REGENERATIVE CHATTER IN END MILLING ON MOULD ALUMINUM VIA EXPERIMENTAL

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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.

ABSTRAK

Operasi milling banyak dilaksanakan secara meluas dalam industri pembuatan bagi tujuan pemotongan bahan logam. Untuk proses milling yang berkesan, permintaan yang tinggi kepada kadar pemotongan bahan dan permukaan adalah diperlukan. Namun begitu, parameter-parameter ini terutamanya kadar pemotongan bahan adalah terhad terhadap terjadinya getaran. Getaran adalah fenomena yang tidak dikehendaki, menyebabkan terhasilnya produk yang berkualiti rendah dan menghauskan mata alat dengan cepat. Dalam kajian ini, getaran diramal dalam proses milling, dengan cara melaksanakan eksperimen mengkaji ke atas sifat-sifat bahan dan mata alat serta kedinamikaan mesin. Kemudian, eksperimen dilakukan bagi menganggar sifat getaran ini secara praktikal. Semua eksperimen ini membuktikan bahawa kedua-dua sifat bahan dan kedinamikaan mesin adalah bergantung kepada halaju spindle. Graf F-T analisis yang diperolehi kemudiannya akan dibanding antara satu sama lain dan dianalisis. Dan akhirnya, kombinasi parameter mesin yang stabil (halaju spindle dan kedalaman pemotongan) akan diperkenalkan dan dilaksanakan dalam proses milling bagi tujuan mengurangkan kadar peratusan berlakunya getaran ini. Kaitan yang terdapat di antara paramater mesin dan kemungkinan berlaku getaran adalah sangat menakjubkan untuk dikongsi bersama. Inilah antara tujuan yang menjadi motivasi bagi meneruskan kajian ini.

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CHAPTER 1

INTRODUCTION

1.1. Project Background

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.

1.2. Project Title

Regenerative Chatter in End Milling On Mould Aluminum via Experimental

1.3. Problem Statement

1. Unstable chatter vibration occurrences due to interaction of end mill cutter tool and workpiece in end milling.
2. Higher percentage of chatter vibration in end milling process as a function to increase metal removal rate.

1.4. Defined Questions

1. How to predict regenerative chatter by vary cutting parameters and tools geometry?
2. Can stability lobes diagrams used as guidance to have high metal removal rate with low percentage of vibration produce?

1.5. Objectives Of Research

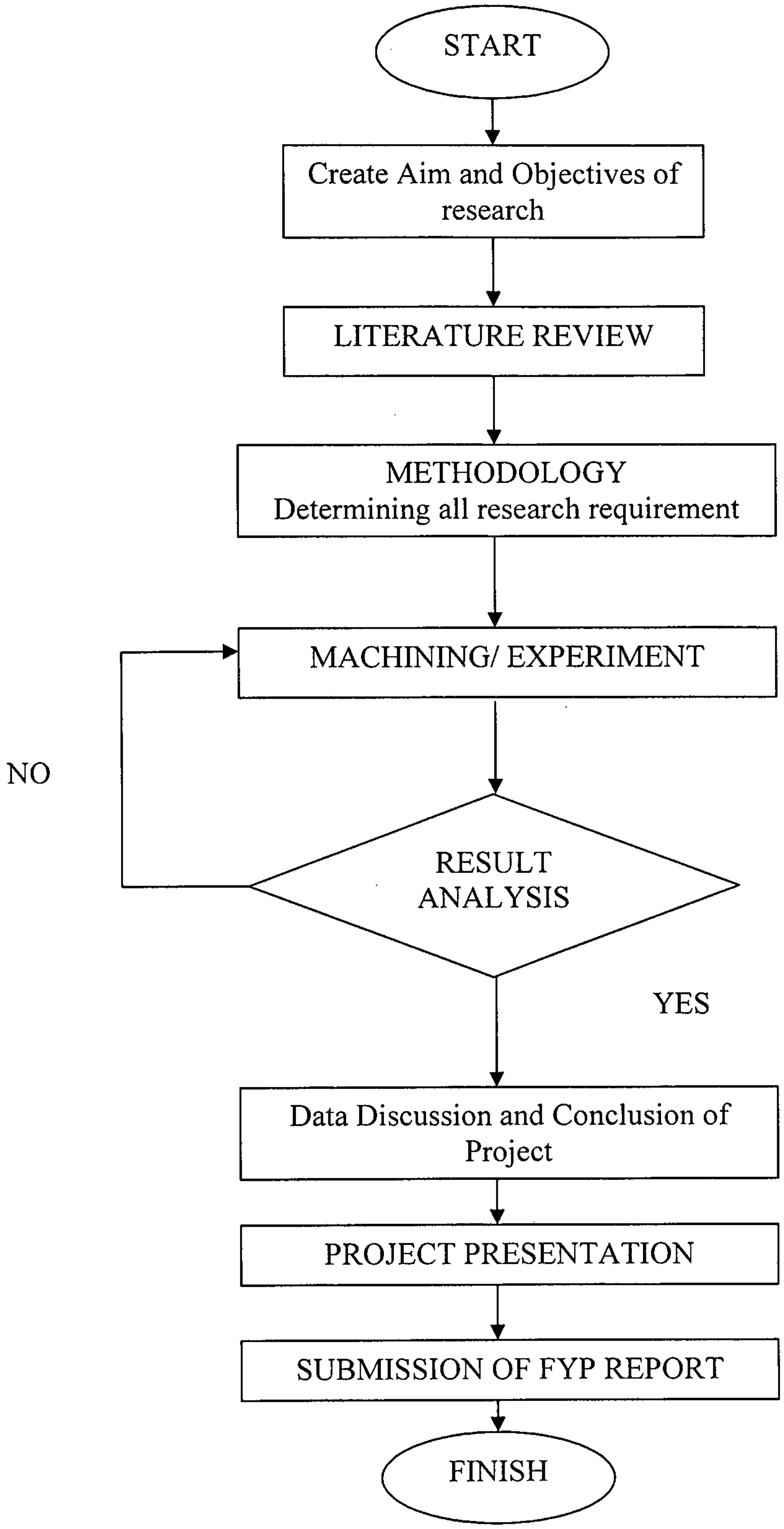
1. To investigate regenerative chatter occurrence of end milling machining via experimental in term of cutting forces.
2. To predict the most significant parameters between spindle speeds, depth of cut and number of flutes which contribute to occurrence of regenerative chatter during end milling machining on mould aluminum.
3. To determine specific combinations of cutting parameters for optimum performance of end milling machining on mould aluminum.

1.6. Scopes

In order to achieve the objectives notified earlier, the following scopes have been identified:

1. Predict regenerative chatter of end milling operation on heat-tempered Aluminum 6061-T651 mould.
2. Study regenerative chatter of end milling operation via experimental in which using Kistler® force Dynamometer to obtain result value and Force-Time graphical data during machining operation.
3. Optimize regenerative chatter of end milling operation by using 16mm in diameter High Speed Steel cutter tools (HSS) with different number of flutes.
4. Determine optimum performance of milling operation on mould aluminum by vary machining parameter namely, cutting speed, Ω and depth of cut, a_p.

1.7. Project Flow Chart



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The metal cutting technology growth rapidly and has enrolled as important aspect in manufacturing industry especially for the aerospace industry and also in producing high precision part. In modern cutting technology, the trend continues unabated toward higher availability with more flexibility. Milling is the most important and widely useful operation process for material removal compared to turning, grinding and drilling. Milling can be defined as machining process in which metal is removed by a rotating multiple-tooth cutter with each tooth removes small amount of metal in each revolution of the spindle. Because both workpiece and cutter can be moved in more than one direction at the same time, surfaces having almost any orientation can be machined. In accordance to Denis R. Cormier (2005), milling is metal removal machining process for generate machined surface by removing a predetermined amount of material progressively from the specimen. In milling process, a milling cutter is held in a rotating spindle, while the workpiece clamped in the table is linearly moved toward the cutter (Y. Altintas, 2000). A schematic representation of milling process is shown in Figure 2.1

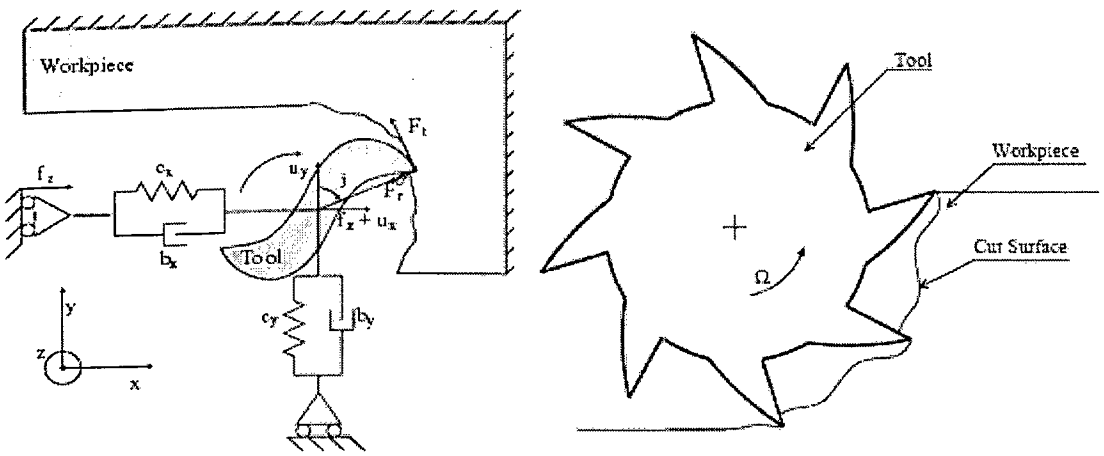


Figure 2.1: schematic representation of milling process (Y. Altintas, 2000)

2.2 Application of High-Speed Machining

The term High-Speed Machining (HSM) commonly refers to end milling at high rotational speeds and high surface feeds. HSM has been applied to a wide range of metallic and non-metallic materials, including the production of components with specific surface topography requirements and machining of materials with hardness of 50 HB and above. With regard to attainable cutting speeds, it is suggested that the term HSM is standing for operating at cutting speeds significantly higher than those typically utilized for a particular material. The figure below indicated the attainable speeds in the machining of various materials.

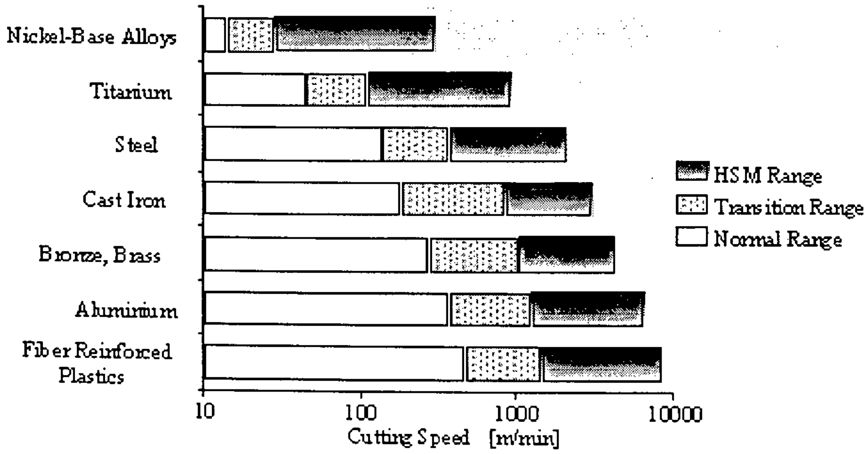


Figure 2.2: Attainable speeds in the machining of various materials

But in practical definition, HSM is not simply high cutting speed. It should be regarded as a process where the operations are performed with very specific methods and production equipment. HSM is also not necessarily high spindle speed machining. Many HSM applications are performed with moderate spindle speeds and large sized cutters.

There are several factors for choosing High-speed Machining (HSM). The ever-increasing competition on the marketplace is setting new standards all the time. The demands on time and cost efficiency are getting higher and higher, forcing the development of new processes and production techniques to take place. HSM usage will guaranteed in time saving nonetheless provide much in product quality and quantity compared to conventional milling operation. The other factor is the development of new; more difficult to machine materials which has underlined the necessity to find new machining solutions. The die and mold industry mainly has to face the problem of machining highly hardened tool steels, from roughing to finishing. With regard to this problem, HSM has technically proved a better performance in finishing in hardened steel with high speeds and feeds, often with 4-6 times conventional cutting data. On the other hand, high-speed machining is a potentially unstable system, where the forces generated by the cutting process are coupled to the dynamic behavior (stiffness, damping, and inertia) of the machine structure, tool, and workpiece (Sims, 2004). A common form of instability during machining, known as *regenerative chatter*, is due to the generation of surface waviness which modulates the cutting force.

2.3 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). Figure below indicate plots of amplitude versus time for self-excited vibration.

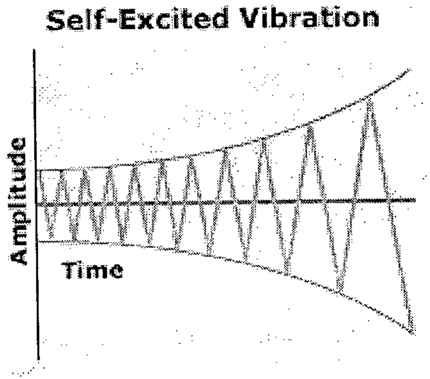


Figure 2.3: Graph amplitude vs. time for self-excited vibration

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 (David A. Stephenson, 2005). The characteristic features of self-excited vibrations are: (a) the amplitude increases with time, until a stable limiting value is attained; (b) the frequency of the vibration approximately equal to natural frequency of the system; and (c) the energy supporting the vibration is obtained from steady internal source. This is indicated by the control loop schematics in Figure 2.4. This type of vibration is the least desirable vibration because of the structure enters an unstable vibration condition.

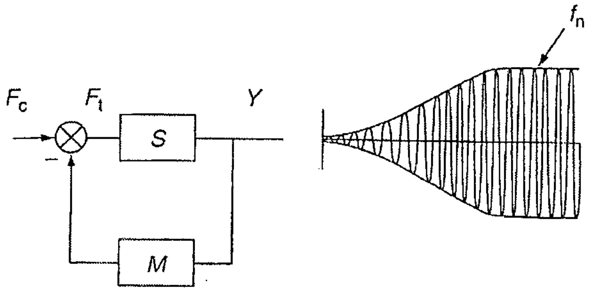


Figure 2.4: schematic of unstable self excited vibration (Courtesy of D3 Vibration, Inc)

During the milling process, chatter may occur at certain combinations of axial depth-of-cut, a_p and spindle speed, Ω. 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 them 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).

2.4 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, Fc, acts in the direction of cutting speed, V, and supply the energy required for cutting. The thrust force, Ft 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 2.5 illustrated the force acting on the tool in orthogonal cutting method.

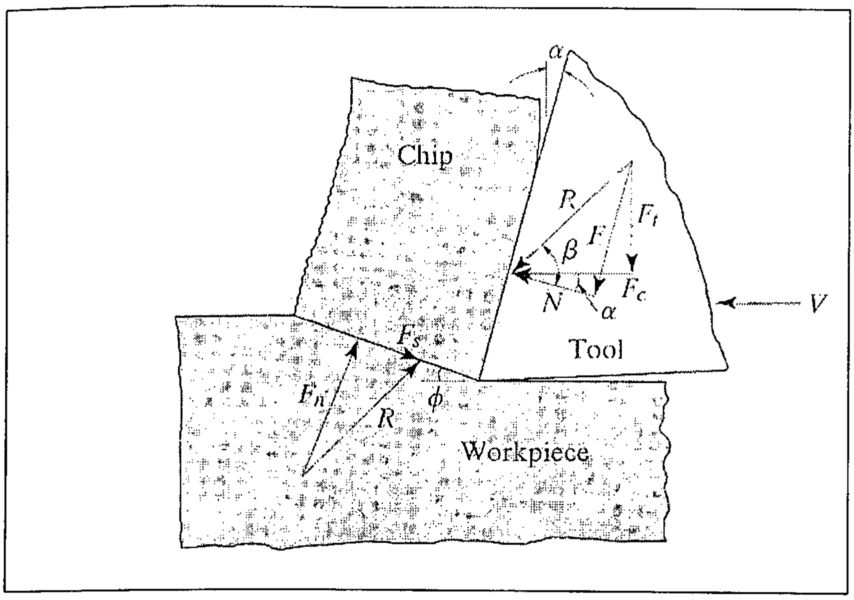


Figure 2.5: Force acting on a tool in two dimensional cutting

The resultant force is balanced by an equal and opposite force along a shear plane and is revolved into shear force, Fs and a normal force, Fn. These forces can be expressed in equation as:

$$Fs = Fc \cos \emptyset - Ft \sin \emptyset \quad (2.1)$$

$$Fn = Fc \sin \emptyset + Ft \cos \emptyset \quad (2.2)$$

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).

2.5 Type of Cutter Tool

The important tasks of cutting tools are to resist extreme heat, high pressure, abrasion and shock. Temperatures at the cutting edge can exceed till 982.2 °C. Extreme heat degrades binders and other tool constituents, and can also trigger detrimental chemical reactions between the tool and workpiece. Abrasion is always part of the cutting process. While in the cut, the tool is in constant contact with the workpiece, under pressures greater than 2,000 psi. (Johnson, 2003)

High Speed Steel (HSS) is a baseline tool steel. It is used for many basic machining applications and is useful for very short runs on older milling machines. High speed- tool steels are so named primarily because of their ability to machine materials at high cutting speeds. According to the American Iron and Steel Institute (AISI), there are presently more than 40 individual classifications of high speed-tool steels which can be divided into two main types, Molybdenum (M-series) and Tungsten (T-series). They are complex iron-base alloys of carbon, chromium, vanadium, molybdenum, or tungsten, or combinations of both, and in some cases substantial amounts of cobalt. The carbon and alloy contents are balanced at levels to give high attainable hardening response, high wear resistance, high resistance to the softening effect of heat, and good toughness for effective use in industrial cutting operations. The M-series steels are often used in machining industry because generally have higher abrasion resistance than the T series steels and less distortion in heat treatment, also the price are less expensive to compare with. For workpieces made from hardened materials (over 300 HB), a grade such as T15, M42, or M33 is more effective than general-purpose high speed tool steels M1, M2, M7 and M10. Increased cutting speeds can be used with these high speed tool steels because of their improved hot hardness which is the ability to retain high hardness at elevated temperatures.

2.6 Cutting Parameter and Tool Geometry

Both spindle speed, **Ω** 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.

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

$$V = d \times \pi \times N \quad (\text{m/min})$$

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.

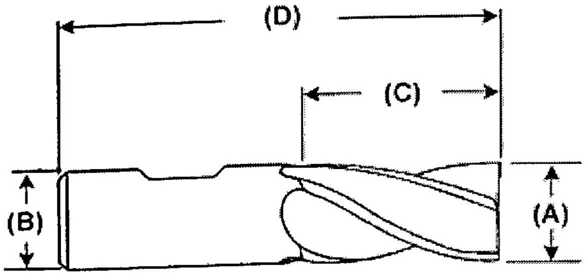
Table 2.1: Cutting speed for HSS and Carbide cutter tool

Material type	**meters per min**	**feet per min**
Steel (tough)	15 - 18	50 - 60
Mild steel	30-38	100-125
Cast iron (medium)	18-24	60-80
Bronzes	24-45	80-150
Brass (soft)	45-60	150-200
Aluminum	75-105	250-350

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, dia of cutter tools, rake angle, overall length always gives a greater influence to chatter during machining. End mill cutter tool can be defined as in design figure shown below.



A - Mill size or cutting dia
B - shank diameter
C - length of cut or flute length
D - overall length

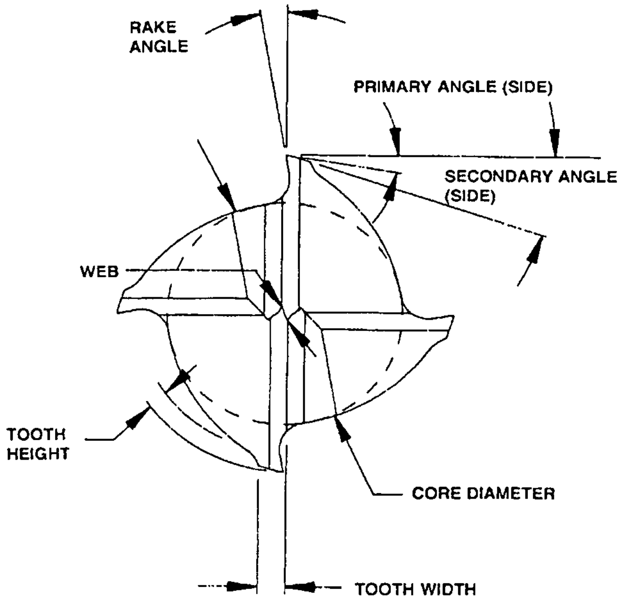


Figure 2.6: Design Criteria of End Mill Cutter tool

Flute is the space for chip flow between the teeth. Flute also can be recognized as spiral cutting edge on the end mill. Different number of flute means for different purpose of metal removing work. Two flute end mills usually being used for plunge cutting. They are also called center cutting because they can start their own hole. It allows maximum space for chip ejection but as tradeoffs, possibility of chatter occurrence for two flute end mills are among the highest. Three flute end mills are specially design for slotting task which provide an acceptable surface finish. Four flute end mills only cut on their periphery and can plunge cut when a starting hole is pre-drilled. They are generally stronger than a two or three flute end mill, therefore allowing for increased feed rates.

They also provide a better surface finish compare to less number of flute tools. In theoretical principles, with the same feed rate and depth of cut, four flute end mills have the lowest percentage for chatter to happen during machining due to its dynamic stability and rigidity.

2.7 Stability Lobes Diagram

Regenerative chatter have been studies since late 1950's by Tobias & Fishwick, Tlusty & Polacek, Merrit, and Altintas and led to the development of stability lobe diagrams (SLD) which is outmost important for chatter prediction and avoidance. The machined quality level is often associated with a stability lobes diagram, which defines regions of stable and unstable cutting zones as a function of depth of cut and spindle speed. The diagrams are usually plotted as axial depth of cut, a_p versus cutting speed, Ω (R.P.H. Faassen, 2003).Example of present research, Lacerda & Lima, 2004 has plotted stability lobes diagram of Steel and iron material under face milling condition based on chatter prediction modeled by Altintas, 2000. Budak and Altintas developed a stability lobe algorithm for two-dimensional coupled systems and validated the model for a range of conditions. With these diagrams, it is possible for machinists and engineers to use as a guideline for finding certain combination of cutting speed and depth of cut which result in maximum chatter-free material removal rate (MRR). The plot included below (Figure 2.7) is from the Faassen and A. Ganguli which applies to a modeled high-speed milling operation. Below the curve is a region of predicted stable cutting and above is the unstable cutting domain where chatter highly possible can occur. The lobed borderline of stability is the exact line which separated between stable and unstable region.

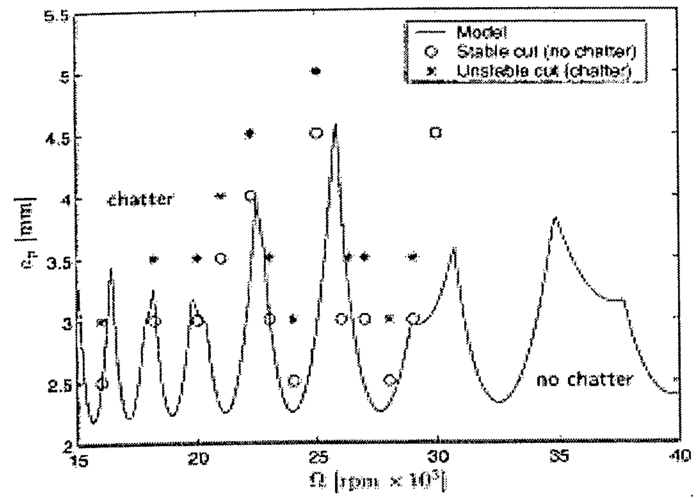


Figure 2.7.1: Modeled stability lobes diagram of milling operation by Faasen (2003)

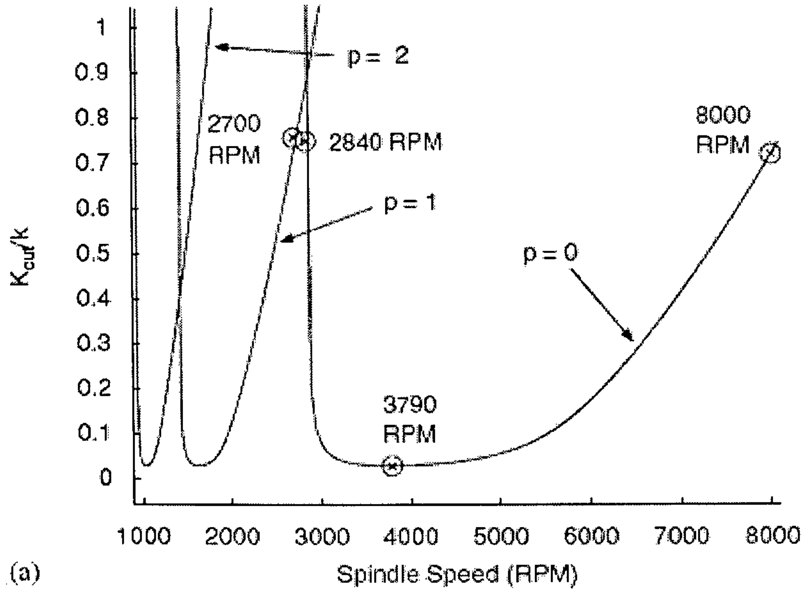


Figure 2.7.2: Modeled stability lobes diagram of milling operation by Ganguli (2006)

The effects of the cutting parameters on stability lobes diagram are as follows: (a) the limit of stability is controlled by the axial depth of cut in milling; (b) the axial depth of cut is affected by the number of teeth in the cut; (c) the axial depth of cut decreased with increasing of work material hardness; and (d) the spindle rpm, N, and the number of teeth in cutter affect the stability lobes and the selection of depth of cut.