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Application of Permanent Magnets for Chatter Control in End Milling of Titanium Alloy Ti-6Al-4V

Syidatul Akma Sulaiman[1,a], A.K.M. Nurul Amin[1,b] and M. D. Arif[1,c]

[1]Department of Manufacturing and Materials Engineering

Kulliyyah of Engineering, International Islamic University Malaysia

[a]sas_1309@yahoo.com, [b]akamin@iium.edu.my

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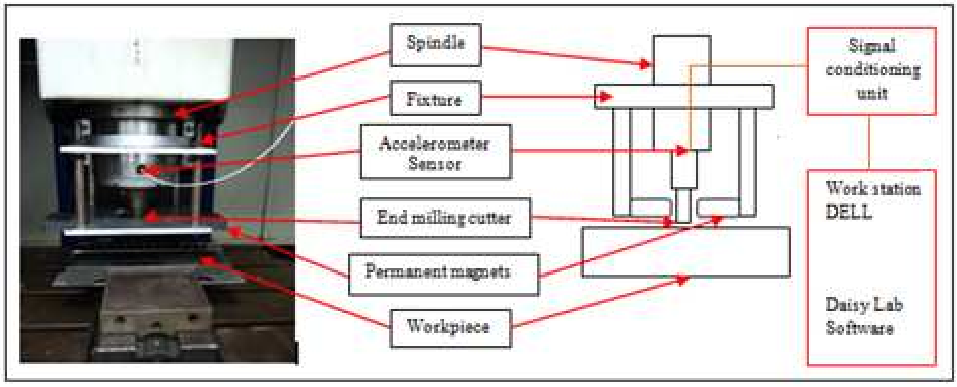
Abstract. Machining of metals is generally accompanied by a violent relative vibration between work and tool, known as chatter. Chatter is undesirable due to its adverse effects on product quality, operation cost, machining accuracy, tool life, and productivity. This paper presents an innovative approach to chatter control during end milling of titanium alloy Ti-6Al-4V using ferrite permanent magnets to reduce the unwanted vibrations. A special fixture was fabricated and mounted on a Vertical Machining Center's spindle for holding the permanent magnet bars, used in suppressing the vibration amplitudes. DASY Lab 5.6 was used for signal analysis and processing to compare the intensity of chatter under normal and magnet application conditions. Fast Fourier Transform (FFT) was subsequently used to transform the vibration data to a function of frequency domain. The experiments focused on monitoring the vibration amplitudes and analysis of chip formation process during metal cutting. It was observed that the magnetic fields contributed to reduction of chatter amplitudes. It was apparent that a reduction of chatter amplitude would result in improved surface finish of the work-piece and lead to uniform chip formation.

Introduction

Chatter is an abnormal tool behavior and is one of the most critical problems in machining processes. It must be avoided in order to improve the dimensional accuracy and surface quality of the product [1]. Wiercigrocch et al. [2] stated that the mode of coupling resulted when the vibration in the thrust force direction generated oscillations in the thrust and cutting force directions. Patwari et al. [3] found that the root cause of chatter was in the coincidence of the frequency of the instability of chip formation with one of the natural mode frequencies of the machine-spindle-tool system during end milling operations. Several researchers have tried to address the chatter phenomenon. A fuzzy logic approach for chatter suppression in end milling process was discussed by Liang et al. [4]. In their work, chatter was detected using the peak sound spectrum amplitudes at chatter frequency ranges. Ning et al. [5] indicated that chatter behavior could be recognized by analysis of chips in high speed ball-nose end milling of hardened steel ASSAB 8407 (AISI H13). In addition, Deshpande et al. [6] showed the effect of the third order term in the nonlinear cutting stiffness through the difference in resultant phase portraits obtained by a numerical method. In this study, the influence of permanent magnets in suppressing chatter in end milling operations on Ti-6Al-4V using uncoated WC-Co insert was investigated.

Experimental Details

Experimental machining were conducted on a Vertical Machining Center (VMC ZPS, Model: 1060) with a maximum spindle speed of 8000 rpm. Machining was done under normal conditions and under the influence of magnetic fields from permanent magnets. Two ferrite magnet bars (dimensions: 1″ x 6″ x 3″) were mounted near the cutting tool by a specially designed fixture. The strength of these magnets was 2500-2700 Gauss. Machining was performed with a 20 mm diameter end mill tool holder fitted with one uncoated WC-Co insert. For monitoring the vibrations, a vibration monitoring system consisting of an accelerometer, a 16 channel rack, and a DAQ card were used. Datalog DASY Lab 5.6 was used for signal analysis. The vibration data was transformed into a function in the frequency domain by using Fast Fourier Transform (FFT) analyzer, included in the software. Fig. 1, below, displays the schematics diagram and photograph of the setup:



(a) (b)

Fig. 1: Experimental set up for end milling operations: (a) Photograph and (b) Schematic view

Central Composite Design (CCD) of Response Surface Methodology (RSM) was used for the design experiments (DOE) and Design Expert software version 7.0 was used for this purpose. The design structure is shown in Table 1 along with the results on vibration amplitude.

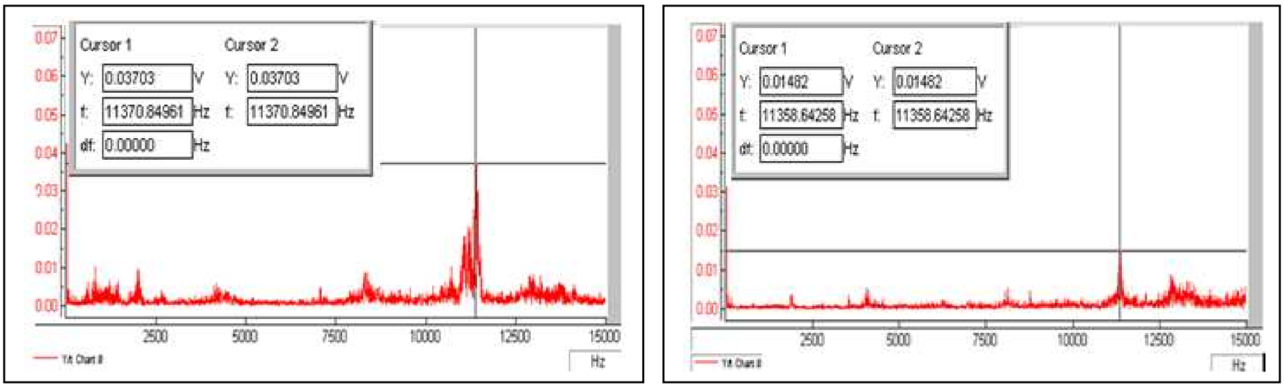
Results and Discussions

Vibration Amplitude. Table 1 displays the vibration amplitude results for the 15 runs of the experiment:

Table 1: Comparison of vibration amplitudes for the two cases: with and without magnets

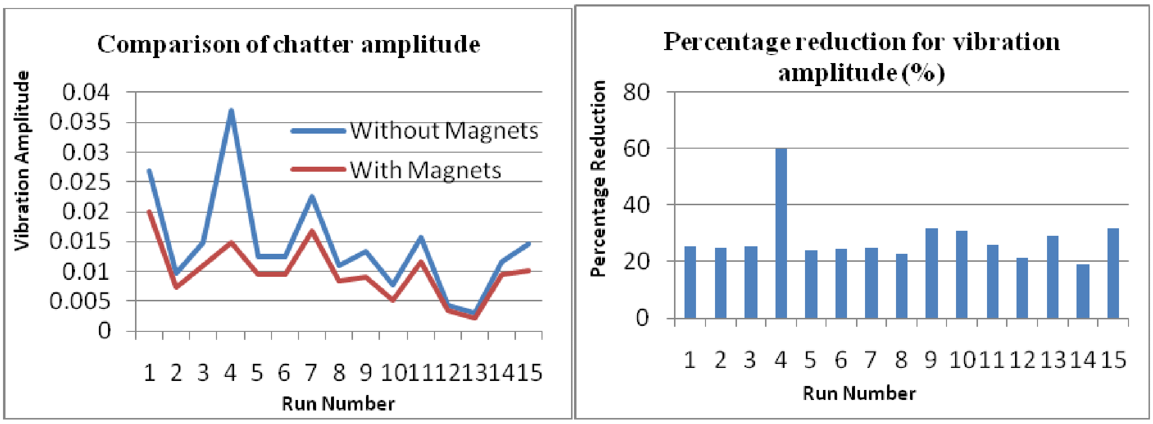
Run	Cutting Speed [m/min]	Feed [mm/tooth]	DOC [mm]	Vibration Amplitude (V)		Percentage Reduction
				Without Magnets	With Magnets	
1	70	0.1	1.51	0.02689	0.02004	25.47
2	70	0.1	0.24	0.00975	0.00731	25.03
3	100	0.05	1.25	0.01483	0.01109	25.21
4	**100**	**0.15**	**0.5**	**0.03703**	**0.01482**	**59.97**
5	70	0.1	0.88	0.01241	0.00943	24.01
6	70	0.1	0.88	0.01241	0.00939	24.34
7	70	0.18	0.88	0.02249	0.01689	24.89
8	70	0.1	0.88	0.01102	0.00851	22.77
9	40	0.15	1.25	0.01336	0.00913	31.66
10	70	0.02	0.88	0.00767	0.00529	31.03
11	120.45	0.1	0.88	0.01577	0.01168	25.94
12	40	0.05	0.5	0.00439	0.00346	21.18
13	19.55	0.1	0.88	0.00301	0.00213	29.24
14	70	0.1	0.88	0.01168	0.00943	19.26
15	70	0.1	0.88	0.01474	0.01003	31.95

It was clear from Table 1 that with the increase of cutting speed, feed, and depth of cut, vibration amplitude increased (for both with/without magnets case). Nonetheless, cutting under the influence of magnetic fields reduced the vibration amplitude, compared to the corresponding cases without magnet. For FFT output, illustrated by graphs in Fig. 2 below, it was observed that chatter appeared in the system when milling was done at higher cutting speed, feed, and depth of cut. The highest percentage of reduction was observed when cutting the work material at 100 mm/min speed, 0.15 mm/tooth feed, and 0.5 mm depth of cut. As shown in Fig. 3 (b), the highest percentage reduction was observed in run number 4. Chatter was reduced from 0.03703 (V) to 0.01482 (V) when magnets were added to the system and the percentage of reduction at this cutting condition was approximately 60%. It may observed that the best results of application is at the speed of 100 m/min at relatively low depth of cut (0.5 mm) and high feed (0.15 mm/tooth). Finally, it may be concluded from these results that, the presence of permanent magnets contributed to an average reduction of the vibration ampiltudes by approximately 30%. This reduction was due to the damping effect of the magnets on the vibratory motion of the tool. This is caused due to the forces of attaction from the magnets, located in diagonally opposite direction, on the vibrationg tool. Under the effect of the magnetic forces the tool requires higher energy to vibrate around its neutral position and hence its vibration is damped.



(a) (b)

Fig. 2: Fast Fourier Transform (FFT) analysis results (cutting speed 100 m/min, feed 0.15 mm/tooth, and depth of cut 0.5 mm): (a) Vibration amplitude (without magnet) and (b) Vibration amplitude (with magnets).



(a) (b)

Fig. 3: (a) Influence of magnets on vibration amplitudes and (b) Percentage reduction of amplitudes

Chip Morphology. The chips formed during machining under different cutting parameters (15 experimental runs) were collected and analyzed for the with respect to the primary and secondary serrated teeth to investigate the effect of magnet application on chip serration frequency and amplitude. It was observed from Fig. 4, below, that the formation of primary serration was more prominent in the case of this work material (Ti6Al4V). The primary serrated teeth were formed at the main body of the chip, at almost equal pacing. Cutting under the presence of magnets made the chips more stable with comparatively higher frequency (Fig. 4(b,d)) lower height of primary serration teeth (Fig. 4(a,c)) and thus, reduced chatter vibrations. It is to be noted here that the formation of primary serration of chips is difficult to avoid during machining of titanium and its alloys. However, chatter appears in the system when these serrated teeth get amplified and their frequencies are lowered to align with the natural frequencies of the system components as a result of resonance [3]. The application of magnet appears to have made the system more stable and as a result the chips are formed at the nominal frequencies of the work material without getting biased by the system.

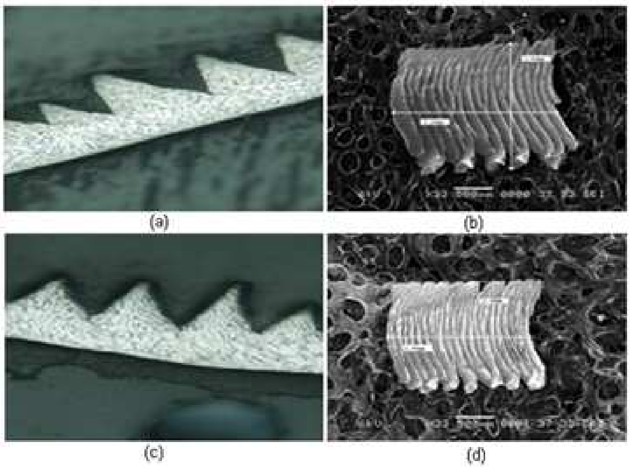


Fig. 4: SEM micrograph of chips obtained for the two cases (cutting speed 100 m/min, feed 0.15 mm/tooth, and depth of cut 0.5 mm) (a) Sectional view, (b) SEM view of chip (cutting without magnet), (c) Sectional view, and (d) SEM view of chip (cutting with magnets).

Conclusion

The following specific conclusions were drawn from the research work:

1. Chatter or vibration with the highest amplitude appeared in the system during end milling at cutting speed 100 m/min, feed 0.15 mm/tooth, and depth of cut 0.5 mm within the selected rages of these parameters while under normal conditions. The amplitude of the chatter was reduced at this cutting condition by approximately 60% when magnets were applied.
2. Application of magnet resulted in reduction of the height of primary serrated teeth i.e. to the formation of more stable chip formation as a result of suppression of chatter under this condition. This in turn is expected to aid in obtaining better surface finish.

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