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Optimization of Tool Wear Using Coupled RSM-GA Approach in Turning of Stainless Steel AISI 304 with Magnetic Damping of Tool Shank

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Abstract. Tool wear, especially flank wear, is a major concern in the manufacturing industry. Increased tool wear is caused by chatter and leads to increased surface roughness, reduced productivity and higher operating costs. It is more pronounced in the machining of difficult to cut materials such as stainless steel, tool steel, Inconel and hardened Ti alloys. Additionally, unpredictable tool wear can lead to frequent shutdowns of the machining process making it difficult for full automation. Therefore, to increase productivity and to reduce costs associated with increased and unpredictable tool wear, numerous research studies have been carried out. In this research, two permanent ferrite bar magnets of 1500 Gauss strength were used to dampen the vibration of the tool shank in the turning of stainless steel AISI 304 using titanium nitride (TiN) coated carbide inserts. Mild steel fixtures were used to place the magnets beside and below the tool shank in the carraige of a Harrison M390 engine lathe. The tool overhang was kept constant at 120 mm. A small central composite design (CCD) approach in response surface methodology (RSM) was used to model the tool wear as a response of the three primary cutting parameters: cutting speed, feed, and depth of cut. Design Expert software (version 6) was used to generate the 14 experimental runs needed to develop and verify the empirical mathematical model of tool flank wear. The resultant tool flank wear was measured using both optical and scanning electron microscopes (SEM). Finally, an empirical quadratic mathematical model of tool wear was found. This model was then used as the objective function in the optimization of tool wear using genetic algorithms (GA). The optimization results predicted that the minimum tool wear was 0.0427 mm. This prediction was subsequently validated experimentally.

Introduction

Tool wear, such as flank wear, is an unavoidable consequence in machining, especially in the turning of hardened metal alloys. Excessive and unpredictable tool wear can lead to premature tool failure and unscheduled shutdown of automated machining processes. It also causes poor surface finish, unsatisfactory output, and increased tooling costs [1]. Thus, it is very important in the metal cutting industry to reduce tool wear and to be able to predict it. Researchers have investigated the factors which affect tool wear and the effect of tool wear on surface finish, dimensional accuracy, and productivity [2].

Metals play a very vital role in modern consumer market and infrastructure, and one of the most common methods of fabricating metal components is machining, especially turning. However, the productivity in such operations is constrained by tool wear, which indirectly represents a significant portion of the machining costs. Thus, the performance of cutting tools is generally evaluated based on their life and wear. Flank wear is usually considered, as it affects the stability of the cutting edge, and consequently the dimensional tolerance and surface finish of the machined surface [3].

Many researchers have therefore attempted to develop tool life models. For instance, tool life model in end-milling of titanium alloy (Ti-6Al-4V) with uncoated tungsten carbide inserts was developed using response surface methodology (RSM) [3]. It was found that the cutting speed was the main factor in determining tool life, followed by feed and axial depth of cut. In addition, the authors claimed that machining chatter resulted in unpredictable tool wear. Kaye et al. [4] used RSM to predict tool flank wear and its relation with spindle speed change. Others have used a combined RSM and genetic algorithm (GA) approach to modeling and optimization of machining response such as surface finish [5]. The reason behind the popularity of RSM in modeling and optimization of experimental research is that it entails relatively smaller number of designed experiments to be carried out in order to obtain the crucial information for modeling purposes [6].

Yet others have tried to reduce chatter and the associated tool wear using novel methods such as magnetic damping [7]. In this research, tool wear is lowered by reducing the machining vibrations using a magnetic damping technique in the turning of stainless steel (AISI 304) using TiN coated carbide inserts. Two powerful magnets were applied to reduce the vibration of the tool shank in the Z and X directions. The research philosophy was based on the idea that reduced vibration amplitude during machining translates into lower tool wear—especially flank wear. Subsequently, RSM was used to design experimental runs needed to gain perspective on the influence of primary cutting parameters (cutting speed, feed, and depth of cut) on tool (flank) wear. From the empirical results a quadratic mathematical model was produced which was later used as an objective function in the GA optimization of the cutting process for minimum tool wear. Further experiments then demonstrated the effectiveness of the modeling and hybrid optimization process.

Experimental Details

Experimental study was conducted using an engine lathe (Harrison M390) powered by a 5.5 kW motor with a maximum spindle speed of 2000 rpm. Special fixtures for affixing the two ferrite bar magnets (1500 Gauss each) to the lathe's carriage were made from mild steel plates. The magnets' setup ensured damping in X and Z directions (fig. 1). The tool overhang was set at 120 mm and titanium nitride (TiN) coated carbide inserts were used as the cutting surface. A 100 mm diameter (AISI 304) stainless steel cylinder was used as the work material. RSM was used to design the 14 experimental runs by following the central composite design (CCD) model in Design Expert software (DOE, version 6.0.8). The primary machining parameters served as the input variables for the response modeling of tool flank wear: cutting speed (*'V_c'*, 50-200 m/min), feed (*'f'*, 0.1-0.22 mm/min), and depth of cut (*'DOC'*, 1-2 mm). A 3 level and 3 factor small CCD approach was used with an α value of $\pm\sqrt{2}$. The developed model was then verified using built-in statistical tools in the DOE software, such as fit and summary test, lack of fit, and ANOVA. The verified model was later coupled with GA optimization in order to predict the conditions needed for and the value of minimum tool wear. The optimization predictions were subsequently validated using actual physical experiments.

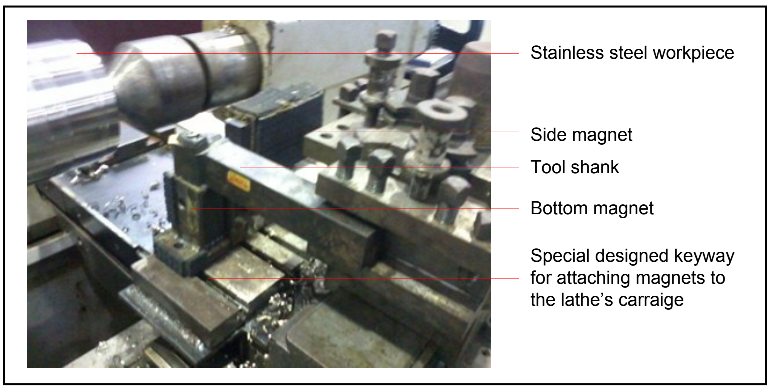

Fig. 1: Photograph of the magnetic damping setup.

Results and Discussions

RSM Model. Tool flank wear was measured after each experimental run using both optical and scanning electron microscopes (SEM) (fig. 2). The tool wear measurements (table 1) were then fed into the CCD model to obtain an empirical quadratic mathematical model for tool wear in terms of the primary cutting parameters (Eq. 1, below). Model summary statistics and ANOVA were performed to check the significance of the developed model (tables 2 & 3). The analyses showed that the model was significant to 95% confidence level in explaining the experimental observations.

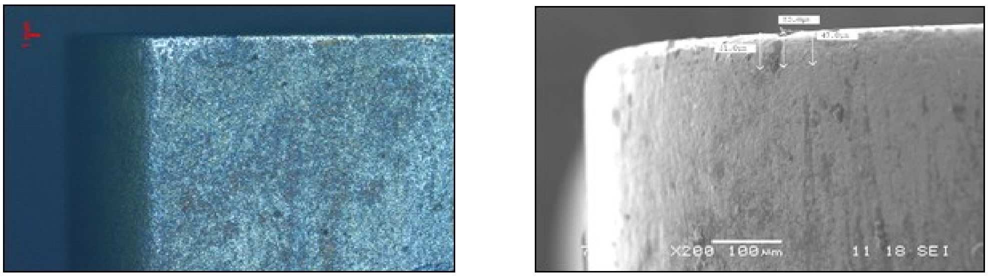

Fig. 2: Microphotographs of tool wear (run 11): optical microscope (left) and SEM (right).

Table 1: Tool flank wear for the 14 experimental runs

Run	Cutting speed (m/min)	Feed (mm/min)	Depth of cut (mm)	Tool wear (mm)
1	200	0.22	1	0.131
2	50	0.22	2	0.046
3	125	0.16	2.21	0.099
4	231	0.16	1.5	0.139
5	50	0.1	1	0.095
6	125	0.16	1.5	0.05
7	125	0.16	0.8	0.055
8	125	0.16	1.5	0.063
9	125	0.16	1.5	0.048
10	125	0.08	1.5	0.122
11	18.93	0.16	1.5	0.072
12	200	0.1	2	0.063
13	125	0.16	1.5	0.063
14	125	0.24	1.5	0.049

$$\begin{aligned}\textit{Tool flank wear} &= +0.060 + 0.024 * V_c - 0.026 * f + 0.018 * DOC + 0.047 * V_c * f \\ &- 0.031 * V_c * DOC + 0.010 * f * DOC + 0.019 * V_c^2 + 9.091E^{-03} * f^2 \\ &+ 3.341E^{-03} * DOC^2. \end{aligned} \quad (1)$$

Table 2: Model summary statistics

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.032	0.2717	0.0532	-0.6920	0.024	
2FI	0.024	0.7256	0.4904	-0.1235	0.016	
Quadratic	0.014	0.9423	0.8126	-3.8486	0.069	Suggested
Cubic	8.124E-003	0.9862	0.9400		+	Aliased

From the model summary test above it is noted that the quadratic model has the highest R-squared value of 0.9423. This value, which is very close to 1, indicates that the model can predict outcomes with high confidence. ANOVA and lack of fit analyses were then made for this model.

Table 3: ANOVA and Lack of fit analysis

Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.013	9	1.497E-003	7.26	0.0359	significant
A-Cutting spee	2.245E-003	1	2.245E-003	10.89	0.0299	
B-Feed	2.665E-003	1	2.665E-003	12.93	0.0228	
C-Depth of cut	1.250E-003	1	1.250E-003	6.07	0.0695	
AB	4.404E-003	1	4.404E-003	21.37	0.0099	
AC	1.868E-003	1	1.868E-003	9.06	0.0395	
BC	2.179E-004	1	2.179E-004	1.06	0.3619	
A^2	2.673E-003	1	2.673E-003	12.97	0.0227	
B^2	6.061E-004	1	6.061E-004	2.94	0.1615	
C^2	8.185E-005	1	8.185E-005	0.40	0.5627	
Residual	8.243E-004	4	2.061E-004			
Lack of Fit	6.263E-004	1	6.263E-004	9.49	0.0541	not significant
Pure Error	1.980E-004	3	6.600E-005			
Cor Total	0.014	13				

The ANOVA analysis above shows that the Prob > F value is very small at 0.0359 which indicates that the quadratic model is significant (95% confidence level). It is also seen that the terms A (V_c), B (*f*), AB (V_c and *f*), AC (V_c and *DOC*), and A^2 are significant. The other terms, although insignificant, are needed to support the quadratic hierarchy of the model. The "Lack of Fit" is also not significant relative to the pure error, implying the overall fitness of the model. Fig. 3 represents the 3D contour plots of the interactions of V_c and *f*, and V_c and *DOC* on tool flank wear.

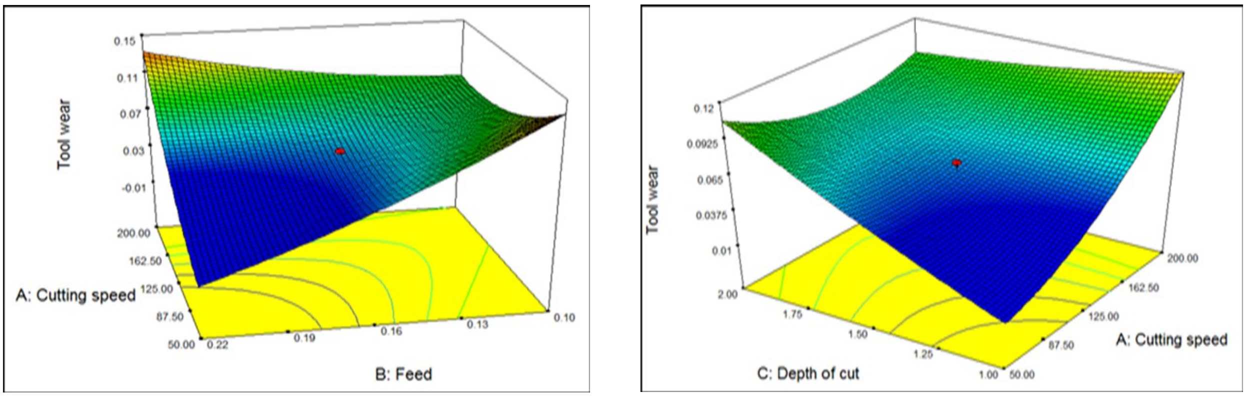

Fig. 3: 3D contour plots of the response surface (tool wear) vs. cutting speed and feed (left) and cutting speed and depth of cut (right)

Optimization using Genetic Algorithms. The GA toolbox in Matlab 2010 was used to predict the minimum flank wear attainable within the range of the input parameters. The optimization was formulated using standard mathematical format with the empirical quadratic mathematical model, the output of RSM, as the fitness criteria function. Fig. 4 is a graph showing the convergence of GA. The optimization predictions, along with the corresponding experimental validation, is shown in table 4. It can be observed form the table that the experimental outcome matches the GA predictions very closely (around 5% error in prediction).

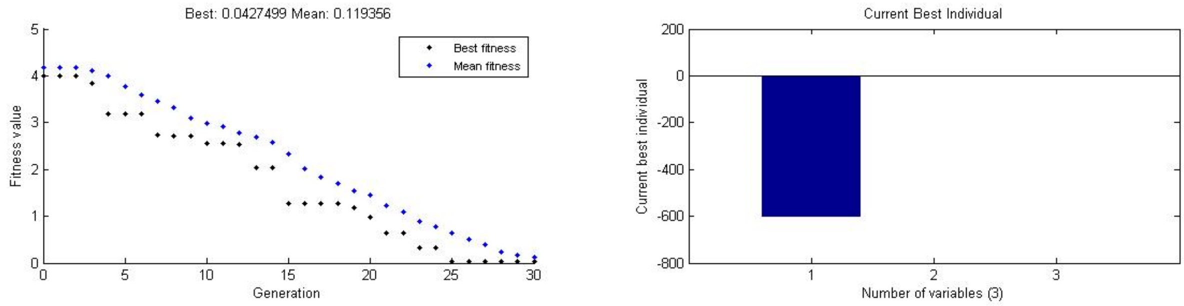

Fig. 4: Graphical representations of tool wear optimization by GA

Table 4: Predictions and validation of the GA optimization

Cutting speed V_c (m/min)	Feed *f* (mm/min)	Depth of cut *DOC* (mm)	Tool flank wear predicted by GA (mm)	Experimentally determined tool wear (mm)	Error %
115	0.2	1.54	0.0427	0.0452	5.531

Conclusions

This research developed a simple and viable chatter damping apparatus using two permanent ferrite magnets. As was seen from the resultant tool wear, the magnetic damping device reduced machining vibrations and its benefit was realized in terms of reduced tool wear. The empirical quadratic mathematical model of tool flank wear proved to be significant in determining experimental outcomes. Also, the coupled RSM-GA approach predicted the optimum combination of the machining parameters for minimum tool flank wear of 0.0427 mm. This was validated using subsequent experimental tests.

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