Regenerative Chatter in End Milling on Mould Aluminum Alloys

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Abstract: Milling operation is widely used in the manufacturing industry for the metal cutting purpose. For the efficiency of the milling process, high demands on the material removal rate and the surface generation rate are posed. The process parameters, determining these two rates, are restricted by the occurrence of regenerative chatter. Chatter is an undesired instability phenomenon, which causes both a reduced product quality and rapid tool wear. In this paper, the regenerative chatter are predicted during milling process, based on dedicated experiments on both the material behavior of the workpiece material and the machine dynamics. Then, experiments are performed to estimate these chatter occurrence in practice. These experiments show that both the material properties and the machine dynamics are dependent on the spindle speed. The resultants F-T analysis graphs obtained are compared to each other and being analyzed. Finally, a stable combination of machining parameter (spindle rotation speed and depth of cut) is proposed and applied during milling process in order to reduce the tendency of chatter occurrence. This cross linking between the machining parameter and the subject matter, regenerative chatter occurrence, is exciting to share. This is the primary motivation in pursuing this study.

KEYWORDS: Milling process, Regenerative chatter, Machine dynamics, Stability, Aluminum alloys.

Introduction

The metal removal and cutting process has long being known as one most important and widely used process in manufacturing industry since World War I. In modern cutting technology, milling process has enrolled a play as one of essential metal removal and cutting process in manufactured and fabricating products especially in producing high-precision part and also die and mould machining. The efficiency of machining operation especially milling process is always determined by the material removal rate, tool wear and cycle time. The milling process is most efficient if the material removal rate is as large as possible, while maintaining a high quality level. But, the material removal rate is often limited due to tool wear and failure. Optimizing chip removal will ensure in sacrificing product quality. Chatter occurrence between tool and workpiece are exerts a great influence to this limitation.

The paper contains a practical perspective on regenerative machine tool chatter. As a consequence of this research, a significant factor that contributes for this undesirable chatter occurrence during end milling cutting tools will be determined by using ANOVA. Those results will represent stability information by defining between stable chatter-free region and unstable region. Optimization of material removal rate with less chatter occurrences for aluminum milling operation also can be achieved by varying cutting parameters for instance, depth of cut and spindle speed. Certain combination of spindle speed (rpm) and depth of cut (mm) can introduce stable condition during machining.
Regenerative Chatter and Causes

The milling process is most efficient if the material removal rate is as large as possible, while maintaining a high quality level. In other hand, high material removal rate could cause chatter and vibration during process. Chatter is a well known phenomenon, occurrence of which is undesired in manufacturing. There are two groups of machine tool chatter as accepted in the engineering community; regenerative and nonregenerative. Regenerative chatter occurs due to the undulations on the earlier cut surface, and nonregenerative chatter has to do with mode coupling among the existing modal oscillations. When the dynamic cutting force is out of phase with the surface oscillations, this leads to the development of regenerative chatter. In accordance to Tlusty (2000), states that “Chatter is a self-excited type of vibration that occurs in metal cutting if the chip width is too large with respect to the dynamic stiffness of the system”. As theoretical, self-excited vibration occurs when a steady input of energy in certain condition is modulated into vibration. In lieu, the amplitude of self-excited vibration increases with time (Urmaze, 2002).

Chatter is a complex phenomenon which depends on the design and configuration of both the machine and tooling structures, on workpiece and cutting tool materials, and on machining regimes. Chatter is induced by variations in the cutting forces (caused by changes in the cutting velocity or chip cross section), stick-slip dry friction, built-up edge, metallurgical variations in the workpiece material, and regenerative effects (Stephenson, 2005). This type of vibration is the least desirable vibration because of the structure enters an unstable vibration condition. Figure 1 shows the schematic diagram of unstable self excited vibration.

![Figure 1: Schematic of unstable self excited vibration (Courtesy of D3 Vibration, Inc)](image)

During the milling process, chatter may occur at certain combinations of axial depth-of-cut, \( a_p \) and spindle speed, \( \Omega \). Aggressive machining conditions, in the sense of removing more metal rapidly, usually produce chatter. By increasing cutting speeds, chatter will becomes more significant since the exciting forces approach natural frequencies of the system. Chatter also occurs because the damping of the machine is not sufficient enough to absorb the portion of cutting energy transmitted to the system (ASME Standard, 1992). This is an undesired phenomenon, since the surface of the workpiece becomes wavy and non-smooth as a result of heavy vibrations of the cutter. Into other words, it reduces machined surface quality. Moreover, the cutting tool and machine wear out rapidly and shortened lifespan and a lot of noise is produced when chatter occurs. The vibration also accelerates wear of the spindle, locators, and machine bearings. It also will limit material removal rate which cause low production less than optimal rate.

There is several aspects influence in causing chatter vibration during milling process such as cutting stiffness of tool and work metal; for example steels have a greater tendency to cause a chatter than aluminum. Cutting parameters such as depth of cut, spindle speed, material removal rate MRR etc., and tool geometry: diameter, length, helical angle, number of flute etc. also greatly affect the onset of chatter. However, chatter occurrence may not be easily detected during the runoff stage unless the machine tool is thoroughly tested. In addition, because it is a complex and nonlinear phenomenon, chatter may occur only under certain condition in which frequently can be avoided by finding specified combination of spindle speed and depth of cut during machining. It is often so difficult to overcome chatter, but progress can be made through the proper selection of cutting conditions, improved design of the machine tool structure and spindle, and improved vibration isolation. As regarding to David A. Stephenson (2005) statement, two approaches may be taken to solve chatter problems.
The first is by choosing or changing cutting conditions such as feed, cutting speed, tool geometry, coolant etc., to optimize the material removal rate (MRR) while operating in a stable regime. This is the test cuts approach (that detects and corrects). The second is to analyze the dynamic characteristics of the machining system to determine the stable operating range, and then suggesting improvements to the system design which can extend this range. The second approach is often called as the stability chart method or stability lobes diagram (prediction and avoidance).

Cutting Force as Significant Factor to Onset Chatter Vibration

Cutting force has been recognized as among the significant factors that contribute to the onset of chatter vibration. Excessive metal removal rate will lead in producing high cutting force and thus, act as a trigger to chatter occurrence. The cutting force, $F_c$, acts in the direction of cutting speed, $V$, and supply the energy required for cutting. The thrust force, $F_t$ act in the direction of normal to the cutting velocity, which is perpendicular to the workpiece. Combination of those two kinds of forces will produce the resultant force. Figure 2 illustrated the force acting on the tool in orthogonal cutting method. The resultant force is balanced by an equal and opposite force along a shear plane and is revolved into shear force, $F_s$ and a normal force, $F_n$. These forces can be expressed in equation as:

$$F_s = F_c \cos \theta - F_t \sin \theta$$  \hspace{1cm} (1)

$$F_n = F_c \sin \theta + F_t \cos \theta$$  \hspace{1cm} (2)

The knowledge of the force involved in cutting operation is important because the power requirement must be known to enable the selection of a machine tool with adequate power and as to avoid excessive distortion of the machine element. It is also vital as to maintain the desired dimension tolerances for the finished part, tooling and tool holders and work holding device (Smith, 1991).

Figure 2: Force acting on a tool in two dimensional cutting

Cutting Parameter and Tool Geometry

Both spindle speed, $\Omega$ and axial depth-of-cut, $a_p$ are the importance keys in reducing regenerative chatter in end milling operation. By finding the specific combination of these two parameters, regenerative of waviness during machining can be eliminated. The spindle speed, $N$ for milling is defined as the speed at which the spindle of a milling machine rotates per minute. Spindle speed can be expressed in revolution per minute (RPM) or in surface feet per minute (SFM). Excessive spindle speed will cause premature tool wear, breakages, and can cause tool chatter, all of which can lead to potentially dangerous conditions. Using the correct spindle speed for the material and tools will greatly affect tool life and the quality of the surface finish. One of the most important factors affecting the efficiency of a milling operation is cutting speed. Cutting speed can be determined if spindle speed are known.

$$\text{Cutting speed} = \text{diameter of cutter} \times \pi \times \text{spindle speed}$$

$$V = d \times \pi \times N \text{ (m/min)}$$
If the cutter is run too slowly, valuable time will be wasted, while excessive speed results in loss of time in tool replacing and regrinding cutters. In order to be able to work economically and efficiently, it is important to select the cutting speed best suitable for doing the job. The cutting speed of a metal is defined as the speed in meters per minute at which the metal can be machined efficiently. Its symbol is $V$. It is expressed in meter/min. The selection of cutting speed are depends on the type of material to be machined, type of tool material, rigidity and condition of the machine, and types of cutting operations. Since different types of materials vary in hardness, structure and machinability, different cutting speeds must be used for each type of metal. The cutting speeds for the more common metals are shown below. When starting a new job, use a lower range of cutting speed and then gradually increase to higher range if conditions permit.

Axial depth-of-cut, $a_p$ terms can be defined as depth of cutter tool of the end mill into the part surface axially in which always being expressed in milli, $mm$. In milling operation, it is measured in the $Z$-axis direction. Increasing depth of cut means for maximum material removal rate but as consequence, chatter vibration will occur during machining and then, lead to wavy surface finish and tool failure due to breakage and tool wear. By decreasing depth of cut, time and cost consumption for machining process will be multiple even three times, thus cause low production less than optimal rate.

In accordance to ASM Machining Handbook, feed rate, $f$ can expressed as the rate at which the workpiece moves past the cutter or vice versa in milli per minute (mm/min) or in milli per tooth (mm/tooth). For the highest efficiency of metal removal and the least susceptibility to chatter, the feed rate should be high as possible in any milling operation. However, several factors influence and limiting the rate of feed in which is type of cutter, number of teeth, cutter material, work metal composition and hardness, depth-of-cut, speed, rigidity of setup and available power. Tool geometry also affects the percentage of chatter occurrence in milling operation. Usage of different number of flute, diameter of cutter tools, rake angle, overall length always gives a greater influence to chatter during machining.

Experimental Procedures

In this project, milling process will be executed on mould Aluminum 6061-T651 workpiece by using 16mm in diameter flat end mill with different number of flute. The conditions lead to chatter vibration occurrence which causes tool wear, rough and wavy surface finish, and spindle failure will be predicted using Force Dynamometer. In process to determine work and tools material, and suitable cutting method, a lot of decision making and critical- thinking has been involved. Example, there have a lot of argument whether to use plain Aluminum Alloy 2014-O or heat-tempered Aluminum 6061-T651 as work material. By doing some consideration on both material properties and characteristics, we have decided in using Aluminum 6061-T651 after regarding to its better mechanical properties, higher hardness (more than 95 HB) and better demands in industry market especially in high-precision automotive industry. In other words, regarding to its high demanding in producing high-precision parts such as automotive parts, industry machinists and researchers gained most benefit from the outcomes of this projects.

As for the cutter tools material, High-speed tool steel (HSS) have become among the premier choices beside Solid Carbide and Coated Carbide cutter tools. Even though both Solid and Coated Carbide have better hardness and can undergo higher cutting speed and material removal rate without fracture, but HSS cutter tools are more effective due to high resistance to softening effects of heat in which they are capable to attain a high hardness at elevated temperature. Moreover, HSS have a less distortion in heat treatment and also, they are less expensive if compared on prices with both Carbide cutter tools. The preferred method of milling operation for our experiment is slot milling. Research will be carried on using Conventional Milling machine FU-251, so we do not require developing any G-codes and NC program for machining job setup.

Referring to Hermann Jütz (1998), the cutting speeds for Aluminum alloys are in ranges from 60m/min - 100m/min for general purpose milling operation. So, we have decided on using 62.83m/min, 80.43m/min and 100.53m/min as our variable parameters. Since spindle speed, $N$ can be obtained by using $V = \frac{d \times \pi \times N}{60}$, for each cutting speed mention above, the approximate values of spindle speed rpm are 1250rpm, 1600rpm, and

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respectively. The reason in selecting notified cutting speed are because these three high spindle speeds are the only speed available in operating Universal Milling Machine FU-251. For feed rate, \( f \), we have decided to leave it as a constant parameter in which the value of feed rate for standard end milling operation is \( f = 125\text{mm/min} \). We have also varying the axial depth of cut, \( a_p \) as variable parameters in which this parameter will be used (with function to spindle speed) in developing stability lobes diagram (SLD). In this experiment, we have agreed to machine work material under five different depth of cut which the \( a_p \) values are 0.2mm, 0.4mm, 0.6mm, 0.8mm, and 1.0mm. So, that means workpieces will undergo milling operation in five different depth of cut, \( a_p \) under same feed rate, \( f \) for each variation of spindle speed, \( N \) which make there are approximately 30 experiments altogether.

**Machining Process**

After gathering all the relevant information, the project undergoes a process in preparing mould aluminum work material. In this phase, band saw machine have been utilized for this purposed to cut a billet of Aluminum 6061-T651 into 3 pieces with dimension 100x100x30mm each. As consequence in using band saw machine for workpiece cutting purpose, surfaces of finished products have become wavy and rough. Therefore, in order to obtained more precise result of chatter vibration during milling operation later, all 3 workpieces will have to undergo one more machining process; face milling in purpose to get rid rough and wavy surface and thus, produced a better surface finish. Since workpieces need to be mounted onto the force dynamometer, drilling process are compulsory to create holes for fastening purpose. After that, the progress will proceed into most important level which is machining process. At first, workpieces undergoes slot milling with specific combination of spindle speed and axial depth of cut using 2 flute flat endmill cutter tools. For this process, we have agreed to use standard Universal Milling - FU251 as our preferred machine due to its dynamic stability and rigidity. In purpose to study regenerative chatter occurrence during machining and thus obtaining result value and graphical data, workpieces will be mounted on force dynamometer which has been clamped on milling worktable. Before starting the machining process, workpiece need to go through face milling once again; purposed as to ensure a parallel contact between cutter tools and surface will be formed in experiment later on. After that, machining process will be carried out via using end-to-end slotting method and data will be collected by dynamometer. Experiment procedures then are repeated by using 4 flute cutter tools.

**Results and Discussion**

The cutting force data obtained from previous machining process will be used in determining significant factors which have the greatest tendency to onset the chatter vibration. This task will be done by using ANOVA method. Repetition of experiment is optional if the data achieved from machining seems to be irrelevant and unrealistic to the vibration theory. Several charts will be developing as a consequence from this analysis. Then, from the diagrams, we will be able to find specific combination of both axial depth-of-cut and spindle speed for optimum performance of end milling machining. With regard to prior result analysis, a final discussion will be carried on. In this discussion, we will determine which parameters have a greatest tendency to onset the regenerative chatter and which numbers of flute will have a highest percentage of vibration occurrences. The analysis concluded from experiment will be used for chatter prediction and avoidance.

The results gained from force dynamometer came in four different outputs which is cutting force in x, y and z-direction (\( F_x \), \( F_y \), \( F_z \)) and moment in z-direction (\( M_z \)). However, only a cutting force in x-axis, \( F_x \) and y-axis, \( F_y \) will be considered to be analyzing as these two functions enrolled the major part in causing the regenerative chatter. By using Kistler® Dynoware, the x-axis and y-axis force reading for milling is gather and being converted directly into force-time graphical figure where it is much better to understand compared to the raw data obtained. Then, a mean value of each graph is taken as these data will be used in identifying significant factor in chatter occurrence. Analysis of variance (ANOVA) method has been selected as main medium to find the significant factor in chatter occurrence.
Table 1: x-directional Cutting Forces

<table>
<thead>
<tr>
<th>Source</th>
<th>Degree of freedom</th>
<th>Sum of squares (Q)</th>
<th>Variance (s²)</th>
<th>F-ratio (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of cut</td>
<td>4</td>
<td>2536.81</td>
<td>634.20</td>
<td>16.58</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>2</td>
<td>246.17</td>
<td>123.09</td>
<td>3.22</td>
</tr>
<tr>
<td>Flute</td>
<td>1</td>
<td>1.80</td>
<td>1.80</td>
<td>0.05</td>
</tr>
<tr>
<td>Residual Error</td>
<td>22</td>
<td>841.73</td>
<td>38.26</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>3626.51</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based from table, the F-ratio for each source is list as;

\[ F_{dc} = 16.58 \]
\[ F_{cp} = 3.22 \]
\[ F_f = 0.05 \]

Referring to the table for F Values in the appendix, the critical value of F-distribution is;

\[ F_{dc} (0.05; 4; 22) = 2.87 \]
\[ F_{cp} (0.05; 2; 22) = 3.44 \]
\[ F_f (0.05; 1; 22) = 4.3 \]

\[ F_{dc} > F_{dc} \] * significant (depth of cut as a core factor develop cutting force)
\[ F_{cp} < F_{cp} \] * insignificant
\[ F_f < F_f \] * insignificant

Table 2: y-directional Cutting Forces

<table>
<thead>
<tr>
<th>Source</th>
<th>Degree of freedom</th>
<th>Sum of squares (Q)</th>
<th>Variance (s²)</th>
<th>F-ratio (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of cut</td>
<td>4</td>
<td>6215.09</td>
<td>1553.77</td>
<td>19.01</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>2</td>
<td>948.91</td>
<td>474.45</td>
<td>5.80</td>
</tr>
<tr>
<td>Flute</td>
<td>1</td>
<td>6.66</td>
<td>6.66</td>
<td>0.08</td>
</tr>
<tr>
<td>Residual Error</td>
<td>22</td>
<td>1798.31</td>
<td>81.74</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>8968.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based from table, the F-ratio for each source is list as;

\[ F_{dc} = 19.01 \]
\[ F_{cp} = 5.80 \]
\[ F_f = 0.08 \]

Referring to the table for F Values in the appendix, the critical value of F-distribution is;

\[ F_{dc} (0.05; 4; 22) = 2.87 \]
\[ F_{cp} (0.05; 2; 22) = 3.44 \]
\[ F_f (0.05; 1; 22) = 4.3 \]

\[ F_{dc} > F_{dc} \] * significant (depth of cut as a core factor develop cutting force)
\[ F_{cp} < F_{cp} \] * significant (cutting speed as a core factor develop cutting force)
\[ F_f < F_f \] * insignificant
With regard to ANOVA Tables above, the process in identifying significant and insignificant parameters is done with ease. On the other hand, this significant parameter is not constant; it turns to be differing for each type of forces. For cutting force in x-direction \( (F_x) \), the significant factor was the depth of cut only. As for cutting force in y-direction \( (F_y) \), depth of cut and cutting speed have been the significant parameters contributed to cutting force while number of flute was insignificant for both of cutting forces. Several deductions have been made from those finding results. These explain that in every direction of forces has its own significant and insignificant factor that enrolled a major play in producing cutting forces, even though all forces above was originate from the same cutting force. But, still every parameter involved have it very own role even these parameters are quite insignificant to the cutting forces. Referring to the ANOVA Table for x-direction cutting force, the difference between \( F_{cp} \) \( (F\)-ratio) and \( F_{tcp} \) (critical value for F-distribution) for cutting speed, \( v \) are quite small which indicates that cutting speed is still play it roles even though it is insignificant for cutting force development. Only when in y-direction cutting force, cutting speed together with depth of cut became a core yet significant parameter contributed in producing cutting force.

For flute parameter, in accordance to the previous research by Faasen, it does becoming a significant parameter but only took a count in z-axis direction. This is because only in z-axis direction, flutes do affect so much in producing cutting force when cutter tools came in contact with workpiece surface. In the other words, the number of flute still becomes a large consideration while selecting a cutter tools, depends on the type of machining either roughing or finishing, pocketing or contouring. According to the discussion above, the most contributing factor was the depth of cut and follow by the cutting speed. Thus, it support the vibration theory and the preliminary finding indicating that the increase of cutting forces are proportional with the increase of cutting speed, axial and radial depth. As have been stated in previous discussion, depth of cut had become the most significant factor, giving the greatest tendency to onset the chatter vibration. The depth of cut is the main parameter relative to chatter vibrations: selecting a spindle speed and increasing the depth of cut, a limit is found when these vibrations start with the characteristic sound and workpiece surface marks.

Based on the Figure 3, the highest cutting force in x-direction, \( F_x \) happened when the depth of cut was 1.0mm using 2-flute HSS end mill at the cutting speed 62.83m/min. Meanwhile, the lowest cutting force gained when the depth of cut was 0.2, using 4 flute cutting tool at the speed of 80.42m/min. As illustrated in the graph, a clear formation of pattern can be seen through all of the setting. It obviously showed that the increasing of cutting force is proportional to the increase of depth of cut, even though at the 0.6mm depth of cut, the graph showed a slightly drop in cutting force \( F_x \). The similar pattern also formed in the y-direction cutting force, \( F_y \) (Figure 4) in which obviously proved the statement above. From the very own understanding, it can be deduced that the ideal depth of cut for all three type of cutting speed is 0.6mm depth of cut. An optimization of chip removal rate with less chatter occurrence can be achieved at this specific depth of cut.

![Figure 3: Cutting Force in x-direction versus depth-of-cut](image-url)
Figures 5 and 6 specified that for most of the cutting speed and depth of cut, 4-flute cutter tools produced less cutting forces if being compared to 2-flute cutter tools. The slotting method that has been utilized in this research influenced a lot to the occurrence of this phenomenon. This finding proved that the 4-flute cutter tools performed better for most of milling method. However, 4-flute cutter tools do have a limitation of usage. Four flute end mills only cut on their periphery and can plunge cut when a starting hole is pre-drilled. It differs with 2-flute cutter tools capability in plunging and starts their own holes. Two-flute end mills features allow maximum space for chip ejection but as tradeoffs, possibility of chatter occurrence for 2-flute end mills are among the highest.
Conclusion

The following conclusion can be drawn from the present study:

(i) Cutting force increased with increasing feed rate, cutting speed and depth of cut.

(ii) The most significant factor for the producing cutting forces in x-direction is the depth-of-cut. As for force in y-direction, significant factors are the depth-of-cut and cutting speed. Number of flutes only influenced a lot in producing z-direction cutting force.

(iii) From the plotted graph, it can be concluded that for the most of cutting speeds recommended, the ideal setting of depth-of-cut is at 0.6 mm.

(iv) 4-flute cutter tools performed better than 2-flute for most of milling method.

By applying these results in aluminum milling operation, one can even predict and avoid chatter occurrence and thus, elongates the tool lifespan and increased the production rate with less distortion.

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