7 shows that the fourth experimental design leads to minimum flank wear and minimum surface roughness. Similarly, the fourth experimental design leads to the minimum variation in flank wear and the second minimum variation in surface roughness.

Table 7 Robust choice of optimal cutting parameters (the smallest value in each category is marked in bold font for ease of comparison)

Design	V_c (m/min)	a_p (mm)	f (mm/rev)	VB_{max} (median)	R_a (median)	VB_{max} (stdev)	R_a (stdev)
1	50	0.05	0.05	0.235	0.352	0.213	0.183
2	50	0.05	0.1	0.318	0.806	0.657	0.302
3	50	0.1	0.05	0.185	0.27	0.087	**0.030**
4	50	0.1	0.1	**0.179**	**0.13**	**0.043**	0.044
5	100	0.05	0.05	0.539	0.28	0.200	0.410
6	100	0.05	0.1	0.779	0.411	0.111	0.332
7	100	0.1	0.05	0.945	0.357	0.118	0.310
8	100	0.1	0.1	1.095	0.457	0.222	0.102

5 CONCLUSIONS

In this paper, Taguchi's techniques were used to perform an experimental study to explore the effects of cutting speed, feed rate, and depth of cut on flank wear and surface roughness. The following conclusions can be drawn from the results of this study.

For the flank wear, it was found that:

(a) the experimental results obtained for the flank wear were statistically significant;
(b) the cutting speed was found to be the most important parameter, and the feed rate was found to be the least important parameter for the flank wear;
(c) when the cutting speed was small, the accumulative flank wear with a small depth of cut is greater than the flank wear with a large depth of cut;

(d) when the cutting speed was large, the accumulated flank wear with a small depth of cut is smaller than the flank wear with a large depth of cut.

For the surface roughness, it was found that:

(a) the experimental results obtained for the surface roughness were statistically insignificant;
(b) the depth of cut was the most important parameter amongst the main terms, while its interaction with cutting speed was the most important term overall;
(c) the cutting speed was found to be the least important parameter for the surface roughness, whereas it was the most important parameter for the flank wear;
(d) when the depth of cut was small, the cutting speed needs to be increased to decrease the surface roughness;
(e) when the depth of cut was large, the cutting speed needs to be reduced to decrease the surface roughness;
(f) when the depth of cut was small, the feed rate should be reduced to decrease the surface roughness;
(g) when the depth of cut was large, the feed rate was ineffective.

For the last point it has been argued that the minimal cutting conditions resulted in the insensitivity of the surface roughness to the feed rate, since the feed rate is ordinarily a dominant process parameter in a milling process.

Finally, the optimal cutting parameters for minimum flank wear and surface roughness were obtained. It was found that the choice of cutting parameters of $V_c = 50$ m/min, $a_p = 0.1$ mm, and $f = 0.05$ mm/rev led to the minimum flank wear and minimum surface roughness. It was also found that this selection minimizes the variations of the flank wear and the surface roughness. Thus, $V_c = 50$ m/min, $a_p = 0.1$ mm, and $f = 0.05$ mm/rev combination was a robust optimum for the milling of AISI 420 martensitic stainless steel with a hardness of 48 HRC.

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