Influence of damping coefficient from permanent magnets on chatter formation during end milling of titanium alloy (Ti-6Al-4V)

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Abstract. In machining operations, chatter is undesirable due to its adverse effects on the product quality, operation cost, machining accuracy and machine tool life. It is also responsible for reducing output. Chatter is a self-excitation phenomenon occurring in machine tools, in which the cutting process tends to lower the damping capacity of the machine structural components ending in an unstable behavior of the system. Chatter arises due to resonance when the vibrations of the instability of chip formation and the natural vibration modes of the machine-system components coincide. This paper focuses on the influence of damping coefficient from permanent magnets on chip serration frequency as an approach of minimizing chatter in end milling of Titanium alloy (Ti6Al4V). The method consists of two ferrite permanent magnet bars (dimensions: 1” x 6” x 3”), mounted 5mm from the cutting tool using a specially designed fixture which provided a uniform magnetic field of 2500-2700 Gausses. A titanium alloy Ti6Al4V block was then end milled using uncoated WC-Co inserts. A sequence of 15 experimental runs was conducted based on a small Central Composite Design (CCD) model in Response Surface Methodology (RSM). The primary (independent) parameters were: cutting speed, feed, and depth of cut. The data acquisition system comprised a vibration sensor (accelerometer) and a signal conditioning unit was used to measure the vibration data. The resultant vibrations were then analyzed using the DASYLab 5.6 software. Machining tests were conducted for two different conditions – with and without the application of magnets. Scanning Electron Microscope (SEM) was used to measure the chip segmentations. The SEM analysis of chip serrations demonstrated that the chip serration frequency were more stable while cutting under the presence of permanent magnets due to lower intensity of chatter.

1. Introduction
Milling process could be considered the most efficient method of metal cutting which provides high material removal rate while maintaining a high quality level. The most critical limitation in machining productivity and part quality is the occurrence of the instability phenomenon called regenerative chatter [1]. Several hypotheses have been developed, over the years, to address chatter formation phenomenon and its suppression methods. Piezoelectric actuators [2], magnetostrictive actuators [3]

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and multiple time-varying parameters (MTVP) [4] have been employed to reduce chatter in turning. Stone [5] extended the non-uniform pitch concept by proposing end mills with a different helix on adjacent flutes. Alternating the helix increased the pitch variations along the axial depth of cut hence both the chatter free performance and the speed range were improved. Although, chatter has been extensively investigated over the past 70 years and several hypotheses and theories have been developed, the root cause of chatter still remains controversial [6]. Thus the use of permanent magnets has become a new approach to control chatter.

Identification of chip frequency is important since chatter is thought to occur when the chip serration frequency (primary or secondary) coincides with or get close to, or becomes an integer multiple of any of the natural frequencies of a system [7]. Chatter occurred at nearly constant frequencies, close to the natural frequencies of prominent system components over a range of cutting speed for a given set of cutting conditions [8]. Chatter is an abnormal tool behavior which it is one of the most critical problems in machining process and must be avoided to improve the dimensional accuracy and surface quality of the product [9]. Chatter arising during end milling and turning is a result of resonance, caused by mutual interaction of the vibrations due to serrated elements of the chip and the natural vibrations of the system components, e.g. the spindle and the tool holder. Moreover, serrated behavior is the outcome of the discrete nature of the chip formation process that exists in the entire cross section of the chip. Serrated edges appear either as primary and/or secondary saw/serrated teeth depending on the material properties and cutting conditions [10, 11]. The main objective of this research is to study the influence of magnetic field from permanent magnets in end milling of titanium alloy on chip serration frequency. Investigation on method of chatter suppression is much desired to improve the efficiency of the milling operation. The use of permanent magnet has potential application in controlling chatter. Since magnets have strong attractive forces, they were applied to increase the damping capacity of the vibration component/system.

2. Methodology
Experimental test was conducted on Vertical Machining Center (VMC ZPS, Model: 1060) with a maximum spindle speed of 8000 rpm under the influence of magnetic field from permanent magnets. Two ferrite magnets bar with dimension of 1 inch x 6 inch x 3 inches were mounted 5mm from the cutting tool by specially designed fixture. The strength of these magnets was 2500-2700 Gauss. Titanium alloy (Ti6Al4V) block was used as a workpiece material. Machining was performed with a 20 mm diameter end mill tool holder fitted with one uncoated WC-Co insert. Machining process was done under two different conditions. First condition is under room temperature and the other one is under the influence of magnetic field from permanent magnets bar. Scanning Electron Microscope (SEM) was employed in order to investigate the chip segmentations. Figure 1 includes the photograph of the experimental setup.

![Figure 1](image-url)
The experiments were designed based on the Response Surface Methodology (RSM) approach using DESIGN EXPERT (DOE) software. Three independent variable are tested which are cutting speed, feed and depth of cut. The ranges for the independent variable are $19.55 \leq \text{cutting speed} \leq 120.45 \text{m/min}$, $0.05 \text{mm/tooth} \leq \text{feed} \leq 0.18 \text{mm/tooth}$ and $0.24 \text{mm} \leq \text{depth of cut} \geq 1.51 \text{mm}$. The effect of different cutting parameters on chip serration frequencies and its interaction with the mode frequencies of the end milled components has been investigated considering the vibration data that are recorded during machining using an online data acquisition system. Initially, knocking test has been done to measure the natural frequency of the system component. The accelerometers are connected to the component and the natural mode frequency data from the FFT graph were recorded by knocking the spindle using impact hammer as shown in figure 2.

3. Results and Discussion

Experimental studies are conducted on the instabilities of chip formation in end milling operations to investigate the mechanisms of formation of chip serration under different cutting conditions. The details calculation procedure for chip serration frequencies in end milling of titanium alloy for two different cutting conditions (magnets and without magnets) are shown in table 1.

Sample SEM photographs of the top view of the chips formed during these two operations are presented to have a clear understanding of the mechanism of serrated chip formation. During end milling operation there is instability of chip formation in the form of serrated teeth and the serrated teeth are observed on both the lengthwise edges of the chip. The calculated chip frequency and the recorded vibration amplitude for all runs were presented in table 2.

Result shows that the calculated chip serration frequencies are higher when magnets were added to the system compared to those under normal cutting. Cutting under the presence of magnets made the chips more stable with comparatively higher frequency of primary serration teeth as compared to normal cutting. From this observation, chatter appears in the system when these serrated teeth get amplified and their frequencies are lowered and coincides with the natural frequency of any one of the system components, leading to resonance [9]. The increment in chip serration frequency is due to the damping effect of the magnets on the oscillatory motion of the tool. This results due to the retarding forces of attraction from the magnets, located in diagonally opposite direction, on the vibrating tool.

3.1. Resonance theory without application of magnets

This section is mainly designed to investigate the chatter formation as an outcome of resonance effect due to interaction between the chip serration frequency and prominent mode frequencies of the spindle. Initially, the knocking test was done to find the natural frequency of the spindle with and without fixture attachment. From knocking test (without fixture) the natural frequencies ($f_n$) for spindle are appeared at 8,758 Hz and 11,291 Hz as shown in figure 3. But since the highest peak amplitude

![Figure 2. Knocking test to determine the natural frequencies of the spindle.](image-url)
was at 11.291Hz, thus it is selected as the prominent natural frequency of the spindle. According to the resonance theory of chatter; chatter occurs when the chip serration frequency approaches the prominent natural frequency of a component or one of its higher harmonic frequencies.

### Table 1. Chip serration frequency calculation for end milling of titanium alloy under the influence of magnetic field and normal cutting.

| Cutting without magnets | Cutting with magnets |
|-------------------------|----------------------|
| Cutting Speed(V)=70m/min| Cutting Speed(V)=70m/min |
| No of serrated teeth(n) = 13 | No of serrated teeth(n) =11 |
| Length in SEM (L) = 2.18mm | Length in SEM(L) = 2.02mm |
| Chip shrinkage coefficient (K) = 1.205 | Chip shrinkage coefficient(K)=1.048 |

Determinion of chip serration frequency considering the SEM view

\[ f_c = \frac{70 \times 1000 \times 13}{50 \times 2.18 \times 1.205} = 5.773 \text{Hz} \]

\[ f_c = \frac{70 \times 1000 \times 11}{50 \times 2.02 \times 1.048} = 6.062 \text{Hz} \]

Where

\[ f_c \] - Chip Frequency

To investigate the resonance effect, the calculated primary chip serration frequencies for five cutting conditions are compared with the dominating mode frequencies of the spindle. The summary of the relationship between calculated chip serration frequency and vibration amplitude are presented in table 3. From the experimental results (without magnet) the highest vibration amplitude (run 4) was observed when \( f_c \) was nearly equal to \( f_n \) or \( f_c/f_n \approx 1 \) (see table 3).

For clear understanding, the relationship of vibration amplitude and chip serration frequency over natural frequency \( (f_c/f_n) \) is plotted in figure 4. It has been observed that when the ratio of the primary chip serration frequency and the dominating mode frequency of the spindle is close to one, there is a peak in acceleration amplitude (0.03703volt) which proves that chatter is formed as a result of resonance.
Table 2. Chip serration frequency for normal cutting and cutting under the influence of magnetic field from permanent magnets.

| Run Number | Cutting Speed (m/min) | Feed (mm/tooth) | Depth of Cut (mm) | Chip frequency (Hz) Without magnets | Chip frequency (Hz) With magnets | Vibration Amplitude (V) Without magnets | Vibration Amplitude (V) With magnets |
|------------|-----------------------|-----------------|------------------|------------------------------------|----------------------------------|----------------------------------------|------------------------------------|
| 1          | 70                    | 0.1             | 1.51             | 14,625                             | 15,420                           | 0.02689                                | 0.02004                            |
| 2          | 70                    | 0.1             | 0.24             | 9,845                              | 10,465                           | 0.00975                                | 0.00731                            |
| 3          | 100                   | 0.05            | 1.25             | 11,241                             | 17,074                           | 0.01483                                | 0.01109                            |
| 4          | 100                   | 0.15            | 0.5              | 11,182                             | 14,405                           | 0.03703                                | 0.01482                            |
| 5          | 70                    | 0.1             | 0.88             | 8,199                              | 9,512                            | 0.01241                                | 0.00943                            |
| 6          | 70                    | 0.1             | 0.88             | 9,841                              | 10,762                           | 0.01241                                | 0.00939                            |
| 7          | 70                    | 0.18            | 0.88             | 5,773                              | 6,062                            | 0.002249                               | 0.001689                           |
| 8          | 70                    | 0.1             | 0.88             | 9,427                              | 10,179                           | 0.01102                                | 0.00851                            |
| 9          | 40                    | 0.15            | 1.25             | 5,116                              | 5,146                            | 0.01336                                | 0.00913                            |
| 10         | 70                    | 0.02            | 0.88             | 14,319                             | 18,884                           | 0.00767                                | 0.00529                            |
| 11         | 120.45                | 0.1             | 0.88             | 15,840                             | 16,672                           | 0.01577                                | 0.01168                            |
| 12         | 40                    | 0.05            | 0.5              | 12,622                             | 14,759                           | 0.00439                                | 0.00346                            |
| 13         | 19.55                 | 0.1             | 0.88             | 6,101                              | 6,758                            | 0.00301                                | 0.00213                            |
| 14         | 70                    | 0.1             | 0.88             | 9,410                              | 10,076                           | 0.01168                                | 0.00943                            |
| 15         | 70                    | 0.1             | 0.88             | 9,986                              | 10,259                           | 0.01474                                | 0.01003                            |

Figure 3. FFT for natural frequency of spindle (without fixture attachment).
Table 3. Relation of $f_c/f_n$ with vibration amplitude (without magnets)

| Natural frequency ($f_n$) | Chip serration frequency ($f_c$) | $f_c/f_n$ | Vibration amplitude | Run number |
|---------------------------|---------------------------------|----------|---------------------|------------|
| 11291                     | 5116                            | 0.453104 | 0.01241             | 9          |
| 11291                     | 9845                            | 0.871933 | 0.00723             | 2          |
| 11291                     | 11241                           | 0.995572 | 0.03703             | 4          |
| 11291                     | 12622                           | 1.117881 | 0.00541             | 12         |
| 11291                     | 15840                           | 1.402887 | 0.00922             | 11         |

Figure 4. Effect of chip serration frequency/natural frequency ratio (without magnets) on vibration amplitude.

3.2. Resonance theory with application of magnets

The fixture with the magnet attachment has its own mass which reduces the natural frequency of the spindle. From FFT plot in figure 5, the prominent natural frequency was shifted to the left as compare with the FFT for natural frequency in figure 3. This happened due to the addition of mass from fixture when it was clamped on the spindle. From knocking test it was found that the spindle with fixture attachment had natural frequencies as shown in table 4.

From table 4, it can be inferred that the second peak of natural frequency had more probability of interacting with the calculated $f_c$ as the first one was too low and the vibration amplitude for the third peak was too low as well. From the calculated primary chip frequency (with magnet), chip serration frequency ($f_c$) starts from more than 5000 Hz. So, resonance in this case was seen whenever $f_c$ approached any higher harmonic of the second $f_n$ peak of 4,500 Hz. The higher harmonics after 4,500 Hz are at 9,000 Hz (double) and 13,500 Hz (three times higher).
Figure 5. FFT for natural frequency of the spindle with fixture attachment.

Table 4. Natural frequency of the spindle (with fixture attachment).

| Natural frequency of the spindle (Hz) |
|--------------------------------------|
| First peak                           |
| Second peak                          |
| Third peak                           |
| Fourth peak                          |
| 750                                  |
| 4500                                 |
| 11250                                |
| 13670                                |

From table 5 and figure 6, it has been observed that chatter occurred when chip serration frequency was equal to 9,512 and 14,759 Hz, which are near to the higher harmonic (9,000 and 13,500Hz) of natural frequency 4,500. However, the peak amplitudes are much smaller with the magnets, with the maximum amplitude of 0.009 volts with magnets against 0.037 volts without magnet, showing the damping action of the magnets.

Table 5. Relation of $f_c/f_n$ with vibration amplitude (with magnets).

| Natural frequency ($f_n$) | Chip serration frequency ($f_c$) | $f_c/f_n$ | Vibration amplitude | Run number |
|---------------------------|---------------------------------|-----------|---------------------|------------|
| 4500                      | 5146                            | 1.143556  | 0.00471             | 9          |
| 4500                      | 6062                            | 1.347111  | 0.00560             | 7          |
| 4500                      | 9512                            | 2.113778  | 0.00817             | 5          |
| 4500                      | 10762                           | 2.391556  | 0.00657             | 6          |
| 4500                      | 14759                           | 3.279778  | 0.00913             | 12         |
| 4500                      | 17074                           | 3.794222  | 0.00531             | 3          |
Chatter occurred due to the resonance between the chip serration frequencies with any prominent mode frequency of the different machine components [9]. Since these high peaks are caused by resonance and the amplitude of vibration in resonance is a function of the damping coefficient of the system, so any factor that would lead to the increase in the damping factor is expected to lower the amplitude of chatter. These findings have once again proven the resonance theory of chatter formation. figure 7 illustrates the frequency response of a system during resonance. The maximum response amplitude during resonance depends on how much damping the system has. The less the damping there is (i.e. the smaller is $\zeta$) the larger it gets, and if there is more damping in the system, then the amplitude will be at minimum level.

Hence the application of magnets definitely increased the damping coefficient, i.e. increased the $\zeta$ value of the system which resulted in approximately 4 times lower value of the maximum acceleration amplitude peak during machining.
4. Conclusion
The main objective of this research is to find the effect of application of permanent magnets on chip serration frequencies. Based on the findings on end milling of Titanium alloy (Ti6Al4V) it has been concluded that machining under the influence of magnetic field resulted in suppression of chatter. This is because, cutting under the presence of magnets made the chips more stable with comparatively higher frequency compared to those under normal cutting, due to the absence or reduction of chatter amplitude. This phenomenon occurred because of the damping effect of the magnets on the oscillatory motion of the tool and the formation of unbiased serrated teeth, characteristic of the materials and the applied cutting parameters. It was also concluded that when the ratio of the primary chip serration frequency and the dominating mode frequency of the spindle are close to 1 or higher integer number (2,3), there is a peak in acceleration amplitude which proves that chatter is formed as a result of resonance. Since chatter occurs due to the resonance any factor that would lead to the increase in the damping factor of the system is expected to lower the amplitude of chatter. This is why the application of magnet contributed to a drastic reduction (4 times) of chatter acceleration amplitude.

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