Experimental evaluation of critical axial depth of cut with magneto rheological damping in end milling process

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Abstract- An end milling process is widely used in fabrication of complex contours and shape parts at high spindle speeds. Many researchers try to investigate one of important aspect, which come across during machining is the self exited chatter vibration which causes severe damage of the tool and quality of the machined surface. The present work is focused on the Magneto-Rheological Damping effect on stability of chatter in an end milling process during machining. The end mill cutter was modeled as a rotating Euler Beam with an attached MR Damper as bar element and its first five modes of vibrations are considered. The stability analysis has been carried out by considering the two degrees of freedom of the model. End Mill cutter considered as a uniform rotating cantilever beam with attached active Magneto-Rheological Damper to it was investigated. The Dynamic force of an Magneto-Rheological Damper is generated by varying damper Input current The cutter is discrtized by using finite element Method. The governing equation of motion of the end mill cutter was derived by using D Alembert's Principle. The results obtained from the simulation reveal that how the allocation of Magneto-Rheological Damper affects the dynamic properties of the end mill cutter. In this paper an attempt has been made to utilize the remarkable dynamic properties of MR fluid to control the vibrations and suppress the chatter. The natural and chatter frequencies of the end mill cutter under the influence of Magneto-Rheological damping has been found at different machining parameters Such as Depth of cut, Spindle speed, and Feed rate. In the present paper we have investigated the presented chatter, the effect of Magneto Rheological damping on stability limits by considering the different machining parameters. A series of experiments have been performed and evaluated the chatter frequency and the limit of axial depth during end milling. The acceleration of the four Flute HSS End mill cutters was measured during the machining of aluminum work piece. Power spectral analysis have been carried out to evaluate the dynamic characteristics of the end mill cutter under the influence of Magneto Rheological Damping by considering different machining parameters.

Index Terms- End Mill cutter, Magneto-Rheological damping, Chatter frequency, Critical axial depth of cut.

I. Introduction

The Major part of the production industries requires quality based economical cost reduction and ability to develop the parts with good surface finish, dimensional accuracy and desired contours on the complex part. Maximum material removal is prime criteria to have optimum machining parameters during manufacturing. In the industrial , automotive and aerospace sector the most demanding features is to have high precision with desired level of tolerance and productivity requires to develop a methodology which can adopt to have its extensive application and one of the machining operation which is widely used in manufacturing industry is an end milling operation. In factors which adversely affects the dynamics of the end mill cutter are the geometry of the tool , material properties, self exited vibrations due to machining forces and parameters like spindle speed, depth of cut and radial depth of cut. The dynamic cutting conditions causes' large magnitude of vibrations between the end mill cutter and work piece and leads to undesired phenomenon known as chatter. Chatter not only affects the cutting tool dimensional accuracy, tools wear and quality of the surface and it is mainly associated with regenerative and self exited force oscillations. The earlier work of Polacek and Tobias was showed mechanism involved which causes the vibration of the chatter. Tulsty and Arnold showed the occurrence of chatter effects by an increasing of the cutting speed. Fish wick in his work showed the effect of axial depth of cut, spindle speed and feed rate parameters on the stability of the milling process. In these work remarkable Magneto rheological properties of the fluid is used to study the stability of the end milling process, under the influence of magneto rheological damping during the machining .In order to achieve the stability limit various influential machining parameters like axial depth of cut, spindle speed, and feed rate are considered and experimentally evaluated the critical axial depth of cut to ensure the maximum stability of the end mill cutter. The experimental data has been validated with the analytical solution of the stability and the trends of stability are discuses with different depth of cut and spindle speed. The prediction of rotating frequencies by using finite element methods is an active area of research. Most vibration analysis works on rotating beams seek to predict the first 3–5 frequencies accurately. Beams with low translational rigidity at root and high rotating speeds, the fundamental frequency can become imaginary leading to divergence issues leads to instability. Therefore, accurate prediction of the fundamental mode is essential for rotating beams as it shows a strong influence of rotational speed and in general accurate prediction of the fundamental mode is essential in structural dynamics. In this paper, In order to simplify the analysis required to derive the shape functions, the centrifugal force is assumed as a constant for an element Chatter is an unstable, self-excited vibration that occurs as a result of an interaction between the dynamics of the machine tool and the work. In traditional regenerative chatter stability, the occurrence of chatter is dependent on three factors such as cutting conditions, work piece material properties, and the dynamics of the machine tool spindle system. End mill cutter has been modeled rotating euler cantilever beam and the majority of spindle research has dealt with static stiffness optimization rather than dynamic performance. Little work has been done and few papers addressing the utilization of the Magneto rheological fluid properties in manufacturing field. In this work an attempt has been made to evaluate the critical axial depth of cut under the influence of Magneto rheological damping during machining at different combination of machining parameters and validated experimentally.

II. DYNAMIC 2-DOF MILLING FORCE MODEL

In the present study a remarkable and effective force model is used which was developed by Altitntas and Budak is used to determine the chatter effect on stability of end mill cutter during machining under various machining conditions.

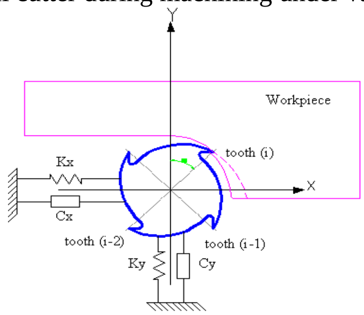

Fig 1: Dynamic 2-DOF Milling Force model

The end mill cutter is having number of teeth's as T_N and immersion at an angle θ with a particular tooth *i* at a particular instant, measuring in clockwise direction from the Y-axis. The Radial and Tangential cutting forces are F_R and F_T respectively and it is given by

$$F_{Ri} = K_T K_R a_d t_c \text{ Or } F_{Ri} = K_T K_R F_{Ti} \quad (1)$$
$$F_{Ti} = k_T a_d t_c \quad (2)$$

Where t_c is the chip thickness, a_d is the axial depth of cut, K_T^c is the tangential metal cutting force coefficients, K_R^c is the tangential metal cutting force coefficients theses coefficients are dependent on chip thickness. The formation of chip thickness during end milling is mainly depend on machining conditions like feed rate, diameter of the cutter, axial depth of cut. The major cutting forces for a particular tooth *i* will be represented in XY-coordinate system in feed and normal directions. Therefore the resultant metal cutting forces can be expressed as

$$F_X = \sum_{i=0}^{T_N-1}(F_{xi}) \text{ or } F_X = \sum_{i=0}^{T_N-1}(-F_{Ri}\sin\theta_i - F_{Ti}\cos\theta_i) \quad (3)$$
$$F_Y = \sum_{i=0}^{T_N-1}(F_{yi}) \text{ or } F_Y = \sum_{i=0}^{T_N-1}(-F_{Ri}\cos\theta_i + F_{Ti}\sin\theta_i) \quad (4)$$

The chip thickness at a particular instance of time is expressed as

$$t_c(\theta) = -x\sin\theta_i - y\cos\theta_i \quad (5)$$

Angular immersion θ varies with respect to cutting time and nominal chip thickness when the angle of the cutting edge equals to zero is given by

$$t_c(\theta) = f_r \sin\theta_i \quad (6)$$

Where f_r is the feed rate, chip thickness formed during machining usually consists of static part given in equation 6 and dynamic components generated due to self exited vibrations of the tool between the successive tooth having time period τ, due to these vibrations the variation in chip thickness occurs. The resultant chip thickness can be determined by summation of nominal chip thickness to the present and previous tooth deflection modulations and it is expressed as

$$t_c = [\, f_r \sin\theta_i + (t_{i0} - t_i)]\, S(\theta_i) \quad (7)$$

Where S (θ_i) is a step function express whether the tooth is in cut or out of cut during machining. If θ_{start} and θ_{exit} angles of end mill cutter to and cut from the cut respectively and the step function can be found from

$$S(\theta) = \begin{cases} 1, if & \theta_{start} < \theta_i < \theta_{exit} \\ 0, if & \theta_i < \theta_{start} \text{ or } \theta_i > \theta_{exit} \end{cases} \quad (8)$$

Table 1: Immersion Angles for different machining process

Type of Machining	θ_{start}	θ_{exit}
Up-cut Milling	0^0	Depends on the radial depth of cut
Down-cut Milling	0^0	180^0

If $t_c(\theta_i) < 0$, this shows that the tooth is out of cut and the force on the tooth is assumed to be zero and if $t_c(\theta_i) > 0$, the tooth will be in cut along the direction of the arc being generated during machining then the forces are determined in terms of chip thickness accordingly. The total metal cutting force expression which includes regenerative effect will be in this form

$$F = F_X \cos\theta_i + F_Y \sin\theta_i \qquad (9)$$

The end mill cutter will be in remain in contact during machining along the length of the arc being generated during machining then the time delay period is assumed to be constant and is equal to $\tau = 2\pi/\omega$, The metal cutting force model can be determined as

$$\begin{pmatrix} F_X \\ F_Y \end{pmatrix} = \frac{1}{2} a_d K_T [P(t)] \left\{ \begin{matrix} x(t) - x(t-\tau) \\ y(t) - y(t-\tau) \end{matrix} \right\}$$

$$\begin{pmatrix} F_X \\ F_Y \end{pmatrix} = \frac{1}{2} a_d (1 - e^{-\tau D}) K_T \begin{pmatrix} p_1 & p_2 \\ p_3 & p_4 \end{pmatrix} \left\{ \begin{matrix} x(t) \\ y(t) \end{matrix} \right\} \qquad (10)$$

$$p_1 = \sum_{i=0}^{N_T} -[\sin 2\theta_i + K_R (1 - \cos 2\theta_i)]\, S(\theta)$$

$$p_2 = \sum_{i=0}^{N_T} -[K_R \sin 2\theta_i + (1 + \cos 2\theta_i)]\, S(\theta)$$

$$p_3 = \sum_{i=0}^{N_T} -[-K_R \sin 2\theta_i + (1 - \cos 2\theta_i)]\, S(\theta)$$

$$p_4 = \sum_{i=0}^{N_T} -[\sin 2\theta_i - K_R (1 + \cos 2\theta_i)]\, S(\theta)$$

In the above equation $e^{-\tau D}$ is a time delay operator, x and y are the displacements of the end mill cutter in the X and Y directions respectively. [P(t)] is the periodically varying directional metal cutting force coefficients matrix. This directional coefficient matrix is only difference between milling and other machining process like turning in which direction of the cutting force is constant. In the Milling process [P(t)] is periodic having frequency which is known as tooth passes frequency with successive cuts on work piece and equals to $\omega_f = T_n * N$, and can be evaluated by using Fourier series expansion

$$p(t) = \sum_{l=-\infty}^{\infty} [p_k]\, e^{ik\omega_f t} \qquad (11)$$

Where $[p_k] = \frac{1}{\tau} \int_0^{\tau} [p(t)]\, e^{ik\omega_f t}\, dt$, $\tau = 2\pi/\omega_f$ is the period of the tooth passing between the successive cuts. By taking only the components of expansion having value k = 0

$$[p_0] = \frac{1}{\tau} \int_0^{\tau} [p(t)]\, dt \qquad (12)$$

The above equation is valid only for cutting angles of the cutter and $S(\theta) = 1$, then $[p(t)]$ will be equal to average at the pitch angle at the cutter $\theta_p = 2\pi / T_n$

$$[p_0] = \frac{1}{\theta_p} \int_{\theta_{start}}^{\theta_{exit}} [p(\theta)]\, d\theta$$

$$[p_0] = \frac{T_N}{4\pi} a_d K_r^c [A(\theta)]$$

$$[p_0] = \frac{T_N}{2\pi} \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \qquad (13)$$

The above integrand is evaluated between the entry and exit angles of the cutter and a_1, a_2, a_3, and a_4 are the constants of time invariant coefficient matrix depends on radial immersion conditions and it is given by

$$a_1 = [K_r^c \sin 2\theta + \cos 2\theta - 2K_r^c \theta]_{\theta_{start}}^{\theta_{exit}}$$

$$a_2 = [K_r^c \cos 2\theta - \sin 2\theta - 2\theta]_{\theta_{start}}^{\theta_{exit}}$$

$$a_3 = [K_r^c \cos 2\theta - \sin 2\theta + 2\theta]_{\theta_{start}}^{\theta_{exit}}$$

$$a_4 = [-K_r^c \sin 2\theta - \cos 2\theta - 2K_r^c \theta]_{\theta_{start}}^{\theta_{exit}} \qquad (14)$$

The metal cutting forces now can be expressed as

$$\begin{pmatrix} F_X \\ F_Y \end{pmatrix} = \frac{T_N}{4\pi} a_d\, K_t^c [A(\theta)] \begin{Bmatrix} x(t) - x(t-\tau) \\ y(t) - y(t-\tau) \end{Bmatrix}$$

$$\begin{pmatrix} F_X \\ F_Y \end{pmatrix} = \frac{T_N}{4\pi} a_d\, K_t^c (1 - e^{-\tau D}) \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix} \qquad (15)$$

III. EVALUATION OF THE METAL CUTTING COEFFICIENTS

Metal cutting forces are of most important for evaluating the coefficients in the end milling process based on different machining parameters. An empirical equation was proposed to relate the tangential cutting force and chip thickness by tangential cutting coefficients K_t^c, which was determined by experimental force data measured form milling tool dynamometer. The tangential cutting coefficients were shown to be a function of the chip thickness for end milling. The model was based on the assumption that the tangential cutting force is proportional to the uncut chip area and the radial cutting force is proportional to the tangential cutting force. Finally, the new model for cutting coefficients in end milling operations is presented. The Forces F_x and F_y can be expressed in the matrix form as

$$\begin{pmatrix} F_X \\ F_Y \end{pmatrix} = \frac{t_c\, r}{2\tan\gamma} \begin{pmatrix} R_1 & R_2 \\ R_2 & -R_1 \end{pmatrix} \begin{Bmatrix} K_t^c \\ K_r^c \end{Bmatrix} \qquad (16)$$

Where the constants R_1 and R_2 are evaluated by using the analytical expression involving the cutter rotation angle and chip thickness and it is given by

$$R_1 = [\sin^2\theta + \frac{N_t f_t}{3\pi r}\cos^3\theta + \frac{f_t}{r}(\sin\theta - \sin^3\theta/3)]_{\theta_{start}}^{\theta_{exit}}.$$

$$R_2 = [\theta - \frac{\sin 2\theta}{2} - \frac{N_t}{3\pi r}\sin^3\theta - \frac{f_t}{r}\cos^3\theta/3)]_{\theta_{start}}^{\theta_{exit}}.$$

$$\begin{pmatrix} K_t^c \\ K_t^c K_r^c \end{pmatrix} = \frac{2\tan\gamma}{t_c\, r}\, \frac{1}{(R_1^2 + R_2^2)} \begin{pmatrix} R_1 & R_2 \\ R_2 & -R_1 \end{pmatrix} \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} \qquad (17)$$

Thereby the measured forces from the experimental data are used in determining the metal cutting coefficients. It has been observed that as the chip thicknesses increases the resultant forces are also experienced by the end mill cutter. F_t and F_r are the forces that will determine the coefficients effectively when compare to F_x and F_y .

IV. FE MODEL OF MAGNETO-RHEOLOGICAL DAMPER WITH AN END MILL CUTTER

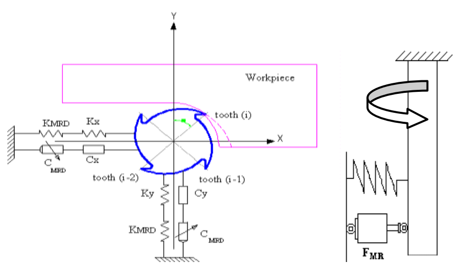

Fig 2. 2: DOF Magneto-rheological damper with an end mill cutter

In the matrix notation the equation of motion can be represented as

$$K^* d(t) + C^* \dot{d}(t) + M^* \ddot{d}(t) = F(t)_{cutting} + F_{MR}$$

Where $[C^*] = [C_s] + [C_{MR}]$

$$[K^*] = [K_s] + [K_{MR}]$$
$$[M^*] = [M_s] + [M_{MR}] \qquad (18)$$

$\ddot{d}, \dot{d}, d$ are the nodal acceleration, velocity, displacement of the end mill cutter . The mass of the Magneto rheological damper is lumped at the connected nodes in the FE model for the combination of the end mill cutter and an attached damper is presented. The analysis gives the valuable information regarding the limits of chatter during machining. Regenerative chatter is the main source of instability of chatter. In this section of the paper analysis of stability is conducted with the conventional analytical and methods. The characteristics equation roots gives the information of the stability of the metal cutting process and it must be noted that it should contain only negative real part, In this work Euler beam is considered for stability analysis.

V. EULER BEAM MODEL

$$K^{*}d(t) + C^{*}\dot{d}(t) + M^{*}\ddot{d}(t) = F \qquad (19)$$

Where the matrices K^{*}, C^{*}, M^{*} are the matrices of stiffness, damping, mass matrices of the end mill cutter and MR damper and d(t) are the displacements of the nodes F(t) represents the force vector

$$Kd(t) + C\dot{d}(t) + M\ddot{d}(t) = \{f_1, f_2, f_3 \ldots . f_n\} \qquad (20)$$

By rearranging the above equation for n degrees of freedom we have

$$\begin{Bmatrix} F1 \\ F2 \end{Bmatrix} = \frac{Nt}{4\pi} a_d K_t (1- e^{\tau D}) \begin{bmatrix} C1 & C2 \\ C3 & C4 \end{bmatrix} \begin{Bmatrix} d1(t) \\ d2(t) \end{Bmatrix} \qquad (21)$$

$$Kd(t) + C\dot{d}(t) + M\ddot{d}(t) = [B(t)]\{d(t)\} \qquad (22)$$

Where [B (t)] is given by

$$[B(t)] = \frac{Nt}{4\pi} a_d K_t [C] \begin{bmatrix} C1 & C2 & \cdots & 0 \\ C3 & C4 & & 0 \\ & \vdots & \ddots & \vdots \\ 0 & & \cdots & 0 \end{bmatrix} \qquad (23)$$

$e^{\tau D}$ is the time delay operator and τ is the time delay period between successive teeth in cut with the work piece . By applying the Laplace transform to the above characteristics equation which yields

$$\{[K] + s[C] + s^2 [M]\}\, d(s) - (1- e^{\tau s})\, [B(s)]\, \{d(s)\} = 0 \qquad (24)$$

The stability of the characteristics equation has been analyzed on s-plane by using the parameters given in the table 4.

Table 2: Parameters used for stability analysis of an End Milling Cutter

1.	Length of the tool L_t (mm)	75
2.	Diameter of the tool d_t (mm)	6
3.	Modulus of Elasticity E (GPa)	200
4.	Poison's ratio ν	0.3
6.	Area of the End Mill Cutter mm^2 A	28.26
7.	Moment of Inertia I mm^4	63.58

VI. ANALYTICAL APPROACH

The transfer function matrix of the eq(24) is given by

$$H(s) = ([K] + s[C] + s^2 [M])^{-1} \qquad (25)$$

Consider the nodal displacement vectors at the previous and present cuts at *t*-τ and *t* are

$\{d\} = \{d_1, d_2, d_3, d_4 \ldots d_n\}^T$
$\{d_0\} = \{d_1(t-\tau), d_2(t-\tau), d_3(t-\tau) \ldots\ldots\ldots\ldots dn(t-\tau)\}^T$
$\{d(s)\} = [H(s)]\{F\}e^{st}$
$\{d_0(s)\} = e^{-st}\{d(s)\}$
$\{\Delta s\} = \{d(s)\} - \{d_o(s)\}$
$= [1- e^{-s\tau}]\, e^{st.}\, [H(s)]\{F\}$ (26)

During machining at successive cuts the phase delay is $\omega_c\tau$ and by replacing the s with jω we get a nontrivial solution if the determinant of the corresponding equation is zero.

$$\{F\} e^{j\omega_c t} = \frac{Nt}{4\pi} a_d K_t [1- e^{-j\omega_c t}] [H(j\omega_c)] \{F\} e^{j\omega_c t}$$

$$\det\{[I] - \frac{Nt}{4\pi} a_d K_t [1- e^{-j\omega_c t}][C][H(j\omega_c)]\} = 0 \qquad (27)$$

From the above equation one gets the Eigen value and it is given by

$$E = - \frac{Nt}{4\pi} a_d K_t [1- e^{-j\omega c\tau}]$$

$$E_r + jE_i = - \frac{Nt}{4\pi} a_d K_t [1- e^{-j\omega c\tau}] \qquad (28)$$

From trigonometric relation $e^{-i\theta} = \cos\theta - j\sin\theta$ and

$c = \cos\omega_c\tau$ and $s = \sin\omega_c\tau$ we get

$$E_r + jE_i = -\frac{Nt}{4\pi} a_d K_t [1-(c - s)] \qquad (29)$$

At the chatter frequency ω_c the critical axial depth of cut can be evaluated by using the analytical expression

$$\dot{a}_{Critical} = -\frac{2\pi}{NtKt}\left(\frac{Er(1-c)+Eis}{1-c} + j\frac{Ei(1-c)-Ers}{1-c}\right) \qquad (30)$$

Imaginary part of the above equation must be zero since the critical axial depth of cut is a real number therefore,

$$\kappa = \frac{Ei}{Er} = \frac{s}{1-c} \qquad (31)$$

$$\dot{a}_{Critical} = -\frac{2\pi Er}{NtKt}(1+\kappa^2) \qquad (32)$$

$$\dot{a}_{Critical} = -\frac{2\pi Er}{NtKt}\left[1+\left(\frac{Ei}{Er}\right)^2\right] \qquad (33)$$

VII. EXPERIMENTAL VALIDATION

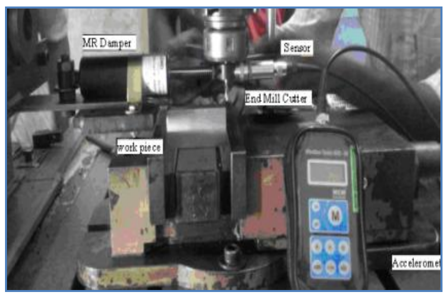

Fig 3: Photographic view of an experimental Setup.

In the present study for experimental work cases considered are a web and "I" structures. This section details the size and shape of each feature and illustrates the different thicknesses. Each studied feature combines to form complex geometric structures such as, boxes, ribs, fins, slots etc. Each thickness and height of the feature in this investigation stays constant and the thickness changes. The approach was to change the thickness of each feature while maintaining a constant length (3 in) and height (1.5 in). Table 4 tabulates a dimensional description of the features and outlines range thickness. The Magnetorheologically control end mill cutter vibration and MR damper is placed allocated with a tight fit of end mill cutter at the eye end of the MR Damper piston as shown in fig 5. The end mill cutter with different diameters of the shank can be placed in the assembly consisting of required of the bearing and the outer recess of the bearing is in tight fit with the holder assembly. The damper is placed on the work piece table at the desired orientation so that it should guide the tool with more flexibility in order to minimize the run out effect, displacement of the cutter from the mean position was measured and for acceleration an accelerometer is employed in the closed vicinity of the end mill cutter , the response of the acceleration and velocity response of end mill cutter and hence then determining the frequency with which end mill cutter displaces the piston rod of MR damper. In order to activate the magnetic field flux along the passage in MR damper, the magnetic coil is supplied with current (I) having frequency equivalent to the frequency of the velocity from the end mill cutter, the response from the End Mill Cutter is in sinusoidal which is given as input to the assembly holder (AH). The energy dissipated by the end mill cutter is absorbed by the MR damper due to which the run out effect, displacement of the end mill cutter can be minimized; The Test's were conducted with different axial depth of cut, spindle speed, feed rate. The displacement of cutter in the axial direction was measured during the machining of the aluminum work piece with 4 flute end mill cutter with different combinations of the machining parameters. Chatter in end milling process leads to inaccurate dimensions, poor surface finish of the work pieces and excessive tool wear. The stability charts are ordinarily made through the detection of the deflection of the tool or displacement of the end mill cutter in the direction perpendicular to the rotational axis of the cutter .The direction of resultant metal cutting force during end milling varies instantaneously due to the presence of periodic directional coefficients. In this present paper the displacement of cutter in the axial direction was measured by an accelerometer under the influence of magneto-rheological damper which is attached to the end mill cutter and coupled with the help of bearing.The inner recess of the bearing rotates with same RPM of the cutter. Machined surface by end cutting edges was also observed in order to judge whether chatter occurred or not.

VIII. CHATTER FREQUENCY MARKS ON WORK PIECE

The chatter marks are observed on work piece and comparison has been observed by incorporating magneto-rheological damper during machining and power spectral analysis has been done at machining conditions. The PSD plots are shown in Fig 8, these plots showed the dissipation of the energy by the magneto-rheological damper by varying the damper input current from 0 Amps to maximum 2 Amps, which absorbs the vibration of cutter during machining and reduces the chatter marks on work piece surface.

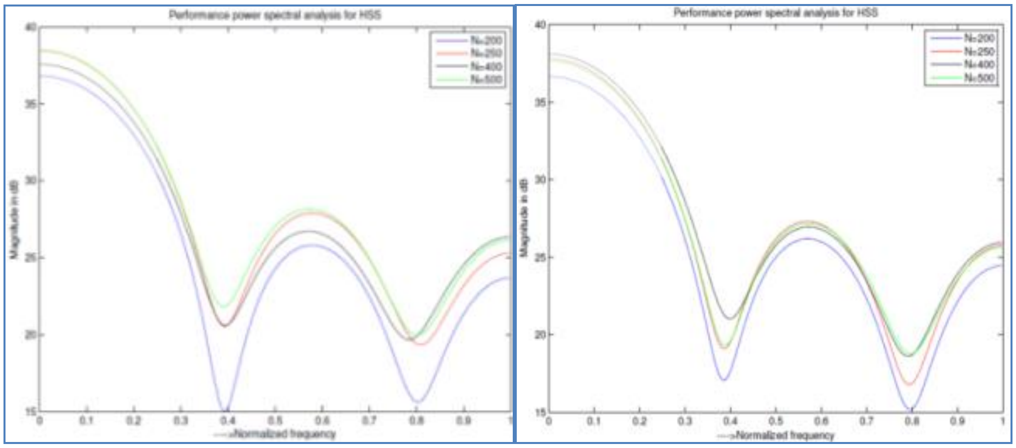

Fig 4: The PSD plots of the displacement of end mill cutter.

The chatter vibration observed on machined profile and therefore, by examining the machined surface the length of the chatter marks is measured at magnification scale in detail. Fig 5 shows the magnification of work piece. The distance of the peak to peak of chatter mark along the path of a metal cutting edge was measured in the photo at the magnification scale. The length, L_{ch} was about 0.70 mm. assuming that the path of a cutting edge was circular which diameter is denoted by d_c , the chatter frequency f_{ch}, is calculated from the following equation,

$$F_{ch} = \left(\frac{\sin^{-1}(L_{ch}/d_c)}{\pi N/60}\right)^{-1} \qquad (34)$$

Where N denotes the spindle speed RPM. We obtain the chatter frequency for the different combinations of the machining parameters a series of 27 experiments conducted and data has been analyzed and it has been found that the chatter frequency increases as the spindle speed and depth of cut increases.

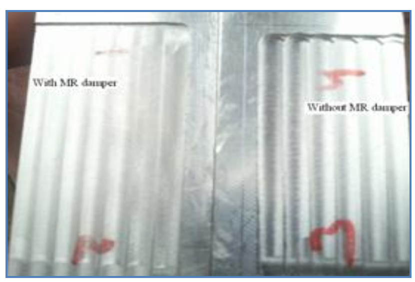

Fig 5: Chatter marks on the machined surface

The acceleration of the spindle head in the axial direction was measured in slotting of aluminum by an accelerometer. Machined surface by end cutting edges was also observed in order to judge whether chatter occurred or not and the largest intensity agreed precisely with the one of the chatter mark along the path of each cutting edge under unstable cutting conditions was available to detect the chatter in slotting process with an end mill.

Table 3: Chatter frequency at different spindle speeds.

Spindle speed RPM	Chatter frequency F_{ch} Hz	Chatter frequency ω_c rad/sec
200	1.823	11.453
300	5.479	34.414
400	10.958	69.122
500	13.698	86.026

IX. CHATTER ANALYSIS USING ROOT LOCUS METHOD

In this subsection, the Root Locus method is presented to analyze chatter instability. The method provides a control engineering perspective of the phenomenon. Equ can be viewed as the characteristic equation of a classical closed loop system with unit feedback, as shown in Fig 6. G(s) $(1 - e^{-sT})$ is the open loop transfer function and K_T is the feedback gain. The closed loop poles follow the corresponding root locus for increasing K_{cut} and the stability limit is reached when at least a couple of conjugate roots cross the imaginary axis.

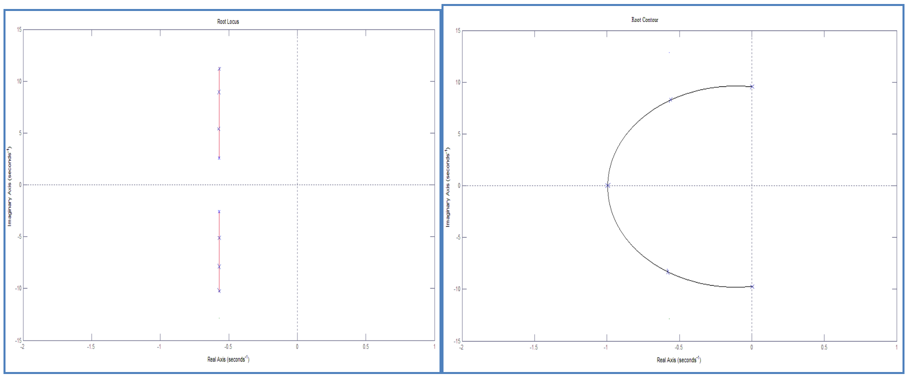

Fig 6: Stability of an end mill cutter with and without damper using roots locus method

The closed loop equation is

$$1+G(s)\,H(s)=0$$

$$(0.54s^2+3.8)\left(1+\frac{cs}{0.54s^2+3.8}\right)=0$$

$$1+\frac{cs}{0.54s^2+3.8}=0 \text{ or } G(S)=\frac{cs}{0.5s^2+3.8} \qquad (35)$$

The characteristic equation is $0.54s^2$+CS+3.8=0For c=0; the poles are $\pm$j2.75 i.e., the poles lie on the imaginary axis. For C>0; the poles lie on the left hand of S-plane i.e., the locus tends towards stability.

X. OPTIMIZATION OF CHATTER STABILITY

In order to increase overall manufacturing output, metal cutting requires higher axial depth of cut and spindle speeds for higher material removal rates along with minimizing tool deflection and reduction in chatter active vibration control has been used in end milling process.

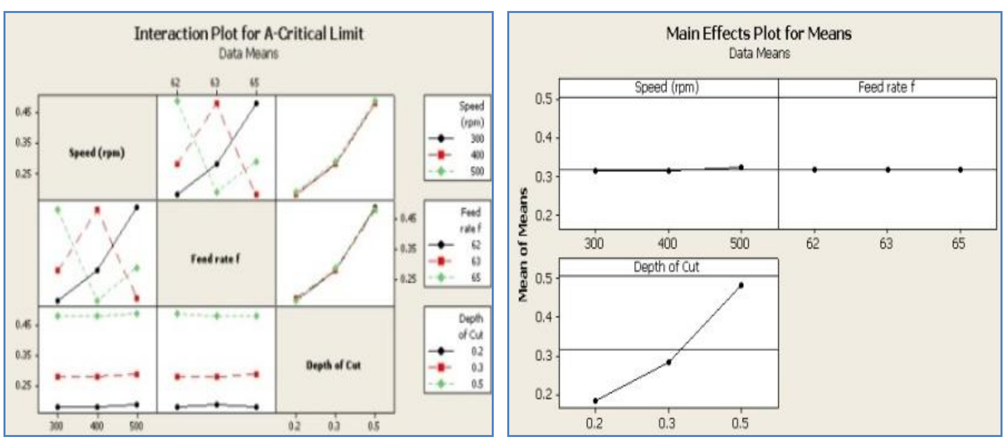

Fig 7: Interaction plots for critical axial depth of cut and Main effects plots for critical axial depth of cut.

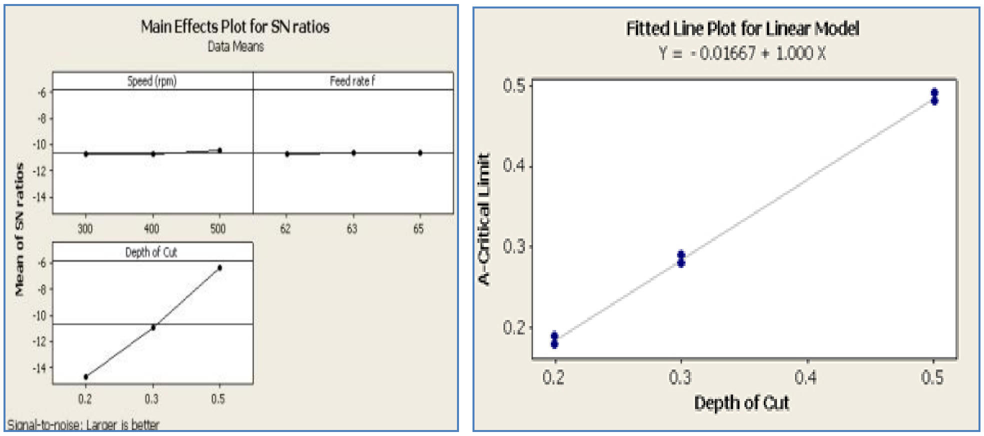

Fig 8: Main Effects plots for S/N ratios and Fitted Line plot for linear model.

Table 4 .Response Table for means

Level	Spindle speed RPM	Feed rate mm/min	Axial depth of cut mm
1	0.3133	0.3167	0.1833
2	0.3133	0.3167	0.2833
3	0.3233	0.3167	0.4833
Delta	0.0100	0.0000	0.3000
Rank	2	3	1

XI. IMPROVEMENT IN STABILITY OF CHATTER

Fig 8. Shows the S/N ratio graph where the horizontal line is the value of the total mean of the S/N ratio. Basically, the larger the S/N ratio, the better is the quality characteristic for the Impact Strength. As per the S/N ratio analysis from graph the levels of parameters to be set for getting optimum value for critical axial depth of cut are A2 B3 $C_{1.}$ According to this, depth of cut was found to be the major factor effecting the critical axial depth of cut(52.76%) whereas speed , feed rate was found to be the Second factor (35.81). the percentage contribution of Current is much lower, being 5%. After observing the Main Effect Plots for S/N ratio and Means we can see that, for improving the critical axial depth of cut (Response) the factor's levels which are giving higher S/N ratio are A2 B3 C1. The Regression analysis has been carried out and it was found that the Axial critical depth of cut is statistically significant that is $p< 0.05$ and percentage of variation in axial critical limit can be accounted by the regression model analysis. It has also been observed that the depth of cut at higher spindle speed increases therefore axial critical limit tends to increase thereby stable during machining.

Table 5: Minitab worksheet results.

Speed (rpm)	Feed rate f	Depth of Cut	A-Critical Limit	SNRA3	PSNRA3	PMEAN3
300	62	0.2	0.18	14.8945	6.05299	0.49
300	63	0.3	0.28	11.0568		
300	65	0.5	0.48	6.37518		
400	62	0.3	0.28	11.0568		
400	63	0.5	0.48	6.37518		
400	65	0.2	0.18	14.8945		
500	62	0.5	0.49	6.19608		
500	63	0.2	0.19	14.4249		
500	65	0.3	0.29	10.752		

Table 6: Comparison of Results and Initial process Parameters

	Initial process parameter	Optimal process parameter	Improvement in S/N ratio (%)	Improvement in Axial critical depth of cut (%)
		Predicted	Predicted	Predicted
Level	A3 B3 C2	A2 B3 C1	10.31	41.97
Axial critical depth of cut	0.35	0.49		
S/N (dB)	5.4594	6.05299		

$$\text{Axial critical depth of cut} = -0.01667 + 1.000*(\text{Depth of cut}) \quad (36)$$

This equation can be used for to predict the axial critical depth of cut for a value of depth of cut or find the settings of depth of cut in order to achieve the desired value or range of values for axial depth of cut.

XII. Results and Discussions

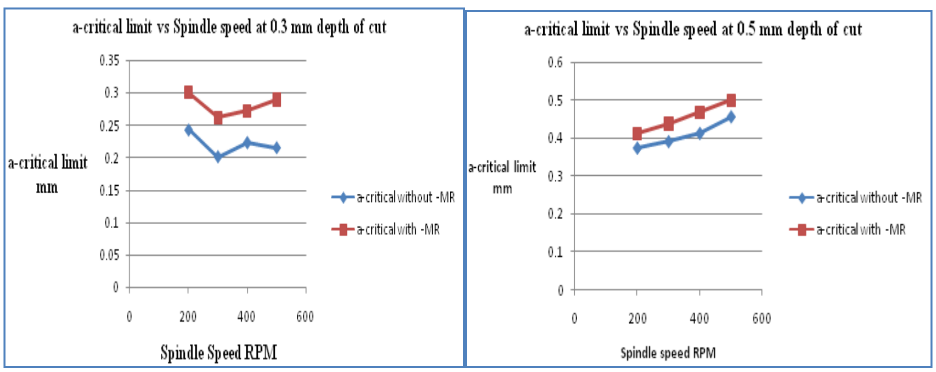

Fig 9: Enhancement of critical axial depth of cut limit at 0.3 mm and 0.5 mm depth of cut with different spindle speeds

XIII. Conclusions

In this paper the chatter in the end milling process is studied experimentally under the influence of magneto rheological damping during end milling operations. This shows the effective capability of the magneto rheological damper to control the vibrations of the cutter and improves the chatter stability and increases the critical axial depth of cut .The experimental results shows that active damping by means of magneto rheological properties of the fluid as a chatter control strategy is also implemented in the setup. It is shown that magneto rheological damping is able to stable end milling operations by raising the critical axial depth of cut and the damping is more effective at higher depths of cut. Therefore damping can be proposed as an effective means for stabilization of chatter in real machining operations. In this paper an attempt has been made to study the effect of magneto rheological damping to reduce the chatter and increase the critical depth of cut during end milling and a comparative study has been done by the application of with and without Magneto rheological damper. This is followed by the experimental validation and optimization of the machining parameters or attaining the desired critical depth of cut. A general rise in the critical axial depth of cut due to active damping is observed for end milling and magneto rheological active damping is found to be more effective and proves to be advantageous.

Nomenclature

Chip thickness t_c^{*}
Helix angle γ_c
Entry angle of the cut θ^1_{entry}
Exit angle of the cut θ^2_{exit}
Average chip thickness $\overline{t_c^{*}}$
Feed rate f_r
Spindle speed N
Number of flutes on cutter N_t

Cutter radius r_c
Tangential cutting force coefficients K_t^c
Radial cutting force coefficients K_r^c
Cutting force along the direction of feed F_x
Cutting force perpendicular to the direction of feed F_y
Axial Depth of Cut d_c
Diameter of End mill cutter d_t
Modulus of Elasticity of the cutter E_t^c
Area of cross section of the cutter A_s
Moment of Inertia I_t^c
Length of the cutter L_c

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