Empirical Modeling the Effects of Cutting Parameters in High-Speed End Milling of Hardened AISI D2 under MQL Environment

Asif Iqbal, Ning He, Liang Li

***Abstract*— In high-speed milling (HSM) of the hardened steels, the reduced tool life has always been a concerning issue. Moreover, in the case of finish HSM, the requirement of minimizing the workpiece surface roughness also gains considerable importance. In this research work, series of experiments were conducted in order to quantify the effects of three cutting parameters – namely: cutting speed; feed rate; and radial depth of cut – upon tool life and surface roughness. In total, 16 experiments were conducted following Central Composite Rotational Design (CCRD) Method. The machining of AISI D2 (~62HRc) was performed using TiAlN coated carbide cutters, under MQL environment. The experimental data were used to develop empirical models for determining performance measures. Application of MQL was proved beneficial for enhancement of tool life. SEM photographs and EDS analyses revealed that chipping and adhesion were the dominant tool damage mechanisms in majority of the experiments.**

***Index* Empirical modeling, tool life, hardened steels, MQL, surface roughness**

I. INTRODUCTION

After the advent of high-speed milling (HSM) technology, it was quickly applied to the cutting of steels in their hardened states, and the process was named as ‘Hard-Milling’. The hard-milling process offered numerous advantages like attainment of workpiece compressive residual stresses, reduction in workpiece micro-structure alterations, elimination of surface micro-hardness increases, and improvement in fatigue life besides other benefits of HSM like reduction of lead time and cutting forces [1–4]. On the other hand the hard milling process comes also with a major demerit of reduced tool life. The useful life of cutting tool is drastically reduced when it is applied to machining of hardened steels, especially, in the high-speed range [5]. The higher the hardness of the workpiece material, the lower is the life of the cutter [6]. Finding the ways for enhancement of tool life in the hard milling domain is a hot topic of research these days. Moreover, in the case of finish hard-milling, the objective of ‘minimizing workpiece surface roughness’ also gains considerable importance.

From the previous research work, in which the hard-milling experiments were performed mostly in dry condition, it can be concluded that the cutting speed is the most influential cutting parameter upon tool life. Higher values of this parameter, as well as of feed rate and depths of cut have proved to be detrimental for tool life [3, 5, 7, 8, 9]. For the case of workpiece surface roughness, the most influential cutting parameter has been reported as feed rate, followed by cutting speed and depths of cut [10]. Some opposing observations have been reported related to the effects of cutting speed and feed rate upon workpiece surface roughness [3, 6, 11].

Machining with minimum quantity of lubrication (MQL) can cut down cost and improve both tool life and surface finish [12]. MQL is the name given to the process in which very small amount of oil (less than 30ml/hr) is pulverized into the flow of compressed air [13]. The air/oil aerosol mixture is then fed to the cutting area through the ducts.

In the current research work, the effects of three cutting parameters – namely cutting speed (V_c), feed rate (f_z), and radial depth of cut (a_e) – have been experimentally sought upon three performance measures – namely: tool life; arithmetic average surface roughness, measured along the direction of feed (R_a *(along)*); and arithmetic average surface roughness, measured across the direction of feed (R_a *(across)*) – in high-speed end milling of hardened AISI D2, using coated carbide cutters, under MQL environment.

II. EXPERIMENTAL WORK

The experiments were performed on Micron UCP 710, 5-axis, vertical milling center having maximum power of 16kW. Flank wear of tools was measured using 10x tool maker’s microscope and the surface roughness was measured using Mahr Perthometer M1. SEM (Scanning Electron Microscope) pictures of all the tools were taken using Joel JSM 5610LV microscope, while Thermo Noran Energy Dispersive Spectrometer along with Vantage digital acquisition engine were used to conduct EDS (Energy Dispersive Spectrometry) analyses at the surfaces of the tools.

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TABLE I
MAXIMUM AND MINIMUM SETTINGS OF PREDICTOR VARIABLES

Level	V_c (m/min)	f_z (mm/tooth)	a_e (mm)
Minimum	175	0.08	0.15
Maximum	275	0.12	0.4

A. DoE and tooling parameters

A full factorial, Central Composite Rotational Design (CCRD) Method was utilized for the design of experiments. See details of CCRD in [14]. A total of sixteen finish hard-milling experiments were performed out of which eight represented regular points, two represented central points, and the remaining six represented star points (or axial points), utilizing the alpha value of 1.68179. Three predictor variables (parameters) were tested in the experiments: cutting speed (V_c), feed rate (f_z), and radial depth of cut (a_e). Table I presents the maximum and minimum settings of these predictor variables. Three response variables were observed: tool life, measured in mm^2 of area of material removed; arithmetic surface roughness – in microns – averaged upon the machined length of workpiece (a) along direction of feed (R_a *(along)*); and (b) across the direction of feed (R_a *(across)*).

In all the experiments fixed tooling parameters were utilized. The cutting tools used were flat end solid K30 carbide cutters with PVD coated mono layer of TiAlN, having diameter (D) of 8mm, corner radius (R) of 1.5mm, helix angle (λ) of 55º, rake angle (γ) of -8º, flank angle (α) of 6º (primary) and 10º (secondary), and number of flutes (Z) equal to 4. The workpiece material utilized was hardened AISI D2 (hardness 62 ~ 63HRc; and workpiece dimensions 50mm × 60mm × 66mm).

The MQL, consisting of UNILUB2032 – a high performance metal cutting lubricant – pulverized into compressed air of 6bars, at a rate of 25ml/hr, was applied directly to the tool using two aerosol ducts arranged at 160º apart. Axial depth of cut (a_p) was kept 4mm for all the experiments and down-milling was employed as milling orientation. The overhang of tool was fixed to 28mm and its radial run-out was maintained <10μm. The milling was performed in straight line and length of each pass was 60mm. Tool failure criterion used, was the maximum width of flank wear land (VB_{max}) of 0.2mm.

III. ANOVA, REGRESSION, AND OPTIMIZATION

Table II presents the tool life and surface roughness results for the sixteen experiments. Only the tool used in experiment number 14 could not complete the run as it was shattered into three pieces when it had removed 2220mm^3 (4mm × 555mm^2) of workpiece material. Following sub-sections describe ANOVA, regression, and optimization applied to the experimental results. All the statistical analyses were performed using a commercial computing package, named Design-Expert [15]. A multi-criteria decision making (MCDM) technique for simultaneous optimization of multiple response variables, developed by G. Derringer and R. Suich and known as Derringer-Suich desirability approach, was utilized for numerical optimization of response variables. The methodology can be studied from [16].

A. Tool Life

Response values for tool life ranged from 302 to 2545.88mm^2 of area of cut, giving the ratio of maximum to minimum equal to 8.43. The ratio was large enough and, thus, natural logarithmic transformation was applied to all of the response values in order to improve efficiency of the regression process. In the next step, a 2-factor interactions (2FI) model was recommended for the transformed tool life values. Table III presents the ANOVA details. The column *F-value* dictates following hierarchy of parameters with respect to significance of their effects: V_c; f_z; interaction between V_c and a_e.

The 2FI empirical model for tool life, in terms of cutting parameters, is as follows:

$$\text{Tool life} = exp[4.0417 + 0.00992V_c + 10.57f_z + 19.38a_e - 0.0164V_cf_z - 0.0537V_ca_e - 74.326f_za_e] \quad (1)$$

The R^2 (multiple correlation coefficient) for the model is 93.5%, the R^2-adjusted is 89.2%, and the R^2-predicted is 69.2%. These values suggest a good fit for the model considering the fact that tool life is an unpredictable and imprecise physical quantity.

TABLE II
MAXIMUM AND MINIMUM SETTINGS OF PREDICTOR VARIABLES

Test	V_c (m/min)	f_z (mm/z)	a_e (mm)	Tool life (mm^2)	R_a*(along)* (μm)	R_a*(across)* (μm)
1	175	0.08	0.15	1062	0.183	0.187
2	175	0.08	0.4	2546	0.214	0.39
3	175	0.12	0.15	1026	0.167	0.22
4	175	0.12	0.4	1360	0.213	0.463
5	275	0.08	0.15	965	0.218	0.252
6	275	0.08	0.4	702	0.255	0.441
7	275	0.12	0.15	1015	0.268	0.323
8	275	0.12	0.4	302	0.292	0.521
9	225	0.1	0.275	1056	0.259	0.317
10	225	0.1	0.275	977	0.261	0.333
11	140.9	0.1	0.275	1735	0.14	0.246
12	309.09	0.1	0.275	694	0.24	0.389
13	225	0.0664	0.275	2116	0.235	0.281
14	225	0.1336	0.275	555	0.258	0.493
15	225	0.1	0.0648	1009	0.189	0.18
16	225	0.1	0.4852	1095	0.265	0.548

TABLE III
ANOVA FOR TOOL LIFE 2FI MODEL

Source	Sum of squares	DoF	Mean squares	F-value	Prob>F	Significance
Model	3.63	6	0.61	21.6	<0.0001	Significant
V_c	1.44	1	1.44	51.5	<0.0001	Significant
f_z	1.01	1	1.01	35.85	0.0002	Significant
a_e	0.0041	1	0.0041	0.15	0.711	Not significant
$V_c \times f_z$	0.00216	1	0.00216	0.077	0.7875	Not significant
$V_c \times a_e$	0.9	1	0.9	32.18	0.0003	Significant
$f_z \times a_e$	0.28	1	0.28	9.85	0.012	Not significant
Lack of fit	0.25	8	0.031	10.31	0.237	Not significant

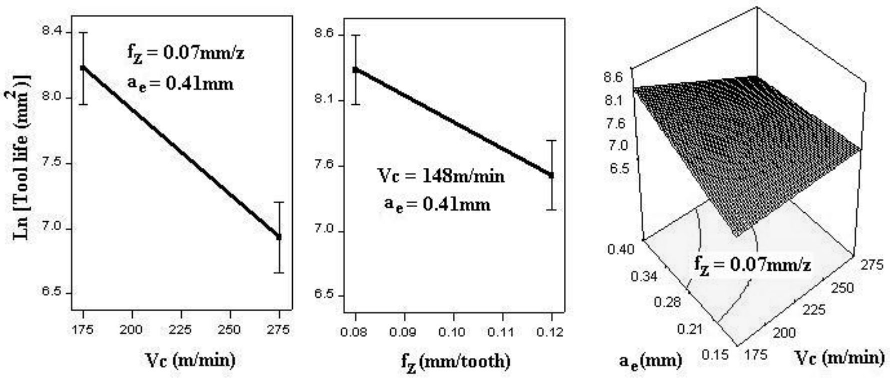

Fig. 1. Effects of significant parameters and interaction, upon tool life

Figure1 shows the effects of V_c, f_z, and interaction between V_c and a_e upon tool life for the recommended 2FI model. From the slopes of the plots it can be judged that effect of V_c is the most significant one. It is also clear from the plots that the lower values of V_c and f_z and higher values of a_e result in higher tool life values.

The numerical optimization, applied for the sake of maximizing tool life, recommended following solution: V_c = 148m/min; f_z = 0.07mm/tooth; a_e = 0.41mm. This combination of cutting parameters is believed to give the tool life of more than 3000mm^2 of area of cut (12000mm^3 of volume of material removed), for tool life criterion of 0.2mm of VB_{max}, provided other milling conditions remain the same. On the other hand, the same combination is also believed to give small material removal rate (MRR) of 2701.2mm^3/min (for a_p = 4mm), as compared to 3939mm^3/min of MRR provided by the mean values of three cutting parameters used (experiments 9 and 10).

B. Averaged Arithmetic Average Surface Roughness, along Feed Direction

Response values for R_a*(along)* ranged from 0.14 to 0.292µm, providing the ratio of maximum to minimum equal to 2.086. The ratio was small and, thus, there was no need to apply any kind of transformation to the data. For the given set of R_a*(along)* values, the statistical software suggested quadratic model. Table IV presents the ANOVA details for the suggested quadratic model. Following is the arrangement of influential cutting parameters in decreasing order of significance: V_c; a_e; interaction between V_c and f_z (marginally significant).

The quadratic model for R_a*(along)*, in terms of cutting parameters, is as follows:

$$R_a(along) = -0.2983 + 0.00364V_c - 0.834f_z + 0.5775a_e - 0.00000931V_c^2 - 8.23f_z^2 - 0.652a_e^2 + 0.0126V_cf_z - 0.00034V_ca_e + 0.15f_za_e \quad (2)$$

TABLE IV
ANOVA FOR R_A(*ALONG*) QUADRATIC MODEL

Source	Sum of squares	DoF	Mean squares	F-value	Prob>F	Significance
Model	0.026	9	0.00291	39.97	0.0001	Significant
V_c	0.013	1	0.013	180.35	<0.0001	Significant
f_z	0.00088	1	0.00088	121.12	0.0131	Not significant
a_e	0.00529	1	0.00529	72.78	0.0001	Significant
V_c^2	0.00502	1	0.00502	68.98	0.0002	Significant
f_z^2	0.0001	1	0.0001	1.38	0.2844	Not significant
a_e^2	0.00096	1	0.00096	13.22	0.0109	Not significant
$V_c \times f_z$	0.00127	1	0.00127	17.54	0.0058	Significant
$V_c \times a_e$	0.000036	1	0.000036	0.5	0.5073	Not significant
$f_z \times a_e$	0.000001	1	0.000001	0.015	0.9015	Not significant
Lack of fit	0.00043	5	0.000086	10.71	0.2278	Not significant

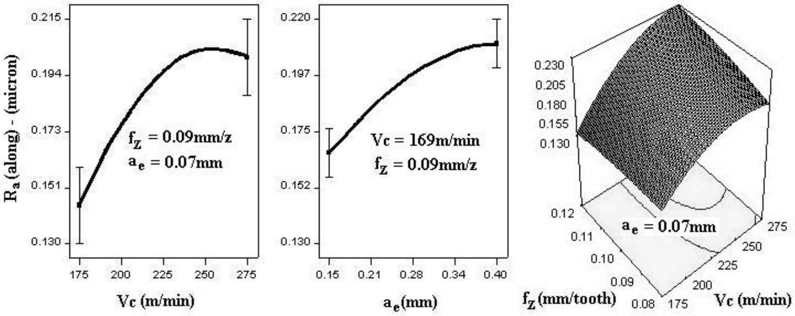

Fig. 2. Effects of significant parameters and interaction, upon R_a*(along)*

TABLE V

ANOVA FOR R_A(*ACROSS*) LINEAR MODEL

Source	Sum of squares	DoF	Mean squares	F-value	Prob>F	Significance
Model	0.2	3	0.067	71.9	<0.0001	Significant
V_c	0.02	1	0.02	20.9	0.006	Significant
f_z	0.027	1	0.027	29.4	0.002	Significant
a_e	0.15	1	0.15	165.42	<0.0001	Significant
Lack of fit	0.011	11	0.001	7.87	0.2717	Not significant

The model possesses $R^2 = 98.36\%$, R^2-adjusted = 95.9%, and R^2-predicted = 87%.

Figure 2 shows the effects of the significant parameters: V_c, a_e, and interaction between V_c and f_z upon R_a*(along)* for the recommended quadratic model. It can be seen that the lower values of R_a*(along)* can be achieved by setting the lower values of all the three cutting parameters. From the detailed analysis of surface roughness data, it was also concluded that effect of flank wear (for $VB_{\max} <0.2$mm) upon instantaneous values of arithmetic average roughness of workpiece's surface was not significant.

C. Averaged Arithmetic Average Surface Roughness, across Feed Direction

Response values for R_a*(across)* ranged from 0.18 to 0.548µm, providing the ratio of maximum to minimum equal to 3.044, and thus, no transformation was required. Linear model was suggested whose ANOVA detail has been provided in table V. Following is the hierarchy of influential cutting parameters: a_e; f_z; and V_c (marginally significant). The linear empirical model is as follows:

$$R_a(across) = -0.27944 + 0.000756V_c + 2.243f_z + 0.851a_e \quad (3)$$

The R^2 for the model is 94.7%, R^2-adjusted is 93.4%, and R^2-predicted is 90.5%.

Figure 3 shows the effects of the three cutting parameters upon R_a*(across)* for the recommended linear model. The effect of a_e is the most significant one, while the effects of other two parameters are almost equally significant. Lower values of all three parameters lead to the attainment of lower values of R_a*(across)*.

Numerical optimization was utilized to simultaneously minimize R_a*(along)* and R_a*(across)*. Following solution was recommended: V_c = 169m/min; f_z = 0.09mm/tooth; a_e = 0.07mm. This combination is expected to give R_a*(along)* values in range of 0.125–0.14µm and R_a*(across)* values in range of 0.115–0.13µm. MRR for the said combination is only 677.8mm^3/min (for a_p = 4mm), which is even smaller than the smallest MRR value provided by the combinations used in 16 experiments.

IV. EFFECT OF USING MQL

Experiments No. 2 and 9 (same as 10) were repeated under dry conditions. For the same tool failure criterion, the experiment number 2, under dry condition, experienced tool life of only 1296mm^2, as compared to 2546mm^2 of life experienced by the same experiment carried under MQL environment. In this case the tool life was reduced to almost half when the cooling environment was changed from MQL to dry. Moving from experiment number 2 to 9 (or 10) means increase in cutting speed and feed rate but decrease in radial depth of cut. The experiment number 9 (or 10), under dry condition, experienced tool life of 942mm^2 as compared to 977mm^2 and 1056mm^2 of tool life values experienced by experiments number 9 and 10, respectively, under MQL environment. In this case the tool life was reduced by 8%, on average. These observations prove that application of MQL to hard-milling process, using carbide cutters, is more beneficial as compared to milling in dry conditions.

V. TOOL WEAR MECHANISMS

Figure 4 shows the SEM photographs of the tools used in experiments 2, 4, 11, and 12. The first two pictures in the figure show the cutting edge of tool used in experiment 2. Small scale chipping is obvious from the first picture while the second one shows the signs of adhesion. The surface of the flank face was micro-analyzed using EDS, which showed the presence of high percentages of iron (*Fe*), chromium (*Cr*), and carbon (*C*), besides small percentage of tungsten (*W*). This observation is strong evidence of occurrence of adhesion at the edge and flank face.

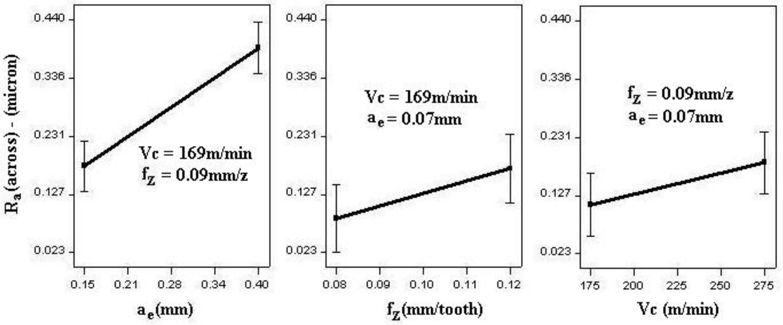

Fig. 3. Effects of significant parameters and interaction, upon R_a*(across)*

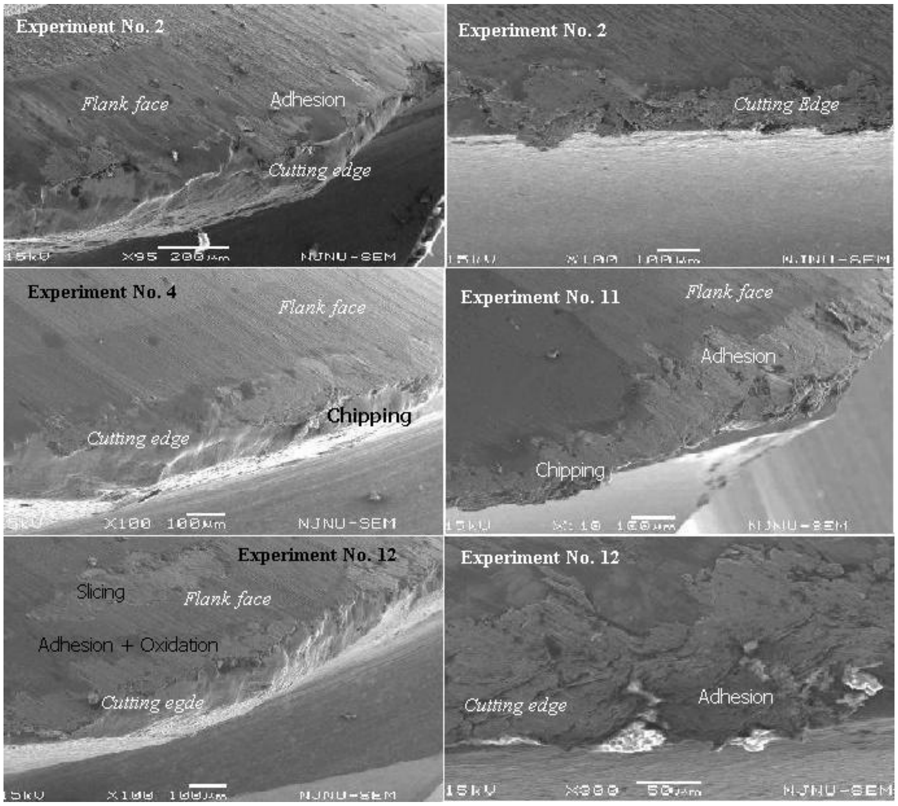

Fig. 4. SEM images of the used tools

The picture related to the experiment 4, shows the cutting edge, which has been damaged by the chipping process. Chipping in this picture appears to be more severe as compared to pictures related to the experiment 2. EDS analysis carried at flank face (near the edge) showed signs of weak adhesion, as high percentages of *W*, and small percentages of *Fe*, were detected.

Moving from experiment 2 to 4 means increase in feed rate from value of 0.08 to 0.12mm/tooth, while keeping all other parameters unchanged. This implies that increase in feed rate in hard milling process changes the dominant mode of tool damage from adhesion to chipping. The reason behind this phenomenon is that the cutting edge takes more chip load at higher feed rates and is, thus, likely to be chipped.

The fourth picture in the figure 4 shows the cutting edge and flank face of the tool used in experiment 11. This experiment was run with the smallest value of cutting speed, i.e. 140.9m/min. The picture shows small scale chipping as well as adhesion. The last two pictures belong to the tool used in experiment 12, the experiment that was run at highest value of cutting speed out of all experiments. The pictures show small scale chipping and very thick adhesion, especially in the last picture. The adhesion was so thick that *W* was rarely detected in EDS. Besides this, oxidation wear was also detected at the flank face. Extremely high temperature because of ultra-high cutting speed was responsible for oxidation and massive adhesion. Slicing away of small flake of tool's flank face, because of weakening by adhesion/oxidation, is also clear in the picture. These observations imply that increasing the cutting speed, in hard milling process, increases the intensity of adhesion wear and besides, it also initiates the oxidation wear.

Comparing the SEM and EDS analyses of the tools used in dry milling to those used in MQL milling, it was concluded that the introduction of MQL to the hard-milling process slightly increases the adhesion rate but, on the other hand, it also slightly decreases the chipping rate.

VI. CONCLUSIONS

1. Cutting speed is the most influential parameter upon tool life, followed by the feed rate. Tool life can be maximized if the HSM is done at low values of cutting speed and feed rate.
2. Cutting speed and radial depth of cut are highly influential upon roughness of workpiece's end surface, while the feed rate is slightly influential. In order to minimize the workpiece surface roughness the HSM should be carried at low values of all the three cutting parameters.
3. Application of MQL improves hard milling process by enhancing the tool life.
4. Increase in feed rate accelerates tool chipping process, while increase in cutting speed intensifies the adhesion wear, and it also initiates the oxidation wear.

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