EXPERIMENTAL VALIDATION FOR CHATTER STABILITY PREDICTION

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Report submitted in partial fulfillment of the requirements
for the award of Bachelor of Mechanical Engineering.

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JUNE 2012

ABSTRACT

This research focused on the experimental validation for chatter stability prediction. An optimum machining was aimed to maximize the material removal rate, whilst maintaining a sufficient stability margin to assure the surface quality. High material removal rate in machining produced self-excited vibration or chatter of the cutting tool and the workpiece. This resulted in a poor surface finish and dimensional accuracy, chipping of the cutter teeth, and also may damage the workpiece as well as machining tool. Frequency response function of a single degree freedom flexural was measured and the cutting stiffness of tools were determined in order to be used in predicting chatter stability using semi discretization method. The aluminium 7075 specimens were used in the milling cutting experiment to validate the chatter stability diagram of mill uniform and variable cutters, where a set of spindle speed and depth of cut had tested. The vibration conditions of machining were identified by analysing the vibration signals and FFT spectrum whether it was stable or in a chatter condition. There are good agreement between predicted stability and cutting experiment for the down-milling operation using uniform 4 flute cutting tool. Stable conditions were shown outside the boundary of chatter region. The optimized cutting tool was predicted to suppress chatter. Machining experiment tests showed there were no chatter vibration conditions during machining process until 1.5 mm depth of cut. According to the results of machining experiment, it was proven that the variable tool had more capability to machining without producing chatter vibration as compared to the regular tool.

ABSTRAK

Penyelidikan ini adalah berkenaan eksperimen pengesahan untuk ramalan kestabilan keterujaan getaran. Sasaran pengoptimuman pemesinan adalah untuk memaksimumkan kadar penyingkiran bahan, pada masa yang sama mengekalkan margin kestabilan untuk memastikan kualiti permukaan. Kadar penyingkiran bahan yang tinggi dalam pemesinan menghasilkan keterujaan getaran oleh alat pemotong dan bahan kerja. Hal ini seterusnya menyebabkan kemasan permukaan dan ketepatan dimensi yang rendah, mengumpil gigi alat memotong, dan boleh merosakkan bahan kerja serta alat pemesinan. Fungsi respon frekuensi bagi struktur fleksibel satu darjah kebebasan telah diukur dan kekukuhan pemotongan bagi alatan pemotong telah ditentukan untuk diaplikasikan dalam meramal kestabilan keterujaan getaran menggunakan kaedah pendiskretan separuh. Spesimen aluminium 7075 digunakan dalam eksperimen pemotongan *milling* untuk mengesahkan rajah kestabilan keterujaan getaran bagi alat pemotong seragam dan berubah-ubah, di mana suatu set kelajuan pengumpar dan kedalaman pemotongan telah diuji. Keadaan getaran pemesinan telah dikenalpasti dengan menganalisis isyarat getaran dan spectrum FFT, sama ada dalam keadaan stabil atau pun keterujaan getaran. Terdapat persetujuan yang memuaskan antara kestabilan yang diramalkan dengan eksperimen pemotongan bagi operasi *down-milling* menggunakan alat memotong 4 ulir seragam. Keadaan stabil ditunjukkan pada luar sempadan kawasan keterujaan getaran. Alat pemotong optimum telah diramalkan dapat menghapuskan keseluruhan keterujaan getaran. Ujian-ujian eksperimen pemotongan menunjukkan bahawa tiada keterujaan getaran berlaku semasa pemesinan sehingga kedalaman pemotongan 1.5 mm. Merujuk kepada hasil eksperimen pemotongan, terbukti bahawa alatan pelbagai adalah lebih berkeupayaan untuk pemesinan tanpa berlakunya keterujaan getaran, berbanding dengan alatan biasa.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

In terms of annual dollars spent, machining is the most important of the manufacturing processes. Machining can be defined as the process of removing material from a workpiece in the form of chips. The term metal cutting is used when the material is metallic. Most machining has very low set-up cost compared to forming, molding, and casting processes. However, machining is much more expensive for high volumes. Machining is necessary where tight tolerances on dimensions and finishes are required.

Optimum machining aims to maximize the material removal rate, whilst maintaining a sufficient stability margin to assure the surface quality. High material removal rate in machining produces self excited vibration or chatter of the cutting tool and the workpiece. When the machining becomes unstable, the excessive vibrations of the cutter and workpiece result in poor surface finish and dimensional accuracy, chipping of the cutter teeth, and may damage the workpiece and machining tool.

In the early stage of the machining chatter research, the presence of negative damping was considered as the only source of chatter. Further research focused on the particular of parameter selections in machining to avoid the build-up of these undesired oscillation and on the analytical predictions of chatter.

In this research project, to predict chatter, analytical stability can be used to define stable and unstable condition for specific spindle speed and depth of cut. The machining can be optimized by determining the best combination of the chip loads and spindle speeds with the constraint of chatter instability.

1.2 OBJECTIVES OF THE RESEARCH

The followings are the objectives of the project:

i. Prepare specimens of material Aluminum 7075.
ii. Validate chatter stability prediction with cutting experiment.
iii. Compare chatter stability of regular and variable milling tool.

1.3 SCOPE OF THE RESEARCH

Scopes for this project is built a single degree of freedom flexural as the first required to be used in the experiment. For the next step, experiment will go through modal testing, (commonly the impact hammer testing) and cutting stiffness determination. The natural (modal) frequencies, modal masses, modal damping ratios and mode shapes of the object under test are determined by modal testing. This information will use to predict chatter stability using semi discretization method.

Then, validate regular tool cutting chatter stability with cutting experiment using CNC milling machine. Experiment is conducted to compare chatter analytical prediction. Cutting experiments will use the variable helix and variable pitch tool to validate chatter milling tool chatter stability.

1.4 FLOW CHART

The sequence of work has been planned as shown in Figure 1.1 in order to achieve the objectives of this research, while Gantt Charts can refer to Appendix A. This flow chart is useful as guideline to ensure that the experiment is carried out smoothly. The process involved in achieving notified objectives are including literature study based on related topic, determining material, method and parameters, conducting experiment, analysis data and data discussion.

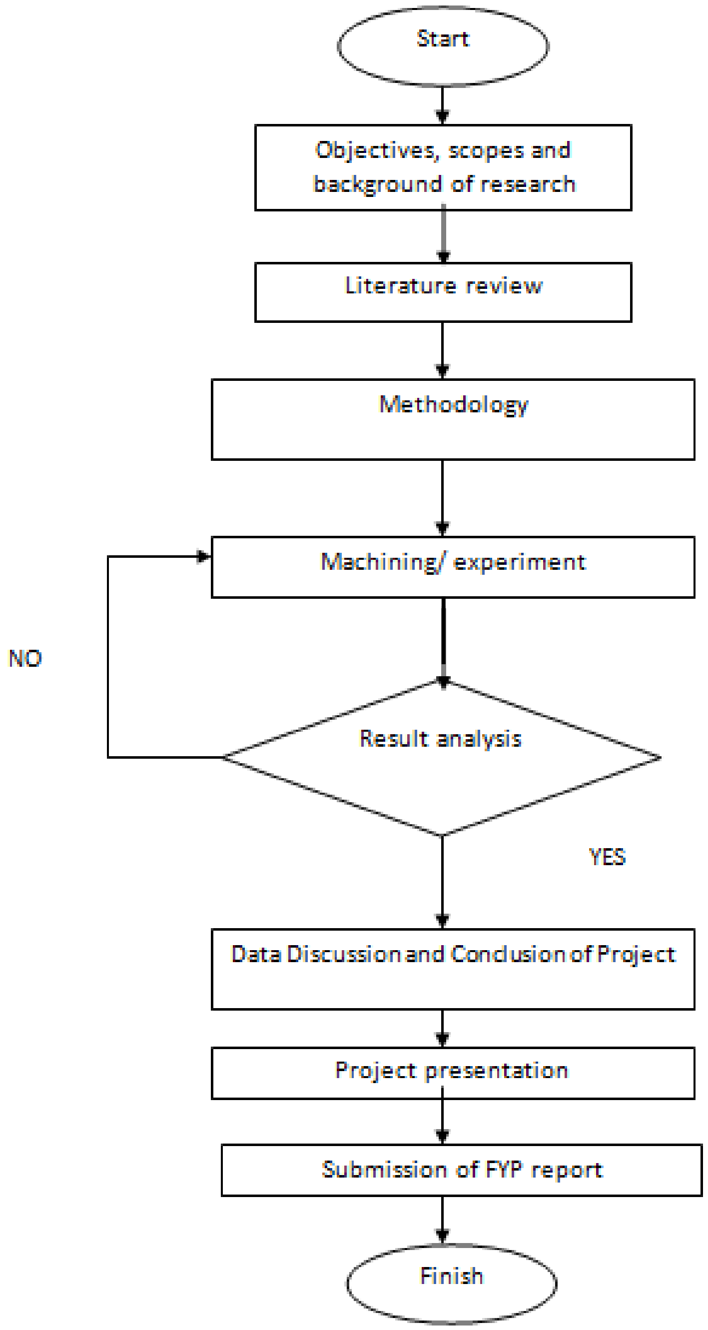


Figure 1.1: Project flow chart

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The science, engineering and technology of manufacturing process and systems continue to move on speedily on a worldwide scale and with major impact on the financial systems of all peoples. This is because with this condition people can invent many products with various shapes. As a result, that science, engineering and technology of manufacturing processes and system people can do many things.

With knowledge of manufacturing, till today many kinds of manufacturing have been generated. To produce parts, need variety of manufacturing processes. These can be broadly classified into five groups (Nagendra and Mittal, 2006). In the casting process, the material is given the desired shape and size of the product by melting it, poured into a cavity and allowing it to solidify. Machining is a removing the unwanted material from a given workpiece to give it the required shape.

Forming is made use of suitable force, pressure or stresses like compression, tension, shear or their combination to cause a permanent deformation of the material to give it the required shape. In powder metallurgy process, fine powdered materials are blended, pressed into a desired shape in an die and then heated in a controlled atmosphere to bond the contacting surfaces of the particles and get the desired properties. In joining process, two or more pieces are joined together permanent, semi-permanent or temporary.

2.2 MACHINING

The parts of products will require further manufacturing operations after it's done through the forming and shaping processes. The situation happens because none of these processes are capable of producing parts with such specific characteristics. Machining is described as a group of processes that consist of the removal of material and modification of the surface of the workpiece after it has been produced by various methods (Kalpakjian and Schmid, 2006).

In general, machining consist of several major types material-removal processes, such as cutting process, typically involving single-point or multipoint cutting tools, each with a clearly defined shape. Another that, abrasive processes, such as grinding and advanced machining processes, for example utilizing electrical, chemical, laser, thermal and hydrodynamic methods.

Machining without qualification usually implies conventional machining and the removal of material. With the recent proliferation of additive manufacturing technologies, conventional machining has been retronymously classified, in thought and language, as a subtractive manufacturing method. In narrow contexts, additive and subtractive methods may compete with each other. In the broad context of entire industries, their relationship is complementary. Each method has its own advantages over the other. While additive manufacturing methods can produce very intricate prototype designs impossible to replicate by machining, strength and material selection maybe limited (Beaman *et al.*, 2004).

The extreme dimensional accuracy can be got by machining process, often more so than any other process alone. Machining can produce sharp corners and flatness on a part that may not be able to be created through other processes. Machining accuracy allows it to produce surface finish and smoothness that can't be achieved any other way, as shown in Figure 2.1. A very complex parts can be made by machining operation, as shown in Figure 2.2.

Figure 2.1: A forged crankshaft before and after machining the bearing surface

Source: Courtesy of Wyman-Gordon Company, 2011

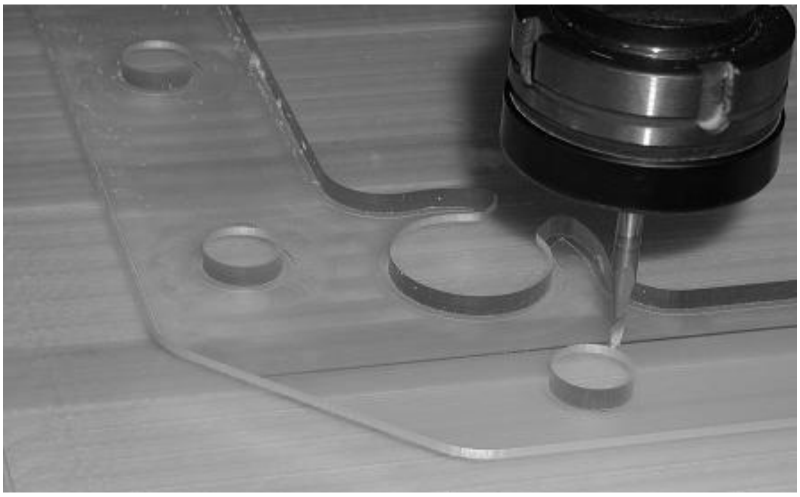


Figure 2.2: The complex parts of product produced using machining

Source: Protogenic Division, Spectrum Plastics Group, 2011

2.3 CHATTER IN MACHINING

The self-excited oscillations of the cutting tool and the workpiece can be referred as machine tool chatter vibrations. If the closed-loop machining system, which include machine tool-cutter dynamic cutting process, become unstable, the excessive vibrations of the cutter and workpiece result in a poor surface finish and dimensional accuracy, chipping of the cutter teeth, and may damage the workpiece and machine tool, as shows in Figures 2.3 and 2.4. Generally, conservative material removal rates, which cause reduced productivity, are used to avoid chatter vibrations (Budak and Altintas, 1998).

Optimum machining aims to maximize the material removal rate, while maintaining a sufficient stability margin to assure the surface quality with avoid the chatter. There are two groups of machine tool chatter, regenerative and non-regenerative (Tlusty, 1985). Regenerative chatter occurs due to the periodic tool passing over the undulations of the previously cut surface, while non-regenerative chatter has to do with mode coupling among the existing modal oscillations.

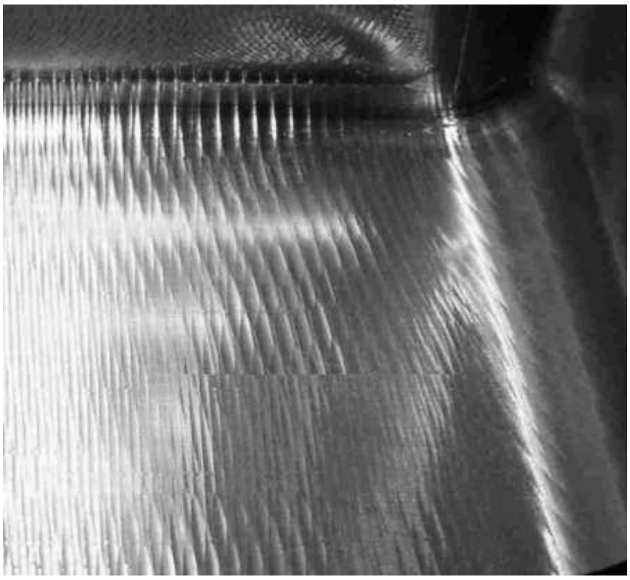


Figure 2.3: Poor surface finish of the product caused by the chatter of machining

Figure 2.4: Chipping of the cutter teeth on the tool

2.3.1 Chatter Phenomenon in Milling

During the milling process, one of the structural modes of the machine tool – workpiece system is excited by cutting force initially. Same as Figure 2.5, an oscillatory surface finish left by one of the tooth is removed by the succeeding oscillatory tooth due to structural vibrations. The resulting chip thickness becomes also oscillatory, this in turn produces oscillatory cutting forces whose magnitudes are proportional to the time varying chip load. This condition makes the self excited cutting system becomes unstable. Then, chatter vibrations grow until the tool jumps out of the cut or break under the excessive cutting forces (Altintas and Budak, 1995). That’s why the major limiting factor in increasing the material removal rates of the machine tools is chatter vibration.

2.3.2 Progression in Chatter Research

The papers about chatter as a regenerative phenomenon were published (Tobias *et al.*, 1958). Later, research presented the problem as a feedback loop, which clarified a lot of formulation (Merritt, 1965). These basic approaches were used, by reducing the dynamics of the machine to an equivalent single degree of freedom system for many years.

Next, the method which enables working with several degree freedom models is presented (Altintas and Budak, 1995) as shown in Figure 2.5. Analysis for the geometrical nonlinearities of the milling process obtained an approach to the solution by using a Fourier series development of the directional factors and solved the system by considering the zero order term only. In next research, researcher worked out the system by considering several terms of the Fourier development, which gives rise to solutions very close to those obtained by using the fundamental term only (Budak and Altintas, 1998).

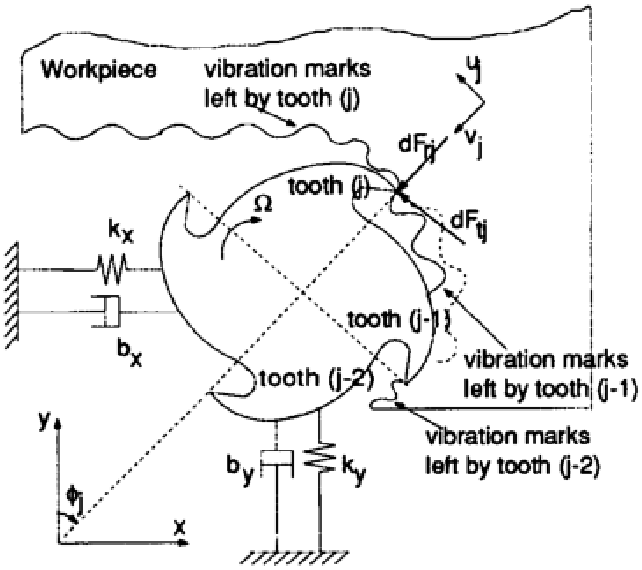


Figure 2.5: Dynamic model of milling with two degrees of freedom

Source: Altintas and Budak, 1995

Researchers have proposed analytical methods that explicitly account for the interrupted nature of milling and have generated stability diagrams analogous to the classical ‘lobes’. The intermittent was captured by including many harmonics in the Fourier series of the time-varying coefficients (Corpus and Endres, 2000). This approach loses accuracy as the relative time in the cut decreases.

The single frequency approach has been shown to be very precise, but when radial immersion of the mill is small, the existence of additional stability lobes was found. A discrete map model for highly interrupted milling processes was used (Davies *et al.*, 2000), where the time in the cut is infinitesimal and the cutting process is modeled as an impact. An approximate expression was derived for the time delay in the form of an integral, time-periodic matrix differential equation, and use Floquet theory to determine stability boundaries (Insperger and Stepen, 2000). Later, the technique of semi-descretization was developed (Insperger and Stepen, 2004), while the similar results using temporal finite elements was obtained (Bayly *et al.*, 2003).

The multifrequency resolution is also able to present accurately the flip instability phenomenon was showed (Merdol and Altintas, 2004). In specific research, just a few papers analyzed the chatter in milling with the inclusion of the effect of the helix angle. Without associated with the helix angle of the milling, some papers present some instability regions with ‘lenticular’ shape (Govekar *et al.*, 2005).

Most commonly chatter research has focused to increase the material removal rate while avoiding the onset of chatter. A natural progressive trend is to increase the productivity through simultaneous (or parallel) machining. This process can be further optimized by determining the best combination of the chip loads and spindle speeds with the constraint the chatter instability (Olgac and Sipahi, 2005).

2.3.3 Chatter Stability Experiment

Many researches were done to investigate the chatter vibration condition in machining. Generally, the milling process was used in cutting test to find out the chatter stability based on the parameters, spindle speed and depth of cut, as shown in Figure 2.6. Chatter that happen can produce an unpleasant sound and noise, lower machining quality, poor surface finish and accuracy. The cutter tools that commonly used have a higher probability to produce excessive vibration and chatter. Thus, the irregular cutting tool was designed using an optimization process like Differential Evolution (DE), to suppress unwanted chatter vibration during milling operations.

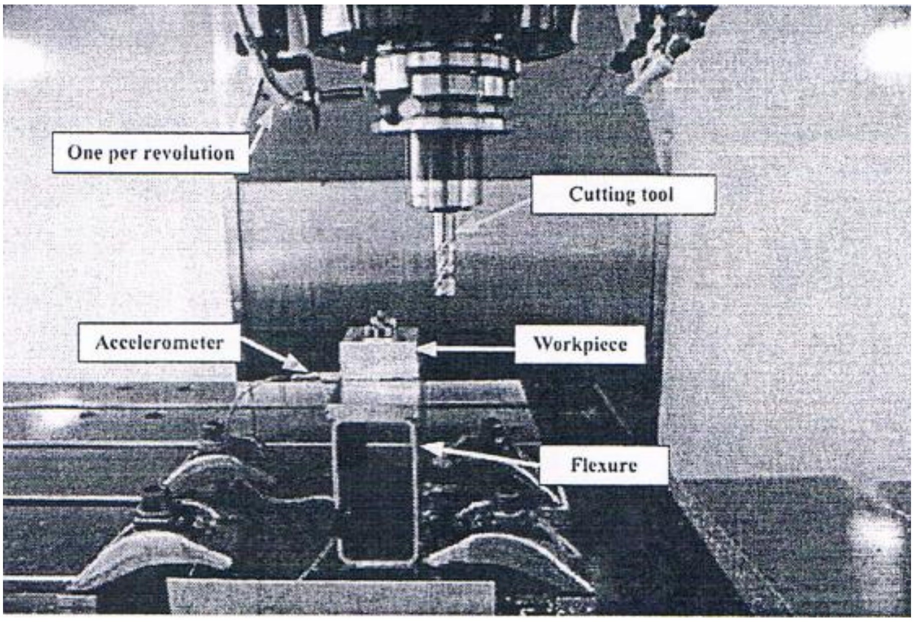


Figure 2.6: Cutting experiment

Source: Yusoff *et al.*, 2011

The identification of chatter can be done when analysis the result of cutting process, such as surface roughness test and analysis of vibration signal during machining. Some investigation has analyzed vibration condition based on the 1/Rev samples and spectrum analysis (Yusoff *et al.*, 2011). The result was classified as chatter if the vibration signal shows that 1/Rev samples approached a fixed point with a variance less 10 mm/s^2 and the FFT amplitude was dominated by the tooth passing harmonics.

2.4 MILLING MACHINING

Milling machine can machine flat or curved surfaces, inside or outside, of almost all shapes and sizes. Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges (in rare cases, a tool with one cutting edge, called as fly-cutter is used). The direction of feed is perpendicular to the axis of rotation of the cutting tool. This orientation between the tool axis and the feed direction is one of the features that distinguish milling from drilling. Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations.

2.4.1 Types of Milling Operations

There are two types of milling operations (Groover, 2007), shown in Figure 2.7. In peripheral milling (plain milling), the surface being machined is parallel to the axis of the tool, and the operation is performed by cutting edges on the outside periphery of the cutter. In face milling, the axis of the cutter is perpendicular to the surface being milled, and machining being performed by cutting edges on both the end and outside periphery of the cutter.

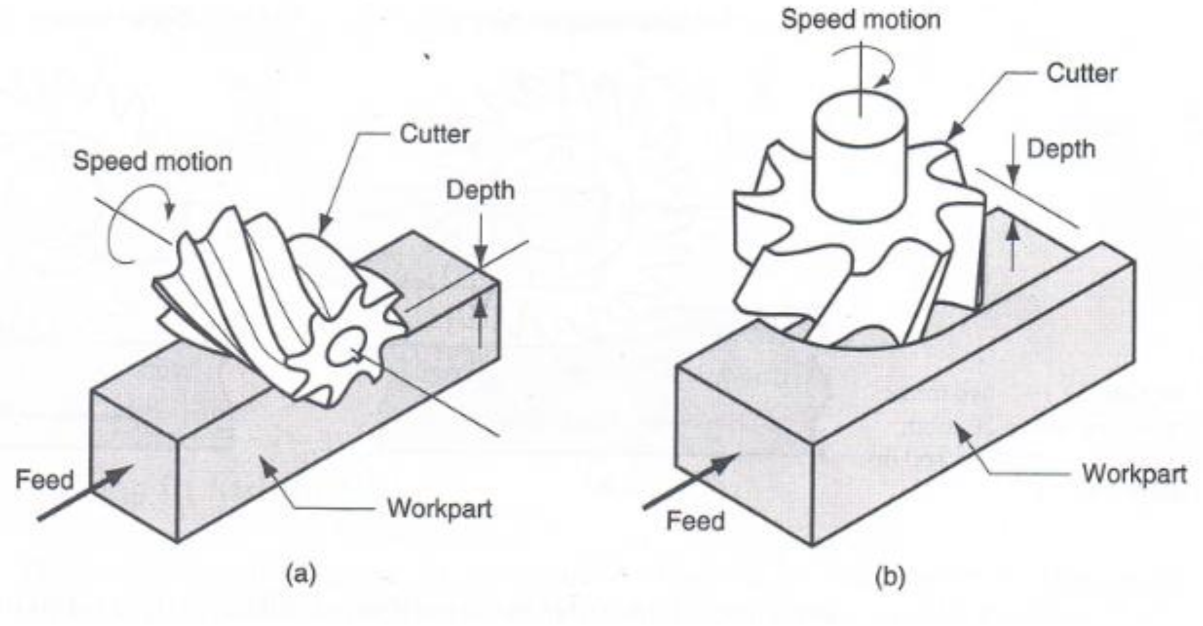


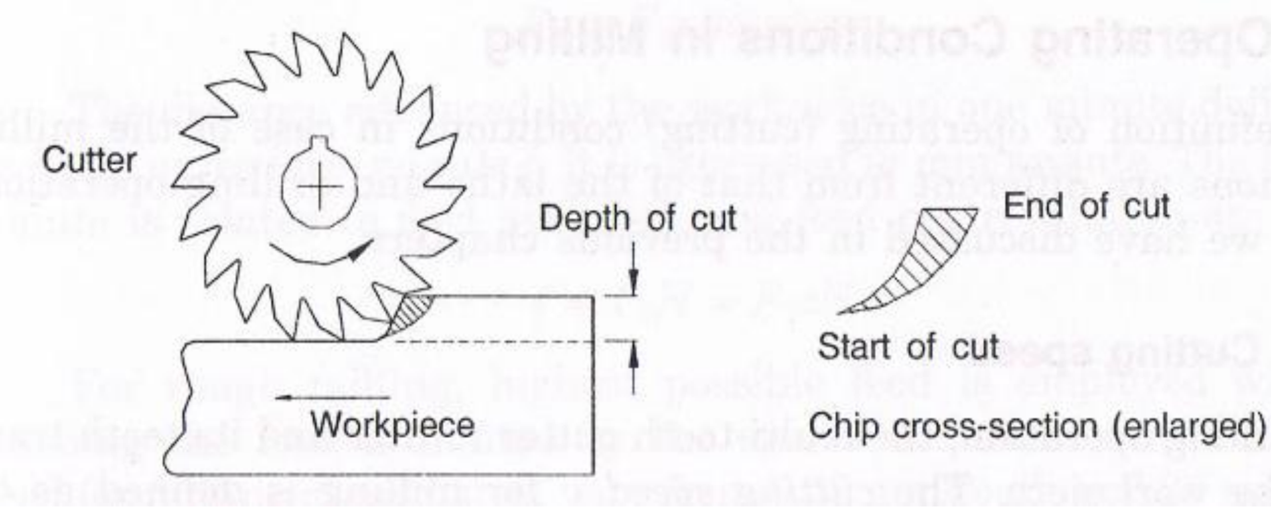
Figure 2.7: Two basic types of milling operations:
(a) peripheral milling and (b) face milling

Source: Groover, 2007

2.4.2 Methods of Metal Cutting

There are two methods of metal cutting in the milling operation, up milling and down milling. The difference of operations lies in the direction along which the workpiece is fed into the rotating milling cutter and the direction of rotation of the cutter (Nagendra and Mittal, 2006).

In up milling (conventional milling), the direction of the cutter rotation is opposite to the feed direction of the workpiece, as shown in Figure 2.8. Each tooth of the cutter starts the cut with zero depth of cut, reaches the maximum value as the tooth leaves the cut. The cutter has to be forced into the material, creating a burning effect with excessive friction and high temperature. The difficulty is experienced in pouring coolant on the cutting edge, make chips accumulate and may be carried over with the cutter, thus spoiling the surface finish (slightly wavy surface).

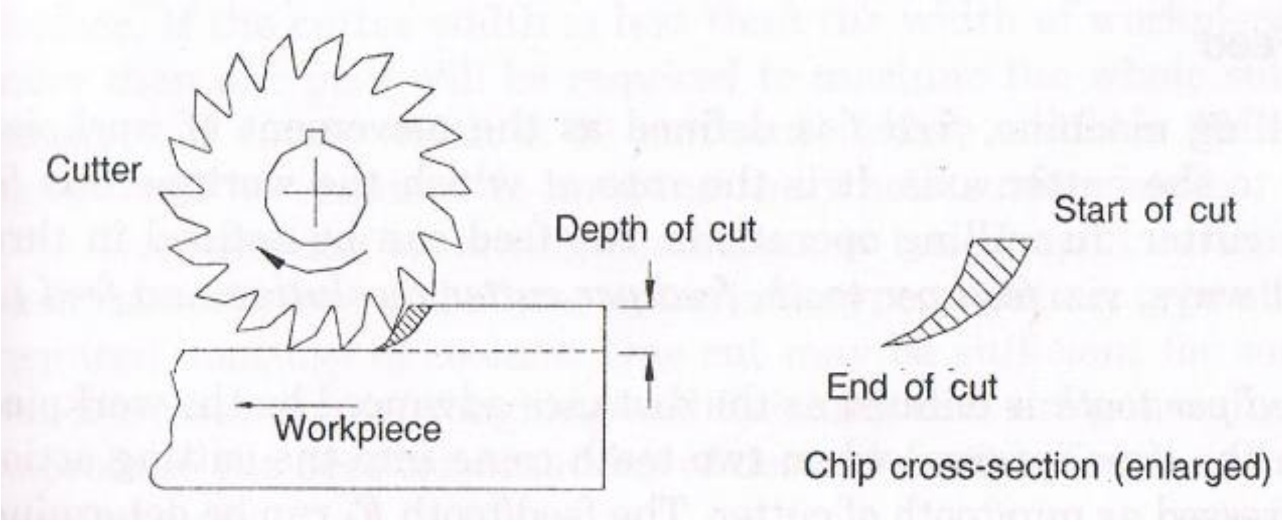


(a) (b)

Figure 2.8: Up milling operation: (a) direction of the cutter rotation and (b) the chip cut by a cutter tooth

Source: Nagendra and Mittal, 2006

In down milling (climb milling), the direction of the cutter rotation is same as the feed direction of the workpiece, as shown in Figure 2.9. The maximum thickness of the chip at the start of the cut decrease to zero thickness at the end of the cut. The cutting force tends to hold the work against the machine table. The process produces a better surface finish and dimensional accuracy. The coolant can be fed easily, chips are disposed off conveniently, thus the machined surface hasn’t spoiled.



(a) (b)

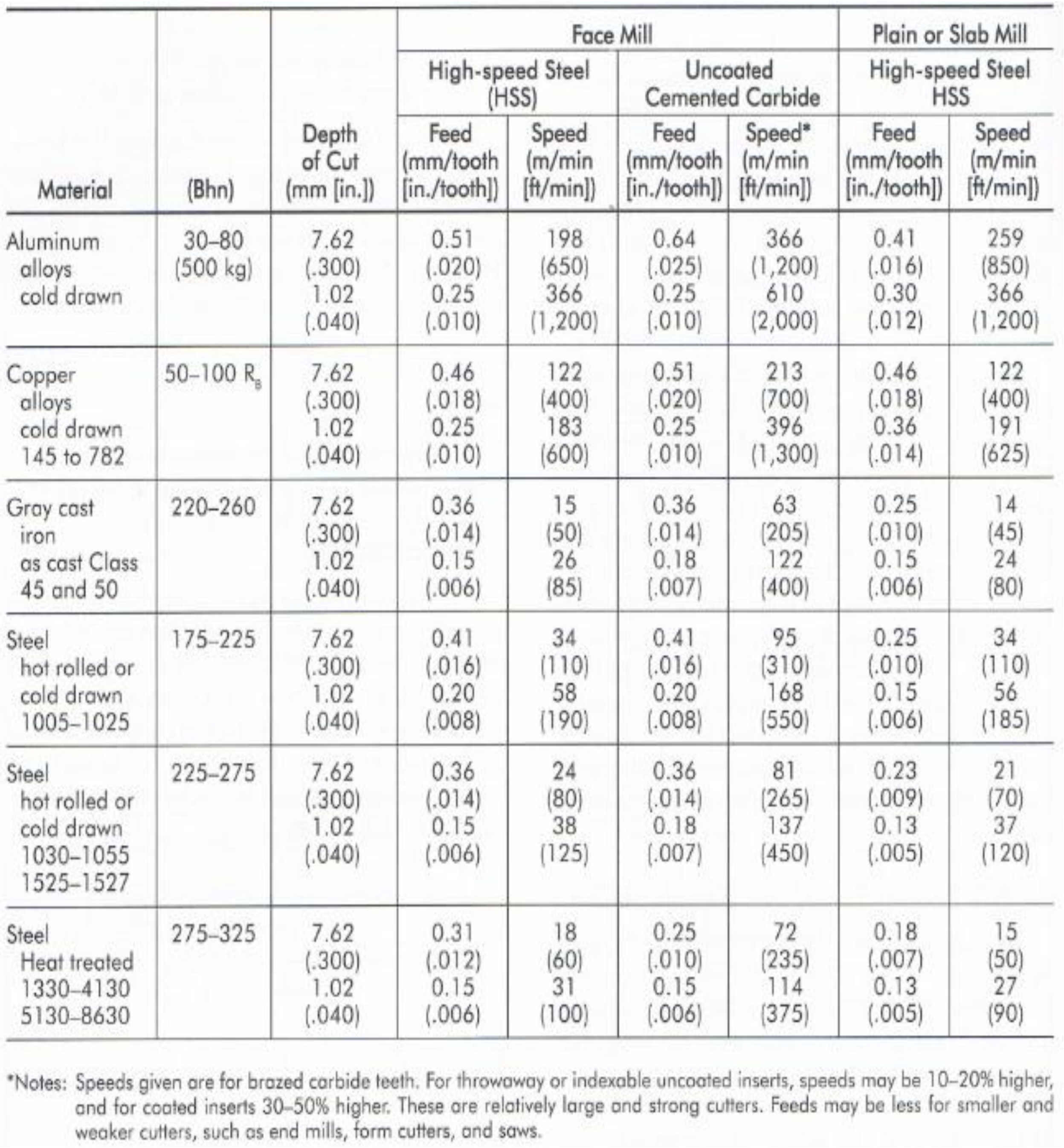
Figure 2.9: Down milling operation: (a) direction of the cutter rotation and (b) the chip cut by a cutter tooth

Source: Nagendra and Mittal, 2006

2.4.3 Speed, Feed and Depth of Cut

Typical recommendations for speeds and feeds are given in Table 2.1 for roughing cuts and finishing cuts with either high-speed steel (HSS) or brazed carbide cutters based on types of workpiece. Feed per tooth also known as chip load is important to calculate the feed rate of machining, while speed is used to determine spindle speed during the milling process.

Table 2.1: Recommended cutting speeds and feeds for milling.



			Face Mill				Plain or Slab Mill	
			High-speed Steel (HSS)		Uncoated Cemented Carbide		High-speed Steel HSS	
Material	(Bhn)	Depth of Cut (mm [in.])	Feed (mm/tooth [in./tooth])	Speed (m/min [ft/min])	Feed (mm/tooth [in./tooth])	Speed* (m/min [ft/min])	Feed (mm/tooth [in./tooth])	Speed (m/min [ft/min])
Aluminum alloys cold drawn	30–80 (500 kg)	7.62 (.300) 1.02 (.040)	0.51 (.020) 0.25 (.010)	198 (650) 366 (1,200)	0.64 (.025) 0.25 (.010)	366 (1,200) 610 (2,000)	0.41 (.016) 0.30 (.012)	259 (850) 366 (1,200)
Copper alloys cold drawn 145 to 782	50–100 R_B	7.62 (.300) 1.02 (.040)	0.46 (.018) 0.25 (.010)	122 (400) 183 (600)	0.51 (.020) 0.25 (.010)	213 (700) 396 (1,300)	0.46 (.018) 0.36 (.014)	122 (400) 191 (625)
Gray cast iron as cast Class 45 and 50	220–260	7.62 (.300) 1.02 (.040)	0.36 (.014) 0.15 (.006)	15 (50) 26 (85)	0.36 (.014) 0.18 (.007)	63 (205) 122 (400)	0.25 (.010) 0.15 (.006)	14 (45) 24 (80)
Steel hot rolled or cold drawn 1005–1025	175–225	7.62 (.300) 1.02 (.040)	0.41 (.016) 0.20 (.008)	34 (110) 58 (190)	0.41 (.016) 0.20 (.008)	95 (310) 168 (550)	0.25 (.010) 0.15 (.006)	34 (110) 56 (185)
Steel hot rolled or cold drawn 1030–1055 1525–1527	225–275	7.62 (.300) 1.02 (.040)	0.36 (.014) 0.15 (.006)	24 (80) 38 (125)	0.36 (.014) 0.18 (.007)	81 (265) 137 (450)	0.23 (.009) 0.13 (.005)	21 (70) 37 (120)
Steel Heat treated 1330–4130 5130–8630	275–325	7.62 (.300) 1.02 (.040)	0.31 (.012) 0.15 (.006)	18 (60) 31 (100)	0.25 (.010) 0.15 (.006)	72 (235) 114 (375)	0.18 (.007) 0.13 (.005)	15 (50) 27 (90)

*Notes: Speeds given are for brazed carbide teeth. For throwaway or indexable uncoated inserts, speeds may be 10–20% higher, and for coated inserts 30–50% higher. These are relatively large and strong cutters. Feeds may be less for smaller and weaker cutters, such as end mills, form cutters, and saws.

Source: Institute of Advance Manufacturing Science, 1980

The spindle speed is based on the cutter diameter because cutting speed for a mill cutter is the linear velocity of a point on the periphery of the cutter, as shown in equation 2.1 bellow.

$$n = (CS \times 1000) / \pi d \tag{2.1}$$

Where
n = spindle speed, rpm
CS = cutting speed, m/min
d = diameter of the cutter, mm

Basic milling feed (feed per tooth) is the distance the workpiece advance in the time between engagements by two successive teeth. The machine feed rate is given as follows:

$$f = f_t \times Z \times n \tag{2.2}$$

Where
f = machine feed, mm/min
f_t = cutter feed/tooth, mm/tooth
Z = number of teeth on the cutter
n = spindle speed, rpm

The actual feed is considerably less than the nominal feed per tooth for shallow cuts as shown in Figure 2.10. When the depth of cut is at least equal to the radius of the cutter, the two components of feed are equal (Schrader and Elshennawy, 2000). For end mill, depth of cut should not exceed half of the diameter of the tool in steel, but in soften metals such as aluminium, it can be more.

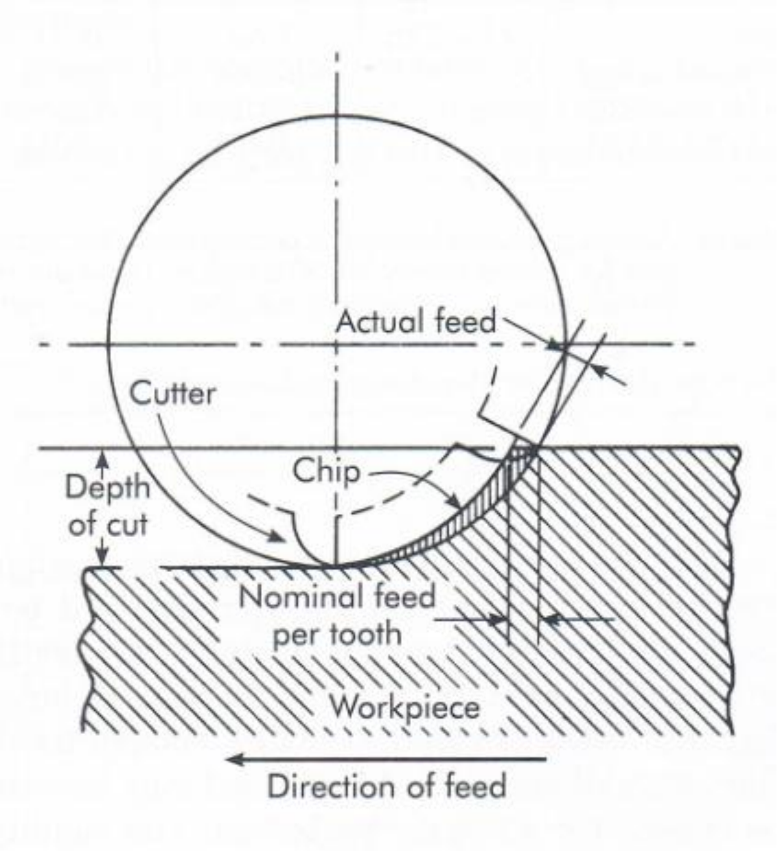


Figure 2.10: Relationship between actual and nominal milling feed

Source: Schrader and Elshennawy, 2000

2.5 FAST FOURIER TRANSFORM (FFT)

FFT is a mathematical technique to convert the signal from the time domain into the frequency domain. The signal at the detector, disability or on the display oscilloscope acoustic emission is usually the time domain signal that shows how the amplitude varies with time. When transformed into the frequency domain display shows how the amplitude varies with frequency. This view is often referred to as the signal frequency spectrum.

One line at a frequency in the frequency domain because single frequency sine wave in the time domain that will give rise sharply in the time domain which gives the spread of frequencies in the frequency domain (Edward *et al.*, 2007). Spike made by adding sine waves of all different frequencies at one point when they were all together to give while the spike at all other times they all cancel to give zero signals. Switch back from the frequency domain to time domain is the inverse FFT.

Changes the Fourier are very useful because they reveal the period of the input data and the relative strengths of any periodic components. The result means the FFT operation, periodic functions will include changing the peak is not one, but two places. However, both these components are symmetric, so it was only necessary to see one to obtain frequency information. And providing information about the frequency, the FFT can be used to apply signal processing techniques such as filtering the signal and image compression is much easier to implement in the frequency domain.

2.6 SUMMARY

Nowadays, a variety of manufacturing processes are needed to produce parts and products, used in human life every day. One of the processes is machining, removing the unwanted material from a workpiece to get it the required shape. If chatter happens during machining, the excessive vibration of the cutter and workpiece result in poor cutting, and may damage the tool and workpiece. Most commonly chatter research has focused to increase the material removal rate while avoiding the onset of chatter. The uniform mill cutter has a higher probability to occur chatter, so the irregular cutting tool was designed to suppress unwanted chatter vibration during cutting operations. Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges.