Advanced Materials Research Vol. 576 (2012) pp 119-122
Online available since 2012/Oct/08 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.576.119

Surface Roughness Optimization in End Milling of Stainless Steel AISI 304 with Uncoated WC-Co Insert Under Magnetic Field

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Keywords: Chatter, Permanent Magnets, Surface Roughness, Uncoated Tungsten Carbide, Optimization, Stainless Steel.

Abstract. Chatter phenomenon is a major issue as it greatly affects the topography of machined parts. Due to the inconsistent character of chatter, it is extremely difficult to predict resultant surface roughness in a machining process, such as end milling. Also, recent studies have shown that chatter can be suitably damped using magnetic fields. This paper, thus, focuses on a novel approach of minimizing surface roughness in end milling of Mild (Low Carbon) Steel using uncoated WC-Co inserts under magnetic field from permanent magnets. In this experiment, Response Surface Methodology (RSM) approach using DESIGN EXPERT 6.0 (DOE) software was used to design the experiments. The experiments were performed under two different cutting conditions. The first one was cutting under normal conditions, while the other was cutting under the application of magnetic fields from two permanent magnets positioned on opposite sides of the cutter. Surface roughness was measured using Mitutoyo SURFTEST SV-500 profilometer. The subsequent analysis showed that surface roughness was significantly reduced (by as much as 67.21%) when machining was done under the influence of magnetic field. The experimental results were then used to develop a second order empirical mathematical model equation for surface roughness and validated to 95% confidence level by using ANOVA. Finally, desirability function approach was used to optimize the surface roughness within the limiting values attainable in end milling.

Introduction

Chatter can be best described as a self-excited vibration that can occur during machining operations. It happens due to resonance when the frequency of chip serration (primary or secondary) and the natural vibration modes (natural frequencies) of the system components coincide. Quintana et al. [1] specified that chatter can be clearly predicted from the loud noise and the poor surface integrity due to the chatter mark. In addition, Campa et al. [2] described chatter as a dynamic problem at high material removal rate condition. It has also been found that vibration of the cutting tool and workpiece is detrimental to product quality, dimensional accuracy, and topographical features. Researchers have applied several approaches to address chatter formation phenomenon and its suppression methods. Magnetostrictive actuators [3] and piezoelectric actuators [4] have been used to reduce chatter in turning operations. Furthermore, Liang et al. [5] developed a fuzzy logic approach for chatter suppression in end milling process. The use of permanent magnets, by the authors, as a chatter suppression method in end milling of stainless steel AISI 304 using uncoated WC-Co insert and analysis of the resultant surface roughness is very new. Response Surface Methodology (RSM) was used for the modeling and optimization purposes, since it has been proven to be very effective by other researchers. Patwari et al. [6] coupled RSM with Genetic Algorithm (GA) for optimizing surface roughness in end milling of medium carbon steel.

Experimental Details

A CNC Vertical Machining Center (VMC ZPS, Model: 106) was used for the experiment. The experiments were done under both normal conditions and in the presence of magnetic fields from permanent magnets. Two ferro-magnet bars (dimensions: 1" x 6" x 3"), mounted at a distance of approximately 5 mm from the cutting tool using a special fixture, generated the magnetic field (2500-2700 Gauss). A 20 mm diameter end mill tool holder with one uncoated WC-Co insert was used as the cutting tool. Cutting speed (V_c), feed per tooth (f), and axial depth of cut (d) were chosen as the primary input variables. Post-machinig surface roughness (R_a) measurements were undertaken using Mitutoyo SURFTEST SV-500 surface profilometer. Fig. 1 includes the photograph and the schematic diagram of the experimental setup:

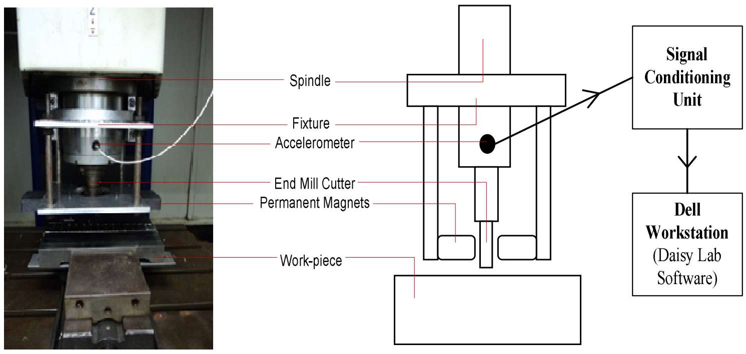


Fig. 1: Experimental set up for end milling operations

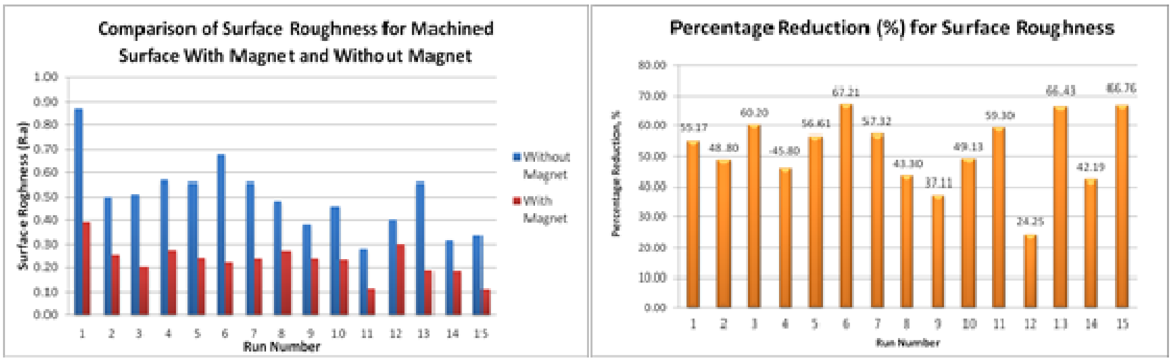
Results and Discussions

Surface Roughness. Table 1, below, shows the resultant surface roughnesses for the two cases:

Table 1: Comparison of surface roughness for the two cases: with and without magnets

No.	Cutting Speed (m/min)	Feed (mm/tooth)	Depth of Cut (mm)	Surface Roughness Ra (µm)		Percentage Reduction (%)
				Without Magnet	With Magnet	
1	160	0.22	1.5	0.870	0.800	8.05
2	160	0.15	0.79	0.500	0.256	48.80
3	250	0.1	2	0.510	0.203	60.20
4	160	0.15	1.5	0.570	0.275	45.80
5	160	0.15	1.5	0.560	0.243	56.61
6	160	0.15	2.21	0.680	0.223	67.21
7	160	0.15	1.5	0.560	0.239	57.32
8	160	0.08	1.5	0.480	0.272	43.30
9	160	0.15	1.5	0.380	0.239	37.11
10	250	0.2	1	0.460	0.234	49.13
11	70	0.1	1	0.280	0.114	59.30
12	160	0.15	1.5	0.400	0.303	24.25
13	287.28	0.15	1.5	0.560	0.188	66.43
14	70	0.2	2	0.320	0.185	42.19
15	32.72	0.15	1.5	0.340	0.113	66.76

From Table 1 it was inferred that with the increase in cutting speed, feed, and depth of cut, surface finish became better. Also, the influence of magnetic fields significantly reduced R_a. The highest percentage reduction for R_a was observed in run 14 (V_c = 70 mm/min, f = 0.10 mm/tooth, and d = 1.0 mm). In this case, R_a was reduced by about 50%, compared to the normal case. This reduction was caused by the damping effect of the magnets on the oscillatory motion of the tool.



(a) (b)

Fig. 2: Influence of magnets: (a) comparison of surface roughnesses and (b) % reduction in surface roughness

A small Central Composite Design (CCD) (α = √2) was used to develop the R_a model. Fit and Summary test suggested that the second order model was most significant. Subsequently, ANOVA was used to check the adequacy of the developed model where the"Model F-Value" of 5.24 implied that the model was significant. There was only a 4.14% chance that a "Model F-Value" this large could occur due to noise. Lack of Fit of 3.97 implied that the LOF was insignificant. Thus, the quadratic model was chosen (Eq. 1).

$$R_a = 0.27+0.027x_1 +0.042x_2 - 0.012x_3 - 0.067x_1^2 +0.0246x_2^2 - 0.022x_3^2 - 0.022\, x_1x_2 +0.016x_1x_3 + 0.0079\, x_2x_3. \quad (1)$$

Where, x_1 is the cutting speed (V_c), x_2 is the feed (f), and x_3 is the depth of cut (d). The quadratic model showed that f had the most significant effect on R_a, followed by d and V_c. Fig. 3 shows the pertubation plot for the three cutting parameters. It is observed from the figure that with the increase in feed (B), R_a increased significantly on either side of the reference point. The effect of Depth of cut (C) on R_a is less significant with a decreasing tendency with any shift in C value beyond the reference point. Cutting speed (A) has a similar effect as that of feed in the cutting speed range below the reference point. However, beyond the reference point the effect of cutting speed on R_a was similar to that of depth of cut. It may be also observed from the figure that Ra increases linearly with feed on either side of the reforence point.

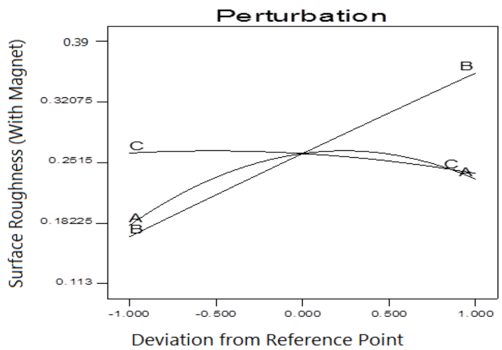
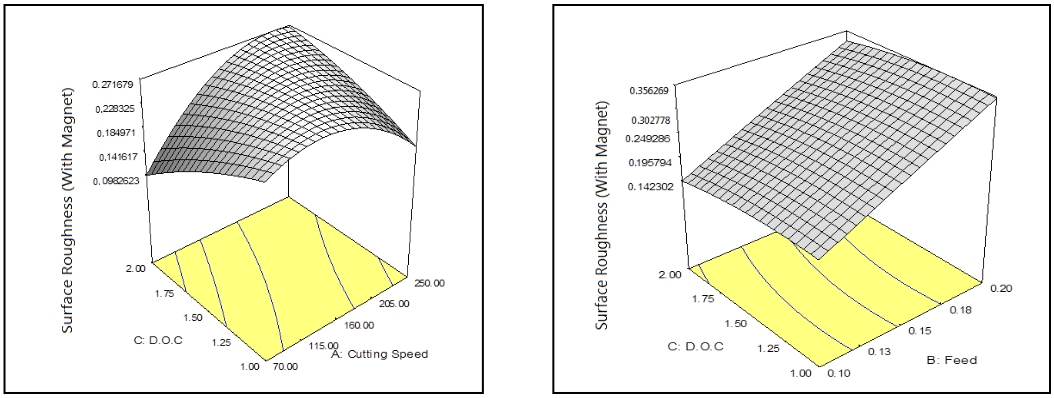


Fig. 3: Pertubation plot for surface roughness

Fig. 4 (a,b) are the interaction plots which illustrate the simultaneous effect of two cutting parameters on R_a. It was noted from the two graphs that all three cutting parameters had substantial influence on R_a and that a combination of higher cutting speed, lower feed, and small depth of cut was needed to produce good surface finish in machined stainless steel specimens.

Optimization. Table 2 shows three possible optimized solutions obtained using desirability function (*DF*). The first one was selected as it predicted the lowest surface roughness of 0.132044 µm with the highest desirability of 93.1%.



(a) (b)

Fig. 4: Interaction plots of R_a vs. (a) cutting speed and depth of cut, and (b) feed and depth of cut

Table 2: Possible optimum solutions for surface roughness in end milling

Solutions						
Number	**Cutting Speed**	**Feed**	**Depth of Cut**	**Surface Roughness**	**Desirability**	
1	70	**0.10**	**1.02**	**0.132044**	**0.931**	**Selected**
2	250	0.12	1.0	0.191352	0.71714	
3	250	0.12	1.01	0.192502	0.71289	

Conclusion

The following conclusions were drawn:

1. The quadratic model generated was tested to be significant and found suitable for effective prediction of resultant surface roughness.
2. The feed had the most significant effect on R_a, followed by speed and depth of cut.
3. The optimum cutting speed, feed, and depth of cut were 70m/min, 0.10mm/tooth, and 1.02 mm, respectively.
4. The significant improvement in surface finish ($R_a < 0.4$µm) eliminates the need for grinding and polishing.

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Advances in Manufacturing and Materials Engineering
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