Investigation and Optimization of the effect of Machine Vibrations on the Dimensional Surface Quality in Milling Operations.

Ph.D Manufacturing Engineering Thesis

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DECLARATION

I Sadaf Zahoor hereby state that my Ph.D thesis titled "Investigation and Optimization of the effect of Machine Vibrations on the Dimensional Surface Quality in Milling Operations" is my own work and has not been submitted previously by me for taking any degree from this university or anywhere else in the country/world.

ABSTRACT

Following an extensive literature review on the vibrations in machining operations, experimental work is undertaken in two main phases on the investigation and optimization of effects of machine vibrations on dimensional surface quality in milling operations.

In Phase IA, forced vibrations are induced in the spindle of CNC machining center comparable to the older machines used in industry. This has been done using external weights with the help of purpose built gripper. Effects of external weight and spindle speed are found significant on vibration amplitudes. In Phase IB, industrial machines are selected to benchmark the vibration amplitudes induced in the machine under study. The selected vibration amplitude levels are used in Phase II to investigate the effects of spindle forced vibrations during milling operations.

Phase IIA and Phase IIB are aimed to carry out experimentation using high speed steel (HSS)and solid carbide end mill cutters in order to investigate the effects of spindle forced vibrations along feed rate and axial depth of cut on dependent parameters including surface roughness and dimensional accuracy. Cutting speed, radial depth of cut, spindle speed, number of flutes and tool hang are taken as fixed parameters. A L9 Taguchi orthogonal array is used for design of experiments. The signal to noise ratio (S/N) analysis followed by analysis of variance (ANOVA) is used for analysis. It is revealed by ANOVA that spindle forced vibrations have strong effects on surface roughness in case of solid carbide end mill cutter.

In Phase IIC, different tool wear patterns are evaluated for HSS and solid carbide end mills. It is found that higher levels of vibration amplitude and feed rate accelerate the propagation of tool wear. A tool failure is also observed at high vibration amplitudes in case of solid carbide end mill cutter.

Based on the results obtained in Phase IIB, optimization is done on the basis of ANOVA and recommends preferred operating parameters for finishing operations using solid carbide end mill cutter.

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CHAPTER 1

INTRODUCTION

This chapter briefly explains the background, aims and objectives of the present research.

1.1 Background of the Present Research

Although the key principle of working for many human senses is vibration but the first formal introduction of vibration to the humanity is happened with the invention of first musical instrument.

After this invention, vibration has been treated on the basis of science and a significant portion of research has been dedicated to investigate the effects of vibration in different applications. The importance of vibrations in daily life is revealed through several examples like working of different human activities (breathing, hearing, talking, walking etc.), use of vibration phenomena in the development of different equipment e.g. washing machine, dentist drill, electrical massager etc.

Despite of the fact that vibrations are desirable in many applications for the proper functioning of the systems, vibrations have also detrimental effects when it comes to machines and machine tools. Failure of different mechanism like shaft and rotor in the mechanical systems e.g. engines, pumps, turbines, prime movers etc. are the few examples indicating the devastating effects of vibrations.

Machine tools and metal cutting processes even cannot escape from the detrimental effects of vibrations. During any machining operation, generally two types of vibrations can be observed; self-excited vibration (chatter) and forced vibrations [1]. Both types of vibrations affect the machining processes in their own way which eventually results into poor surface quality of the machined parts. As the productivity in tandem with the quality become the major concern of any manufacturing organization in the present day, it forces the manufacturers to incorporate the dynamic behavior of cutting processes in order to achieve the optimized surface quality of the parts by reducing the cost of manufacturing.

While investigating the effects of vibrations during machining operations, most of the research reveals the detrimental effects of chatter on different machining characteristics like surface finish, dimensional accuracy, surface integrity and tool life and will be discussed in chapter 3 in detail.

Literature illustrates that a limited work has been carried out on investigating the effects of machine tool spindle forced vibrations on surface quality of the machined parts. This research includes a study that forced vibrations have significant effects during the machining of light alloys [2]. Tobias gives the study that during the machining process, the vibrations on the machine spindle are generated by the unbalanced force caused by the cutting process [3]. Koenigsberger et al present a research that resonance due to machining frequency and spindle forced vibrations has to be carefully watched in order to achieve reduced surface roughness and less tool wear while milling [4]. Orhan et al concludes the study with the results that tool wear and chatter has a direct relationship with forced vibration amplitudes [5].

Lin et al contributes in studying the effects of radial vibrations on surface quality in turning operations and concludes that vibration amplitude levels have effects on surface roughness of machined parts [6]. Risbood et al presents a research for the prediction of surface roughness and dimensional accuracy as a result of cutting forces and machine vibrations in turning operations. The research concludes that surface roughness can be assessed by considering the radial vibrations of tool holder [7]. Abouelatte et al aim at developing a correlation among surface roughness and cutting vibrations during turning operations. The ultimate goal is to develop a mathematical model to predict the surface finish in terms of machining parameters and machine tool spindle vibrations [8]. Munawar et al has worked on forced vibrations and gives the optimization of surface finish in turning operations by considering machine tool spindle vibrations. The research concludes that vibration amplitude levels have moderate effect on surface roughness of the machined component [9].

Reviewed literature suggests that limited work has been carried out to investigate the effects of spindle forced vibrations in milling operations. Therefore, this research aims to investigate the effects of spindle forced vibrations on dimensional surface quality of the machined parts in milling operations. As milling operation is considered one of the important machining operations in the manufacturing of dies and moulds.

AISI P20 tool steel is selected as workpiece material for the present research because it is commonly used mould material for the injection molding of thermoplastic parts used for aerospace industry [10]. Due to its high strength, greater toughness, mechanical and thermal fatigue resistance, AISI P20 tool steel is considered ideal for the high temperature applications.

1.2 Aims and Objectives of the Present Research

The main aim of the research is to investigate the effects of spindle forced vibrations on dimensional surface quality of the machined part during the milling of AISI P20 tool steel and optimize the process for finishing applications with emphasis on the dimensional surface quality. The important objectives of research are listed below:

- To investigate the machine tool spindle forced vibrations along with different machining parameters for dimensional surface quality of the workpiece.
- To investigate the influence of tool materials on different characteristics of machined part in terms of surface finish, dimensional accuracy and tool wear.
- To investigate the effect of spindle forced vibrations on tool wear.
- To optimize the process in terms of machining parameters for better dimensional surface quality.

Figure 1.1 shows hierarchy of the work presented in the forthcoming chapters.

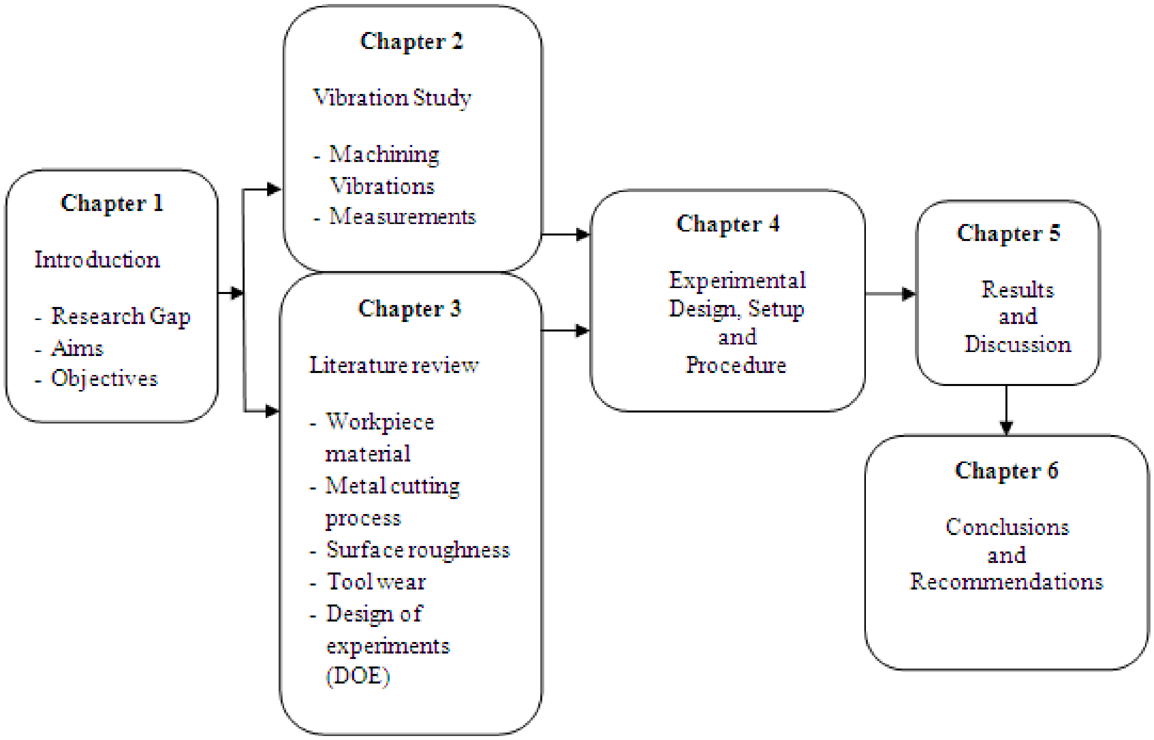


Figure 1.1: Block diagram indicating the hierarchy of work

CHAPTER 2

VIBRATION STUDY

This chapter has been dedicated to introduction of vibrations, cause and effects of vibrations in different applications, its measurement methods. During the chapter, literature review is also illustrated on investigation of different types of vibrations in machine tool and machining operations.

2.1 Brief History and Importance of Vibrations

The history of vibration has been found hundreds of years old, started from the discovery of musical instruments to the electronic speaker built in our cell phones which mimics the vibration codes of voices, musical instruments and many more. Although researchers have dedicated a complete subject to vibrations in order to investigate its causes and effects through science and experimentation, but Pythagoras is the first mathematician who studied vibrations on a scientific basis [11]. In a simple manner, vibration is the repeated motion of matter in a medium through the intervals of time, technically say oscillations. From the swing of pendulum to the earthquake, all is the different modes of vibrations. Some of them can hear and some of them can feel by touching the vibrating body. Random characteristics of vibrations have been found in diverse phenomena like musical instruments, sounds, earthquake, winds, vehicles, jet engine noise and machine tools. For example, first seismograph to precisely measure the vibrations of earthquake invented in china is based on the principle of vibrations itself [11].

Prior to 1877, the research on vibrations is related to sounds and musical instruments. After that, vibration studies are carried out for mechanical and structural system applications. Baron Rayleigh is the first who contributed his work as a form of Rayleigh Ritz method to find the fundamental frequency of vibrations of a conservative system [11]. In 1902, Frahm contributes to the vibration studies by investigating the role of torsional vibration during the propeller shaft design of steamship. Although the nonlinear behavior of vibrations in different basic problems related to mechanics has been recognized long ago. But after 1920, Duffing et al present the first definite solutions for nonlinear vibrations theory into engineering applications [11]. The research carries out by Lin and Rice during 1943 to 1945 led to the new directions for the application of vibrations into different engineering problems [11]. The invention of high speed digital computers in 1950 enables the researchers and engineers to perform the complex analysis of vibrations for mechanical and structural applications having thousands of degrees of freedom which is impossible in the past.

The importance of vibration study can be well understood from the fact that most human activities are based on vibration phenomena like hearing is possible only when eardrums vibrate, light waves vibrations can enable to watch, lungs vibrations facilitate in breathing and walking is possible due to oscillation of legs etc. Early researchers have invested their efforts to understand the natural phenomena of vibrations and formulating the mathematical models and theories which describes the vibration of a physical system. In recent years, most of the research has been carried out involving vibrations into different engineering problems related to machine tool design, machine foundation, structures, turbines and control systems etc.

Despite of the facts that vibrations are essential and desirable for proper functioning of several applications, literature also indicates many examples illustrating the detrimental effects of vibrations. These examples include the deflections and failures of structures and systems due to vibration phenomena. The failure of “Tacoma Narrows Bridge” is an example of structural failure due to resonance. To avoid the devastating effects of resonance and excessive vibrations, vibration testing becomes an integral procedure for the design and development of engineering systems. Figure 2.1(a-b) presents selected examples of structural vibrations.

a) Tacoma Narrow Bridge collapse due to resonance [12]

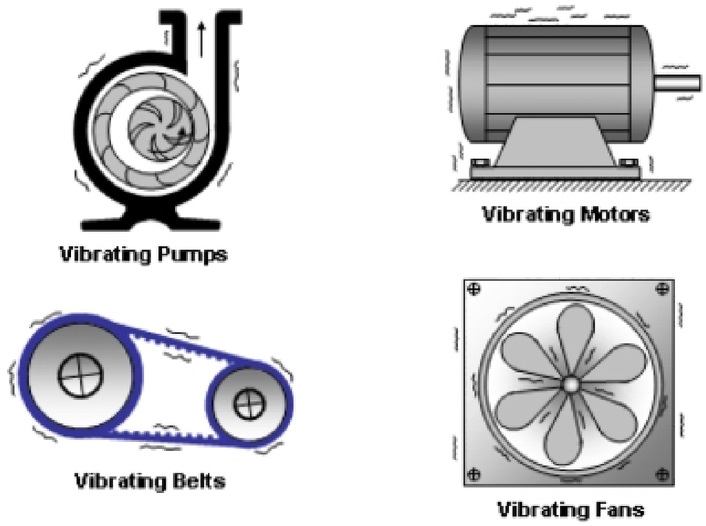
b) Ground vibration testing in aircrafts [13]

Ground vibration testing in aircrafts [13]

Figure 2.1: Structural examples related to vibrations (a) Structure failure (b) Vibration testing

2.2 Introduction to Vibrations in Machines

The mechanical systems and machines like engine, turbines, pumps and motors have not able yet to prevent failure due to vibrations. Several examples can be found which demonstrate the failures caused by vibrations e.g. vibrational problems in prime movers, blade and disk vibrations of turbines, excessive wear of machine parts such as gears and bearings etc. Vibrations also affect the humans who are the integral part of the engineering system and suppose to interact with mechanical systems. The vibrations produce by the engineering systems can transmit to humans causing a discomfort and loss of efficiency. The effects of vibrations in machines are exemplified through Figure 2.2(a-c).



a) Different types of vibrations in machines [14]

b) Breakage of rod due to vibrations caused by crankshaft looseness [12]

Figure 2.2: Vibrations in machines (continued)

c) Motor shaft failure due to vibration [12]

Figure 2.2: Vibrations in machines

2.3 Introduction to Vibrations in Machine Tools

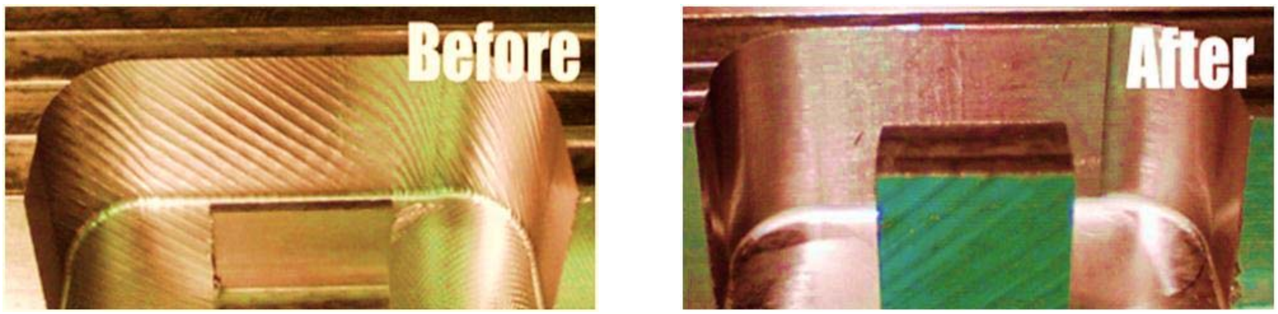
Vibrations also have devastating effects when it comes to machine tools. These effects can be quantified on surface of machined parts because machine tool vibrations finally affect the surface quality of the components produced during any machining operations. Machine tool vibrations are generally of two types; self- excited vibrations (Chatter) and forced vibrations [1, 15].

Forced vibrations are caused by the certain periodical forces existing in the machine. Possible reasons for the forced vibrations are, worn out tools, imbalanced component, misaligned motors or a shaft etc. The natural vibrations caused by the self-excitation, also known as chatter, which can be produced by the interaction of cutting forces generate during cutting process and the mechanical structure of the machine tool. Following are some of the potential reasons that may cause vibrations in machine tools:

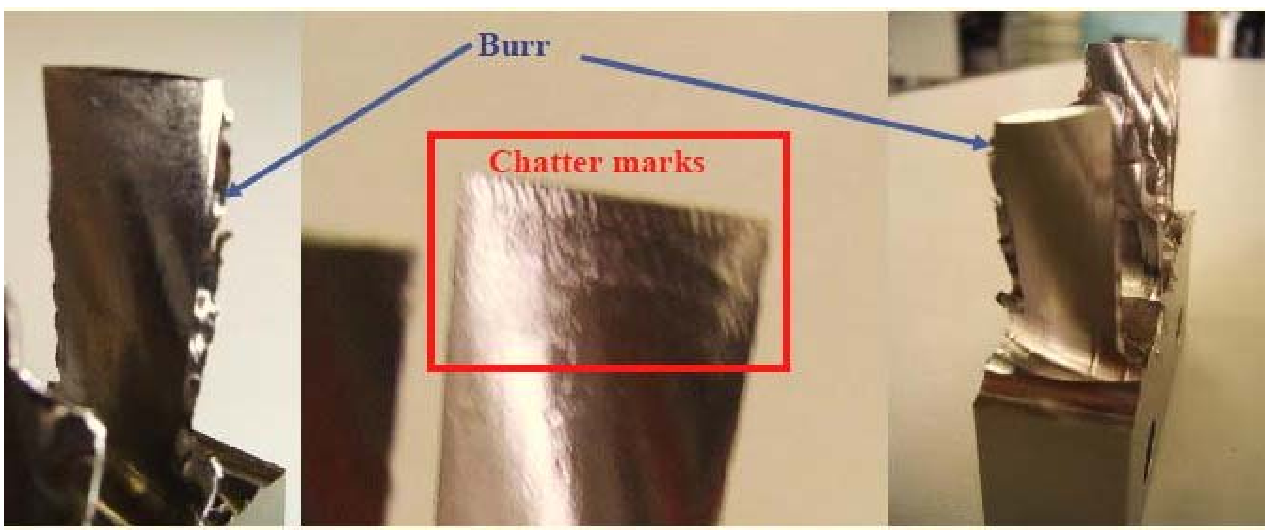
- Imbalanced machine components
- Looseness of machine components
- Material worn-out due to friction
- Hydraulic errors
- Electronic errors in motors and transformers

- Relative resonance in-between different components
- Power transmission methods e.g. chain and V-belts

Figure 2.3(a-b) illustrates effects of vibrations during different machining operations.



a) Chatter marks during machining operation [16] Improved surface [16]



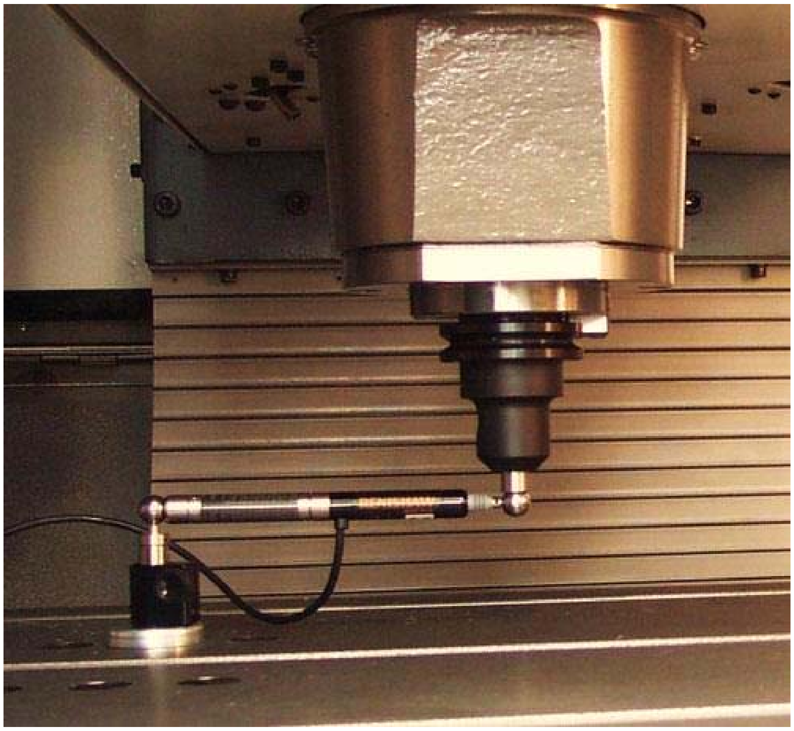
b) Chatter marks during milling [17]

Figure 2.3: Vibrations during machining operations

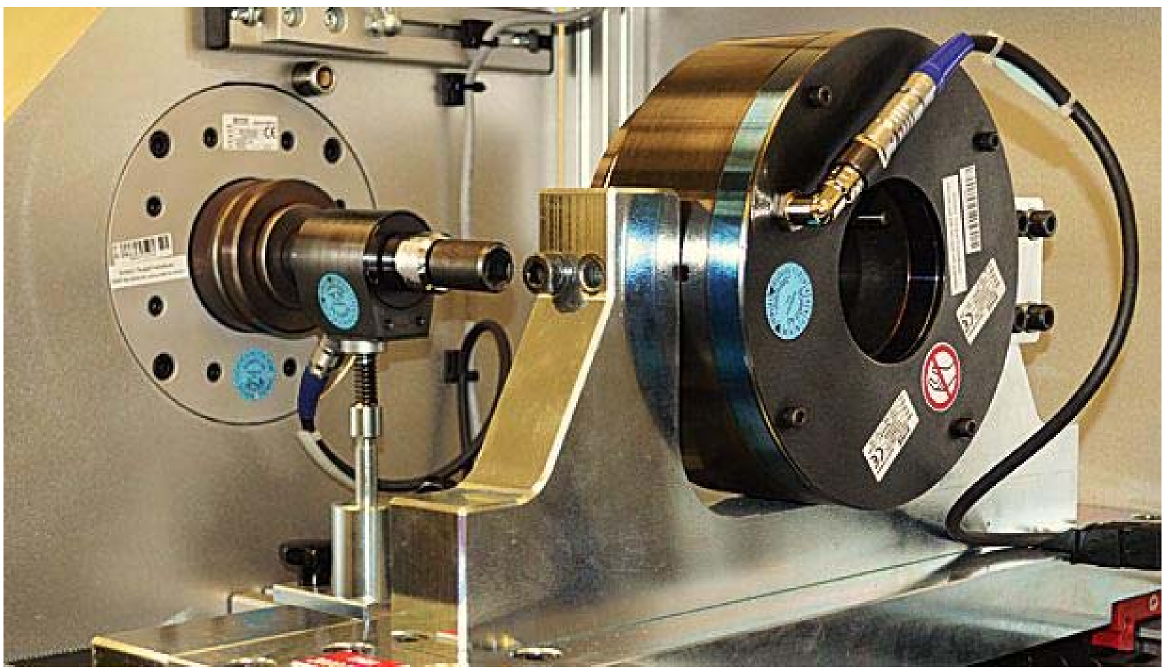
2.4 Machine Tool Condition Monitoring

Machine tool condition is one of the major factors that generate vibrations during machining operations [9]. Vibration levels of machine tool especially of spindle system may change with the usage of machine tool that is reducing the natural frequencies over the time [18]. The change in vibration amplitude levels are unfavorable for metal cutting processes, as it may result poor surface quality of the workpiece and tool failure if the careful selection of cutting parameters is not made. The amplitude levels also cause damage to machine tool itself. Therefore, machine tool's condition monitoring is of great concern. So the aim is to avoid these unwanted vibrations to prevent machine tool from fatigue. An appropriate rectification of these modes of vibrations leads to the longer machine tool life and comparatively lesser maintenance costs [19].

Machine tool condition monitoring involves measurements to detect the problem and analysis of vibrations to identify the cause of the problem. Figure 2.4 demonstrates the recent trends employed for machine tool condition monitoring.



a) Sophisticated condition monitoring method for machine spindle [12]



b) Mounting of transducers for machine condition monitoring [12]

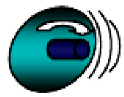
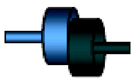
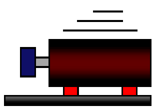
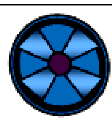
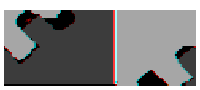
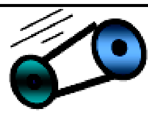
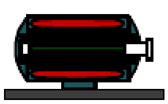
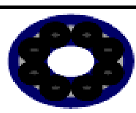
Figure 2.4: Recent trends in machine tool condition monitoring

Condition monitoring gives a clear picture of machine tool condition in a form of vibration signals. As every machine tool problem produces a unique pattern of vibration signals, analysis should be carried out for these patterns in order to identify the cause so that corrective measures can be taken. Therefore, three very important components of vibration are used to analyze the vibration signals i.e. frequency, displacement and spike energy [20].

2.4.1 Vibration Frequency

Frequency can be defined as the number of cycles of an event happens in a given time period. The vibration frequency is considered a powerful diagnostic and analysis tool because the frequency range which generates vibrations is the indication of a machine fault [19]. Ranges of common vibration frequencies corresponding to the common causes against rotating speed are illustrated in Table 2.1.

Table 2.1: Frequency ranges corresponding to the machine tool problem [21]

Typical Fault & Dominant Frequency		Details	Comments
 IMBALANCE	x 1	Imbalance occurs at rotational frequency equal to 1 x rpm of the out of balance part. Usually radial (horizontal or vertical) Sometimes dynamic (axial)	Amplitude is direct indication of degree of imbalance
 MISALIGNMENT	x 2	Typically angular and/or offset problems in couplings Radial + Axial	In both radial and axial directions also apparent at x1rpm because of imbalance inherent to misalignment
 LOOSENESS	X 2 Natural X 1	Mechanical - caused by loose rotating parts or excessive play in machine mountings	Typically a machine will vibrate as it hits a natural resonant frequency during run up or run down - once the associated rpm is passed vibration amplitude decreases
 PASSING	X 1 and (x1)x(No of blades/vanes)	Usually cause a x1 frequency component and a multiple related to the number of vanes/blades	Also referred to as blade pass frequency
 MESHING	No. of teeth x rotational frequency of associated gear	Defects cause low amplitude high frequency vibration and show imbalance, misalignment and tooth damage associated with Gear Mesh Frequencies	Gear Mesh Frequency = output gear rpm x No. teeth in output gear. e.g. 32 tooth gear operating at 300 rpm [300/60 =5Hz] GMF = 32x5 = 160Hz
 BELTS	Related to rotational speed and multiples of rotational speed	Vibration analysis will identify rubbing and misalignment	Use strobe techniques to identify slipping belts
 ELECTRICAL	At supply frequency and multiple of	50Hz(UK)	Vibration will stop when power is turned off!
 BEARINGS	3-10 x rpm & Higher	Bearings indicate problems at high frequency 2- 60KHz (in the early stages of deterioration) and at low amplitude	Range of techniques available with bearing cabability

2.4.2 Vibrations Amplitude

Amplitude is the measure of vibration signal size. As discussed above that the frequency of vibration level is taken as a powerful diagnostic technique in order to detect the mechanical problems [22]. The overall machine vibration monitoring also includes the measurement of vibration amplitudes as it indicates the severity of the problem and resonance. It is also used to locate the source of vibrations. For example, imbalance problem has been detected in machine tool from frequency analysis but vibration amplitudes will indicate the severity of the imbalance in the machine tool. Vibration amplitude can be measured in three different parameters as stated below:

- Displacement
- Velocity
- Acceleration

Figure 2.5 demonstrate the different vibration amplitude parameters. The vibration displacement is just the total distance traveled by the mass attached to spring from one extreme position to the other extreme position. The distance travelled between the two extreme positions is also expressed as the peak-to-peak displacement. The Peak to peak displacement is generally calculated in units identified as micrometer or micron (μm).

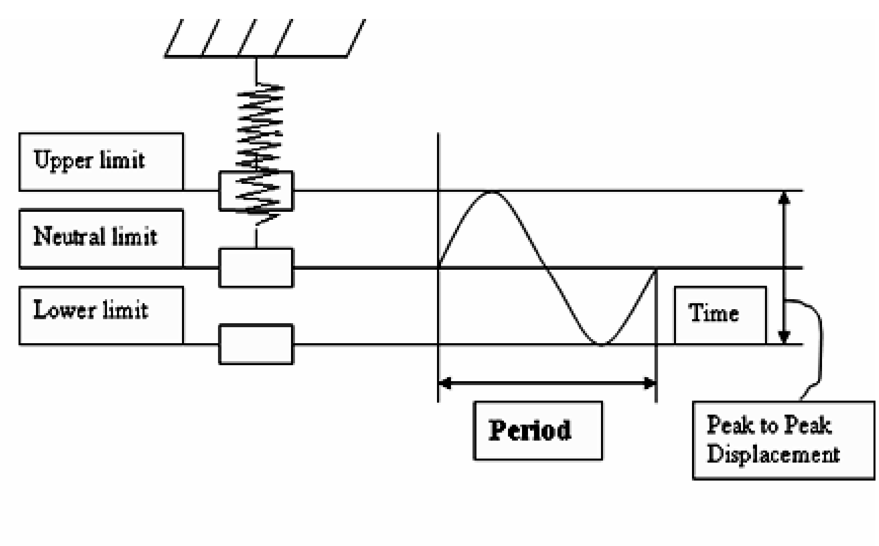


Figure 2.5: Wave form of a mass attached to spring system [23]

The vibration velocity, a measure of amplitude, is just the multiple of displacement and frequency as represented by the equation;

$$\text{Velocity/fatigue} = \text{Displacement} * \text{Frequency} \qquad (2.1)$$

Vibration acceleration is another most significant characteristic to represent amplitude of vibration or in other words magnitude of vibration. By the definition, acceleration is the rate of change in velocity per unit amount of time. Acceleration approaches to its peak values at both extreme ends of the vibration range/limit. Simultaneously at these extreme points the value of velocity becomes zero, conversely where the acceleration is zero the velocity is maximum and vice versa as shown in the Figure 2.6 below.

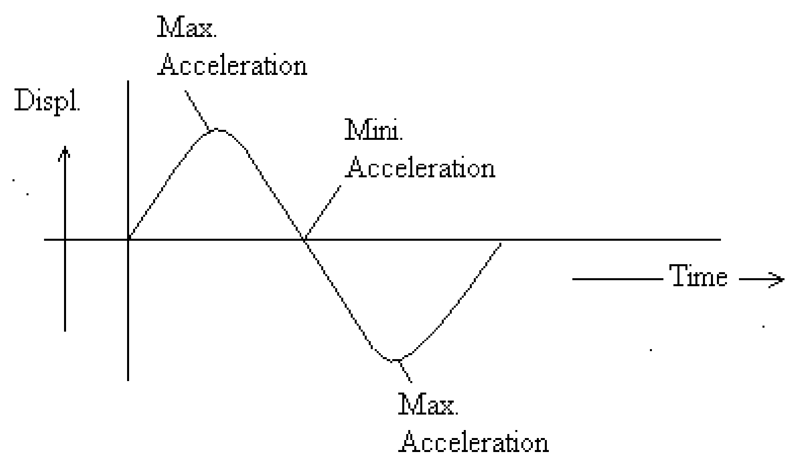


Figure 2.6: Acceleration of a vibrating spring mass system [23]

2.4.3 Spike Energy

Figure 2.7 shows the series of short duration spikes or pulses produced when the bearings of the machine tool get defects. The magnitude of each of these spikes or pulses depends upon the physical size of the error. These are directly related to each other, means the bigger the error, the higher the spike and longer the period of pulse as shown in Figure 2.7. The duration of pulse lasts only for milliseconds. Therefore, the frequency of the vibration can easily be determined through taking inverse of periods.

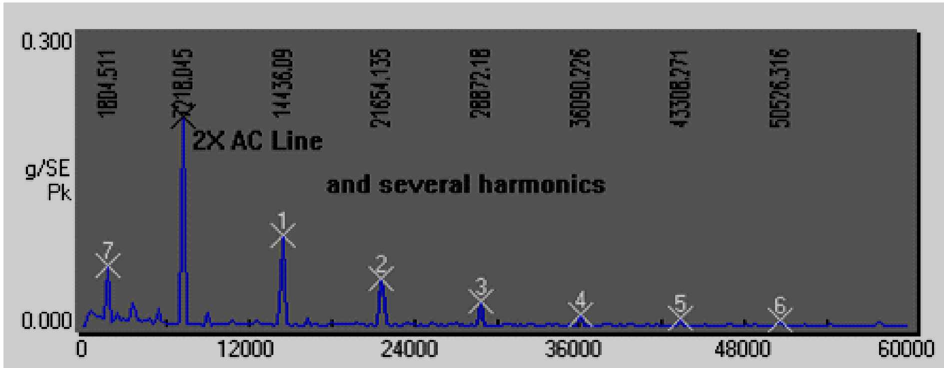


Figure 2.7: Spike energy spectrums [23]

Phase is also an important characteristic to analyze the vibration signals and is defined as the relative difference with respect to time between the two sine waves as shown in the Figure 2.8. It is represented by an angle in radians/degrees. Phase shift is another term used to express the difference between two waveforms. The time delay of one cycle between two waveforms equals to the 360-degree phase shift. It may be positive or negative; means one waveform is leading or lagging to another waveform. This condition is termed as phase lead and phase lag respectively. In Figure 2.8, the upper peak of the wave is moved 90˚ with respect to the lower peak of the wave resulting into a time lag of quarter of the period of the wave which means lower sine wave has a phase lag of 90˚.

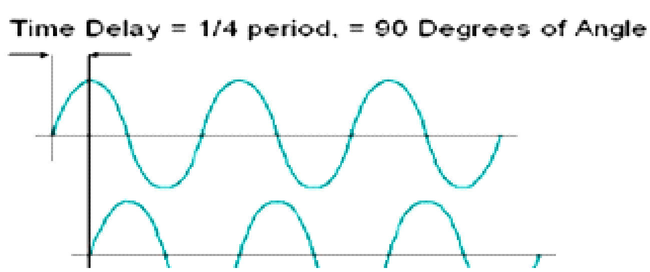


Figure 2.8: Phase difference of two sine waves [23]

2.5 Machine Tool Condition Monitoring and Predictive Maintenance Program

In order to keep manufacturing systems at their optimal efficiency level, predictive maintenance and preventive maintenance approaches are often used in the maintenance program [24]. Preventive maintenance is kind of planned maintenance technique in which maintenance activities are pre-determined and it has been done on the basis of experience, old statistical data and recommendations from manufacturer. For example, oil change in the car has been recommended by car manufacturer after 5000miles to keep the engine at prescribed efficiency level. Any delays in preventive maintenance have detrimental effects on the equipment working which may lead to the equipment failure.

Predictive maintenance is one technique of maintenance in which the condition of a working machine/equipment is assessed to predict when should be the maintenance performed. Predictive maintenance gets edge over preventive maintenance in the form of cost saving where maintenance has to be performed only when failure occurs. Corrective maintenance is the soul of predictive maintenance to permit the correct scheduling of procedures in order to avoid the breakdowns. The both techniques are used simultaneously to maintain the machine at the optimal working conditions. Machine tool condition monitoring is the integral part of predictive maintenance.

2.6 Devices and Techniques for Vibration Measurement

Machine tool measurement is the key technique of vibration condition monitoring. A wide range of vibration sensing devices is available in the market to measure the machine vibrations which are actually the advanced developments of human senses of hearing and feel. For example, human sense cannot detect the initial wear in the machine bearings but the devices can measure the problem. The vibration measuring devices provide consistency, accuracy and reliability for vibration measurements produced as a result of any machine components fault.

2.6.1 Devices for Vibration Measurement

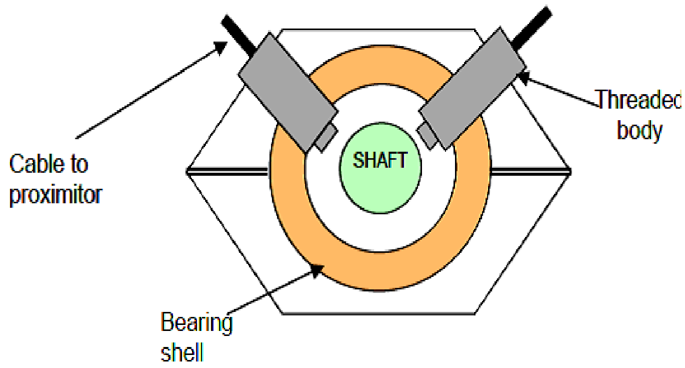
Machine tool vibration measurement is done using different devices which includes data collector devices known as pick-up probes/transducers and is considered the heart of a vibration measuring instrument. This is the device that converts the machine mechanical vibrations into the electrical signals. These signals are processed into the amplitudes, phase shifts, frequencies and many different modes of vibrations viva data analyzer which is further attached to the software for detailed analysis.

There are three different types of pick-up probes used as data collectors i.e. displacement probe, velocity transducers and accelerometer. Their name describes the way they work not necessarily indicating the parameters to be measured.

However, with few exceptions, the transducer provided as standard with nearly all present-day vibration meters, analyzers as a data collector is the accelerometer**.**

i Displacement transducer

It is also known as proximity probe and a non-contact displacement probe. It works on eddy current principle which produces excitation signals. These signals indicate the change in position and hence indicating the fault. It has limited applications because it requires a permanent mounting on the machine tool. Typical low frequency range for proximity probes are 0Hz to 10Hz. The common application involves the condition monitoring of relative shaft movement. Figure 2.9 (a,b) shows the schematic of displacement probe and commercially available probes.



a) Schematic of displacement probe

b) Commercially available probes

Figure 2.9: Displacement transducer [21,25]

ii Velocity transducer

It is commonly used for measuring machine tool condition like imbalance, misalignment and looseness. Primarily there are two kinds of velocity transducers, the piezoelectric and the mocking coil type. It is a self-generating sensor that does not need any amplifier to generate vibration signals. It consists of three major components: coil, permanent magnet and a spring that supports the coil wire. It is filled with an oil to damp the spring oscillation action. A voltage induced when the permanent magnet moves relative to the coil, this relative motion between coil and permanent magnet generates electromagnetic flux which is directly proportional to the magnitude of vibration. So the vibrations can be analyzed through the output volts generated by the velocity transducers.

1KHz is the typical range designed for velocity transducer. It is usually fixed on the larger machines for vibration measurements. It is relatively cheap but quite heavy. It is not recommended for the measurement of bearing defects which is highly unlikely to be identified by velocity transducers until the noteworthy damage has occurred. Figure 2.10 shows schematic of velocity probe.

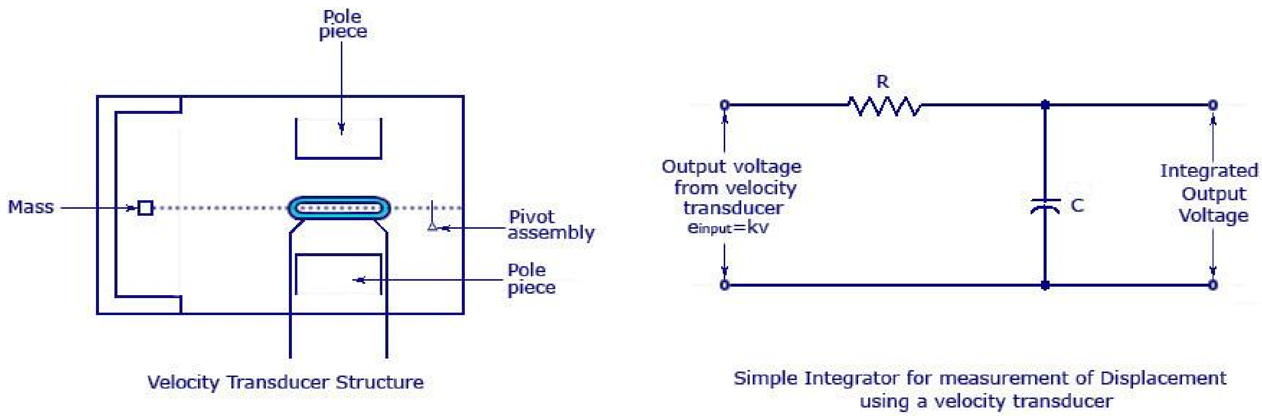
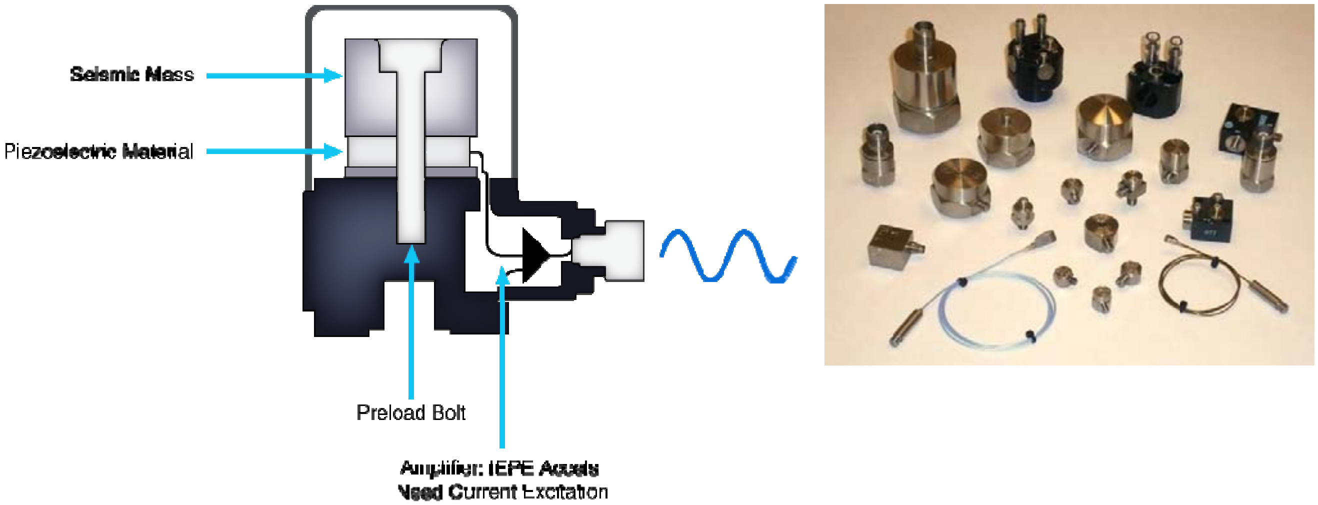


Figure 2.10: Schematic of velocity transducer [26]

iii Accelerometer

These are the most commonly used and versatile transducers these days. The seismic piezoelectric accelerometer produces an output electronic charge when it is in contact to the vibrating surface of the machine. This phenomenon is called piezoelectric effect. In addition, the material is known as piezoelectric material, which is the heart of the transducer. By the expansion and compression between the piezoelectric plates, the electric current produces which is directly proportional to the numerical value of the vibration acceleration as shown in the Figure 2.10(a). Commercially used accelerometers are shown in Figure 2.10(b)

Typically, three different modes of accelerometer mountings are used i.e. magnetic, adhesive and stud mounting. 10Hz to 30 KHz is the typical frequency range for accelerometer. It is robust and portable. It is insensitive to the signals having 5Hz frequency.



a) Schematic of accelerometer

b) Different types of accelerometer available in the market

Figure 2.11: Accelerometer (a) schematic of accelerometer [27] (b) types of accelerometer [12]

There are two main types of frequency vibration analyzers available with different functionalities and wide range of features.

i. Swept or analog filter frequency analyzers.
ii. Digital FFT frequency analyzers

i. Analog frequency analyzers (swept filter)

These analyzers are introduced in 1950's, one of the earliest instruments that are available for performing vibration analysis. The principal resemblance of analog frequency analyzer is with the radio. Majority of the societies have radio broadcasting service that is received by radio when a user tunes the radio frequency by using 'tuner' installed in the radio set. That allows the listener to synchronize the radio set frequency and the radio broadcasting frequency so the listener can hear a particular station. The tuner is basically an electronic filter that accepts the broadcasting frequency while rejecting all the other radio broadcasting frequencies present simultaneously in the air.

In a similar principle swept filter, vibration analyzers are made. A machine can vibrate on the different range of frequencies that depend upon the rotating shafts and motors, running at different frequencies. The task of these analyzers is to detect the problem causing part of the machine under observation that is generating excessive vibrations at a particular frequency simultaneously filtering out the other insignificant levels of vibration frequencies.

Now a day these analog or swept filter vibration analyzers are outdated due to more sophisticated technological advancement. However, some of the manufacturers are still producing these kinds of instruments for particular purpose.

ii. Digital frequency analyzers (FFT)

FFT analyzer is the most common equipment that is used in vibration analysis. It is also famous with the name of "Magic box" into which the vibration signal data is fed for analysis as an input and it provides the spectrum of vibrations as output. The output results are very reliable [29].

2.6.2 Techniques for Vibration Measurements

Accelerometer transducer is used as data collector device in most of the techniques for machine vibration measurements. The technique may be different depending upon the applications.

i. Hand held devices technique
ii. Portable devices technique
iii. Permanent devices (hardwired) technique

i Hand held devices technique

Vibration pens with built in transducers attached with a processing unit are commonly used for the machine vibration monitoring. These devices generally offer a direct readout and optional feature of headphones as shown in the Figure 2.12. These devices have some limitations in usage due to their susceptibility to inconsistent readings. This may happen due to transducer inaccuracy as result of angle of contact to the machine target point and pressure applied.

Figure 2.12: Handheld devices [12, 28]

ii *Portable devices technique*

These devices are more sophisticated than hand held devices with enhanced features. They used data loggers to collect the data which having either direct capability of reading or downloaded through supporting software as shown in Figure 2.13. The main advantage of using these devices is that it can be used for frequency analysis when equipped with analytical software.

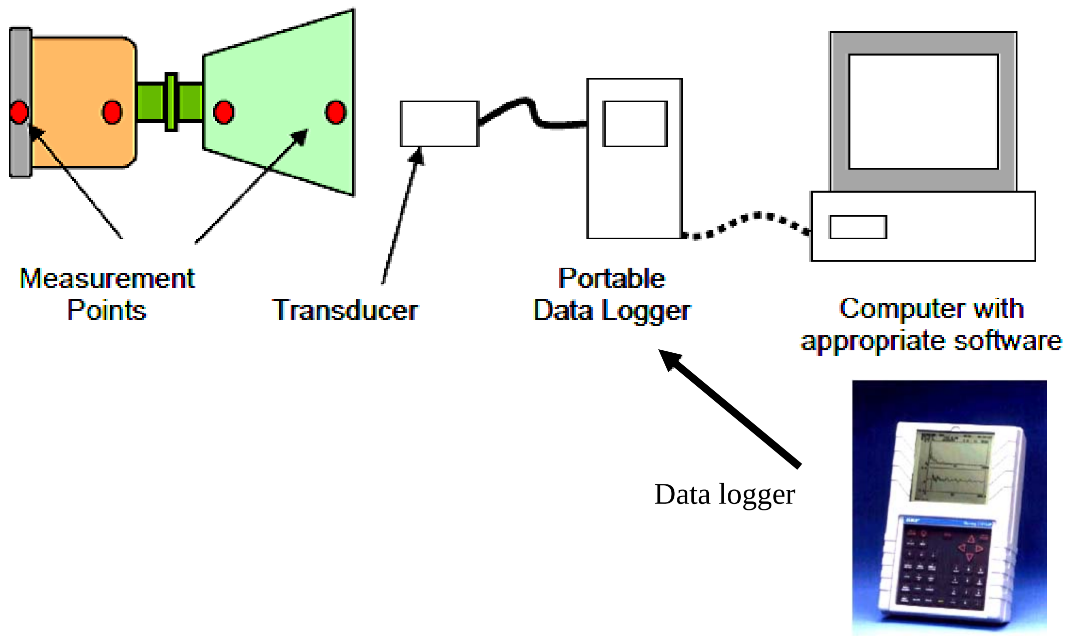


Figure 2.13: Portable devices [21]

iii Permanent devices technique

This technique is used in most critical applications. In this method, the transducers are permanently fitted on the machine as shown in Figure 2.14. It acts as a small control room for the machine which gives information related to vibration measurement including different features like alarm, trend and peak.

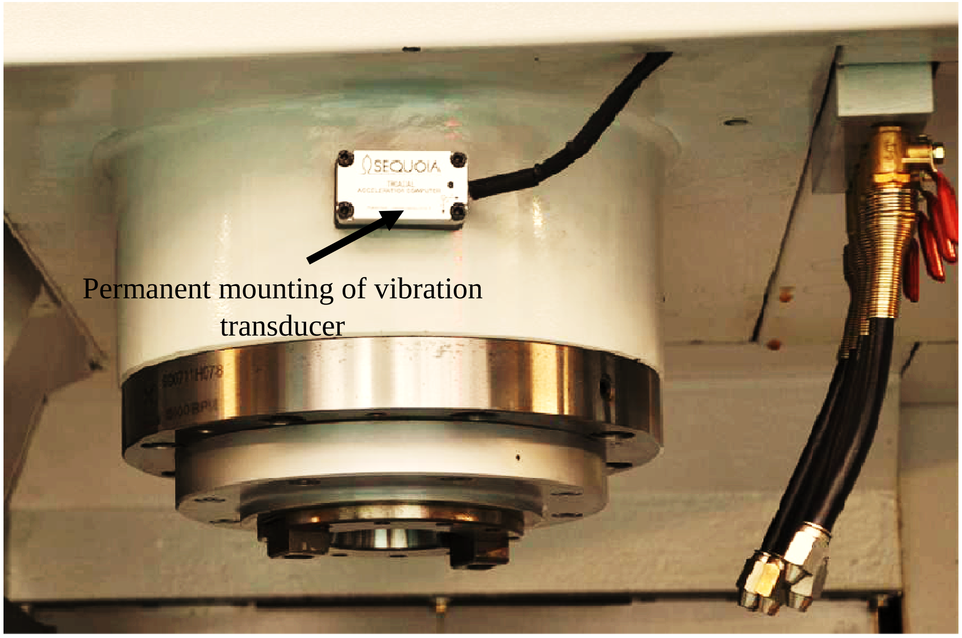


Figure 2.14: Permanent devices [12]

2.7 Literature Review related to Study of Mechanical Vibrations in Machine Tools

Every machine tool industry has a major concern to compete the market by increasing the productivity and quality of the product through optimizing the machining processes. During the fulfillment of the above said objective, it is observed that selection of appropriate machining parameters is not the only factor that is contributing to the quality of the machined part rather the machine vibrations are also needed to pay attention.

Literature indicates that Taylor is the first one who worked on machine tool vibrations (chatter) in 1907 [30]. However, Arnold in 1946 publishes the first brief investigation about the machine tool vibrations and concludes that the machine tool acts as a simple oscillator [31]. Soon after, Gurney et al give a widely believe theory that chatter is a result of wave forms produced on the surface of workpiece by tool passes [32].

Prior to 1961, all the machining processes are taken as steady state processes. On the basis of this idea, heavy structured machines are made for damping of vibrations. But in actual, machining has dynamic properties because of fluctuating cutting forces on tool tips [18]. In the pioneering work 1962, Albrecht gives the knowledge of self–induced vibrations in metal cutting. The study concludes the relationship between cutting forces, share angle and chatter. Research exposes that chatter affects the share angle during cutting which ultimately disturbs the uncut chip thickness and surface roughness [33].

Although literature depicts a good contribution of research on chatter but it is still considered a problem in machining process with the increasing requirements of good surface quality for manufactured parts. Altintas defines chatter as a form of relative structural self-excited vibrations between the cutter and workpiece practiced at the cutting region in milling operations. It is also discovered by the same author from the investigation that regenerative chatter builds up when excessive vibrations influence larger axial and radial depths of cut [34]. Lee et al give the clear picture of workpiece response to chatter in milling operations. Research considered tool as a spring- mass system and workpiece as an Euler beam [35].

Dimla gives the study that during machining operations, chatter in the machines at any level has damaging effects on the machine tool particular the life of machine tool spindle. In this case, time and resources will be used in introducing the additional processes to cancel out the effects [36]. Cao et al give the research with numerical model which exposes that the induced vibrations between tool and workpiece associated with the exciting force acted as a decisive element in machining chatter [37].

Andrew et al give the study to distinguish between chatter and forced vibrations effects in horizontal milling machine. This research concludes that chatter has major importance while machining ferrous alloys and forced vibrations can be significant during the machining of light alloys [2]. Tobias gives a research that during the machining process, the vibrations on the machine spindle are generated by the unbalanced force caused by the cutting process [3]. Koenigsberger et al conclude that the danger of chatter would appear to be slight in the milling machine, but resonance vibrations due to the fundamental frequency of cutting or any of its forced vibrations would have to be vigilantly watched [4].

Gaber et al investigate the causes of mechanical vibrations in machine tools. The study investigates the bearing effects on machine tool spindle vibrations by developing a calibrated dynamic stiffness matrix method. The study concludes that due to wear of bearings, natural frequency of machine tool reduces over the time which changes the vibration levels of spindle system [18]. Kirby et al give the results that turning center spindle running with damaged jaws has different vibration amplitude levels than with new jaws [38].

The above mentioned literature shows the sources and significance of machine tool vibrations. The literature review related to investigations of effects of these machine tool vibrations on different characteristics of workpiece during machining operations will be discussed in chapter 3 in details.

CHAPTER 3
LITERATURE REVIEW

In this chapter detail discussion of workpiece material, historical review of metal cutting, different characteristics of workpiece i.e. surface roughness, dimensional accuracy, tool wear and their requirements in manufacturing processes, design of experiments and analysis techniques are the part of the discussion in this chapter.

3.1 AISI P20 Tool Steel

AISI P20 tool steel (prehardened) is an alloy tool steel which offers good machinability even in the hardened and tempered conditions [39].

3.1.1 Composition and Microstructure

Table 3.1 shows the typical chemical composition for AISI P20 tool steel.

Table 3.1: Chemical composition of AISI P20 tool steel [40]

Composition	C	Mn	Si	Cr	Mo	S	Fe	Hardness (HRC)
Standard	0.28-0.4	0.6-1	0.2-0.8	1.4-2	0.3-0.55	0.03	Balance	30-35

Different alloying elements (Chromium, Molybdenum, Sulfur, Silicon and Manganese) are used to impart the strength. The presence of Chromium enhances the toughness and the hardness of the AISI P20, whereas, the sulfur and molybdenum impart good machinability characteristics [39]. AISI P20 tool steel offers an excellent toughness and resistance to softening, low to medium wear resistance, deep machinability, elevated temperature effects, medium level of grindability, medium distortion towards heat treatment, greater values of resistance to decarburization and polished finish [41]. Figure 3.1 shows the typical microstructure of AISI P20 tool steel.

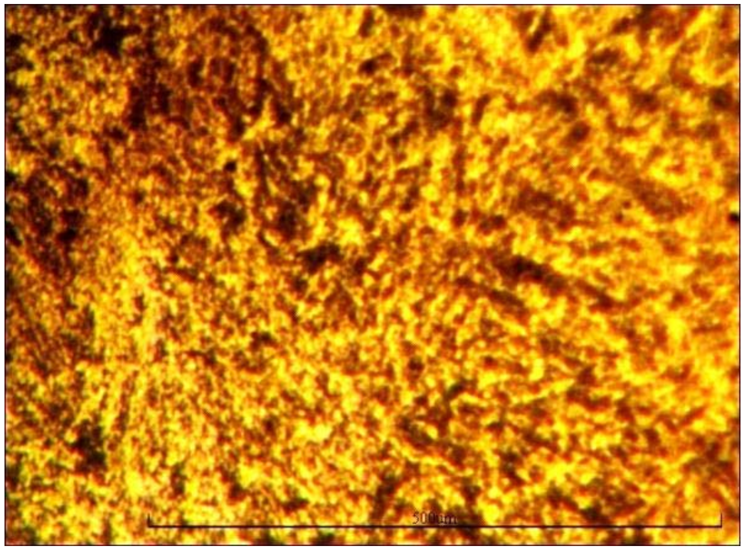


Figure 3.1: Optical micrograph showing microstructure of AISI P20 [46]

3.1.2 Properties

AISI P20 is one of the most widely accepted materials for plastic moulds and casting dies due to better physical and mechanical properties [41]. Table 3.2 and Table 3.3 represent some typical physical properties and mechanical properties of AISI P20 respectively.

Table 3.2: Physical properties of AISI P20 [41]

Physical property	Typical ranges
Density (g/cc)	7.85
Modulus of elasticity (Psi)	2.97×10^6- 20×10^6
Thermal conductivity (Btu in/ft^2h˚F)	202-205
Specific heat (Btu/lb)	0.11

Table 3.3: Mechanical properties of AISI P20 [41]

Mechanical property	Typical ranges
Tensile strength, ultimate (MPa)	965-1030
Tensile strength, yield (MPa)	827-862
Compressive strength (MPa)	862
Elongation at break	20.0%

3.1.3 Industrial Applications

AISI P20 tool steel has been developed with specific properties which relate to its applications. It is typically suitable for medium and large size moulds, injection moulds, extrusion dies, aluminum die casting, forming tools, home equipment and other large daily goods like containers due to excellent weldability with least hardness elevation. If maximum surface hardness is required for compression application like plastic dies and moulds, the steel can be case hardened or nitriding. Good mirror polish ability, excellent weldability with greater toughness and nitriding properties makes it a primary choice of plastic mould makers [42-46].

3.1.4 Comparison of AISI P20 Tool Steel with other Materials

Table 3.4 illustrates a brief comparison of AISI P20 tool steel with other available materials used for mould making.

Table 3.4: Comparison of different materials [47-49]

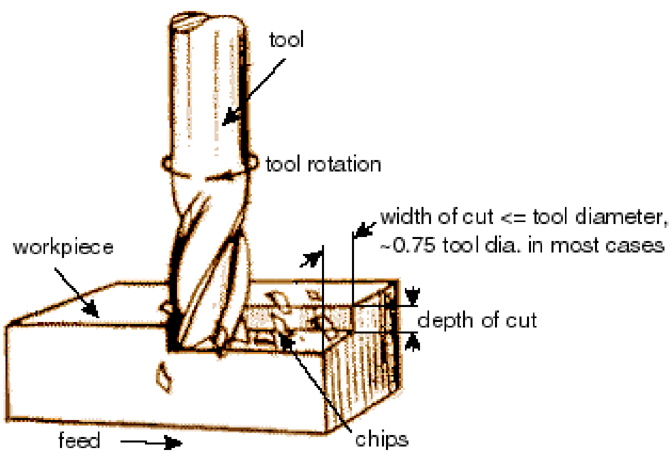
AISI P20 tool steel	Mild steel	High speed steel
Excellent toughness	Less brittle, softer material	Medium toughness
Excellent weldability with less hardness elevation	Medium weldability	Wear resistance
Good performance at elevated temperature application	Malleable	Withstand higher temperature
Greater resistance against decarburization	Poor resistance to corrosion	High abrasion resistance
Mirror like surface polish	Medium surface finish	
Good nitriding properties made it best choice for mould manufacturing	Easily annealed	

3.2 A Review of Metal Cutting Processes

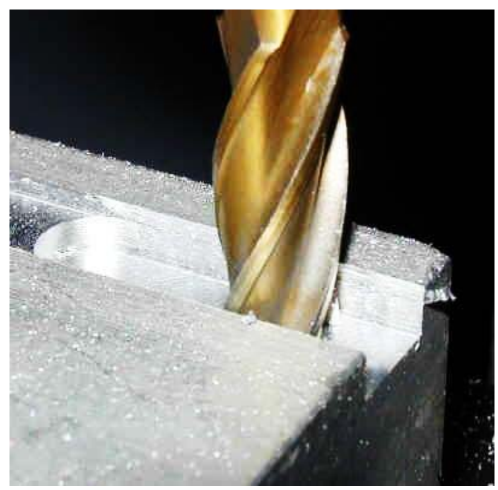
Metal cutting process is considered as the most universally employed metal shaping process to produce different profiles [50]. In literature, removal of a thin layer of metal from a surface of large workpiece with the help of a sharp edge tool is defined as metal cutting process [51]. During any metal cutting process, the material is removed by the tool and workpiece motion relative to each other. Machining processes share a major portion of industrial applications, e.g. aerospace/aircraft, automotive, and home appliances etc. Machining processes history starts from late 18^{th} century, when tool manufacturing starts from carbon steel (hardened) material to machine easy-to-cut materials [51]. The evolution in different aspects of machining technology like in machine tool structures, dynamics, power and stiffness, sophisticated machine tool control (NC and CNC) has been made afterwards. Moreover, development is observed in cutting tools, their materials, coating materials and coating techniques and in the geometry of the tool. Metal cutting process can be categorized into four main types listed below:

- Turning process
- Milling process
- Shaping/Planing process
- Drilling process

Among all mentioned metal cutting processes, milling process is one of the important and widely applicable processes for metal cutting to generate different profiles. Milling operations has a capability to remove material faster than any other machining operations with a reasonably high surface finish [52]. In milling operation, a rotating tool with multiple cutting edges is moved slowly relative to the workpiece to generate a plane or straight surface. The direction of the feed motion is perpendicular to the tool axis of rotation as shown in Figure 3.2.



a) Schematic of end milling operation



b) End milling operation

Figure 3.2: Milling process (a) schematics of end milling operation and (b) end milling operation in practical [12]

3.3 Common Problems in Machining Processes

There are several sources which can generate problems associated with the machining process. The consequences of these problems produced during the machining operations can be observed on the part of workpiece surface in terms of poor surface quality, dimensional inaccuracy as well as tool wear. The major sources responsible for producing machining problems are listed below:

1. Machine tool problem
2. Workpiece problem
3. Cutting tool problem
4. Thermal errors
5. Environmental effects

3.3.1 Machine Tool Problems

All machine tools are composed of different structural elements. During any machining process, a machine tool is exposed to different cutting forces produced in the result of interaction of its structure elements and machining operation. The generation of forces caused problems in the machine tool. Bryan et al carried out research on the machining problems and give the study that the machine tool is contributed to a major portion (60-65%) of the total errors generated in a machined workpiece surface [53]. Therefore, a significant focus has been given to the machine tool's measurements and compensation of sources of problems in the recent years to eventually enhance the accuracy of machine tool [54-57]. Some of most prominent sources of problems affecting machine tool accuracy are listed below:

i. Stiffness
ii. Spindle vibrations
iii. Flatness, Straightness and Smoothness

i Stiffness

Most of the researchers give the findings related to stiffness during the past decades [58-60]. Traditionally, machine tool has heavy foundation structure because of; firstly, high stiffness in the machine is very important to reduce the deformation caused by the forces produced during machining. Secondly, the stiffness is required to reduce the deformation caused by the machine structure itself which can generate problems during machining operation. Besides the above two main influences, stiffness of the machine tool has influences on machining processes as well. The machine tools with stiff structures are less prone to vibrations at higher frequencies than compliant structures.

Vibrations are produced in the structure of machine tool during any machining process. These vibrations can be transmitted to the machine structures having low ability of damping causing a deflection in the structure. This deflection is time dependent and can cause the permanent damage in the structure of machine tool if the compensation will not be provided to the machine tool. The vibrations produced during machining process, if matches to the fundamental frequency of machine would also affect the surface quality of the machined part. So the best way to avoid these vibrations is the periodic measurements of the machine tool stiffness and provides compensation to the structure. Material of machine tool structure also plays an important role in damping these vibrations. For example, the damping characteristics of cast iron are different from the other materials like steel and granite. Therefore, added damping can be achieved in the structure by mixing of granite particles with the base material. To quantify the stiffness of the machine tool structure, few commercially used FEA (finite element analysis) software like ANSYS, and NASTRAN are available to investigate the stiffness [61].

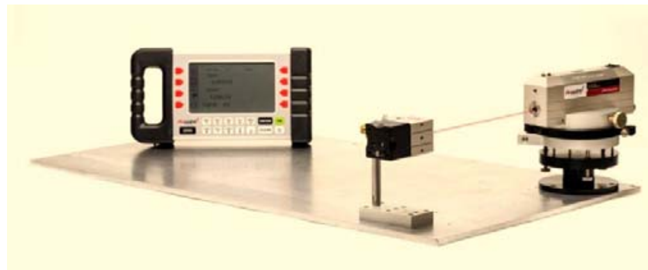
ii Spindle vibration

During any metal cutting operation, spindle of the machine is exposed to the vibrations due to its rotating nature. These vibrations will cause deflection in the machine spindle. The spindle deflection significantly affects the surface quality of machined parts and tool life during the machining operation [62]. The machine tool spindle vibration can propagate within the machine tool structural, causing higher amplitudes of vibrations in the machine tool structure. The natural frequency of machine tool spindle is also important in order to avoid resonance. Therefore, it is required to understand the relationship between machine tool and the machining process. To measure the frequency of each part of the machine structure is difficult, therefore estimation of spindle speeds to avoid the resonance range are recommended.

iii Flatness, straightness and smoothness

A machine tool is the combination of different components with rotating and sliding functions. It is said that a machine tool consists of various degrees of freedom which are kinematically linked to each other's movement. Therefore, for the smooth working of a machine tool during a machining operation, it is required that movements of all the components are having the right degree of freedom actions. Flatness and straightness play an important role to achieve the above mentioned requirements. The level checking of machine to ensure the flatness and straightness as shown in Figure 3.3 (a-d) is an essential procedure during any machining operation.

a) Level check for flatness



b) Modern laser flatness technique employed for surafce flatness check

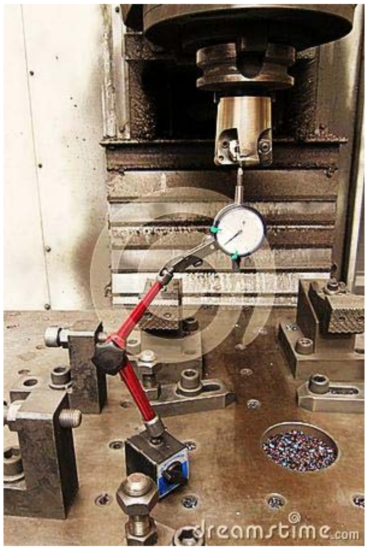
c) Flatness check for machine bed

d) Smoothness check

Figure 3.3: Different checks for machine (a) level check for flatness (b) laser flatness technique (c) flatness check for machine bed (d) for smoothness [12,63]

3.3.2 Cutting Tool Problems

As the machining process is a combination of cutting operation and machine tool. Therefore, even if all the problems on the part of machine tool have been carefully watched, quantified and compensated. Still there is a chance of error occurring during machining operations which is associated with the cutting tool. The cutting tool errors significantly affect the cutting forces, surface quality and tool life as well [64-65]. It is required to get the understanding of cutting tool related problems so that they can be eliminated during cutting operation.



a) Tool offsetting check using dial gauge

b) Machine spindle check

c) Tool holder check

Figure 3.4: Tool checks (a) tool offsetting check using dial gauge (b) machine spindle check (c) tool holder check [12]

3.3.3 Workpiece Problems

Material of workpiece plays an important role in the machining operations. It is generally recommended that material to be cut should be chosen according to the requirements. However, the factors listed below are the factors that can produce nonconformance.

i. Workpiece material and heat treatment process
ii. Part clamping
iii. Working environment

i Workpiece material and heat treatment processes

Different workpiece materials would behave differently during machining which affect the different dependent parameters like surface quality, dimensional accuracy and tool wear. The appropriate selection of tool materials with respect to workpiece material is required for the better machining operations. The best way to quantify the errors of workpiece material is to carefully examine the chemical composition, its microstructure and the hardness of the material so that proper selection of tool material can be made. For example, if softer material likes aluminum 6061-T6 will machine with the help of carbide or high speed steel tool. Aluminum will stick to the cutting edge of the tool producing built-up edge wear to the tool which ultimately affects the surface finish of workpiece and shorten the tool life. A list of workpiece material relative to the tool material for different machining operations as recommended by the machining catalogues is given in the Table 3.5 below [66].

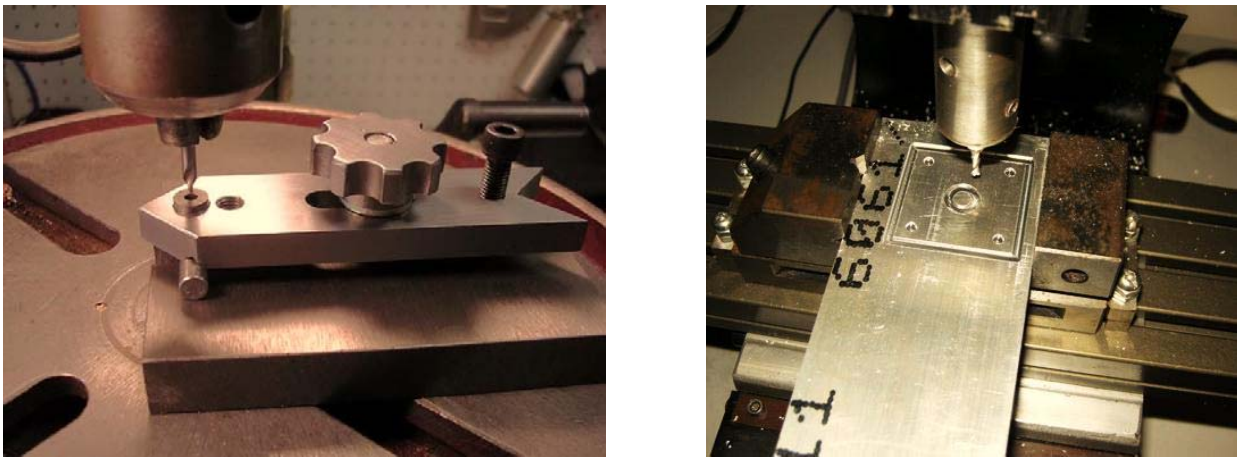
Table 3.5: Recommended workpiece and tool material for different processes [66]

Workpiece material	Recommended tool material	Type of process
High silicon aluminum alloys, non-ferrous, non-metallic	PCD	Roughing, semi finish, finish
Grey ductile malleable iron	Silicon nitride	Roughing, semi finish, finish
High-temperature alloys, hard steels, cast iron	Whisker-reinforced ceramics	Roughing, semi finish, finish
Iron steels	Ceramics (Al_2O_3-TiC)	Roughing, semi finish, finish
Iron and steels above 40HRC, pearlite grey iron below 30HRC	CBN	Roughing, semi finish, finish
Iron steels, stainless steels, high temperature alloys	Triple coated carbides(TiC/Al_2O_3/TiN)	Roughing, semi finish, finish
Iron steels, stainless steels	Ceramic coated carbides	Roughing, semi finish, finish
Iron steels, nickel based, stainless steel	TiN and TiC coated carbides	Roughing, semi finish, finish
Irons, titanium, high temperature alloys, stainless steel	Tungsten carbides	Roughing, semi finish, finish
Iron steels and stainless steels	TiN coated HSS	Heavy roughing
Iron steels, stainless steels	HSS	Roughing, semi finish, finish

Besides some more techniques to avoid workpiece material problem, heat treatment is also employed. This method results into decrease in the ductility of material without affecting specific mechanical properties which are required for workpiece.

ii Part clamping

Part clamping plays an important role in producing the quality product to conform the requirements. Cutting forces produce during a machining operation which will affect not only the machining process but the machine structure as well. Poor clamping of workpiece on machine will result into the shift of workpiece from its original position during cutting operation. This alters the magnitude of cutting forces which results into the failure of cutting process.



a) Finger plate clamping b) Clamping for milling operation

Figure 3.5: Part clamping (a) Finger plate clamping (b) clamping for milling operation [12]

iii Working environment

The use of lubricants in machining has a prime importance associated with the tool life and chip evacuation. The lubricants are used with the purpose to reduce the friction coefficient between cutting edge of the tool and the workpiece [67]. It also lessens the cutting zone temperature, which results into improved tool life by providing small material properties changes. Though, the cutting environment contributes in producing better surface finish in most of the metal cutting processes. It is advised to keep in view that the lubricants usually liquids have higher values of specific heat as compared with cutting tool material and workpiece material. Therefore, if the lubricant has low value of specific heat than cutting tool material and workpiece material, it may cause thermal contraction or expansion errors during cutting operation.

3.3.4 Errors due to Thermal Conditions

With the increase demand of precision quality of the products, the manufacturers are compelled to account the thermal errors influences during the machining operation as they may contribute to the other errors as well [62]. Today's intelligent controls, bearings and actuators of machine tools are capable to a fair degree of control to incorporate the errors before as well as after the machining. However, the effect of thermal errors generally cannot be quickly cured once they initiate.

3.3.5 Environmental Effects

Most of the errors explain above can be eliminated or minimized by paying attention and using few methods. But the environmental effects of the surrounding may be difficult to handle if it will instigate once. It causes permanent damage to the machine tool. Few of the errors cause by environmental effects are listed below:

i. Vibrations from surrounding
ii. Spindle distortion

i Vibrations from surrounding

In addition to the vibrations produce as a result of machine tool structure and cutting process, vibration can be transmitted to the machine from the surroundings through the foundation of the machine tool. Unleveled surface of shop floor, neighboring machine tools, moving people and seismic vibrations produced from vehicles like train, truck and car could be the major sources of these floor vibrations. Therefore, efforts are made to reduce the floor vibrations by providing isolation. The effect of floor vibrations can be significantly reduced if the identification of vibration source and its vibration frequency can be made. Vibration analyzer can be used to measure the frequency of the floor vibration by just attaching the accelerometer to floor. Vibration produced through walking and talking of passerby around machine tools can also cause variations during metal cutting operations.

ii Spindled distortion

Modern CNC machine tools use air in the spindles for the rotation of workpiece or cutting tool. If the spindle remains stationary for a long time period with air, distortion to the spindle takes place due to differential contraction among locations. Eccentric motion and localized size reduction in spindle can be resulted from this distortion and also changing the stiffness and the interior clearances of the spindle. This problem can be remediated by disconnecting the air supply to the spindle if the spindle is required in idle state for a long time period.

3.3.6 Accuracy

Accuracy can be defined as ability of a machine tool to go to a new position as commanded through machine controls [63]. Motion accuracy takes as one of the most important indicator in the evaluation of numeric control (NC) machine tool's performance because it has a direct influence in accuracy of machined parts. Results obtained from the motion accuracy measurements are used as the reference during the adjustment of parameters in an NC machine tool [68-69].

3.3.7 Repeatability

Repeatability is one of the important features of machine tool in which machine tool can attain a position again and again. If the same point can attain by the machine tool, it is said the machine tool is having good repeatability characteristics. International Standard (ISO 230-2) [70] is commonly practiced standard for repeatability of the machine tool worldwide.

3.3.8 Resolution

The term resolution is the representation of the smallest increment of motion for a machine. As the machine is the combination of different components, therefore, the machine resolution should be described in a quantity which represents movements of all the components. For example, let's "m" is the machine tool resolution than all motions of the components in the machine should be represented as the integer multiples of "m". Usually the machine tool manufacturers or the users take the "precision" to represent the resolution of the machine which generally results into a false assumption about the term "accuracy".

3.4 Surface Finish

A surface can be defined as the outer boundary of a material which separates it from the next surface boundary of another material. The envisioned surface is known as nominal surface. This is the surface which usually dimensioned on the drawings.

The surface texture is classified into different types known as waviness and surface roughness as shown in the Figure 3.6.

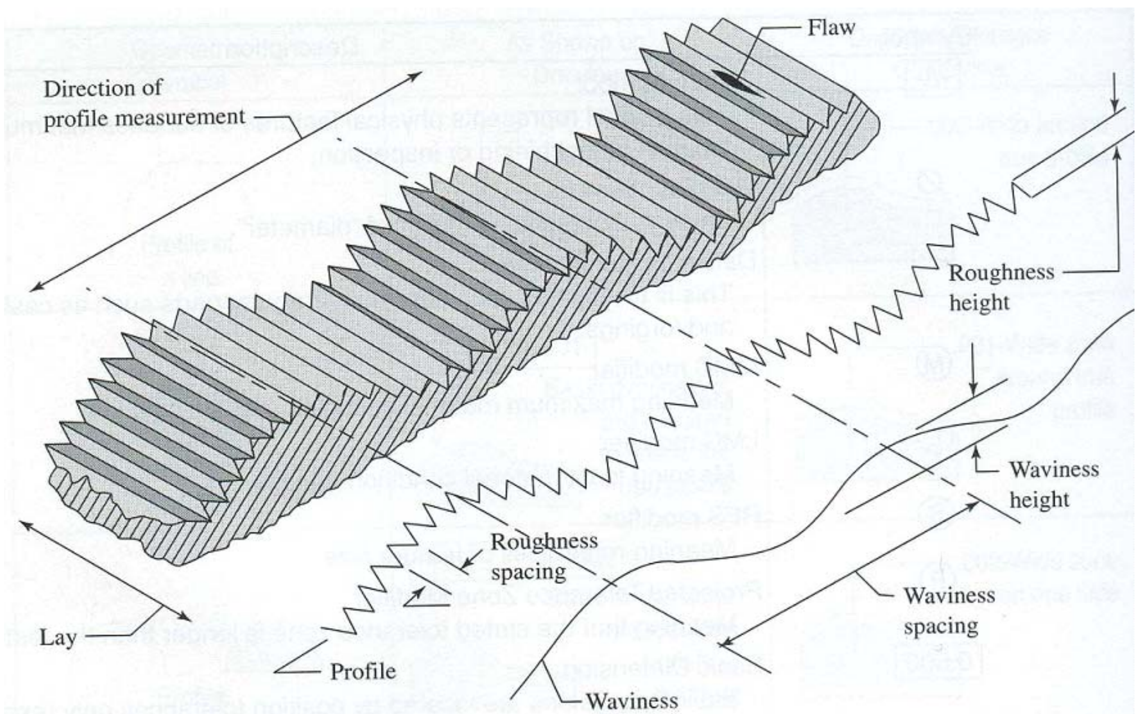


Figure 3.6: Schematic of surface texture [71]

Surface roughness comprises of surface irregularities in the form of wave length. The vertical deviation of surface is considered as the surface roughness values. Larger the vertical deviation greater the surface roughness value, smoother surface represent smaller vertical deviations. Greater the surface roughness will cause the quicker wear due to higher value of friction. So the performance of the component can be predicted by the surface roughness parameter. Generally rough surface is not required in engineering applications and the relationship between surface roughness values and cost of machining is inversely exponential.

3.4.1 Roughness Amplitude Parameters

Surface finish and surface roughness are the most common parameters used for the quantification of smoothness in surface finish [71]. Surface roughness has been defined under the concepts of surface terminology and metrology, such as surface texture, surface roughness, waviness and surface damage. Following parameters used to specify the surface roughness:

i Center-line average (Ra)

It is also known as average roughness [71]. It can be defined as the deviation measurement around the center line for a given evaluation length. This is the most widely used parameter for the measurement of surface roughness. However, in-length measurements, its use are limited due to difference of peaks and valleys of machined surface profile [72]. The formula for Ra is shown below. A schematic representation of Ra value is shown in Figure 3.7.

$$R_a = \frac{1}{L}\int_0^L |r(x)|\,\mathrm{d}x \qquad (3.1) \qquad [73]$$

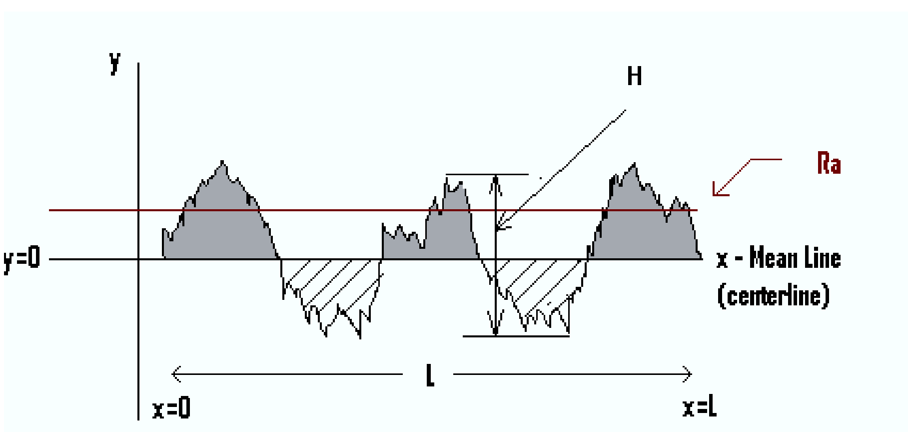


Figure 3.7: Schematic of Ra [12]

ii Maximum peak-to-valley roughness height (Rt)

Maximum peak-to-valley roughness height can be calculated by the taking measurement of distance between two lines that are drawn parallel to the center line. This parameter is used to determine bigger deviations around the mean line. It is used along with Ra parameter as common indicator of roughness [72].

iii Rz, Rq, Rp and Rv parameters for roughness measurement

These are also the parameters used for surface roughness measurements. Rz indicates average height between peaks to valley, Rq represents root mean square values of roughness, Rp is measurement of highest single peak value around the central line and Rv is the value of deepest valley which is below the central line [73].

All the above discussed parameters are used for the two-dimensional measurements of surface roughness. However, the surface roughness measurements are carried out for an area is called three-dimensional surface roughness and is denoted by "S" [74]. Different other types of measuring methods are also employed for surface roughness measurements including visual, electronic scanning probe and optical methods [72].

3.5 Surface Roughness Measurement Techniques

Generally, there are two kinds of surface roughness measurement techniques employed to measure the surface roughness i.e. contact and non-contact.

3.5.1 Contact Measurements

Stylus profile is a technique used for surface roughness measurements. This instrument contains diamond stylus profiler which directly touched the surface and take measurements through moving on the surface and taking roughness values. The stylus is dominantly used in literature and industry. The advantages of the use of this instrument are, it is inexpensive, quick and easy to use, has good repeatability. The value of surface roughness obtained from this method is generally used as an index to compare with other techniques.

Scanning force microscope (SFM) is another surface roughness measuring instrument used as the contact measure techniques [75].

3.5.2 Non-contact Measurements

Measurement of surface roughness by stylus is limited to object's static or dynamic status and location in the system. Therefore, it becomes necessary to invent such instruments that are not bound to these drawbacks of stylus. Fiber optics, ultrasonic, machine vision etc. have developed over the years to improve analysis power of surface roughness measuring instruments. These technologies are faster, accurate and can take measurement in-process. Following are the descriptions of the non-touching surface roughness measurement techniques.

i *Fiber optics*

During this technique, lens and fiber optic guides are used to measure the heights of surface by producing interferometer cavity among the surfaces [76]. It is electronically controlled equipment which converts phase change signals into voltage signals. This technique is used for 0.42~2.89 µm surface roughness measurements.

ii *Ultrasonic*

This technique is capable of measuring in-process surface roughness [77].

iii *Machine vision*

This method is used a high resolution camera (CCD) to obtain the surface roughness as an image. White light is thrown on the surface if the sample under observation at an inclined angle. This image is analyzed by the program installed on the micro-computer. Another application of machine vision is to use in machining process with adaptive control.

iv *Laser technique*

In this technique laser light incident on the object under observation and study the reflected and diffracted beam of laser through a light sensor connected to computer system to examine the surface roughness. This method can be used to measure the surface roughness values ranging from 1-500µinch.

v *Capacitance-based measurement*

In this measurement technique, laser light is used to get an image of surface roughness which is further analyzed by software.

3.6 Surface Damage

Scanning electron microscope is required for a brief examination of workpiece for surface damage. Side flow, built-up edge (BUE), micro cracking, grooves, chip debris, surface tearing, and breakage of carbides are the typical causes influencing the surface damage of a workpiece. Figure 3.8(a-b) demonstrates the defects producing surface damage [78].

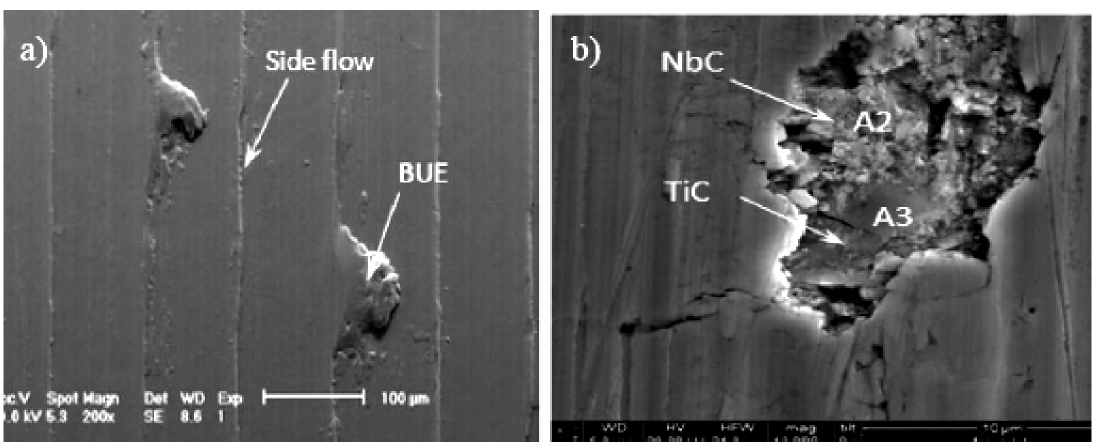


Figure 3.8: Typical surface damage (a) side flow and BUE (b) carbide cracking [78]

Surface roughness may vary for different manufacturing processes as shown in Figure 3.9.

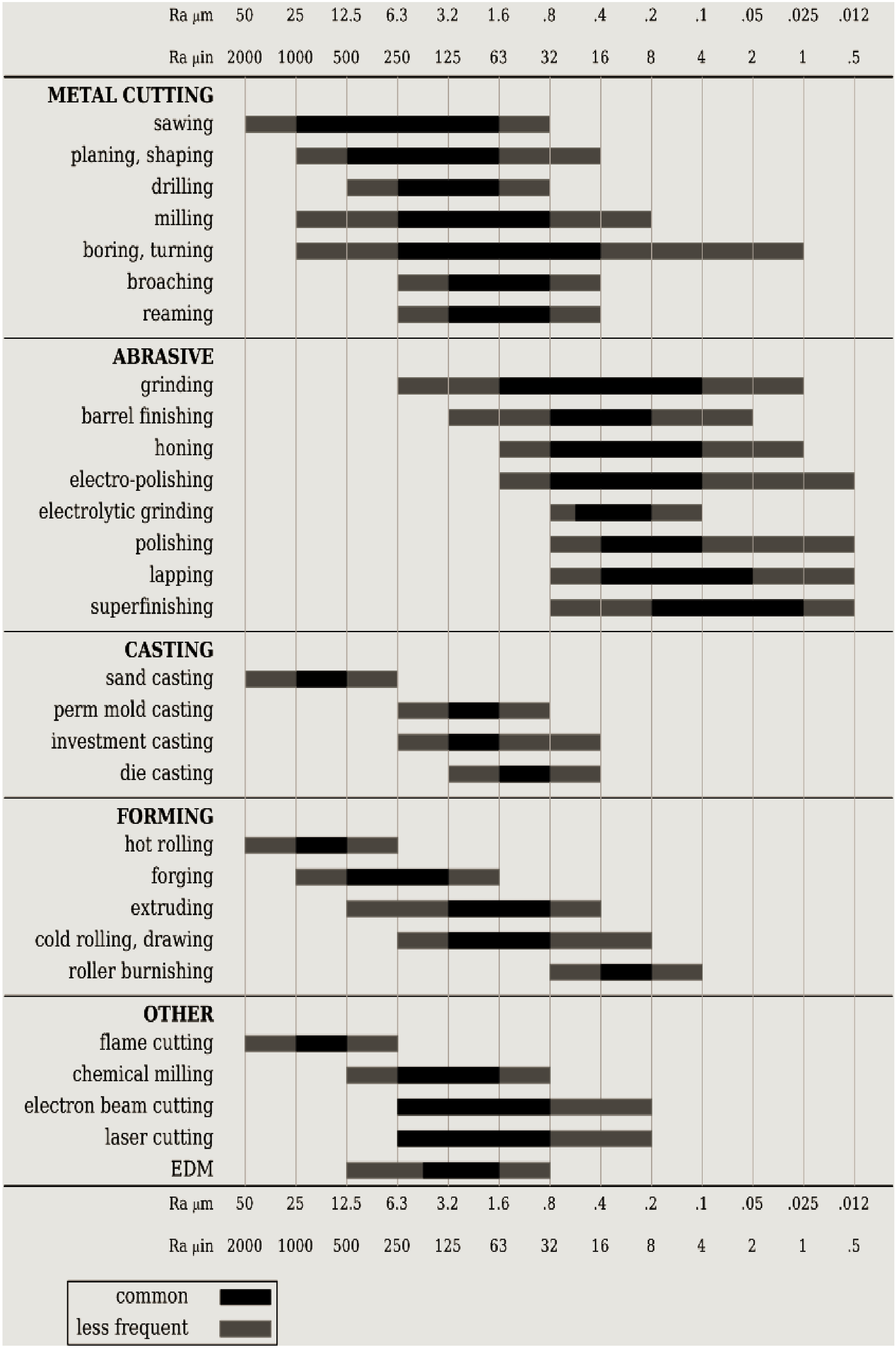


Figure 3.9: Surface roughness values produced in different manufacturing processes [79]

Table 3.6 suggests recommended surface roughness values for different machined components used in different applications.

Table 3.6: General surface roughness values for different components [81-82]

Type of component	Recommended surface roughness values
Shaft running surfaces	0.1, 0.2, 0.5µm
Bearing seats	0.8, 1.6, 3.2 µm
Valves seats	0.012-100 µm
Die casting mold	0.81, 1.0, 1.6 µm
Molds for injection molding	1.0-4.0 µm

3.7 Tool Wear

The material loss from a tool is termed as tool wear. During machining, the higher shear and normal stresses act on the rake and flank faces of the tool can produce high temperature. This high localized temperature can produce wear in the tool and eventually affect the dimensional surface quality (surface finish and dimensional accuracy) [83]. The tool wear also defines the tool life. Therefore, the cost of cutting operations can be optimized by the careful selection of workpiece and cutting tool materials [74].

3.7.1 Types of Tool Wear

The excessive tool wear leads to the tool damage which is further classified as progressive wear or fracture [74]. Progressive wear is further categorized into different forms as listed below:

i. Flank wear
ii. Crater wear
iii. Thermal cracks
iv. Chipping
v. Built-up edges (BUE)
vi. Flaking

i *Flank wear*

The wear occurs on/adjacent to the tool cutting edge is known as flank wear. The tool cutting edge is mainly of three portions i.e. the tool nose, the major flank face and the minor flank face as shown in Figure 3.10(a) [84]. Abrasion by hard particles, shearing of micro weld between tool and workpiece material and low speeds are the general reasons for the generation of flank wear. The possible effects of flank wear are reduced tool life and decrease surface finish of workpiece. Flank wear generally considers as a tool life criteria. According to ISO 8688-2: 1989 standard [85-86], the recommended tool life criteria for end milling:

a) In case of uniform wear;

   The maximum width of flank wear land VB_Bmax.= 0.3mm averaged over all teeth.

b) In case of localized wear;

   The maximum width of flank wear land VB_Bmax = 0.5mm maximum on any individual tooth.

Table 3.7 is indicating general recommendations of flank wear limits for different cutting materials used in general industrial machining practices.

Table 3.7: General recommendations used in industrial practice [12]

Tool material		**HSS**	**Cemented carbides**	**Carbides coateds**	**Ceramics**	
Operation	(mm)				Al_2O_3	Si_3N_4
Roughing	VB_B	0.35–1.0	0.3–0.5	0.3–0.5	0.25–0.3	0.25–0.5
Finishing	VB_B	0.2–0.3	0.1–0.25	0.1–0.25	0.1–0.2	0.1–0.2

ii *Crater wear*

The wear occurs on the rake face of tool is categorized as crater wear as shown in Figure 3.10(b). Crater wear usually causes reduced tool strength and increased temperature and friction between tool rake face and chips. Wear index (q) is used to calculate the tool life by dividing crater depth Kt to the cutting edge distance from the centerline of the crater Km as:

$$q = K_t / Km \quad (3.2) \quad [87]$$

Generally, crater wear is not taken as the tool life criteria because it is difficult to quantify the crater wear [88].

iii Thermal cracks

It usually happens in perpendicular direction to the cutting edge of the tool as shown in the Figure 3.10(c). The major causes of thermal cracks are normally thermo mechanical fatigue in a result of repeated cycles of heating and cooling due to variation in the cutting environment and the interrupted machining. The thermal fatigue results into thermal cracks or torn off some portion of workpiece material [74].

iv Notch wear

Figure 3.10(d) shows the micrograph of notch wear. This type of wear usually occurs on both the major and minor edges of the cutting tool. Literature reports many causes responsible for the occurrence of notch wear including tool material oxidation, work hardening [89] on the workpiece material and saw tooth shape of chips [74]. This type of wear is more dangerous for the workpiece materials prone to work hardening during machining like superalloys and austenitic stainless steel. It usually happens at the cut line depth in contact with the surface to be machined from the previous cut [83]. Notch wear may cause fracture some times, but remedies like use of chamfered cutting edge, applying depth of cut greater than layer of work harden material and use of round inserts can help in order to avoid the fracture [74].

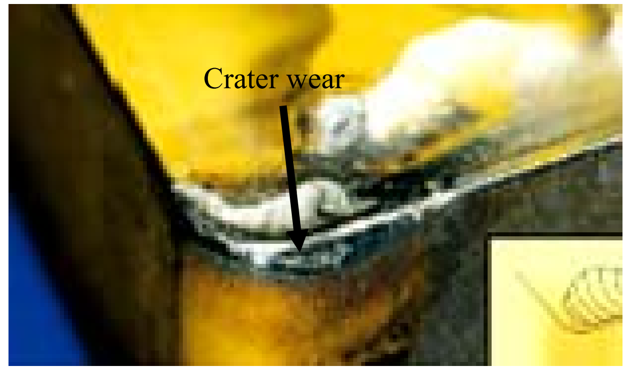
v Built-up edge

Built-up edge (BUE) refers to the type of wear which appears as results of welding of workpiece material on the tip of the tool due to pressure as shown in Figure 3.10(e). Low cutting speed is considered the general cause of BUE due to higher pressure and low temperature values during cutting [90]. It is usually observed during the cutting of non-ferrous materials like, aluminum, cobalt, low carbon steel, titanium alloys, nickel and ductile stainless steel. The breakage of BUE takes away small portion of tool material with it, resulted into tool fracture [90]. BUE can be avoided through selecting high cutting speed which produces higher level of temperatures and stresses during cutting. These higher temperatures generate a flow zone and recrystallization of material [91].

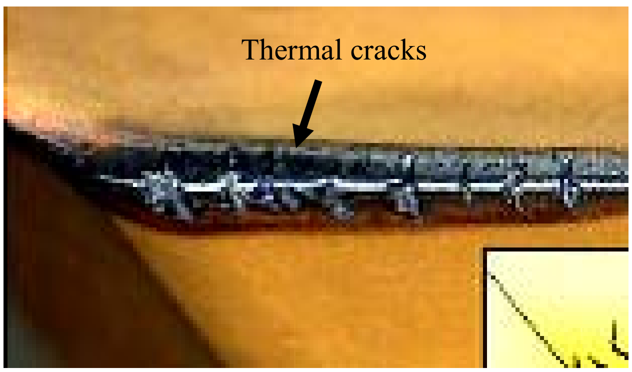
vi Chipping / Fracture

Chipping is the phenomena which occurred at the tool tip as a result of detaching of small pieces of material from the tool tip. When the chipping occurs at the higher scale then it results into fracture as shown in Figure 3.10(f). Unlike flank wear which is generally a gradual phenomenon, Chipping occurs at the higher rates affecting the surface finish, dimensional accuracy and surface integrity of the workpiece. Crater wear propagation towards the tip of the tool can also cause chipping [83].

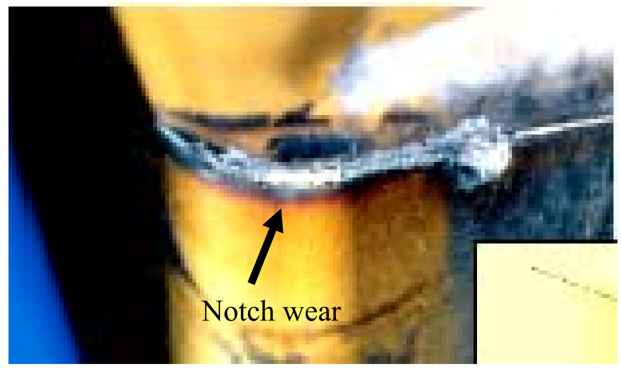
a) Flank wear



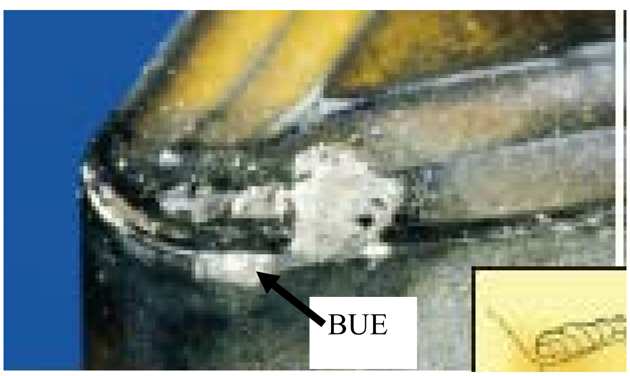
b) Crater wear



c) Thermal cracks



d) Notch wear



e) BUE

f) Chipping/fracture

Figure 3.10: Typical wear pattern (a) flank wear (b) crater wear (c) thermal cracks (d) notch wear (e) BUE (f) chipping/fracture [84, 92]

3.7.2 Tool Wear Mechanisms

The mechanisms which caused the entire above mentioned tool wear are complex. Tool material, workpiece material and their properties, cutting tool geometry and machining parameters are the different factors that can cause different mechanism of tool wear. A description of different type of tool wear mechanism is detailed down [72];

i. Abrasive wear mechanism
ii. Diffusion wear mechanism
iii. Adhesive wear mechanism
iv. Oxidation and corrosion wear mechanism

i Abrasive wear mechanism

Abrasive wear produces in a result of sliding motion of hard particles of workpiece material and cutting tool. Inclusion of hard material present in workpiece material and torn off pieces of cutting edge of tool could be the sources of hard particles present during the machining process [84]. Figure 3.11(a) indicates the schematic representation of abrasive wear. The nature of abrasion wear is mechanical, therefore, it is independent of temperature [72] and cutting speed but it is highly dependent on tool hardness [84].

ii Diffusion wear mechanism

Diffusion wear is chemical kind in nature. It is usually depends on the chemical affinity among the tool and workpiece and their chemical properties as well. Few tool materials show a greater affinity with the workpiece material like polycrystalline diamond responds to the hardened steels but polycrystalline boron nitride tool material is relatively nonreactive. As this mechanism is chemical in nature, therefore, it is independent of tool hardness and has strong dependency on temperature. The higher values of cutting speeds accelerate the diffusion wear during cutting. The metallurgical relation among tool and workpiece material can be used to determine the amount of diffusion wear [84]. Figure 3.11(b) shows the diffusion wear mechanism which explains the diffusion of different atoms of workpiece material into tool material and vice versa.

iii Adhesive wear mechanism

A bond can be formulated between tool and workpiece material due to the close contact during the cutting process results into adhesive wear. The bond is subjected to the condition that it has more strength than the material local strength [93]. The workpiece material may be attached to the tool in the form of layers or the particles which is also known as built-up edge. Some times BUE becomes the part of the cutting edge due to the welding and hardening [84]. The breakage of these layers from the cutting edge results into the tool wear. This wear usually caused by low temperature during metal cutting.

iv Oxidation and corrosion wear mechanism

This mechanism occurs as a result of a reaction between tool materials components and oxygen in the atmosphere. It is usually happened at 800˚C with the direct exposure of oxygen present in the environment and the open surface of tool/chip contact area. Figure 3.11(c) represents the oxidation mechanism. Notch wear on either edge of tool tip is generally caused by the oxidation mechanism [84]. The additives of the cutting fluid like sulphur and chlorine tool material result into chemical products hence cause the abrasion. The abrasion on the tool is known as corrosion wear.

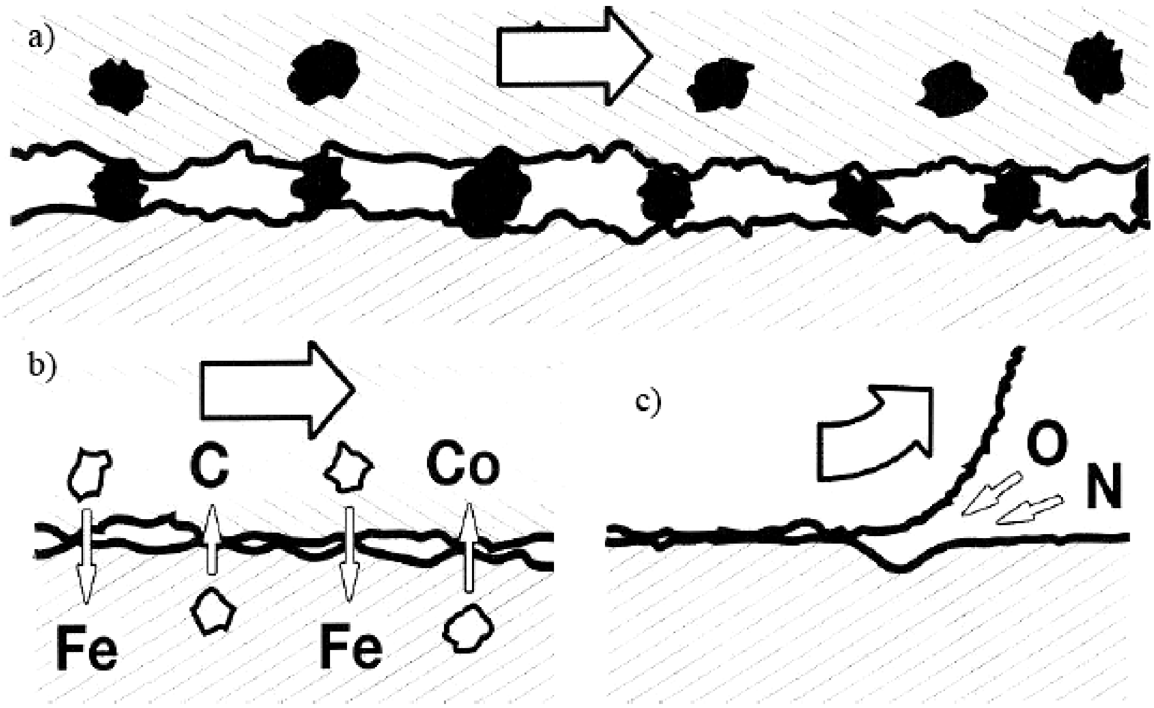


Figure 3.11: A schematic representation of wear mechanism (a) abrasive wear (b) diffusion wear (c) oxidation [84]

3.8 Dimensional Accuracy

In today's market, reduction of cost of the product with conformed quality through the optimize use of materials, energy and machine tool usages is become a constant challenge for the manufacturer. Dimensional accuracy contributed as one of most important factor in the achievement of this challenge [94-97]. Dimensional accuracy is generally defined as error in size of machined surface of profile [98]. During any metal cutting process, usually two kinds of geometrical deviations related to machined surface occur i.e. macro deviation and micro deviation. The former deviations result into surface roughness and the latter cause distortion in dimensions affecting dimensional accuracy [99]. Macro deviations are further classified into three forms.

i. Roundness deviation due to machine error and elastic deformation caused by cutting forces

ii. Second form is linked with waviness which caused by tool-workpiece relative motion

iii. Tool track which is highly dependent on cutting geometrical form

The factors related to tool (shape, material, clamping and overhang), workpiece (material machinability characteristics and clamping), cutting conditions and machine vibrations are considered the most affecting factors for dimensional accuracy [100]. The dimensional accuracy of machined parts can be measured into two ways:

- On-process measurements
- Post-process measurements

For on-process measurements, mechanical, pneumatic, optical and ultrasonic methods are generally employed. Block gauges, micrometers, profile projector and coordinating measuring machine (CMM) are widely used for post-process measurements [98]. During the present research, the post–process measurement mode is selected to measure the dimensional accuracy with the help of CMM.

3.9 Literature Review related to Machine Vibration Effects on Dimensional Surface Quality of Workpiece during Machining Operations

Literature includes a lot of published research which comprised of the investigations related to chatter effects on surface roughness, dimensional accuracy and tool wear.

Chelladurai et al investigate the effects of machining parameters including cutting speeds, depth of cut, feed rate and chatter on flank tool wear during the establishment of artificial neural networks and empirical model using full factorial method for design of experiments. This research determines that chatter accelerates tool wear and hence affects the quality of the surface produced [101]. Sivasakthivel et al propose the use of response surface methodology to design a model for chatter vibration amplitude prediction from cutting parameters (spindle speed, axial and radial depth of cut and feed rate) for end milling process. Helix angle among other machining parameters is proved the most influencing parameter for the chatter reduction [102]. Ghani et al conclude a study involving tool wear, surface finish and vibrations in turning operations. The study presents that chatter remains almost unchanged with propagation of flank wear [103]. Amin et al investigate the chatter effects on surface roughness during end milling. The research concludes that at stable low level of cutting speeds, the chatter has no significant effect of surface roughness values but at high cutting speeds the chatter has a significant effect on surface roughness values [104]. Campa et al present the study that chatter is a dynamic issue at high conditions of removal rate which eventually reveals that chatter affects the end results of machining characteristics [105]. Kim et al show that excessive tool wear, tool fracture, surface quality deterioration and noise are the most common drawbacks of the excessive chatter [106].

Literature also includes some research related to effects of machine tool spindle vibrations on surface quality of workpiece. Risbood et al give the study for the prediction of surface roughness and dimensional accuracy as a result of cutting forces and machine vibrations in turning operations. Study concludes that surface roughness can be assessed by considering the radial vibrations of tool holder [7]. Abouelatte et al has conducted the research which aims at developing a correlation among surface roughness and cutting vibration during turning operations. The ultimate goal is to develop a mathematical model to predict the surface finish in terms of machining parameters and machine tool spindle vibrations [8]. Munawar et al work on forced vibrations and give the optimization of surface finish in turning operations by considering machine tool spindle vibrations. The study reveals that machine vibrations have moderate effects on surface roughness [9]. Zahoor et al contribute with the results that machine tool spindle vibrations have strong effects on surface roughness and tool wear. It is further revealed by the research that higher levels of vibration amplitudes result into tool failure [107]. Khorasani et al present a study which incorporates the effect of unwanted noise (machine vibrations) on surface roughness. The objective of research is to develop dynamic monitoring system for surface roughness in milling operations [108].

3.10 Design of Experiments (DOE)

During any experimentation, an experiment or a series of experiments are conducted in order to evaluate and analyze the effects of different input parameters on the dependent parameters. During the course of experimentation, generally the sequence of activities comprises of planning of experimentation, conduct of experiments according to the design, collection of data in the result of experimentation and then generation of conclusions from the analysis of the collected results [108].

Design of experiments is broadly categorized into two main types i.e. full factorial design and fractional factorial design. While using full factorial, one factor is evaluated against rest of all other factors in order to investigate the net influence on the output parameter. Although all the combinations of main effects and interaction effects can be analyzed in this full factorial but it requires high cost of experimentation including cost of tooling and workpiece materials. For example, for four factors all are at four levels require 256 numbers of experiments. In this case; fractional factorial design is preferred at least for the preliminary trials where few numbers of experiments required setting the base line for the next trial. Taguchi methodology is considered one of the "objective" approaches for design of experiments which reduces the cost of experimentation by eliminating the tests which are not taking part in the results.

3.10.1 Taguchi Methodology for Design of Experiments

This methodology named after Dr. Genechi Taguchi a Japanese scientist. Taguchi spends much of his life time in finding out the ways to enhance the product's quality through design of experiment and analysis techniques. Since the Fisher has introduced the design of experiment (DOE) in the 1920s -1940s. Taguchi initially defined the term "quality" in general form and then established the concept that DOE is not only contributed in quality improvements but quantifying the improvements as well. For the DOE, Taguchi established a number of standard orthogonal arrays [109]. Each orthogonal array can be employed in different DOE situations. For example, L4, L8, L16, L32, L36 are based on 2 and 4 level factors, while L9 and L27 is available for factors at 3 level and L12 and L18 can be facilitated for 2 and 3 level factor combinations. Linear graphs and assignment table are used to assign the factors and their levels in the corresponding orthogonal array. Eventually, the analysis of the data is carried out using different analysis techniques [110]. A detailed discussion on different sets of orthogonal arrays along with linear graphs can be extracted in [111-112]. A brief description about weakness inherent to different DOE methods is given in Table 3.8 below.

Table 3.8: Weakness inherent in different DOE methods [113-115]

Sr. No.	DOE method	Weakness
1	Full Factorial Design	1. It gets larger with several levels of many factors very quickly 2. Enhanced replication than needed for the research 3. Increased time and cost of experimentations
2	Fractional Factorial Design	1. Decreased precision in data due to reduced replication 2. Few interaction can be found among the data
3	Taguchi Design of Experiments	1. Chance to lose an important combinations of factors due to higher interactions are taken in arrays 2. Interactions among the data are not available in every Taguchi array

In order to analyze the results obtained after the experimentation, Taguchi has introduced a new method known as signal to noise ratio (S/N) based on Taguchi loss function [29]. The S/N ratio is used for the analysis and for the prediction of input parameters which optimize the dependent parameters. The S//N ratio is further divided into three categories named as:

i. The Smaller-the-Better
ii. The Larger-the-Better
iii. The Nominal-the-Better

i The smaller-the-better

This category is used when the defect or surface roughness are the response parameters for which the desired value is taken as zero ideally. Equation (3.3) represents the general formula for this category:

$$\text{S/N ratio} = -10\ \text{Log}_{10}\ [\text{mean of sum of squares of measured data}] \quad (3.3)$$

ii *The larger-the-better*

This category is used for the response parameters like dimensional accuracy where the bigger value is desired.

S/N = -10 Log_{10} [mean of sum squares of reciprocal of measured data] (3.4)

iii *The nominal-the-better*

This category is used when the requirement of dependent parameters values are neither large not small. The general formula for the Nominal-the-better calculation is given below:

S/N = 10 Log_{10} [Square of mean/Variance] (3.5)

'η' is representation of S/N ratio. The factor associated with the higher value of S/N ratio is considered the most responsible parameter affecting the response parameters. The main drawback of Taguchi methodology is that it only incorporates the main effects and the interactions are underrated. However, Taguchi is in the view that interaction effect can be eliminated if the careful selection of parameters and their level has made [29].

In addition to this methodology, analysis of variance (ANOVA) is also used to quantify the effects of different factors on the dependent parameters.

3.10.2 An Overview of Analysis of Variance (ANOVA)

Sir Ronald Fisher has established this technique in 1930 to interpret the experimental results in order to make the optimized decisions. In ANOVA, the difference in the performance of combination of input factors can be statistically examined on the dependent parameters by allocating the total variability into distinct components. ANOVA analysis compares the variation in the mean of a factor with the total error of the experiment. It also forecast the optimal combination of input parameters that can produce the required results. At the end, a confirmation trial is run to validate the estimation achieved from the analysis. A detailed comprehension can be established from Ross [111, 116].

CHAPTER 4

EXPERIMENTAL DESIGN SETUP AND PROCEDURE

Experimental design includes two major phases. Phase I comprises in developing a method for the induction of forced vibrations in the spindle of CNC machining center and benchmarking of induced vibration amplitude with the amplitude of older industrial machines, while Phase II involves investigation and optimization of effects of spindle forced vibrations and machining parameters during the end milling of AISI P20 tool steel. Suitable sub-phases under each major phase are designed as describe below;

- Phase IA: Method for inducing forced vibrations in the spindle of CNC machining center using external weights
- Phase IB: Benchmarking of induced vibration amplitude levels with the vibration amplitude levels of selected industrial machines
- Phase IIA: Investigation of effects of spindle forced vibrations on surface roughness and dimensional accuracy using cobalt coated high speed steel (HSSco) end mill cutters
- Phase IIB: Investigation of effects of spindle forced vibrations on surface roughness and dimensional accuracy using titanium aluminum nitride (TiAlN) coated solid carbide end mill cutters
- Phase IIC: Tool wear evaluation in order to assess the effects of spindle forced vibrations in case of HSSco and TiAlN coated solid carbide cutters

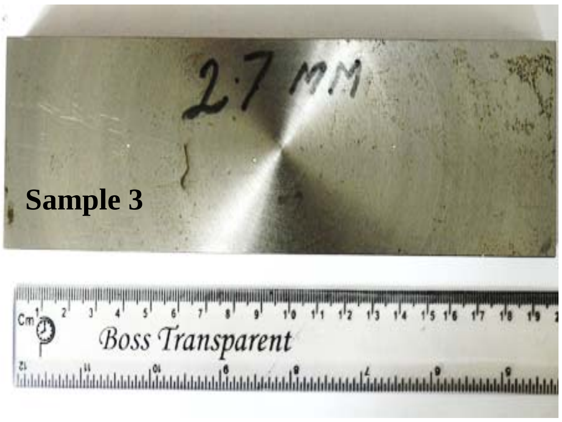
From the main phase IB, the levels of induced vibration amplitude are selected for the further experimentation. In phase IIA and IIB, effect of spindle forced vibration along with machining parameters are investigated for dimensional surface quality of the machined parts i.e. surface roughness, dimensional accuracy. Optimization is done based on results obtained in phase IIA and IIB. In phase IIC, different patterns of tool wear are evaluated in order to measure the effects of spindle forced vibration.

A detail description of workpiece material, equipment, end mill cutters, variable and fixed parameters and design of experiments are described in the sections below.

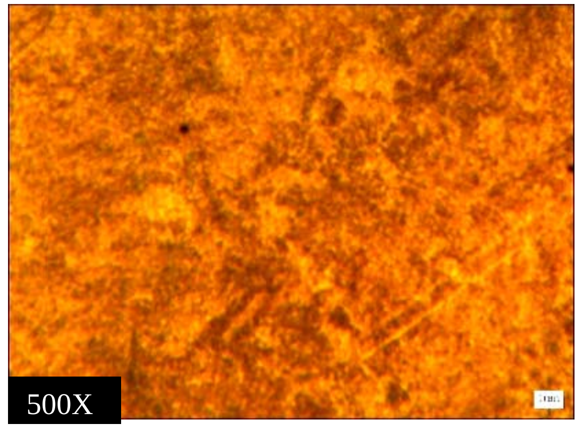
CHAPTER 4: EXPERIMENTAL DESIGN, SETUP AND PROCEDURE

4.1 Workpiece Material

AISI P20 tool steel is used as workpiece material as shown in the Figure 4.1 (a,b).



a) Workpiece used for experimentation



b) Microstructure of the workpiece material

Figure 4.1: Details of workpiece material

Table 4.1 shows the chemical composition of the workpiece after spectroscopy results.

Table 4.1: Chemical composition of AISI P20 tool steel workpiece (wt. %)

Composition	**C**	**Mn**	**Si**	**Cr**	**Mo**	**S**	**Fe**	**Hardness (HRC)**
Workpiece	0.299	1.07	0.404	1.92	0.15	0.037	Balance	32

A rectangular bar of workpiece material (190×60×19mm) is prepared for machining. A 3mm scale is removed from the top face (machining surface) of the rectangular bar by facing it on four jaw lathe machine. Its four sides are then faced to maintain orthogonality, so as to ensure an appropriate clamping on the CNC machining center table to avoid vibrations.

4.2 Cutting Tools

During the experimentation of phase IIA and IIB, cobalt coated high speed steel (HSSco) end mill cutters and titanium aluminum nitride coated (TiAlN) solid carbide end mill cutters are used.

4.2.1 High Speed Steel and Solid Carbide End Mill Cutters

Cobalt coated high speed steel end mill cutters and TiAlN coated solid carbide end mill cutters are provided by MS. Dormer UK used in present research. Complete description of end mill cutters specifications, coating types, tool geometry and tool grade are given in Table 4.2 and 4.3 respectively.

Table 4.2: Tool grade and coating type

Type of end mill cutter	**Manufacturer tool grade**	**Coating type**
High speed steel cutter	MS Dormer C247	Cobalt coating
Solid carbide cutter	MS Dormer S944	Titanium Aluminum Nitride

Table 4.3: Tool geometry

Type of end mill cutter	**No. of flutes**	**Helix angle (degree)**	**Shank length (mm)**	**Total length (mm)**
High speed steel cutter	4	35.5	19	57
Solid carbide cutter	4	35.5	19	57

4.3 Equipment

Details of equipment used during present study are given below.

4.3.1 Machine Tool

MCV600 CNC machining center is used to carry out the experimentation as shown in Figure 4.2. Additional details of machine specifications are given in Table 4.4.

Table 4.4: Specifications of MCV600 CNC machining center

Maximum machine weight	4100kg
Maximum X-axis travel	610mm
Maximum Y-axis travel	500mm
Power rating	20KVA
Tool capacity (ATC Automatic tool changer)	20 tools
Machine spindle	BT40 collect type

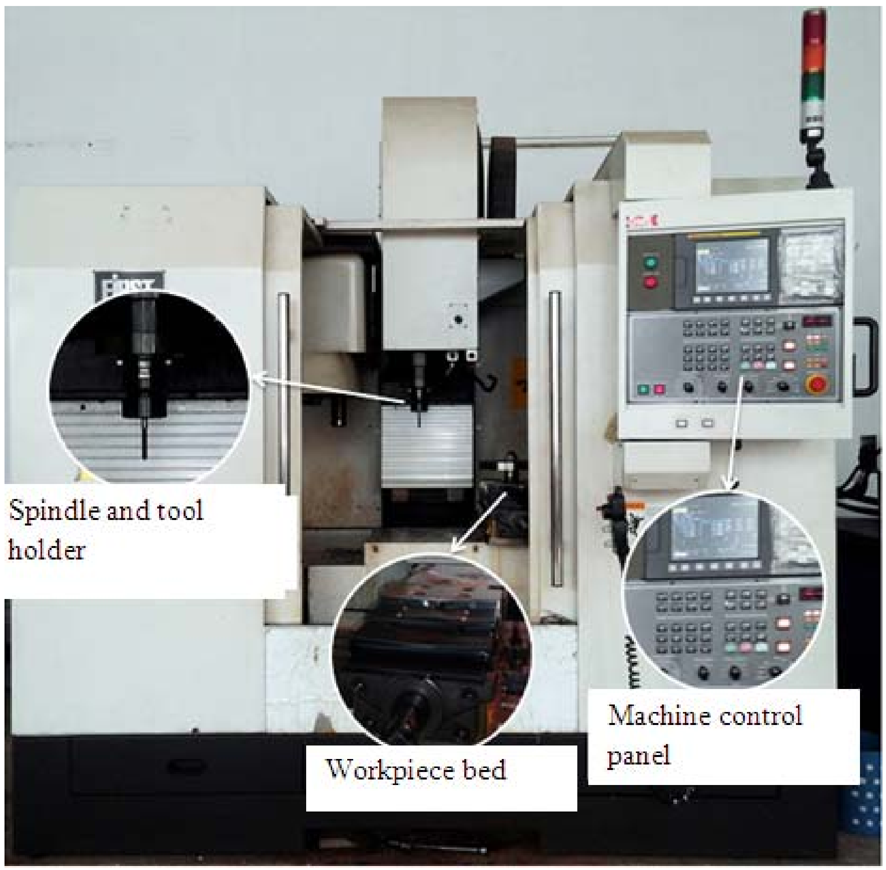


Figure 4.2: MCV600 CNC machining center

4.3.2 Vibration Measurement

The vibration analyzer (Model: 2117A Series RBM Collector) as shown in Figure 4.3 is employed to measure the induced vibrations in the machine spindle.

Figure 4.3: Vibration analyzer

4.3.3 Workpiece Hardness Measurement

Hardness of the workpiece material is measured by using hardness tester (Model: 81508K INDENTIC HARDNESS TESTING MACHINES Ltd. UK) with diamond indenter at load of 150KgF as shown in Figure 4.4.

Figure 4.4: Hardness tester

4.3.4 Dimensional Surface Quality Measurements

Surface Texture meter (Model: Surtronic 25 TAYLOR HOBSON Ltd. ENGLAND) as shown in Figure 4.5 is employed to measure the surface roughness values of the milled surface during the present experimentation. Parameters of surface texture meter (8mm evaluation length and 0.8mm cut of length) are selected for surface roughness measurement during the experimentation.

Figure 4.5: Surface texture meter

Dimensional accuracy assessment is done by measuring the dimensions of milled slot (height and width of slot) by using CMM coordinate measuring machine (Model: CE 450DV CHIEN WEI TAIWAN) as shown in Figure 4.6.

Figure 4.6: Coordinate measuring machine (CMM)

4.3.5 Tool Wear Measurement

An optical measuring microscope (Model: MM6C-AF-2 OLYMPUS Co. JAPAN) equipped with a X-Y digital micrometer platform connected to an Olympus 100D DSLR digital camera as shown in the Figure 4.7(a) is used to measure the different tool wear patterns after machining. A (SEM) scanning electron microscope (Model: JSM 6480LV JEOL USA) as shown in Figure 4.7(b) is employed to investigate the tool failure in detail during the experimentation.

a) Optical microscope b) Scanning electron microscope (SEM)

Figure 4.7: Tool wear measurement (a) Olympus Optical microscope and (b) SEM

4.3.6 Cutting Environment

Cutting Fluid Caltex HD68 straight oil is used as lubricant in flood condition. Four nozzles each having 4mm internal diameter at fixed positions are used for lubrication purpose during the machining. Total flow rate for four nozzles is estimated as 7.5 lit/min approximately.

4.4 Design of Experiments and Procedure

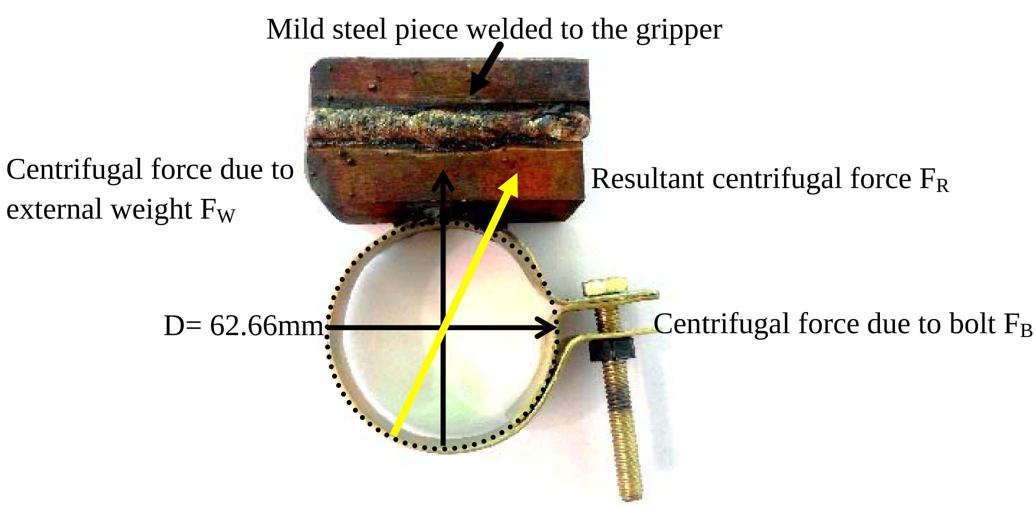
A comprehensive discussion on design of experiments and experimental procedures is given in forthcoming sections.

4.4.1 Phase IA, IB: Inducing Forced Vibrations in CNC Machining Center and Benchmarking of Induced Vibration Amplitude Levels

The method involves in the process of inducing forced vibrations in the spindle of CNC machining center is accomplished by attaching external weights to the tool holder to produce imbalance in the spindle. The rationale of using this approach to produce the imbalance in the spindle is derived from the well-known process of mechanics of machine known as balancing. It is exactly the reverse of the balancing method in which external mass is used to rectify the rotor and shaft imbalance [35, 117].

The main concept behind this method is to generate centrifugal forces which are responsible to produce imbalance in the spindle of the machine. This idea would be considered akin to upsetting the structural rigidity of the spindle which may simulate the different machine tool conditions. A purpose built gripper made from 12 gauge mild steel for the machine spindle diameter62.66mmis used to attach the external weights to spindle of CNC machining center in order to induce vibrations of varying amplitudes as shown in Figure 4.8(a-b).

a) Purpose built gripper



b) Details of the gripper

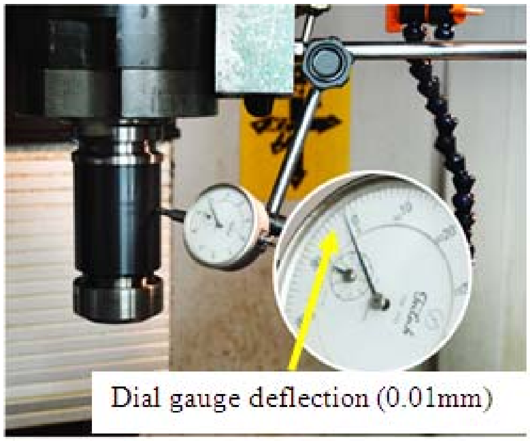
Figure 4.8: Gripper for external weight attachment (a) purpose built gripper (b) details of gripper

The parameters of the CNC machining center recommended by the manufacturer as shown in the Table 4.5 are set before starting the experimentation of Phase IA.

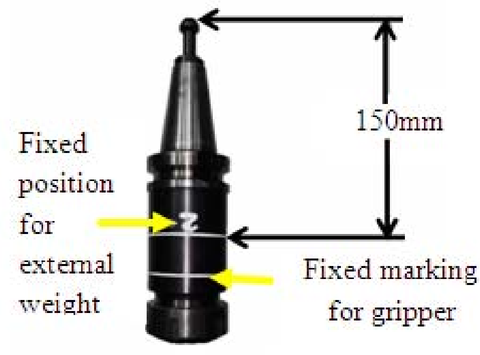
Table 4.5: Parameters recommended by manufacturer

Air compressor pressure (MP_a)	**Machine air blow (MP_a)**	**Spindle bearings air blow (MP_a)**	**Operating temperature (˚c)**	**Machine warm up time (Min)**
0.6	0.6	0.2	20±5Airconditioned controlled	15 at 100 rpm

The CNC machining center is calibrated using ball bar laser calibration systems. The machine is bolted on reinforced floor to avoid any vibrations from the surroundings and operating temperature of the machine recommended by the manufacturer is maintained through air conditioning provided throughout the experimentation. The ovality check of the machine spindle is carried out with the help of dial gauge (least count: 0.01mm) as shown in Figure 4.9(a) to ensure any prior deflection in the spindle. After ensuring the rigidity of spindle, fixed location at 150mm from the spindle end of the tool holder as shown in Figure 4.9(b) is identified to position the gripper and external weights during the course of experiments. Initially external weight is positioned at three different positions on the tool holder. It is found than that external weight, when placed at position marked as 2 produces the maximum centrifugal force which eventually resulted into higher amplitudes of vibrations. Thus, the rest of experiments were conducted by positioning the external weight at position 2.



a) Ovality check



b) Fixed marking on tool holder

Figure 4.9: Procedure for inducing vibrations (a) ovality check (b) fixed marking on tool holder to position the gripper

Two input parameters external weights at four levels and spindle speed at 20 levels are selected in order to assess their effect on response parameter i.e. vibration amplitudes. Therefore, full factorial design was used for the design of experiments. Total eighty tests are performed with two variable parameters at different levels. Table 4.6 shows the input parameters and their levels along with dependent parameter for the Phase IA experimentation.

Table 4.6: Input and dependent parameters

Sr. #	Variable parameter	Symbol	Levels	Dependent parameter
1	External weight	gms	200, 300, 400, 500	Vibration Amplitude (in/sec)
2	Spindle speed	rpm	100-2000	

Machine is run for the range of spindle speeds designed to investigate the default vibration levels of CNC machining center spindle. After loading the roots from the software to the RBM collector [118], accelerometer of vibration analyzer is attached at fixed plate of the spindle near the bearing housing of the CNC machining center as shown in Figure 4.10. The spindle vibrations are measured radially [20-21] as recommended by the vibration diagnostic manual in case of imbalance.

Figure 4.10: Experimental setup for inducing forced vibrations

The vibration amplitudes are noted using vibration analyzer by varying the spindle speeds (100-2000 RPM) and analyzed with the help of "Machinery Health Management Platinum" software provided with the vibration analyzer. The values of vibration amplitudes are acquired both in the digital form (in/sec) and graphical form (i.e. FFT spectrum and waveform).

Though, the linear unit for vibration amplitude has been commonly used to represent the amplitude values of a wave signal however it is also reported in the literature that vibration amplitudes can be represented in three different interconvertable parameters i.e. displacement, velocity and acceleration [22,29, 102]. Keeping in view, that conversion of one unit into other unit will yield an error in the final results, the units for vibration amplitudes are taken as in/sec the same as measured directly from the vibration analyzer. The range of magnitude of external weights is selected through preliminary experimentation. The repeatability of vibration analyzer is checked at 500gms external weight.

The default vibration amplitude levels of the machine are first noted for the range of RPM selected for the experimentation. Then, the same procedure is repeated by attaching the external weights (200gms ~ 500gms; step: 100gms) and outputs of vibration analyzer are collected in the form of digital readings and spectrum as well.

ANOVA and main effects plots are generated using Minitab software (Version 16) at 95% confidence interval.

Three industrial machines from different manufacturers and with different machine tool conditions as shown in Table 4.7 below are selected to benchmark the vibration amplitude levels which are induced in the CNC machining center using external weights. The selected machines used for benchmarking are chosen on the basis of same machining operations.

Table 4.7: Industrial machine's profile

Machine no.	**Manufacturer's name**	**No of axis**	**Total life (Years)**	**Year of making**	**Operation type**
Machine 1	CINNCINATI-CNC	4-axis	25	1989	Drilling/Milling
Machine 2	KIRA-CNC	3-axis	17	1997	Drilling/Milling
Machine 3	BRIDGPORT-CNC Retrofitting in 2007	3-axis	20	2007 Retrofitted	Drilling/Milling

After benchmarking the vibration amplitude levels, three different levels of vibration amplitude are selected for the future experimentation.

4.4.2 Phase IIA: Investigation of Effects of Forced Vibrations on Surface Roughness and Dimensional Accuracy using HSSco End Mill Cutters

Phase IIA aims at performing the experimentation to investigate the effects of spindle forced vibrations on the surface roughness and dimensional accuracy. Experimentation involves two set of machining input parameters. Table 4.8 and 4.9 show the details of input parameters, fixed parameters and dependent parameters for set I & II experimentation.

Table 4.8: Input and fixed parameters

Variable input parameters	Unit	Level 1	Level 2	Level 3
For set I				
Vibration Amplitude (VA)	mm/min	0.09522 (Default)	0.11889 (Induced)	0.185929 (Induced)
Feed Rate (F)	mm/min	320	640	1280
Axial Depth of Cut (A_p)	mm	0.2	0.3	0.4
For set II				
Vibration Amplitude (VA)	mm/min	0.09522 (Default)	0.11889 (Induced)	0.185929 (Induced)
Feed Rate (F)	mm/min	256	288	320
Axial Depth of Cut (A_p)	mm	0.2	0.25	0.3
Fixed input parameters				
Spindle Speed	RPM	1600		
Cutting Speed (V_c)	m/min	30		
Radial Depth of Cut (A_r)	mm	6		
Cutting Fluid Flow/4 nozzles	lit/min	7.5		
Tool Hang	mm	32		
No. of Flutes		4		

Table 4.9: Dependent parameters

Dependent parameters	Unit
Surface Roughness (R_a)	µm
Height of the Slot(H)	mm
Width of the Slot (W)	mm

Set I is based on minimum machining parameters and set II is based on maximum machining parameters as recommended in literature. Taguchi L9 Orthogonal array is used for design of experiments involving three variable parameters at three levels. Table 4.10 and Table 4.11 show the Taguchi L9 orthogonal array for set I & II respectively. The rationale of selecting L9 orthogonal array is the cost of experimentation.

Table 4.10: Taguchi L9 orthogonal array for set I

Exp. No	Vibration amplitude (mm/min)	Feed rate (mm/min)	Axial depth of cut (mm)
1	0.0952	320	0.2
2	0.0952	640	0.3
3	0.0952	1280	0.4
4	0.11889	320	0.3
5	0.11889	640	0.4
6	0.11889	1280	0.2
7	0.185929	320	0.4
8	0.185929	640	0.2
9	0.185929	1280	0.3

Table 4.11: Taguchi L9 orthogonal array for set II

Exp. No	Vibration amplitude (mm/min)	Feed rate (mm/min)	Axial depth of cut (mm)
1	0.0952	256	0.2
2	0.0952	288	0.25
3	0.0952	320	0.3
4	0.11889	256	0.25
5	0.11889	288	0.3
6	0.11889	320	0.2
7	0.185929	256	0.3
8	0.185929	288	0.2
9	0.185929	320	0.25

The slab of 190×60×19mm dimension is prepared on 4 jaw lathe machine and used as a workpiece. The workpiece is clamped on machine bed with the help of two sine bars for rigid clamping in order to avoid vibrations during machining operation. A slot of 6×6×60 mm dimensions is milled in each experiment using new HSSco end mill cutter as shown in Figure 4.11. Surface roughness is measured in terms of R_a value with the help of surface texture meter at three different positions in the direction of machining as shown in the Figure 4.12(a). Coordinate measuring machine (CMM) is used to measure the dimensions of the milled slot and dimensions are taken at three different position. S/N ratio analysis is carried out to rank the parameters according to their influence on dependent parameters. ANOVA analysis and main effects plots are generated to identify the significance of parameters in accordance with the dependent parameter using Minitab 16.

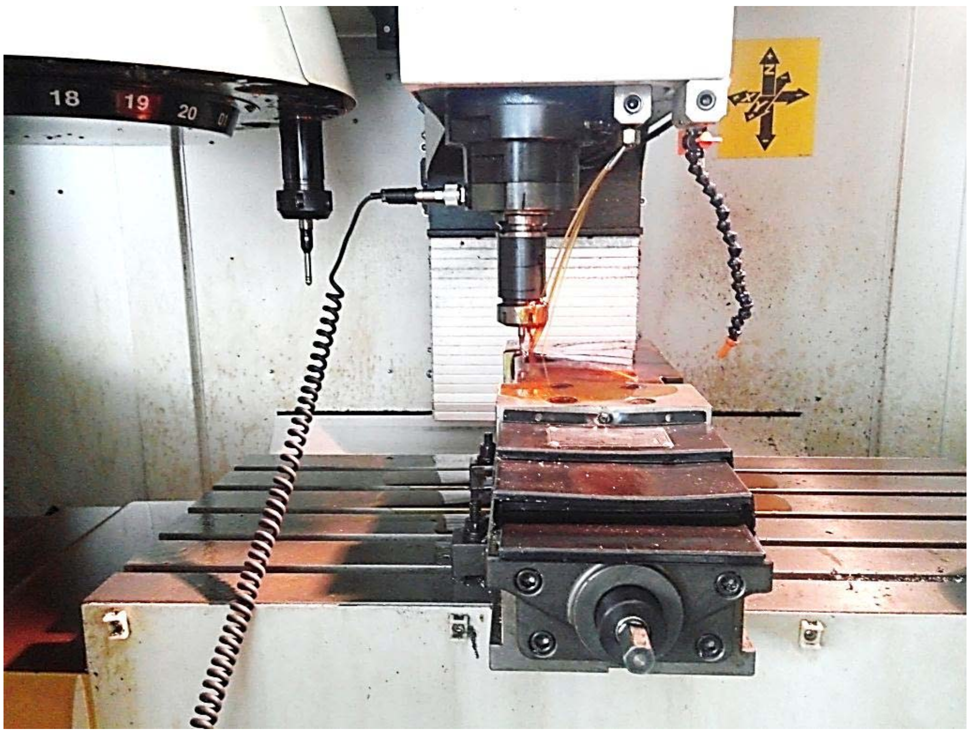
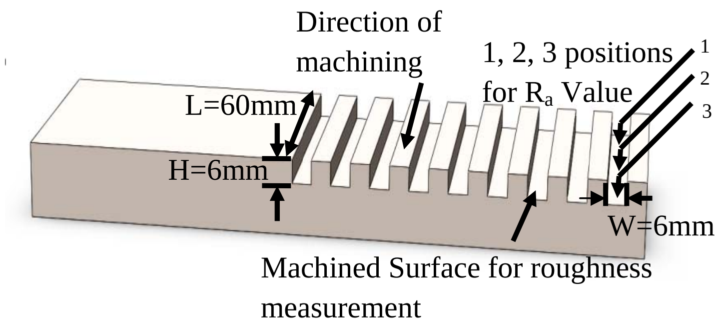


Figure 4.11: Experimental setup during machining



a) Schematic diagram of work piece measurement

b) Surface roughness measurement

Figure 4.12: Surface roughness measurement (a) schematic diagram of work piece measurement and (b) surface roughness measurement

Based on results obtained in phase IIA, phase IIB is designed for further experimentation.

4.4.3 Phase IIB: Investigation of Effects of Forced Vibrations on Surface Roughness and Dimensional Accuracy using TIALN coated Solid Carbide End Mill Cutters

The experimentation is done to investigate the effects of spindle forced vibrations along with machining parameters on surface roughness and dimensional accuracy using a titanium aluminum nitride (TiAlN) coated solid carbide end mill for finishing operations. The three variable parameters at three levels are selected for the machining. Table 4.12 shows the levels of variable parameters and details of fixed parameters. The dependent parameters are the same as used in Phase IIA as shown in Table 4.9. A L9 Taguchi orthogonal array is selected for the design of experiments as shown in Table 4.13.

Table 4.12: Input and fixed parameters

Variable input parameters	Unit	Level 1	Level 2	Level 3
Vibration Amplitude (VA)	mm/min	0.09522 (Default)	0.11889 (Induced)	0.185929 (Induced)
Feed Rate (F)	mm/min	400	500	600
Axial Depth of Cut (A_p)	mm	0.1	0.15	0.2
Fixed input parameter				
Spindle Speed	RPM	1600		
Cutting Speed (V_c)	m/min	30		
Radial Depth of Cut (A_r)	mm	6		
Cutting Fluid Flow/4 nozzles	lit/min	7.5		
Tool Hang	mm	32		
No. of Flutes		4		

Table 4.13: Taguchi L9 orthogonal array

Exp. No	Vibration amplitude (mm/min)	Feed rate (mm/min)	Axial depth of cut (mm)
1	0.0952	400	0.1
2	0.0952	500	0.15
3	0.0952	600	0.2
4	0.11889	400	0.15
5	0.11889	500	0.2
6	0.11889	600	0.1
7	0.185929	400	0.2
8	0.185929	500	0.1
9	0.185929	600	0.15

The procedure is same as discussed in section 4.4.2.

4.4.4 Phase IIC: Tool Wear Evaluation in order to assess the Effects of Forced Vibrations in HSSco and TiAlN Solid Carbide End Mill Cutters

The optical measuring microscope is used to measure the different tool wear patterns (flank wear, crater wear, chipping, flaking and BUE) in accordance with the ISO 8688-2: 1989 [85,86]. The scanning electron microscope is used to investigate causes of tool fracture in details.

CHAPTER 5
RESULTS AND DISCUSSION

The results obtained after the experimentation along with the brief discussion are presented in this chapter.

5.1 Phase IA: Method for Inducing Forced Vibrations in the Spindle of CNC Machining Center using External Weights

Preliminary experimental trails are run in order to assess the magnitude of external weights which can induce the noticeable forced vibrations in the spindle of CNC machining center. During these attempts, the induced vibration amplitude levels are found evident for the magnitude of external weight greater than 200gms. It is also noted that the weights used to induce the vibrations in CNC turning center are much smaller than the weights used in case of CNC machining center under consideration as reveals by the research [8]. The reason behind this behavior is believed firstly, the stability of spindle due to its vertical nature and higher rigidity of the CNC machine spindle provided from the manufacturer end and secondly, in case of CNC turning machine, the rotating component is machine chuck which carries the workpiece. That is why; it responds to very small magnitude of weights. Therefore, heavier weights are used to induce the forced vibrations.

After the confirmation of vibration analyzer repeatability, Table 5.1 and 5.2 show the vibration amplitude levels in X-axis and Y-axis respectively.

Table 5.1: Vibration amplitudes along X-axis

Sr.No	Spindle speed (rpm)	Vibration amplitudes at default level (in/sec)	Vibration amplitudes at 200gms (in/sec)	Vibration amplitudes at 300gms (in/sec)	Vibration amplitudes at 400gms (in/sec)	Vibration amplitudes at 500gms (in/sec)
1	100	0.002100	0.001895	0.002128	0.001961	0.002238
2	200	0.001863	0.002411	0.002100	0.001782	0.002128
3	300	0.001939	0.002079	0.002072	0.002121	0.002404
4	400	0.002316	0.002197	0.002773	0.002878	0.003563
5	500	0.002256	0.002878	0.003711	0.004381	0.007437
6	600	0.006195	0.008112	0.008897	0.01130	0.01769
7	700	0.003621	0.007627	0.01243	0.01868	0.03291
8	800	0.002472	0.001622	0.02968	0.04288	0.09309
9	900	0.002652	0.06720	0.09407	0.07473	0.1453
10	1000	0.003750	0.03383	0.04198	0.04956	0.07654
11	1100	0.002940	0.01381	0.02336	0.02671	0.04436
12	1200	0.003107	0.01503	0.02352	0.03372	0.07266
13	1300	0.004243	0.01395	0.02884	0.03685	0.06089
14	1400	0.004593	0.02148	0.04143	0.04987	0.08941
15	1500	0.004658	0.02501	0.05093	0.06490	0.1269
16	1600	0.004943	0.03057	0.04031	0.05033	0.07871
17	1700	0.004834	0.01388	0.02311	0.02713	0.02606
18	1800	0.004955	0.007580	0.01616	0.02103	0.04832
19	1900	0.005098	0.01703	0.02783	0.04143	0.08593
20	2000	0.004955	0.02486	0.04097	0.06069	0.1145

Table 5.2: Vibration amplitudes along Y-axis

Sr.No	Spindle speed (rpm)	Vibration amplitudes at default level (in/sec)	Vibration amplitudes at 200gms (in/sec)	Vibration amplitudes at 300gms (in/sec)	Vibration amplitudes at 400gms (in/sec)	Vibration amplitudes at 500gms (in/sec)
1	100	0.001316	0.001629	0.004143	0.003782	0.00375
2	200	0.001835	0.001709	0.007873	0.008258	0.008053
3	300	0.002746	0.002773	0.01779	0.01894	0.01909
4	400	0.002847	0.002348	0.03537	0.03984	0.04207
5	500	0.001875	0.002658	0.1719	0.2043	0.2328
6	600	0.00297	0.003521	0.1105	0.1016	0.09568
7	700	0.00294	0.003418	0.06944	0.05413	0.05284
8	800	0.002794	0.006677	0.0435	0.03685	0.03767
9	900	0.00302	0.004721	0.03569	0.04847	0.03337
10	1000	0.003239	0.004931	0.05524	0.04323	0.04454
11	1100	0.003098	0.004991	0.06442	0.06788	0.07074
12	1200	0.003418	0.005736	0.108	0.01105	0.1182
13	1300	0.00299	0.006291	0.06176	0.0625	0.06064
14	1400	0.003521	0.005652	0.0336	0.0345	0.03472
15	1500	0.003039	0.005715	0.05138	0.05483	0.06176
16	1600	0.003356	0.005798	0.07224	0.081	0.08249
17	1700	0.003621	0.005589	0.1228	0.01284	0.1353
18	1800	0.003719	0.008485	0.004143	0.003782	0.00375
19	1900	0.003546	0.008372	0.007873	0.008258	0.008053
20	2000	0.003513	0.007612	0.01779	0.01894	0.01909

As suggested in the vibration diagnostic guide for machine tool condition monitoring [20-21], the most important vibration amplitudes for the analysis of imbalance are the vibration amplitudes along the X-axis. Therefore, the further analysis is carried out by taking vibration amplitudes along X-axis.

The main effects plot is revealed that the external weight shows an almost a linear relationship with vibration amplitudes with profound effect at the highest weight 500gms. The spindle speed, here, shows a near cyclic pattern in connection with vibration amplitudes as shown in Figure 5.1. The cyclic pattern is expected as vibrations are induced in controlled manners.

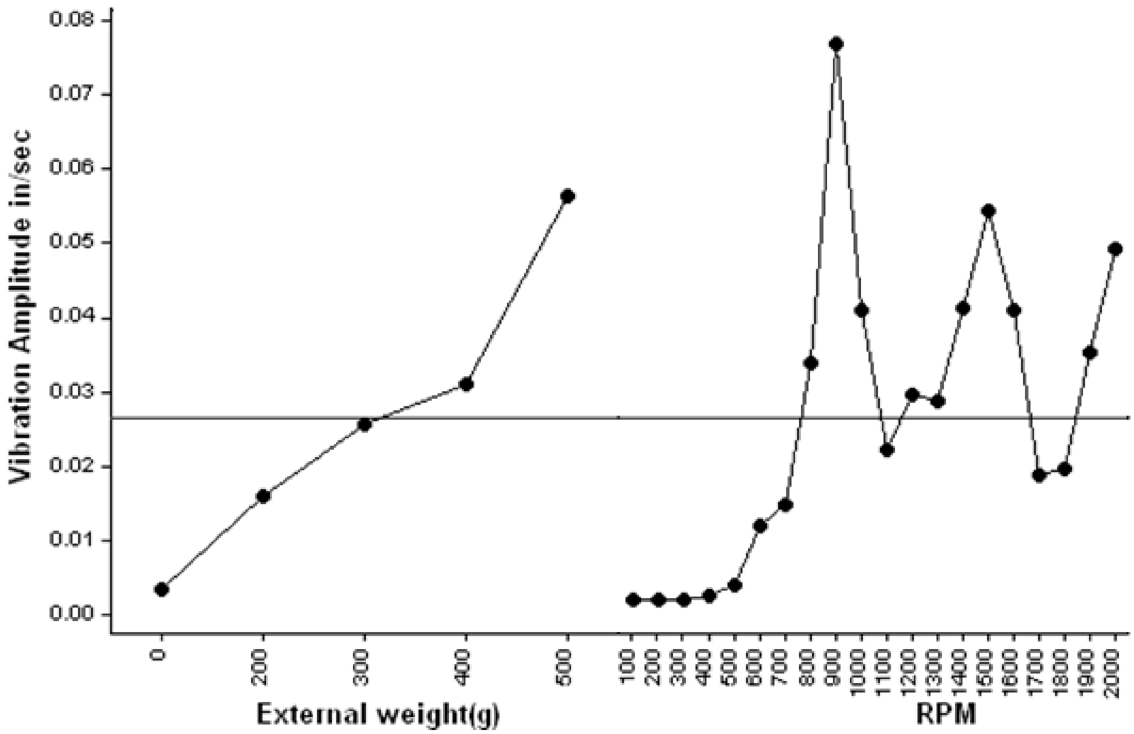


Figure 5.1: Main effects plot for vibration amplitudes

To quantify the results, ANOVA is carried out. Table 5.3 shows the results of analysis of variance at 95 % confidence interval.

Table 5.3: ANOVA results for vibration amplitude

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCR	Remarks
External weight	4	0.0311022	0.0311022	0.0077756	26.31	0.000*	32.09	Significant
Spindle speed	19	0.0396858	0.0396858	0.0020877	7.07	0.000*	36.54	Significant
Error	76	0.0224584	0.0224584	0.0002955				
Total	99	0.0932465						

S = 0.0171903 R-Sq = 75.91 % R-Sq (Adj) = 68.63 %

DF: Degrees of freedom, SS: Sequential sum of squares
MSS: Mean sum of squares, F: F- test value,
P: Probability, PCR: Percentage contribution ratio
*Significant at 5% level

The “p” value (less 5% confidence level) reveals that both the input parameters have significant effects on the dependent parameter i.e. vibration amplitude with the percentage contribution of 32.09%, 36.54% respectively.

5.2 Phase IB: Benchmarking of Induced Vibration Amplitude Levels with selected Industrial Machines

Table 5.4 and 5.5 illustrate the vibration amplitudes levels of three selected industrial machines having different machine tool conditions along X-axis and Y-axis respectively.

Table 5.4: Vibration amplitudes along X-axis (selected industrial machines)

Sr.No	Spindle speed (rpm)	Vibration amplitude for machine 1 (in/sec)	Vibration amplitude for machine 2 (in/sec)	Vibration amplitude for machine 3 (in/sec)
1	100	0.004340	0.002303	0.006348
2	200	0.008597	0.002960	0.009887
3	300	0.01503	0.004696	0.01001
4	400	0.02117	0.005880	0.01155
5	500	0.02949	0.006551	0.01593
6	600	0.03394	0.008053	0.01593
7	700	0.05033	0.009148	0.02076
8	800	0.06039	0.007993	0.007993
9	900	0.07117	0.008541	0.02656
10	1000	0.08156	0.008924	0.03045
11	1100	0.09309	0.008707	0.03221
12	1200	0.09913	0.008141	0.03540
13	1300	0.1153	0.009839	0.04671
14	1400	0.1230	0.01094	0.04925
15	1500	0.1578	0.1578	0.05241
16	1600	0.1672	-	0.05524
17	1700	0.1976	-	0.05794
18	1800	0.1802	-	0.06323
19	1900	0.1836	-	0.06139
20	2000	0.1736	-	0.05950

Table 5.5: Vibration amplitudes along Y-axis (selected industrial machines)

Sr.No	Spindle speed (rpm)	Vibration amplitude for machine 1 (in/sec)	Vibration amplitude for machine 2 (in/sec)	Vibration amplitude for machine 3 (in/sec)
1	100	0.005567	0.003487	0.003546
2	200	0.01296	0.003694	0.006291
3	300	0.02235	0.004158	0.009766
4	400	0.03088	0.004381	0.01118
5	500	0.03483	0.005338	0.01532
6	600	0.03906	0.006099	0.01680
7	700	0.05714	0.007109	0.01933
8	800	0.05820	0.008258	0.01987
9	900	0.06014	0.009790	0.02139
10	1000	0.06089	0.1269	0.02748
11	1100	0.06966	0.009983	0.02769
12	1200	0.08193	0.1795	0.02569
13	1300	0.07773	0.009911	0.02626
14	1400	0.07391	0.009316	0.02463
15	1500	0.08304	0.01212	0.02455
16	1600	0.1140	-	0.02554
17	1700	0.1039	-	0.02656
18	1800	0.09568	-	0.02565
19	1900	0.08646	-	0.02547
20	2000	0.1045	-	0.02531

Figure 5.2 shows the comparison of induced vibration amplitude levels obtained by varying external weights (200gms ~ 500gms) along with default level of vibrations of CNC machining center spindle in contrast to default vibrations of three selected industrial machines with different machine tool conditions used for benchmarking.

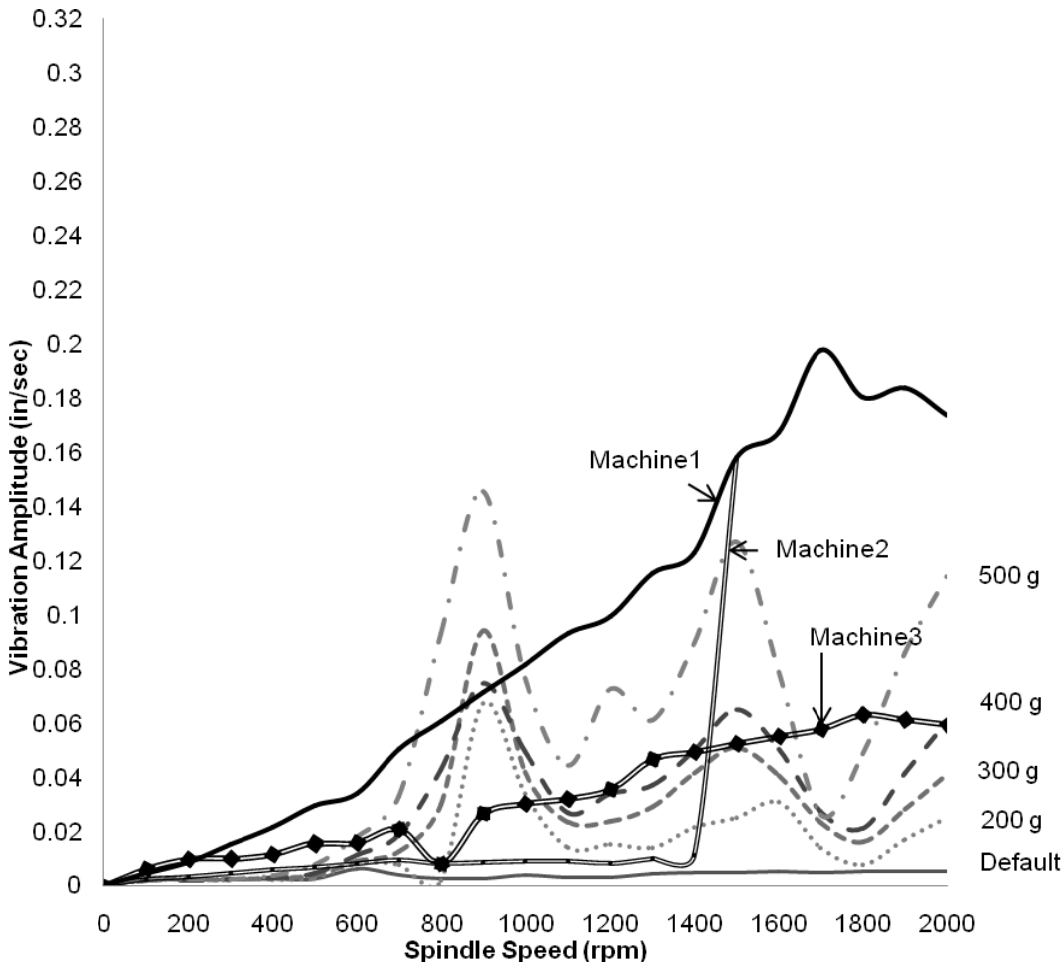


Figure 5.2: Variation in vibration amplitude levels with varying external weights (three selected machines for benchmarking are also plotted)

It can be seen from the figure that the default level of spindle vibrations of the machine under investigation are almost negligible even at high spindle speeds (2000rpm) corresponding to the successive external weights. A near-cyclic pattern is observed with increase in amplitude levels at higher spindle speeds which confirms the findings of main effects plot for spindle speed.

The first peek of vibration amplitude for the CNC machining center is obtained at 900rpm which is considered the first natural frequency of machine spindle. It is very important to identify the natural frequency of machine for the careful selection of machining parameters to avoid resonance during machining [18].

On the other hand, the benchmarking industrial machines1 and 3 exhibit almost a linear pattern. The vibration amplitudes increase as the spindle speed increases. This pattern may be attributed to machine tool conditions depending upon the imbalance in the spindle, wear in the spindle bearings and misalignment of any moving part etc. The benchmarking machine 2 shows very small vibrations till 1400 rpm followed by a sharp increase in value. However detail explanation of this unusual behavior of machine vibrations is not investigated as it is out of the scope of the present research.

It is however obvious that the magnitudes of vibration amplitude levels of benchmarking industrial machines are comparable to those of a CNC machine fitted with external weights. Therefore, it can be concluded that the external weights may simulate to a fair degree of comparable ranges of machine tool conditions of an industrial machine.

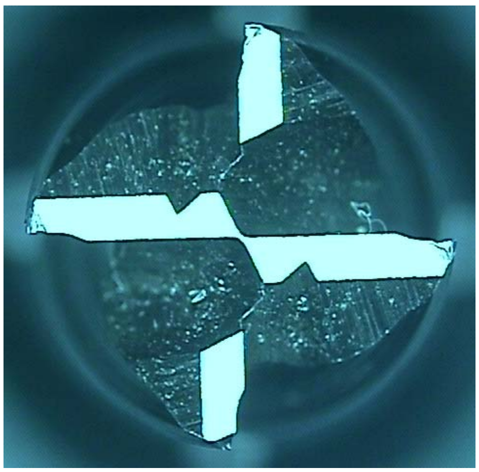
Three vibration amplitude levels are selected from phase IA, IB for phase IIA and IIB.

5.3 Phase IIA: Investigation of Effects of Spindle Forced Vibrations on Surface Roughness and Dimensional Accuracy using HSSco End Mill Cutters

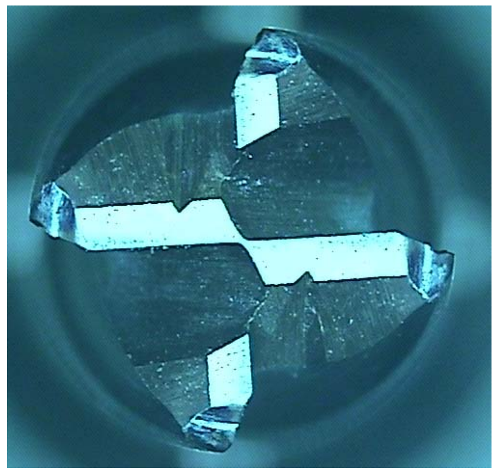
Results obtained after machining are discussed in forthcoming sections.

5.3.1 For Set I

During the experimentation of set I which involves milling of workpiece material using HSSco end mill cutter. It is observed that tool failure occurred in the initial stages of experimentation. Figure 5.3 and 5.4 show the micrographs of CMM and optical micrographs of tool indicating the tool failure on the default level vibration amplitude of machine spindle.

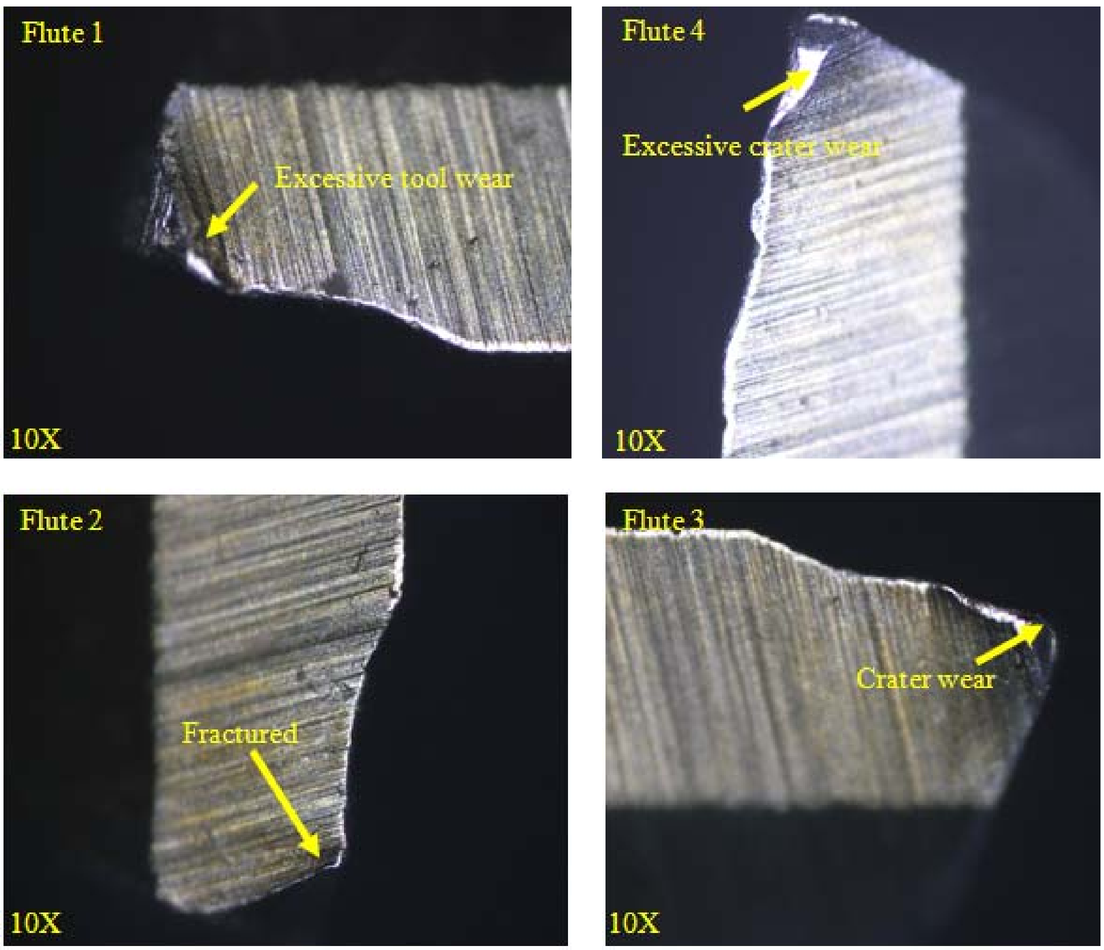


a) Experiment: 2
F =640mm/min, A_P = 0.2mm
VA = 0.09522mm/min



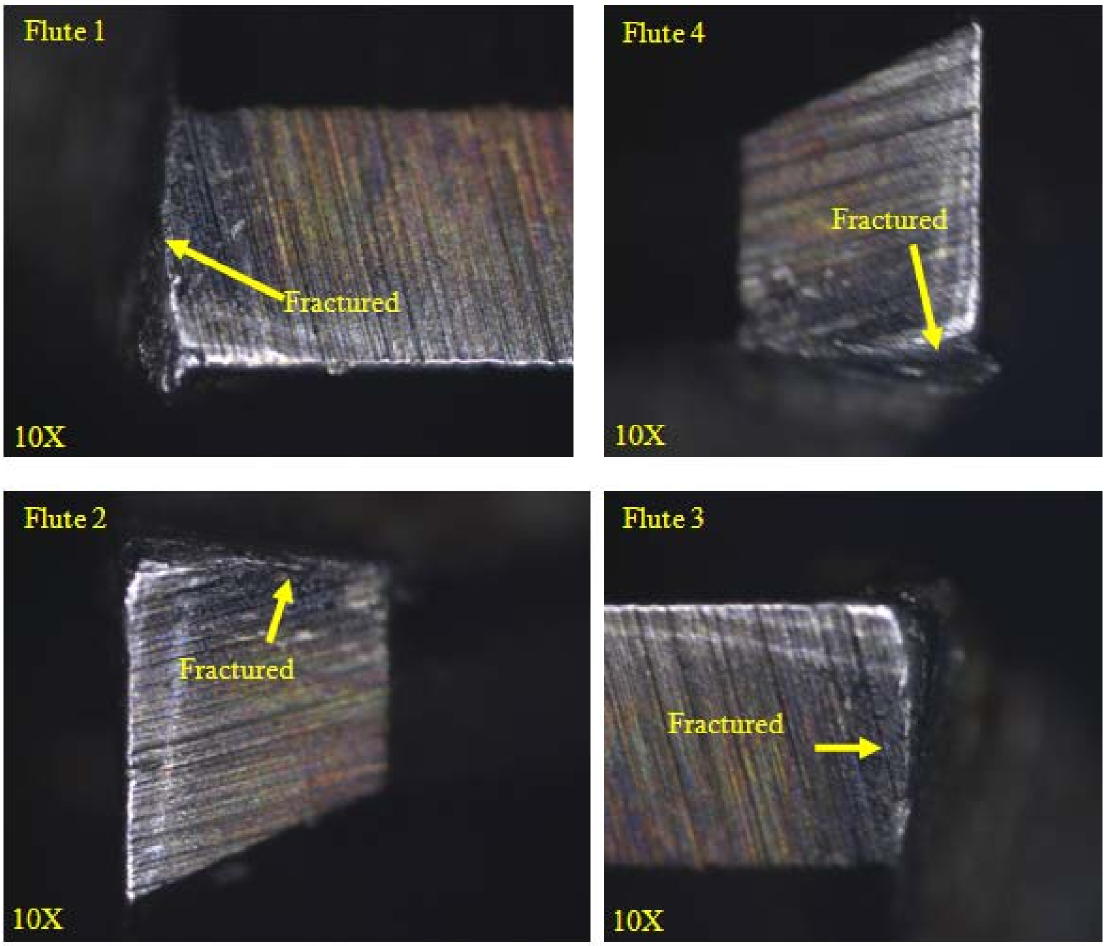
b) Experiment: 3
F =1280mm/min, A_P = 0.4mm
VA = 0.09522mm/min

Figure 5.3: CMM micrographs of fractured tools used in (a) experiment 2 and (b) experiment 3



(a) Tool 2: F = 640mm/min, A_P = 0.2mm, VA = 0.09522mm/m

Figure 5.4: Optical micro graphs of fractured tools (a) Tool 2 (b) Tool 3 (continued)



(b) Tool 3: F = 1280mm/min, A_P = 0.4mm, VA = 0.09522mm/min

Figure 5.4: Optical micro graphs of fractured tools (a) Tool 2 (b) Tool 3

It is considered that high levels of feed rate and depth of cut may be the possible reasons of the tool failure. . Therefore, it is decided not to pursue with the rest of the experiments and experimentation of set II will be conducted. The results obtained for set II experimentation are discussed below:

5.3.2 For Set II (Surface Roughness)

The surface roughness values obtained after the machining from set II experimentation are shown in the Table 5.6 below.

Table 5.6: Surface roughness values for HSSco end mill cutter

Experiment #.	Input parameters			Dependent parameter
	Vibration amplitude level	Feed rate	Axial depth of Cut	Surface roughness
	(mm/min)	(mm/min)	(mm)	(µm)
1	Level 1: 0.0952	256	0.2	2.80
2	0.0952	288	0.25	2.93
3	0.0952	320	0.3	2.13
4	Level 2: 0.11889	256	0.25	2.73
5	0.11889	288	0.3	2.53
6	0.11889	320	0.2	2.33
7	Level 3: 0.185929	256	0.3	3.27
8	0.185929	288	0.2	2.93
9	0.185929	320	0.25	1.87

Table 5.6 exposes that the average surface roughness value is initially decreased 3.58% as the vibration amplitude of machine spindle increases from level 1 to level 2 and then increases by a value of 6% with the increase of vibration amplitudes from level 2 to level 3. It is also noted that 11% increase in feed rate from level 1 to 2 results into 5% decrease in surface roughness and 10% increase in feed rate from level 2 to 3 decreases 32% surface roughness value.

S/N ratio analysis is carried out in order to rank out the input parameters with respect to their effects on surface roughness using “smaller the better” approach. Table 5.7 shows the results of S/N ratio. It can be seen that feed rate ranked as the most affecting parameter with highest value of delta among the three input parameters.

Table 5.7: S/N ratio for surface roughness (Smaller is better)

	Vibration Amplitude (mm/min)	**Feed Rate (mm/min)**	**Axial DOC (mm)**
Level 1	-8.212	-9.224	-8.475
Level 2	-7.940	-8.818	-7.817
Level 3	-8.309	-6.418	-8.169
Delta	0.368	2.806	0.658
Rank	3	1	2

In addition to S/N ratio the Figure 5.5 explains the main effects plot for surface roughness. It can be noted from the figure that surface roughness is inversely proportional to feed rate. As the feed rate increases the surface roughness values have been decreased. This phenomenon could be explained on the basis of that increase feed rate results into increasing distance between successive cuts produced by cutting edges of the cutter [119].

The figure also illustrates that vibration amplitudes and axial depth of cut has a nonlinear relationship with the surface roughness. With the increase in vibration amplitude level and axial depth of cut, the surface roughness has been decreased initially but has an increment with the further increase in vibration amplitude and axial depth of cut.

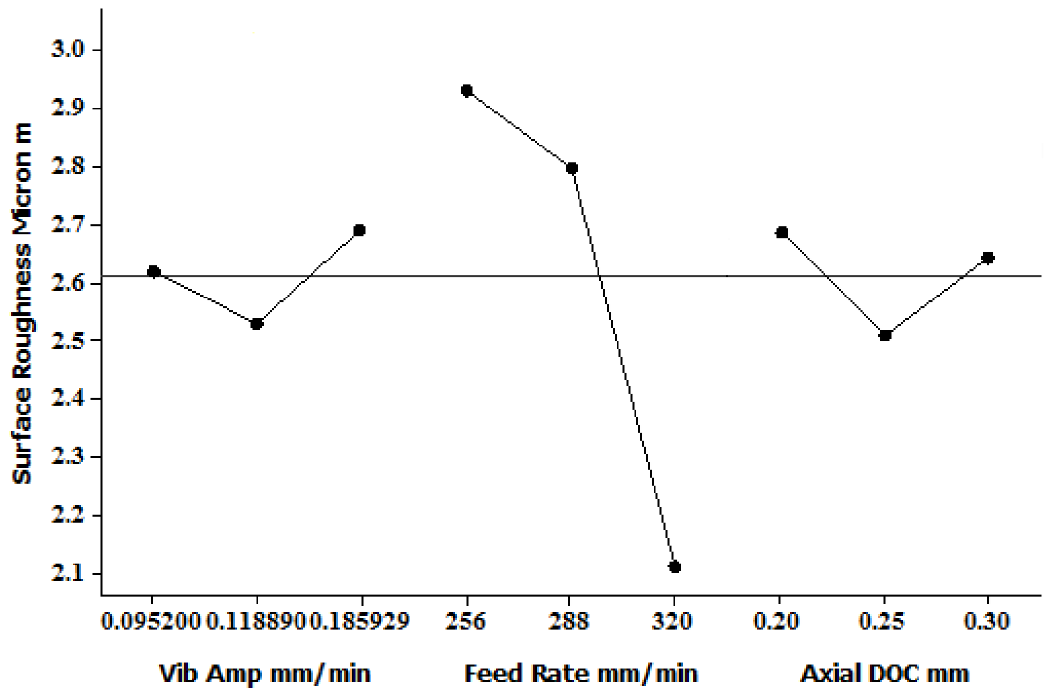


Figure 5.5: Main effects plot for surface roughness

In order to find out the significant parameters affecting the surface roughness, ANOVA is carried out at 95% confidence level as shown in Table 5.8.

Table 5.8: ANOVA results for HSSco cutter

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCR	Remarks
Vibration amplitude	2	0.0289	0.0289	0.0144	0.10	0.907		Not significant
Feed rate	2	1.2022	1.2022	0.6611	1.26	0.190		-
Axial depth of cut	2	0.0622	0.0622	0.0311	0.22	0.819		-
Error	2	0.2822	0.2822	0.1411				
Total	8	1.5756						

S = 0.375684 R-Sq = 82.09 % R-Sq (Adj) = 28.35 %

The ANOVA results reveal that all the three input parameters are statistically not significant at 95% confidence interval which leads the research in the favor of conducting next phase of experimentation

5.3.3 For Set II (Dimensional Accuracy)

Dimensions of milled slot (height and width of slot) are measured in order to investigate the effects of input parameters for dimensional accuracy. Results obtained from CMM are listed in Table 5.9 below.

Table 5.9: Results of CMM for dimensional accuracy

Experiment #	**Input parameters**			**Dependent parameter**			
	Vibration Amplitude Level	**Feed Rate**	**Axial Depth of Cut**	**Measured Dimensions of the Slot (6×6×60)**		**Dimensional Inaccuracy**	
				Height	**Width**	**Height**	**Width**
	(mm/min)	**(mm/min)**	**(mm)**	**(mm)**	**(mm)**	**%**	**%**
1	0.0952	256	0.2	5.95	6.05	0.83	(0.83)
2	0.0952	288	0.25	5.955	6.08	0.83	(1.33)
3	0.0952	320	0.3	5.95	6.08	0.83	(1.33)
4	0.11889	256	0.25	5.84	6.06	2.66	(1)
5	0.11889	288	0.3	5.93	6.06	1.16	(1)
6	0.11889	320	0.2	5.94	6.05	1.2	(0.83)
7	0.185929	256	0.3	5.94	6.07	1.2	(1)
8	0.185929	288	0.2	5.94	6.07	1.2	(0.1)
9	0.185929	320	0.25	5.93	6.08	1.16	(1.33)

S/N ratio analysis is performed for both the height and width of slot in order to rank the input parameters according to their effects on the dimensional accuracy using "larger the better" approach. Table 5.10 presents the S/N ratio analysis results. It is revealed from the analysis that with highest value of delta, vibration amplitude ranked as most affecting parameter.

Table 5.10: S/N ratio values for height and width (Larger is better)

For height of the slot			
	Vibration Amplitude (mm/min)	**Feed Rate (mm/min)**	**Axial DOC (mm)**
Level 1	15.50	15.43	15.49
Level 2	15.42	15.48	15.43
Level 3	15.48	15.48	15.48
Delta	0.07	0.05	0.05
Rank	1	3	2

For width of the slot			
	Vibration Amplitude (mm/min)	**Feed Rate (mm/min)**	**Axial DOC (mm)**
Level 1	15.67	15.65	15.65
Level 2	15.64	15.66	15.67
Level 3	15.67	15.67	15.66
Delta	0.03	0.02	0.02
Rank	1	3	2

Figure 5.6 and 5.7 illustrate the main effects plots for the dimensions of milled slot. It can be seen from the Figure 5.6 that vibration amplitude feed rate and axial depth of cut exhibit a non linear attitude on the height of the slot. Smaller values of vibration amplitude and axial depth of cut give better dimensional accuracy. It can be explained on the basis that high values of vibration amplitudes and axial depth of cut enhance the tool wear and hence affecting the dimensional accuracy. While in case of width as shown in Figure 5.7, feed rate has a linear behavior i.e. the increase in the feed rate resulted into high values of inaccuracy.

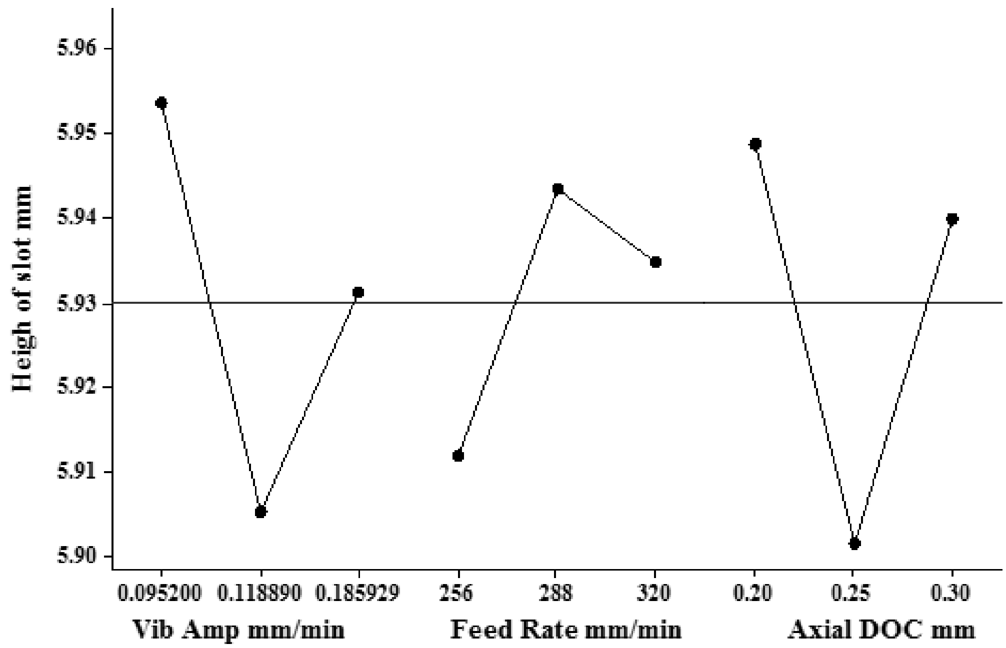


Figure 5.6: Main effects plot for height of slot

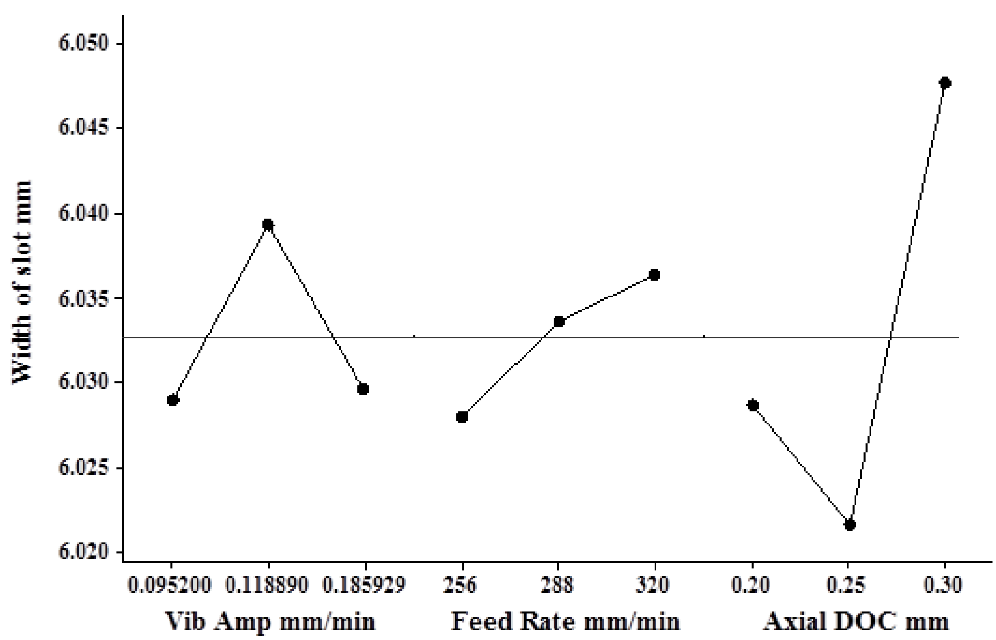


Figure 5.7: Main effects plot for width of slot

Table 5.11 and 5.12 depict the results of analysis of variance which is purposely conducted in order to rule out the significant parameters along with the percentage contribution affecting the dependent parameter.

Table 5.11: ANOVA results for Height

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**PCR**	**Remarks**
Vibration amplitude	2	0.003745	0.003745	0.001872	1.87	0.348		Not significant
Feed rate	2	0.002003	0.002003	0.001002	1.00	0.500		-
Axial depth of cut	2	0.002257	0.002257	0.001128	1.13	0.470		-
Error	2	0.002000	0.002000	0.001000				
Total	8	0.010005						

S = 0.0316236 R-Sq = 80.01% R-Sq(adj) = 20.04%

Table 5.12: ANOVA results for Width

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**PCR**	**Remarks**
Vibration amplitude	2	0.0006969	0.0006969	0.0003484	84.76	0.012		Significant
Feed rate	2	0.0003529	0.0003529	0.0001764	42.92	0.023		Significant
Axial depth of cut	2	0.0004276	0.0004276	0.0002138	52.00	0.019		Significant
Error	2	0.0000082	0.0000082	0.0000041				
Total	8	0.0014856						

S = 0.00202759 R-Sq = 99.45% R-Sq(adj) = 97.79%

It can be seen from the ANOVA results that all input parameters are insignificant for height of the slot at 95% confidence interval while in case of width all the parameters declare significant.

Results of surface roughness and dimensional accuracy obtained in set II experimentation are not showing a clear picture indicating the effects of vibration amplitude. Thus it is decided to conduct second part of this phase with solid carbide end mill cutters.

5.4 Phase IIB: Investigation of Effects of Spindle Forced Vibrations on Surface Roughness and Dimensional Accuracy using Solid Carbide End Mill Cutters

Analysis of surface roughness and dimensional accuracy are presented in this section.

5.4.1 For Surface Roughness

Table 5.13 shows the results of surface roughness along with the standard deviation against the machining input parameters.

Table 5.13: Three values of surface roughness and respective standard deviation

Sr. No.	Height of the slot 6mm		Standard Deviation
1	1.33	1.33	0.005774
		1.33	
		1.34	
2	1.6333(1.6)	1.5	0.11547
		1.7	
		1.7	
3	2.01(2.0)	2.0	0.015275
		2.01	
		2.03	
4	2.7333(2.73)	2.74	0.005774
		2.73	
		2.73	
5	2.7333(2.73)	2.74	0.011547
		2.72	
		2.74	
6	2.43666(2.4)	2.43	0.005774
		2.44	
		2.44	
7	3.3344(3.33)	3.33	0.005774
		3.33	
		3.34	
8	2.6666(2.67)	2.66	0.011547
		2.66	

		2.68	
9	3.5333(3.53)	3.53	0.015275
		3.52	
		3.55	

It can be seen from Table 5.13, standard deviations are negligible for three values of surface roughness. Table 5.14 shows the results of average surface roughness against the variable input parameters.

Table 5.14: Surface roughness results for solid carbide end mill cutter

Experiment #.		**Input parameters**			**Dependent parameter**
		Vibration amplitude level	**Feed rate**	**Axial depth of Cut**	**Surface roughness**
		(mm/min)	**(mm/min)**	**(mm)**	**(µm)**
1		0.0952	400	0.1	1.33
2	Level 1	0.0952	500	0.15	1.6
3		0.0952	600	0.2	2.0
4		0.11889	400	0.15	2.73
5	Level 2	0.11889	500	0.2	2.73
6		0.11889	600	0.1	2.4
7		0.185929	400	0.2	3.33
8	Level 3	0.185929	500	0.1	2.67
9		0.185929	600	0.15	3.53

It can be noted from Table 5.14, the average surface roughness value is increased 36% as the vibration amplitude of machine spindle increases from level 1 to level 2 and a 17% increment is further noted as the machine tool spindle vibration amplitude increases from level 2 to level 3. S/N ratio analysis is performed to rank the input parameters according to their influence on the surface roughness using “smaller the better” approach and results are presented in the Table 5.15 below. The highest delta value of vibration amplitude indicates that it is the most affecting parameter among the three input parameters in case of surface roughness.

Table 5.15: S/N ratio results for surface roughness

	Vibration Amplitude (mm/min)	Feed Rate (mm/min3)	Axial DOC (mm)
Level 1	-4.193	-7.216	-6.204
Level 2	-8.350	-7.112	-7.920
Level 3	-9.978	-8.193	-8.398
Delta	5.785	1.081	2.194
Rank	1	3	2

Figure 5.8 shows the main effects plot for the surface roughness. It can be deduced from the Figure 5.8 that surface roughness is in nearly linear relationship with the vibration amplitude and axial depth of cut. It is showing that as the vibration amplitude of the spindle and depth of cut has been increased, the surface roughness starts deteriorating. It is in an agreement with the results extracting from Table 5.13.

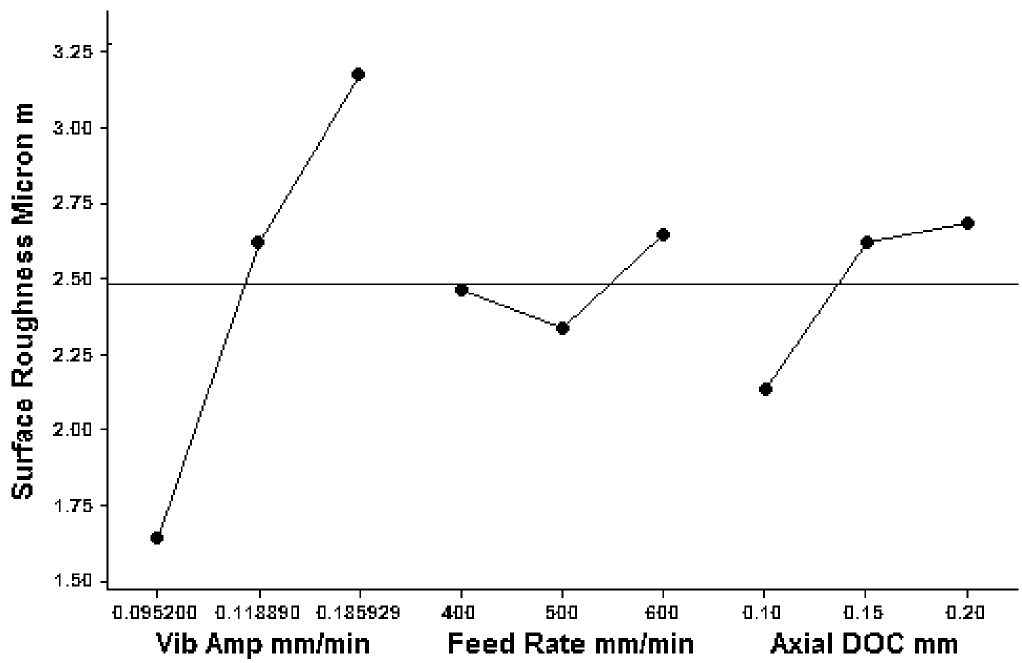


Figure 5.8: Main effects plot for surface roughness

The surface finish deteriorates as the vibration amplitude of machine spindle increases. It may be explained in a way that higher amplitudes of spindle vibrations caused higher values of chatter as chatter produced due to the dynamic interface of machining process and structure of the machine [120]. Any disruption in either, machining process or the structural stiffness will change the level of interface and consequently influence chatter. Therefore, during any machining process, machine tool performs in a closed loop feedback system. Thus, any deflection in the spindle of machine tool (measured as a form of spindle forced vibration amplitudes) would result into the high cutting forces due to the variation of un-deformed chip thickness and hence causing the chatter [120]. Thus, the excessive chatter during machining operation result high values of cutting forces during the machining operations and hence produced poor surface roughness values.

Figure 5.8 also demonstrates the behavior of the axial depth of cut affecting surface roughness. A similar pattern is observed in case of axial depth of cut, the increase depth of produces poor surface roughness. The possible reason of this behavior would be the cutting forces at the cutting tool tip which may be increased due to high values of depth of cut. This may cause chatter which eventually damages the surface finish of the machined parts. However, feed rate exhibits a non-linear behavior. Initially surface roughness is improved with the increase of feed rate due to the increase in the distance between the cuts produced by the cutting tool edges [119]. But a detrimental effect on the surface finish is observed with the further rise in the feed rate value. It could be explained on the basis of machining principles that high value of feed rate causes higher values of cutting forces which have devastating effects on surface finish. . The main effects plots suggested that small vibration amplitude, small axial depth of cut and medium value of feed rate would lower the surface roughness values.

In order to quantify the machining parameters, ANOVA is performed and results are shown in the Table 5.16.

Table 5.16: ANOVA results at 95% confidence interval for surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCR*	Remarks
Vibration amplitude	2	3.61487	3.61487	1.80743	299.57	0.003	83	Significant
Feed rate	2	0.14540	0.14540	0.07270	12.05	0.077		
Depth of cut	2	0.54747	0.54747	0.27373	45.37	0.022	8.77	Significant
Error	2	0.01207	0.01207	0.00603				
Total	8	4.31980						

S = 0.0776745 R-Sq = 99.72 % R-Sq (Adj) = 98.88 %

ANOVA results show that spindle vibration amplitude and axial depth of cut are statistically significant for the surface roughness. The percentage contribution (PCR) of spindle forced vibrations shows that it is the most affecting parameter for the milling operation. It can also be seen that PCR results are aligned with the S/N ratio ranking as are listed in the Table 5.16. The ANOVA results herein are not similar as is reported in case of turning operations [9]. Munawar et al establish a result in case of turning operations that spindle vibrations has moderate effect on machining characteristics like surface roughness [9]. Tool orientation may be one of the possible reasons which bring the difference in the results for milling and turning operations.

5.4.2 For Dimensional Accuracy

Table 5.17 lists the results of dimensional accuracy (height and width of the milled slot) taken at three different positions along with their standard deviation.

Table 5.17: Three values of dimensions along with standard deviation

Sr. No.	Height of the slot 6mm		Standard Deviation	Width of the slot 6mm		Standard Deviation
1	5.9089(5.91)	5.9100	0.000666	5.9711(5.97)	5.9743	0.003512
		5.9088			5.9673	
		5.9089			5.9713	
2	5.9382(5.94)	5.9382	0.000115	5.9956(5.99)	5.9973	0.004726
		5.9384			5.9903	
		5.9384			5.9993	
3	5.9546(5.95)	5.9547	5.77E-05	5.9996(5.99)	6.0083	0.008505
		5.9546			5.9993	
		5.9546			5.9913	
4	5.9094(5.91)	5.9094	0.0001	5.9959(5.99)	5.9843	0.013868
		5.9093			5.9923	
		5.9095			6.0113	
5	5.8738(5.87)	5.8738	1E-04	6.01	6.0064	0.00346
		5.8737			6.0133	
		5.8739			6.0103	
6	5.9306(5.93)	5.9306	5.77E-05	6.0193(6.02)	6.0283	0.012288
		5.9307			6.0243	
		5.9307			6.0053	
7	5.9444(5.94)	5.9444	1E-04	6.0583(6.06)	6.0583	0.01
		5.9443			6.0683	
		5.9445			6.0483	
8	5.9387(5.94)	5.9383	0.000252	6.034(6.03)	6.0283	0.005508
		5.9386			6.0373	
		5.9388			6.0383	
9	5.9455(5.95)	5.9455	5.77E-05	6.045(6.05)	6.0343	0.009452
		5.9456			6.0523	
		5.9455			6.0483	

It can be seen from the Table 5.17 that standard deviations for dimensional accuracy are negligible. Therefore, average dimensional accuracy (height and width of the milled slot) are taken as shown in Table 5.18.

Table 5.18: CMM results of dimensional accuracy for solid carbide end mill cutter

Experiment #	**Input parameters**			**Dependent parameter**			
	Vibration Amplitude Level	**Feed Rate**	**Axial Depth of Cut**	**Measured Dimensions of the Slot (6×6×60)**		**Dimensional Inaccuracy**	
				Height	**Width**	**Height**	**Width**
	(mm/min)	**(mm/min)**	**(mm)**	**(mm)**	**(mm)**	**%**	**%**
1	0.0952	400	0.1	5.91	5.97	1.5	0.5
2	0.0952	500	0.15	5.94	5.99	1	0.16
3	0.0952	600	0.2	5.95	5.99	0.83	0.16
4	0.11889	400	0.15	5.91	5.99	1.5	0.16
5	0.11889	500	0.2	5.87	6.01	2.16	(0.16)
6	0.11889	600	0.1	5.93	6.02	1.16	(0.33)
7	0.185929	400	0.2	5.94	6.06	1	(1)
8	0.185929	500	0.1	5.94	6.03	1	(0.5)
9	0.185929	600	0.15	5.95	6.05	0.83	(0.83)

Table 5.19 shows results of S/N ratio analysis which is carried out to rank the order of the parameter according to the magnitude of their effects on the dependent parameter using “larger the better” approach.

Table 5.19: S/N ratio results for dimensional accuracy (height and width)

For height of the slot			
	Vibration Amplitude (mm/min)	**Feed Rate (mm/min3)**	**Axial DOC (mm)**
Level 1	15.47	15.45	15.46
Level 2	15.42	15.44	15.47
Level 3	15.48	15.48	15.45
Delta	0.06	0.04	0.05
Rank	1	2	3

For width of the slot			
Level	**Vibration Amplitude (mm/min)**	**Feed Rate (mm/min3)**	**Axial DOC (mm)**
Level 1	15.54	15.57	15.57
Level 2	15.57	15.58	15.58
Level 3	15.63	15.59	15.59
Delta	0.09	0.02	0.02
Rank	1	2	3

It is revealed from the Table 5.19 that vibration amplitude ranked the most affecting parameter for height and width of the slot. The main effects plots for height and width of the slot are shown in the Figure 5.9 and Figure 5.10. It can be deduced from the main effects plots that all the input parameters demonstrate a random behavior in case of height and have a near linear relationship in case of width of slot.

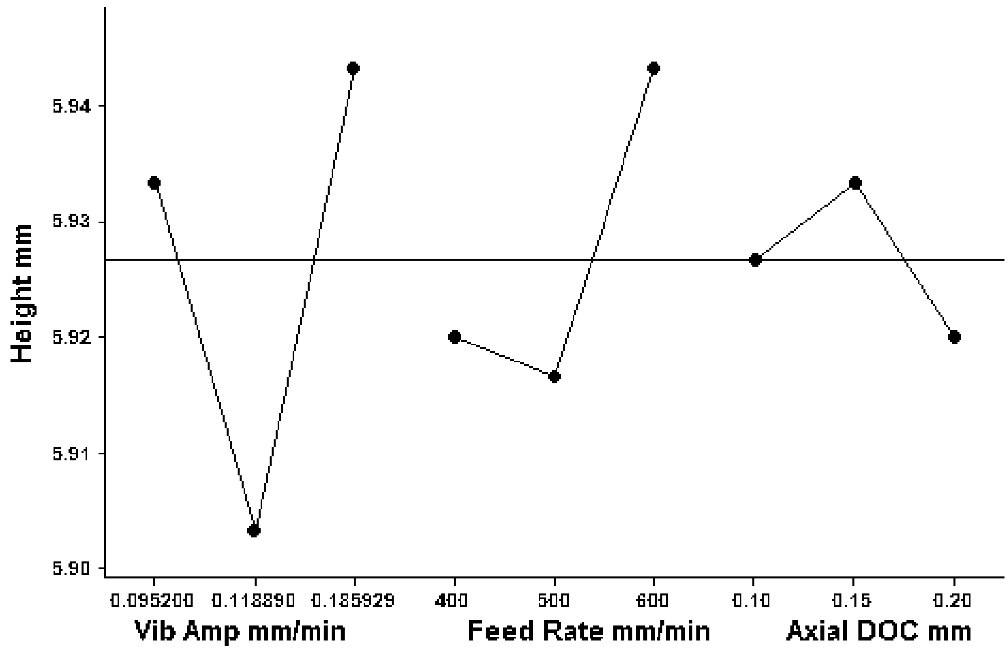


Figure 5.9: Main effect plot for height of slot

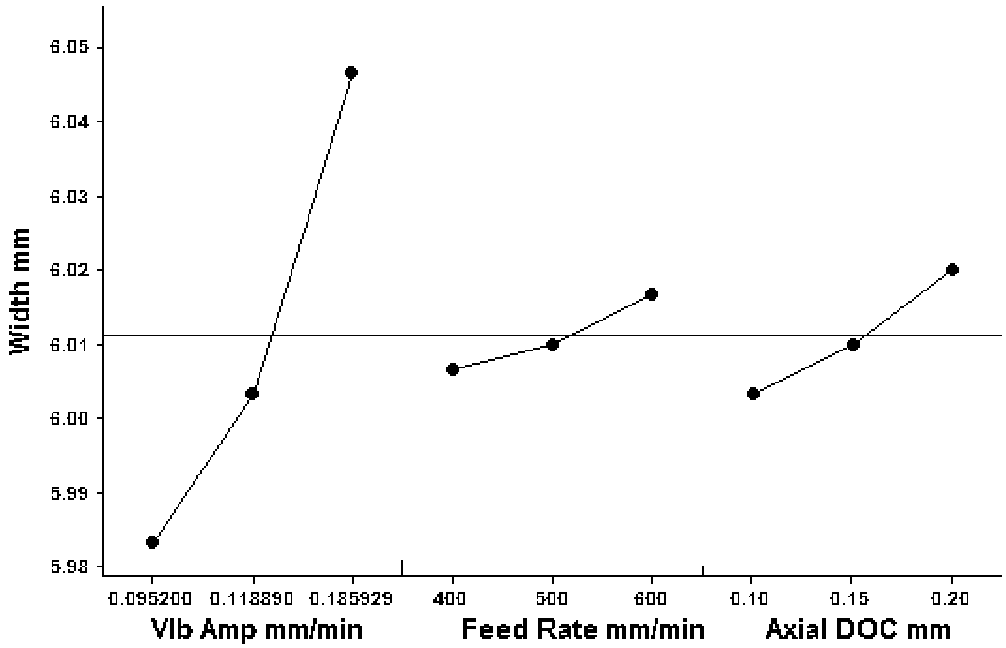


Figure 5.10: Main effect plot for width of slot

Table 5.20 and 5.21 show the ANOVA results for dimensional accuracy (for Height & Width of the slot). The results of ANOVA expose that for the case of dimensional accuracy in terms of height and width, all three parameters become insignificant at the stated confidence level. This could be explained in a way that dimensions of height and width are relatively insensitive to the values of three parameters used in the present experimentation. Therefore, it can be considered that the difference in dimensions may be due to the initial wear in the cutting tool.

Table 5.20: ANOVA results at 95% confidence interval for height

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCR*	Remarks
Vibration amplitude	2	0.0026000	0.0026000	0.0013000	2.05	0.328		Not significant
Feed rate	2	0.0012667	0.0012667	0.0006333	1.00	0.500		-
Depth of cut	2	0.0002667	0.0002667	0.0001333	0.21	0.826		-
Error	2	0.0012667	0.0012667	0.0006333				
Total	8	0.0054000						

S = 0.0251661 R-Sq = 76.54% R-Sq(adj) = 6.17%

Table 5.21: ANOVA results at 95% confidence interval for width

Source	DF	Seq SS	Adj SS	Adj MS	F	P	PCR*	Remarks
Vibration amplitude	2	0.0062889	0.0062889	0.0031444	14.89	0.063		Not significant
Feed rate	2	0.0001556	0.0001556	0.0000778	0.37	0.731		-
Depth of cut	2	0.0004222	0.0004222	0.0002111	1.00	0.500		-
Error	2	0.0004222	0.0004222	0.0002111				
Total	8	0.0072889						

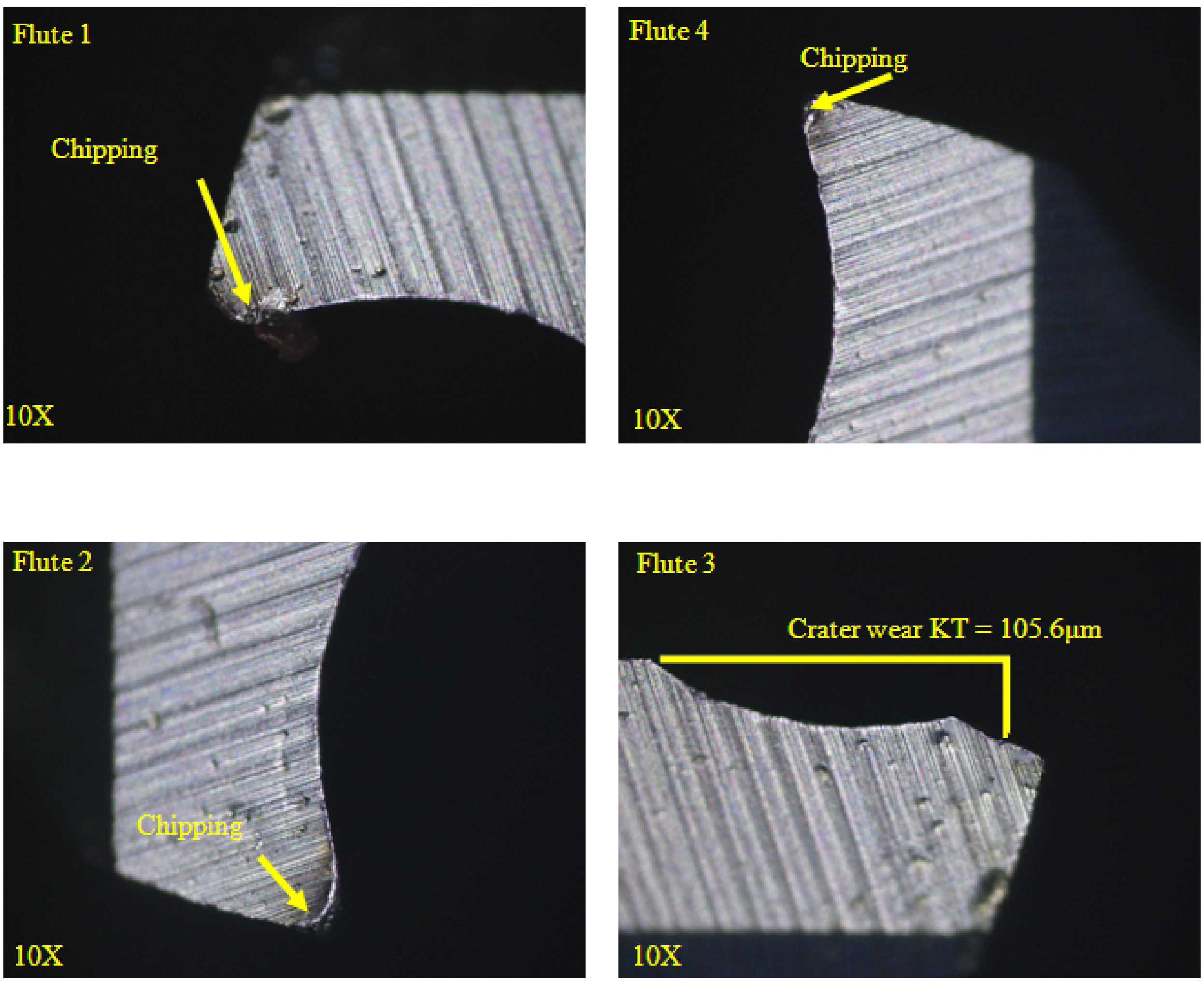
S = 0.0145297 R-Sq = 94.21% R-Sq(adj) = 76.83%

5.5 Phase IIIA: Tool Wear Evaluation in order to assess the Effects of Forced Vibrations in case of HSSco and Solid Carbide End Mill Cutters

Evaluation of different types of tool wear patterns in case of HSSco and TiAlN solid carbide end mill cutters is presented in this section.

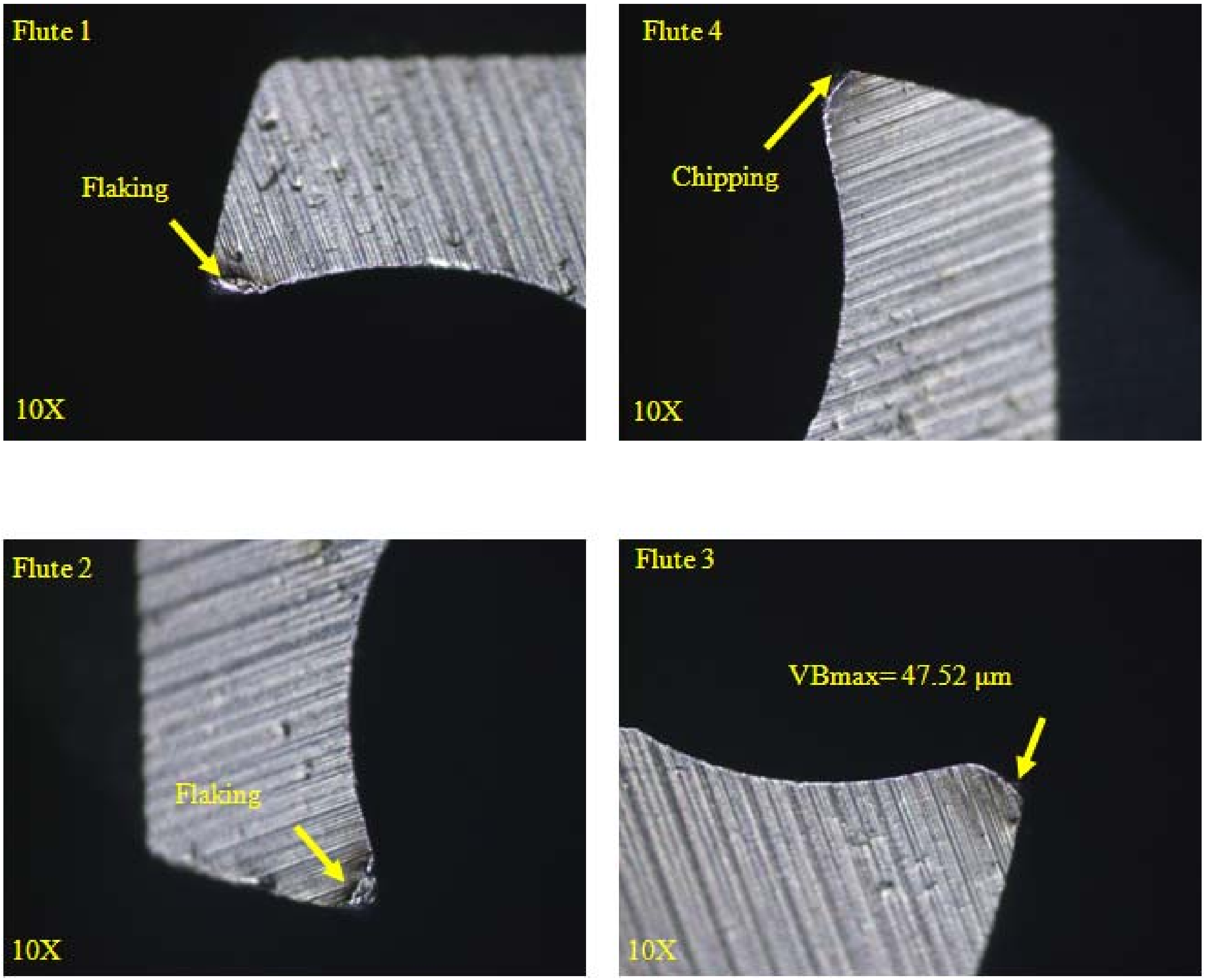
5.5.1 Tool Wear for Cobalt Coated High Speed Steel End Mill Cutter

Figure 5.11(a-i) presents optical micrographs of nine tools indicating different type tool wear patterns i.e. crater wear (KT), , tool flank wear (VB_{max}), built-up edge (BUE), flaking and chipping. VB_{max}, is taken as tool life criteria (ISO 8688-2: 1989 [85].



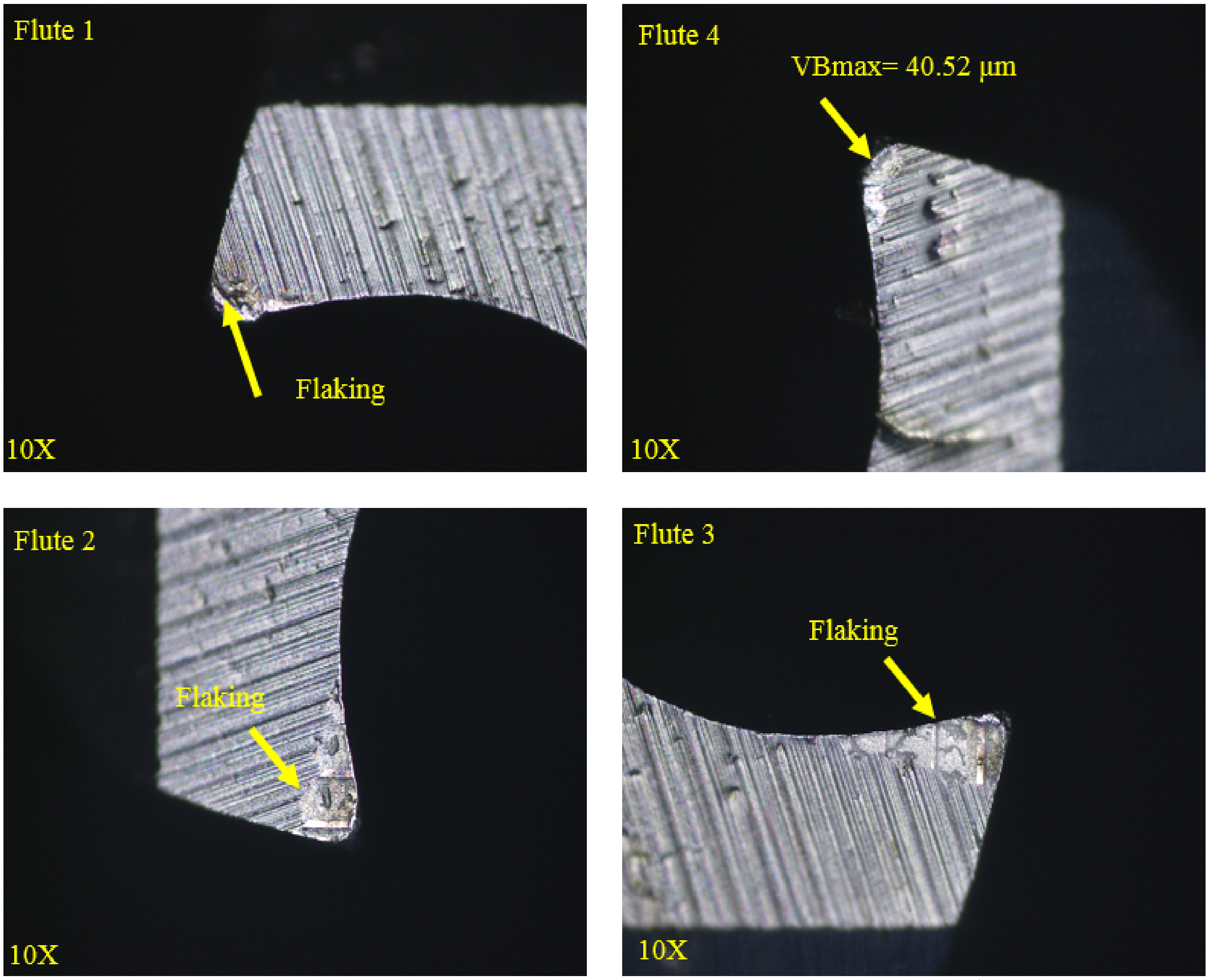
a) Tool 1: VA= 0.0952 mm/min, F =256 mm/min, A_p = 0.2 mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



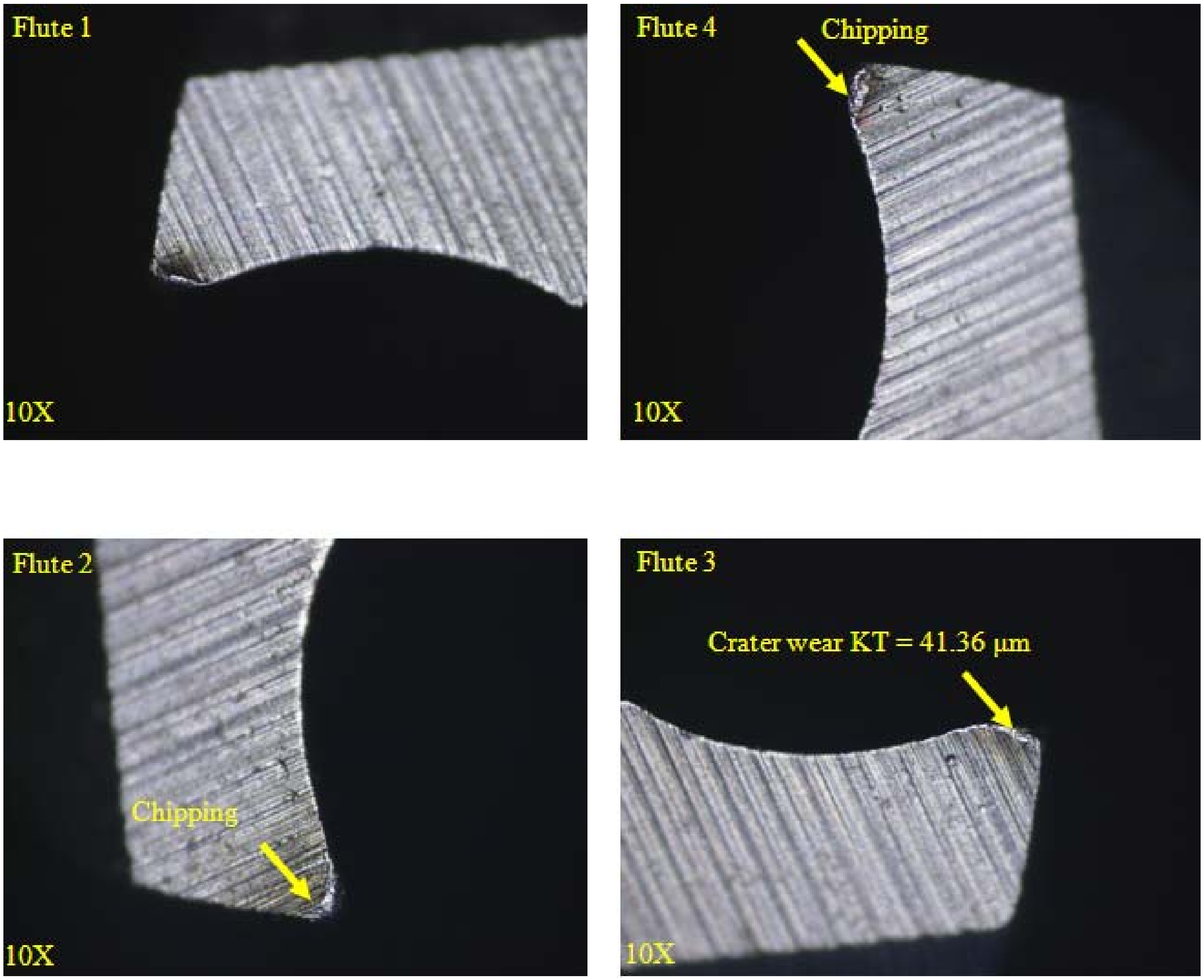
b) Tool 2: VA= 0.0952 mm/min, F = 288 mm/min, A_p = 0.25 mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



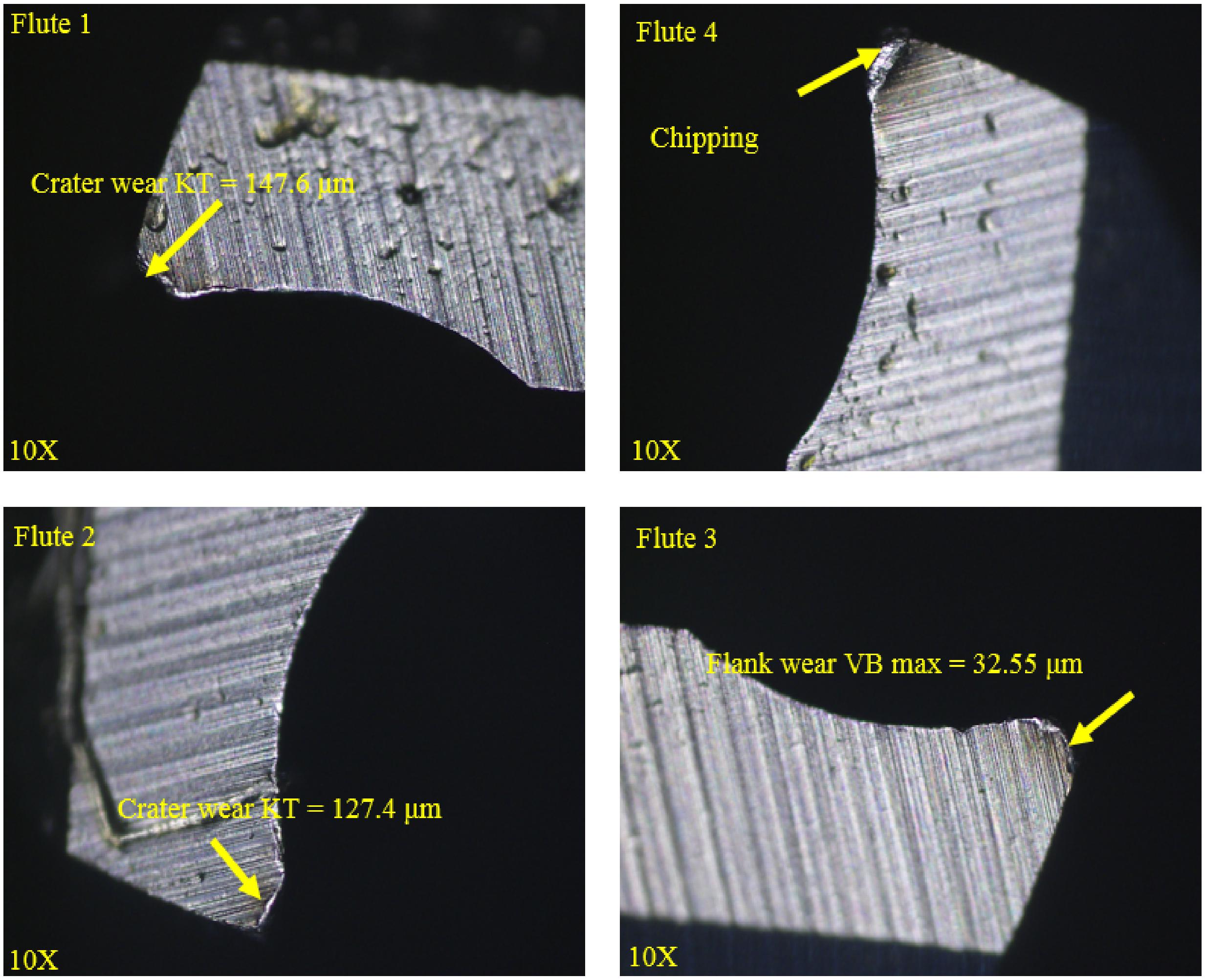
c) Tool 3: VA= 0.0952 mm/min, F = 320 mm/min, A_p = 0.3 mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



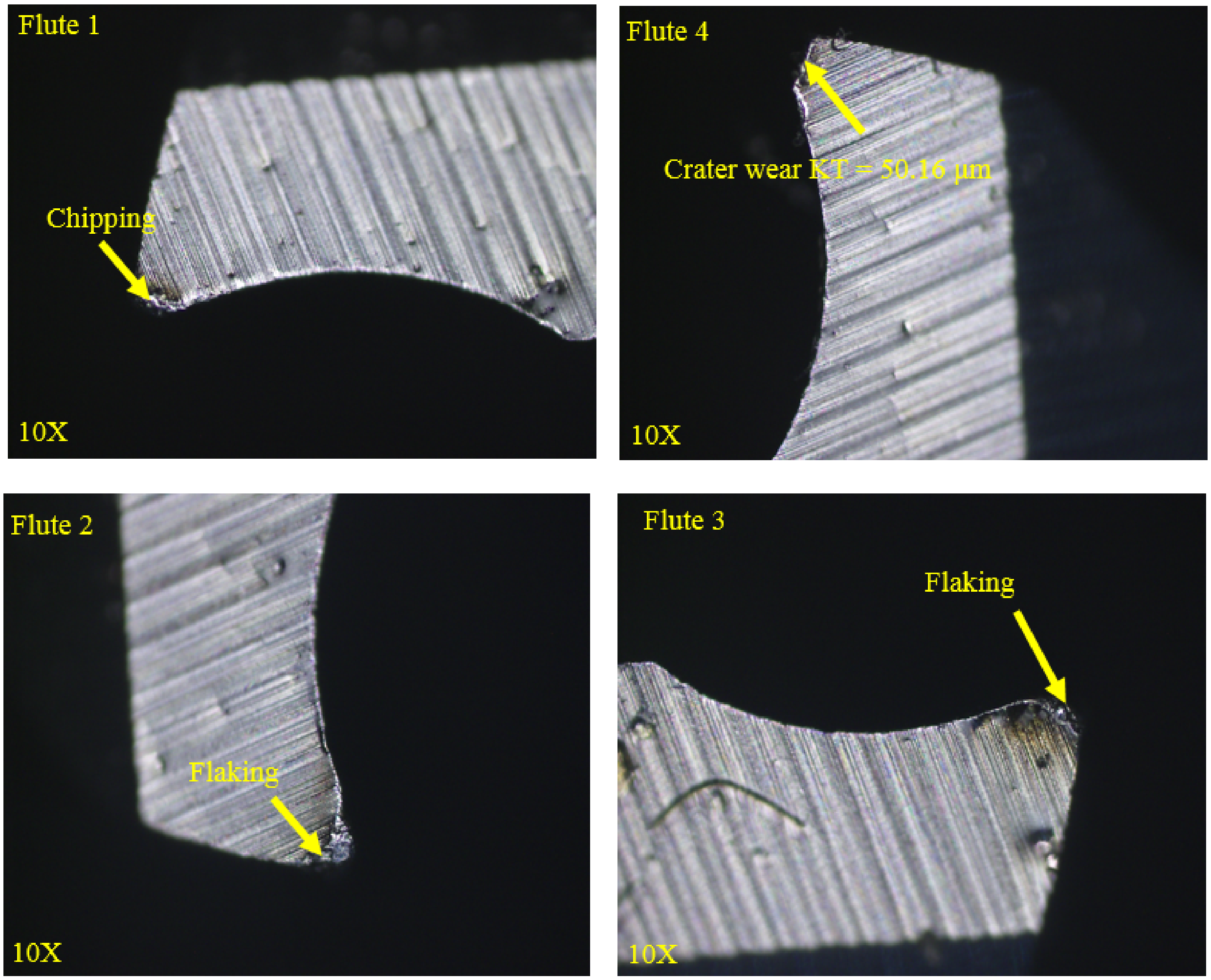
d) Tool 4: VA= 0.11889mm/min, F = 256mm/min, A_p = 0.25mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



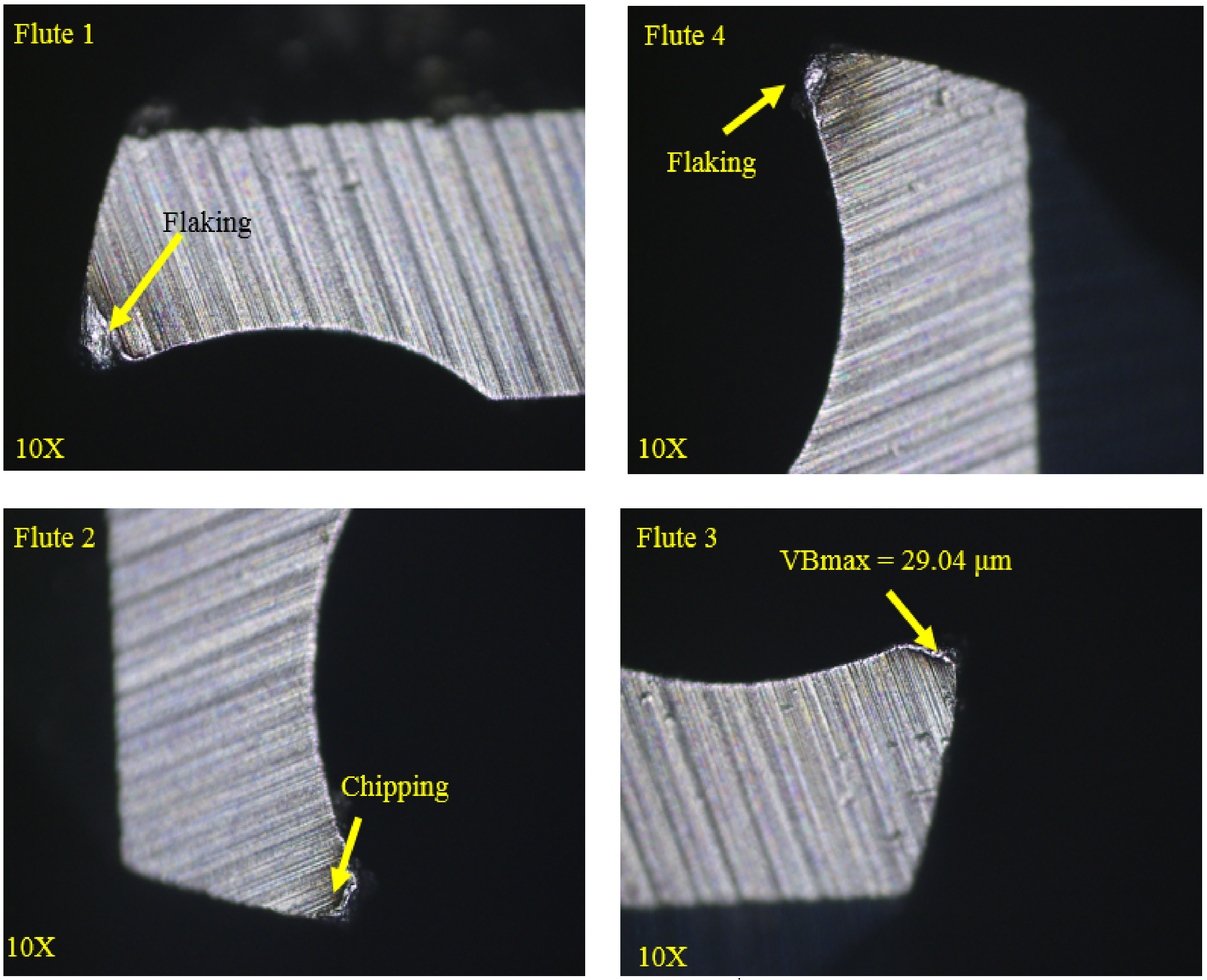
e) Tool 5 VA= 0.11889mm/min, F = 288mm/min, A_p = 0.3mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



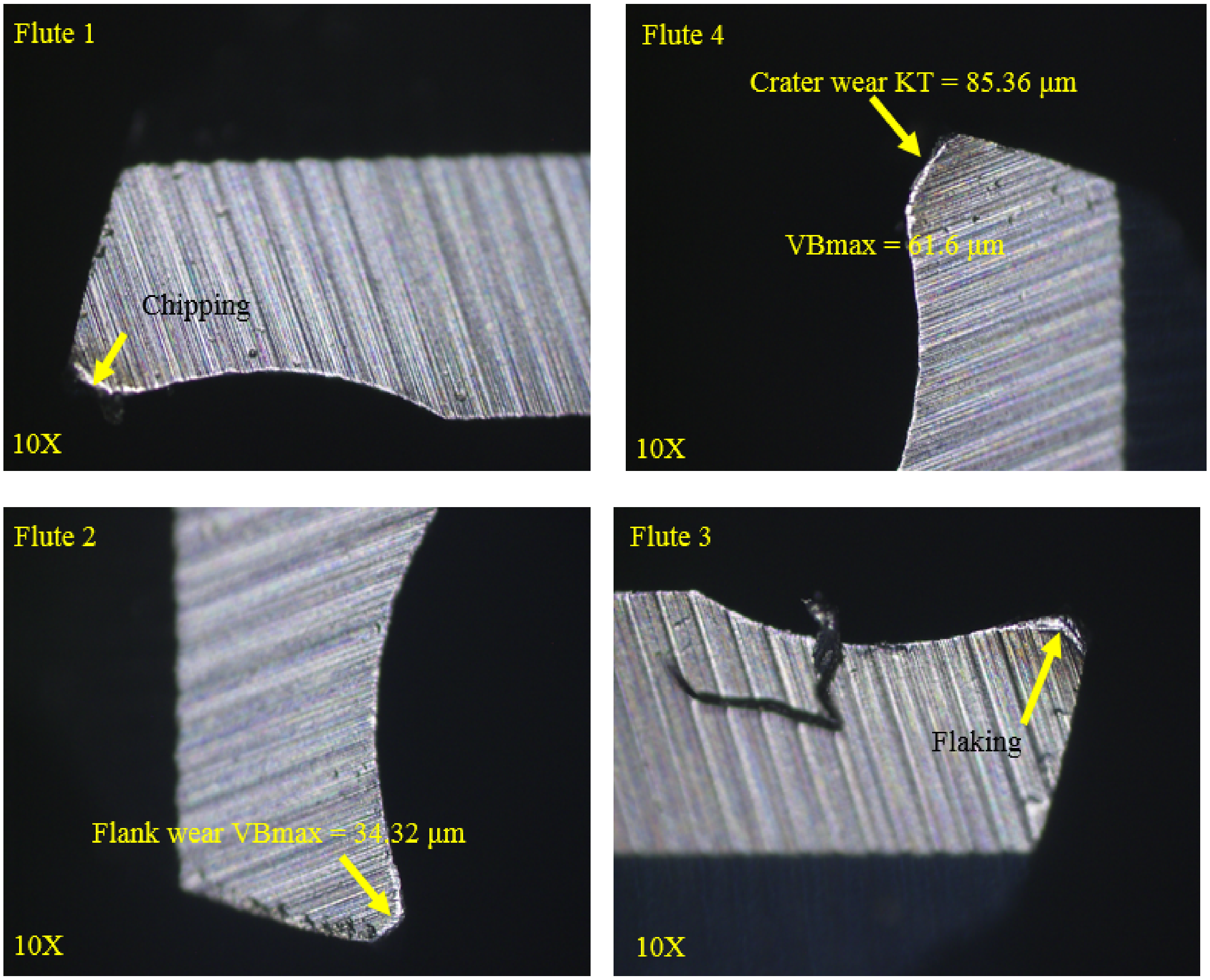
f) Tool 6: VA= 0.11889mm/min, F = 320mm/min, A_p = 0.2mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



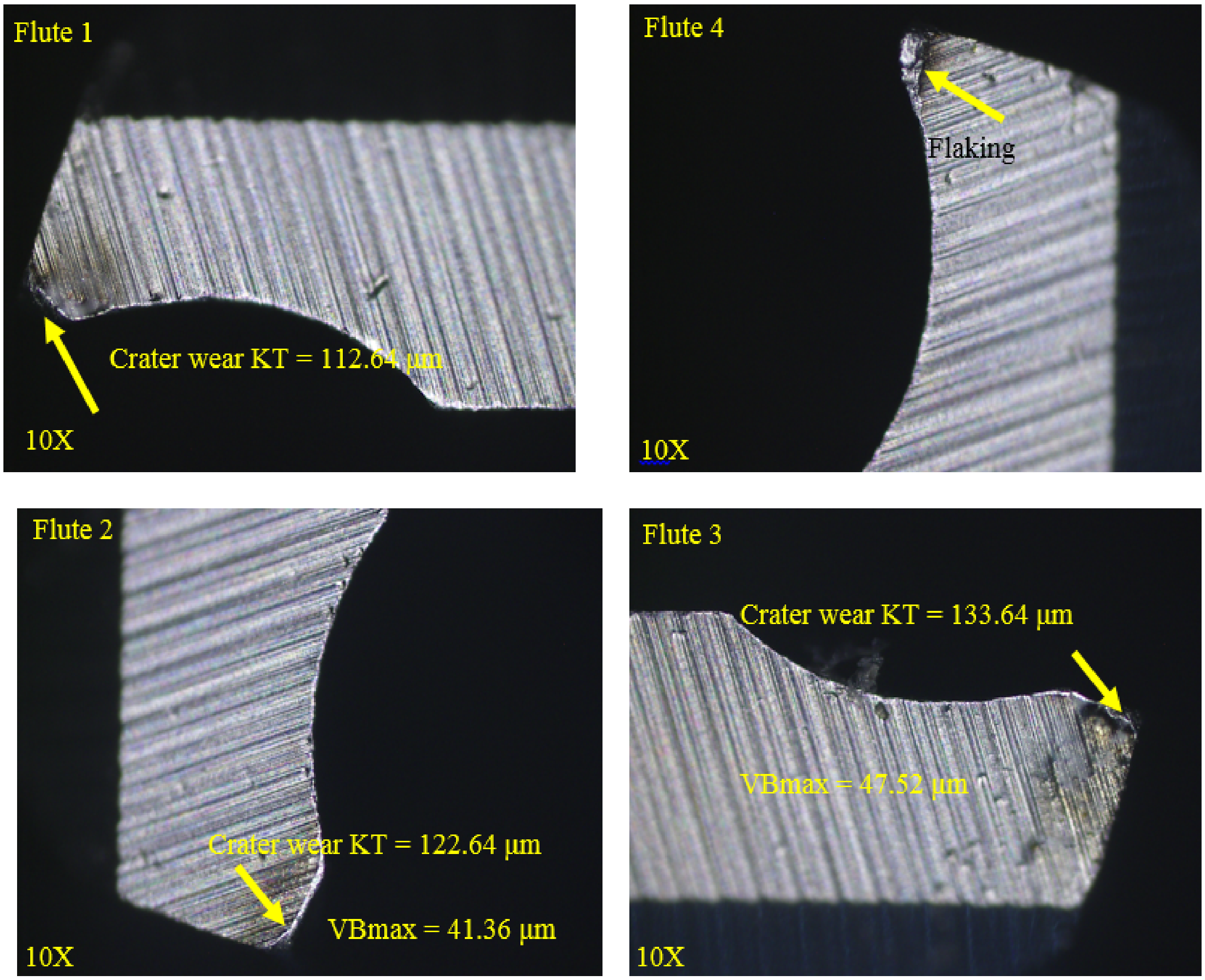
g) Tool 7: VA= 0.185929mm/min, F = 256mm/min, A_p = 0.3mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



h) Tool 8: VA= 0.185929mm/min, F = 288mm/min, A_p = 0.2mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (continued)



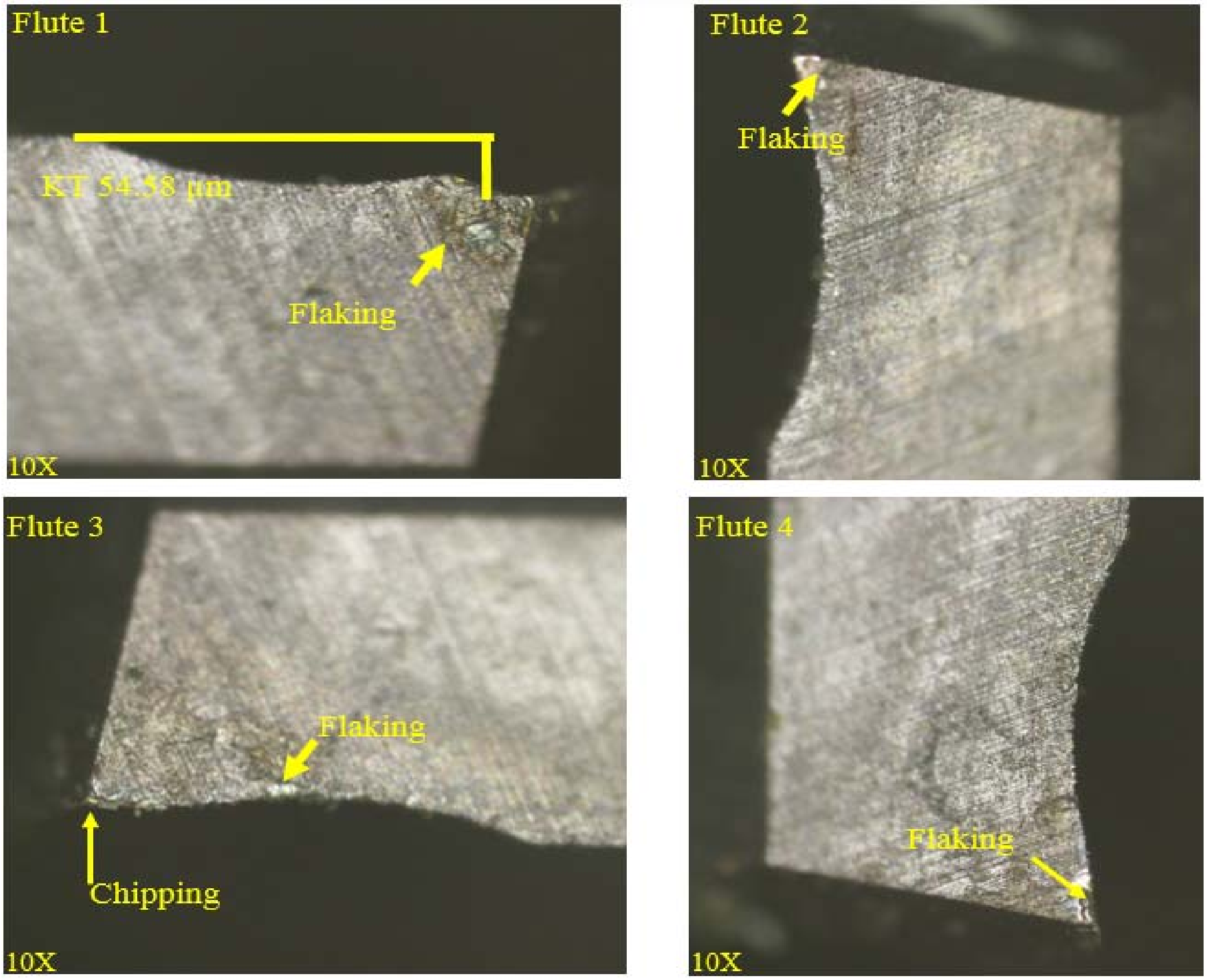
i) Tool 9: VA= 0.185929mm/min, F = 320mm/min, A_p = 0.25mm

Figure 5.11: Optical micrographs of tools indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9

Chipping, flaking and excessive crater wear and flank wear are evident on most of the end mill cutters as reveals by the Figure 5.11. The micrographs results are alienated with the results present in the research [121]. It reveals that high levels of vibration amplitude cause excessive tool wear and hence reducing the tool life.

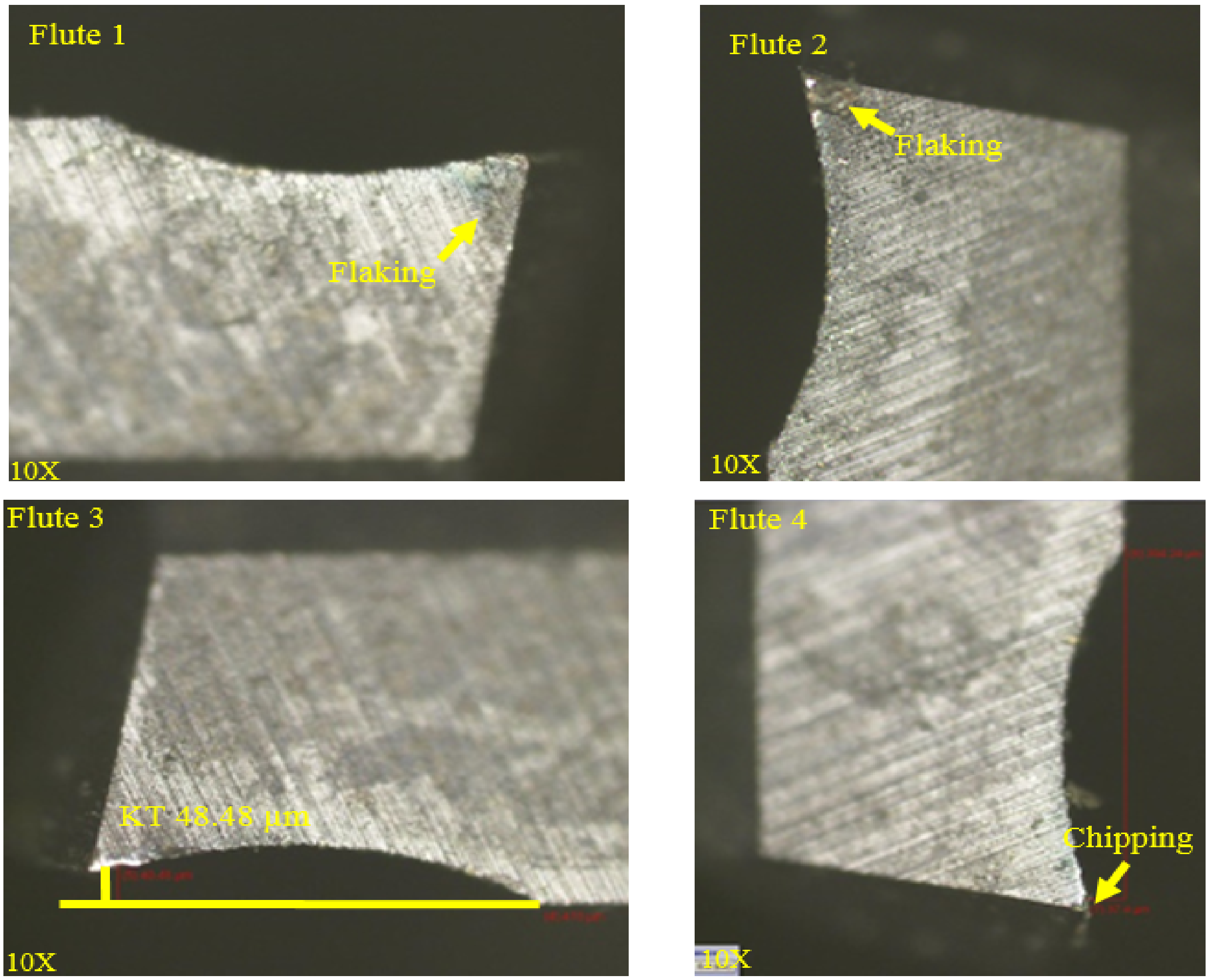
5.5.2 Tool Wear for TiAlN Coated Solid Carbide End Mill Cutter

Figure 5.12(a-i) presents the micrographs of end mill cutters illustrating different tool wear patterns.



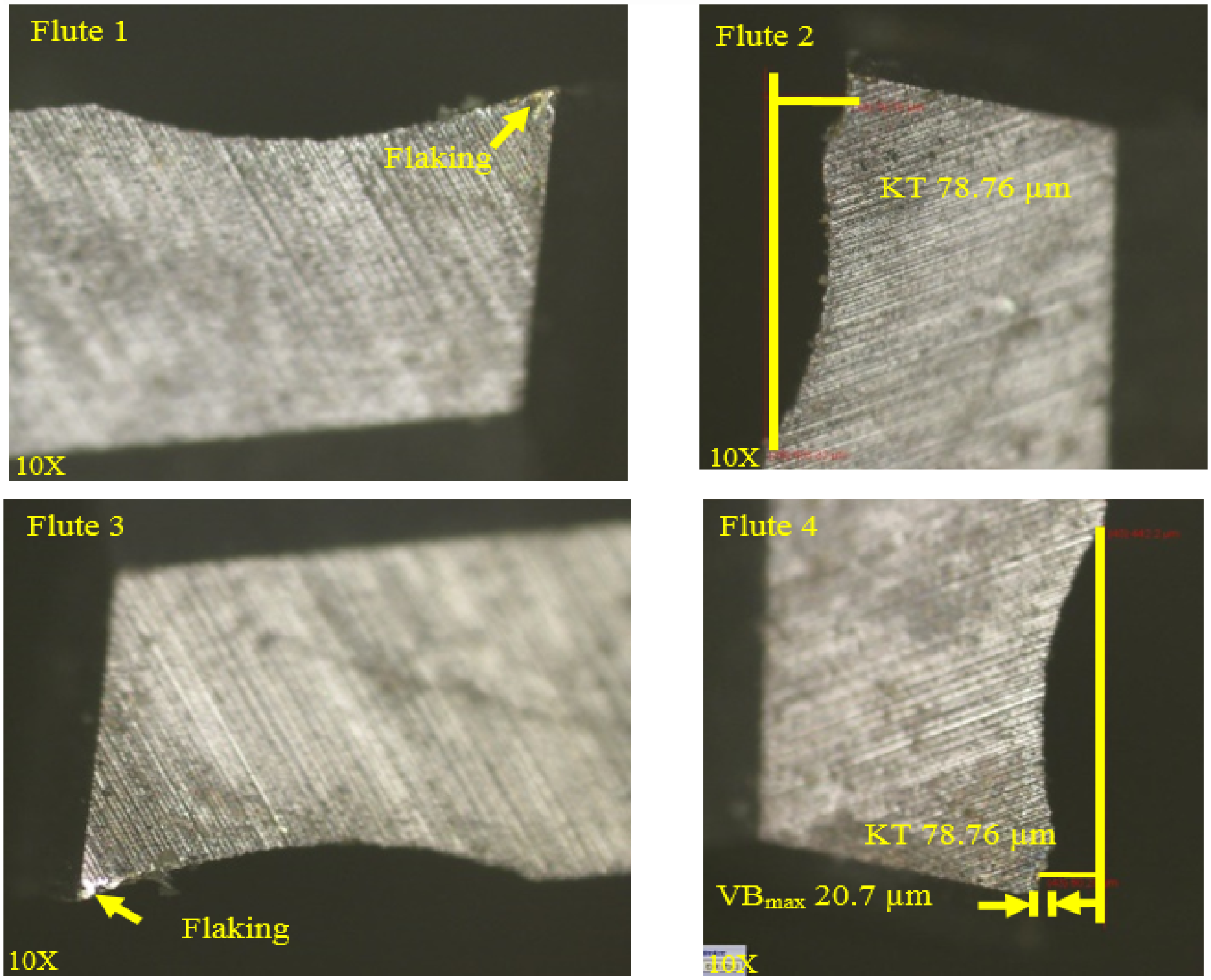
a) Tool 1: VA= 0.0952mm/min, F = 400mm/min, A_p = 0.1mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



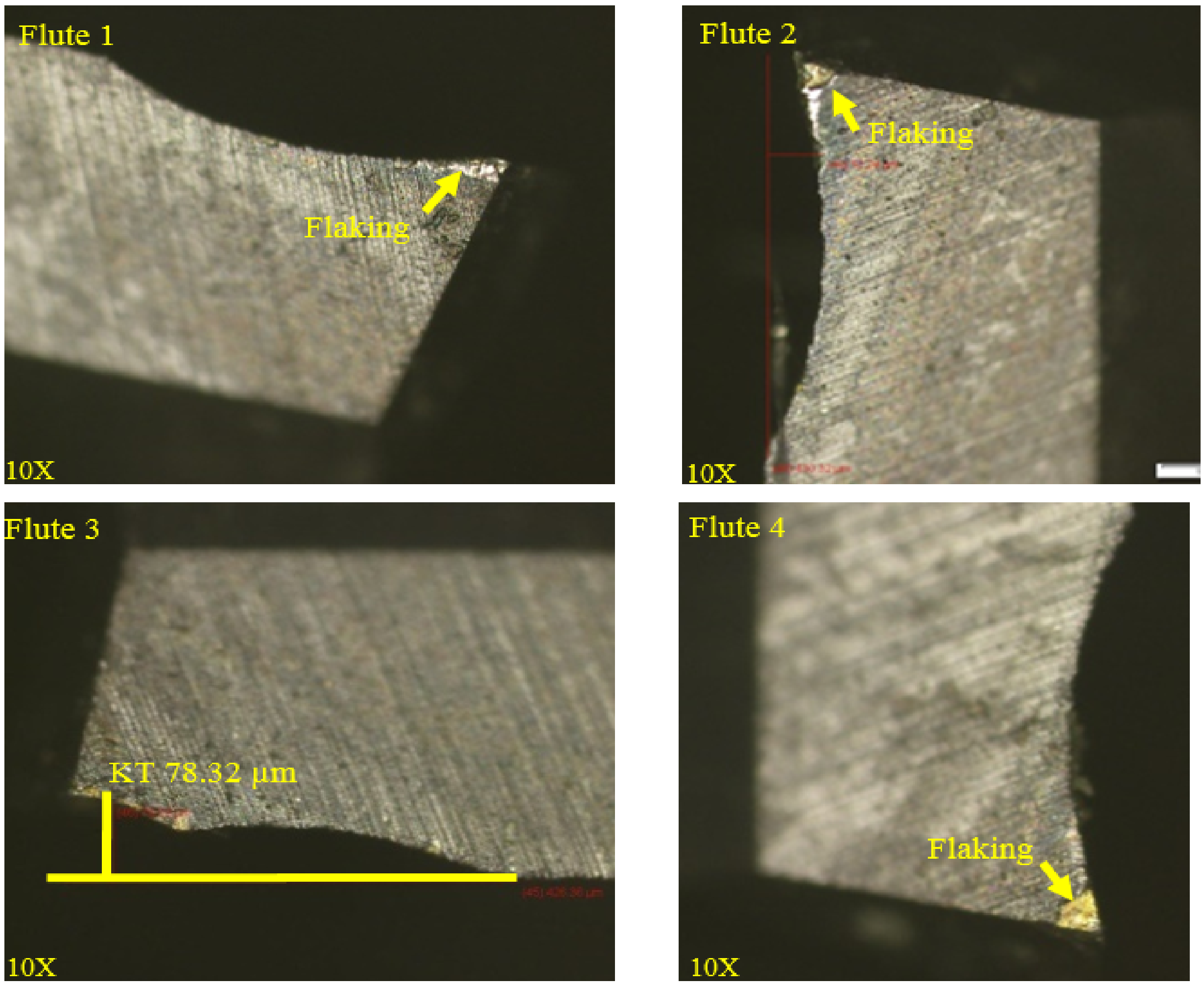
b) Tool 2: VA= 0.0952mm/min, F = 500mm/min, A_p = 0.15mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



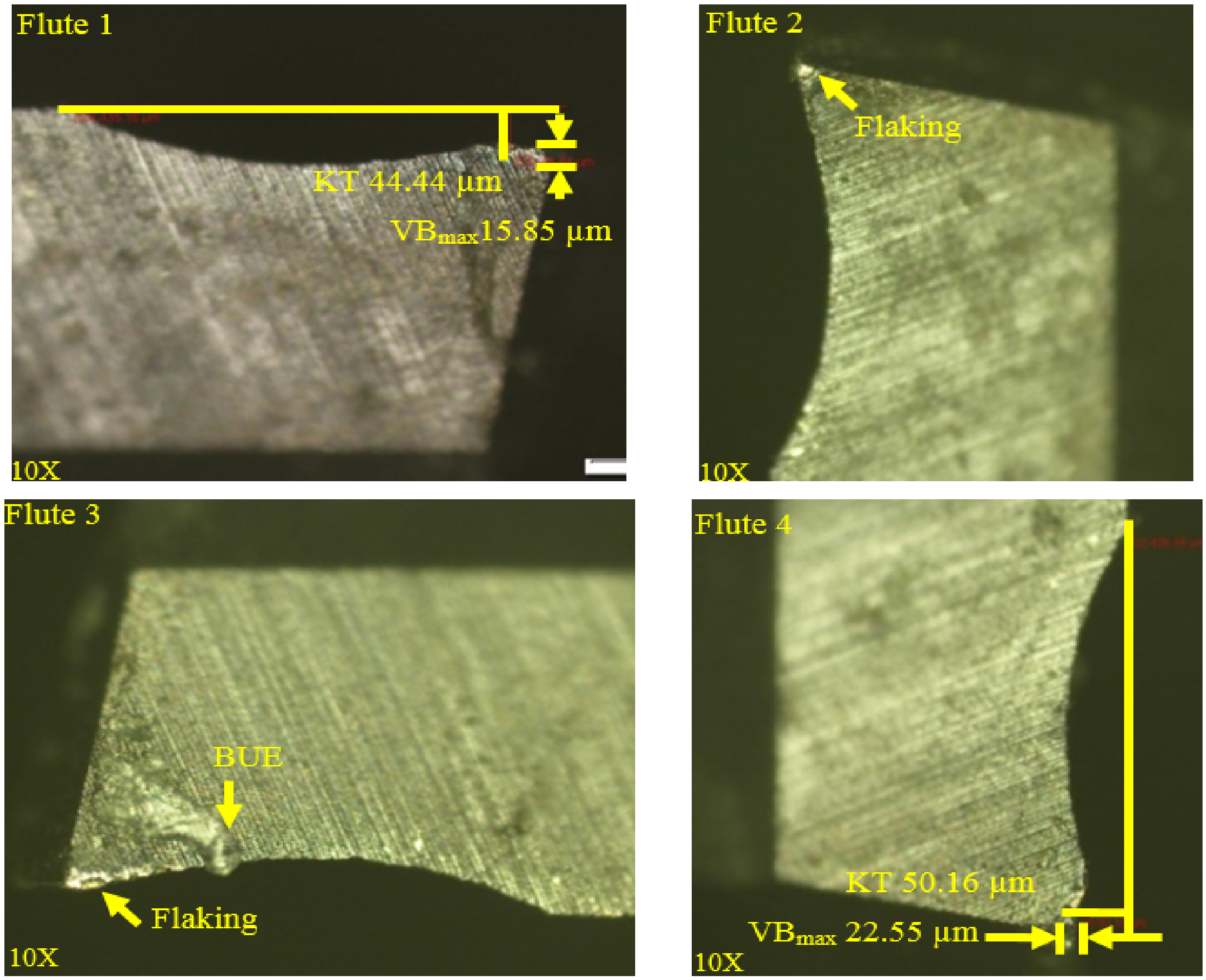
c) Tool 3: VA= 0.0952mm/min, F = 600mm/min, A_p = 0.2mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



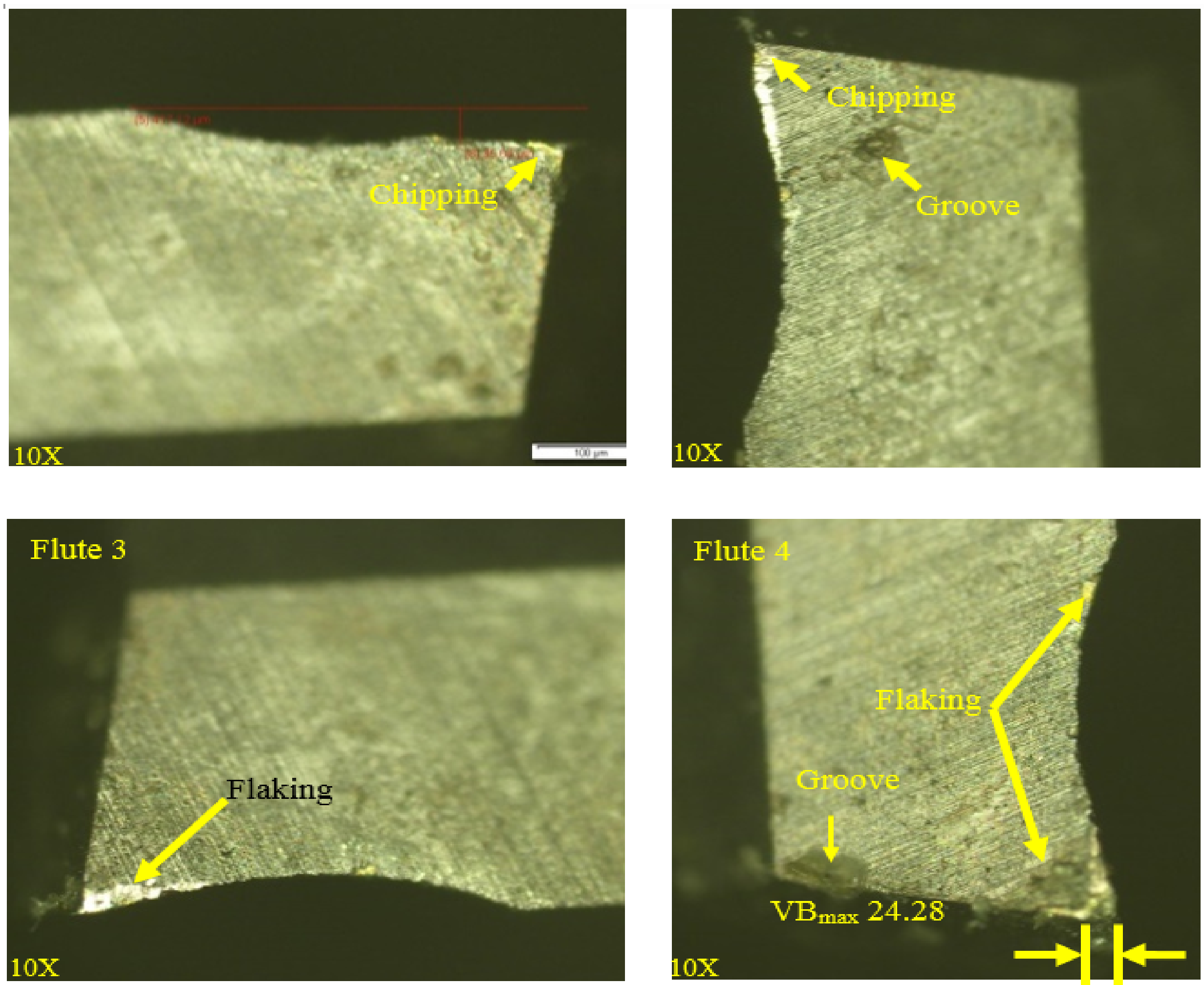
d) Tool 4: VA= 0.11889mm/min, F = 400mm/min, A_p = 0.15mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



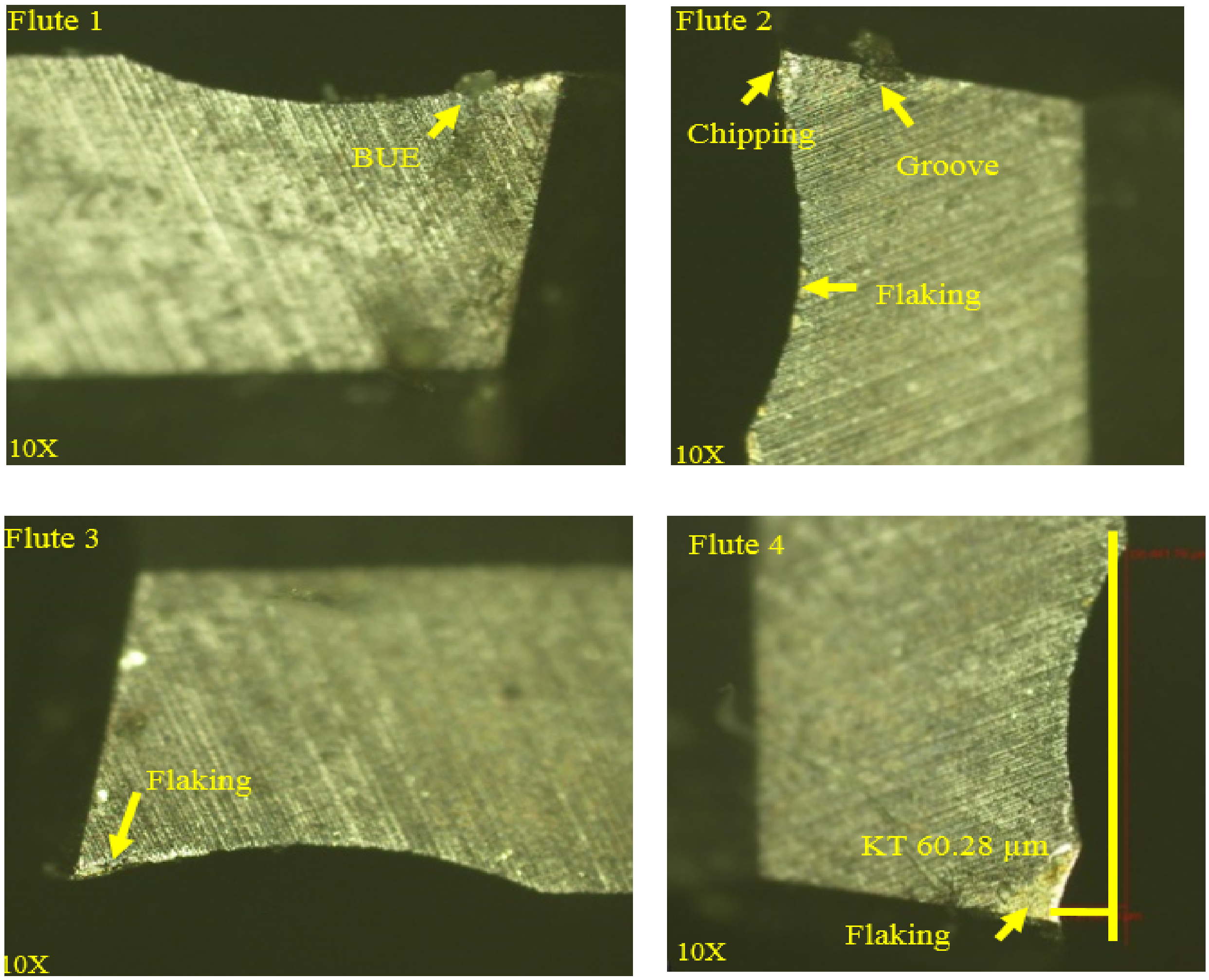
e) Tool 5: VA= 0.11889mm/min, F = 500mm/min, A_p = 0.2mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



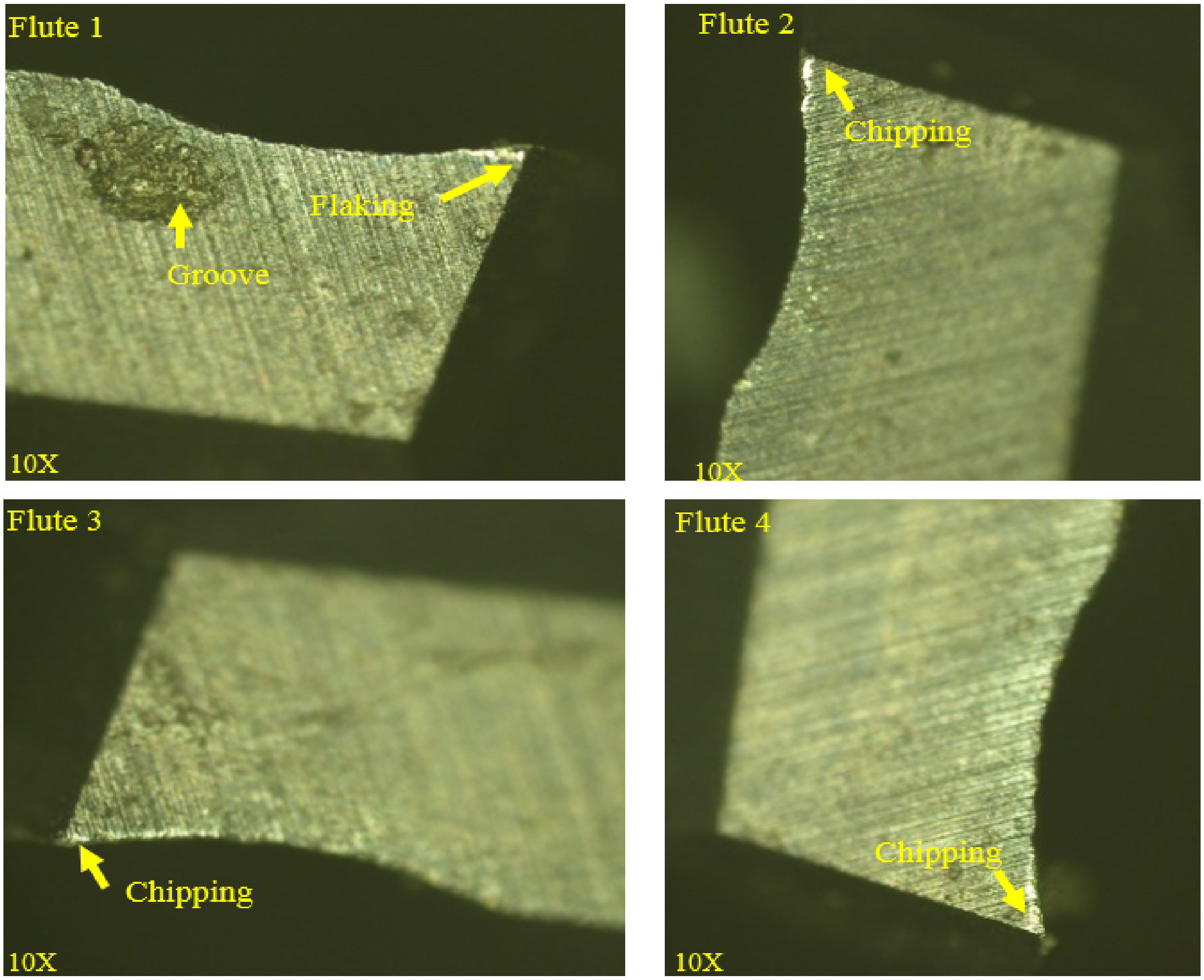
f) Tool 6: VA= 0.11889mm/min, F = 600mm/min, A_p = 0.1mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



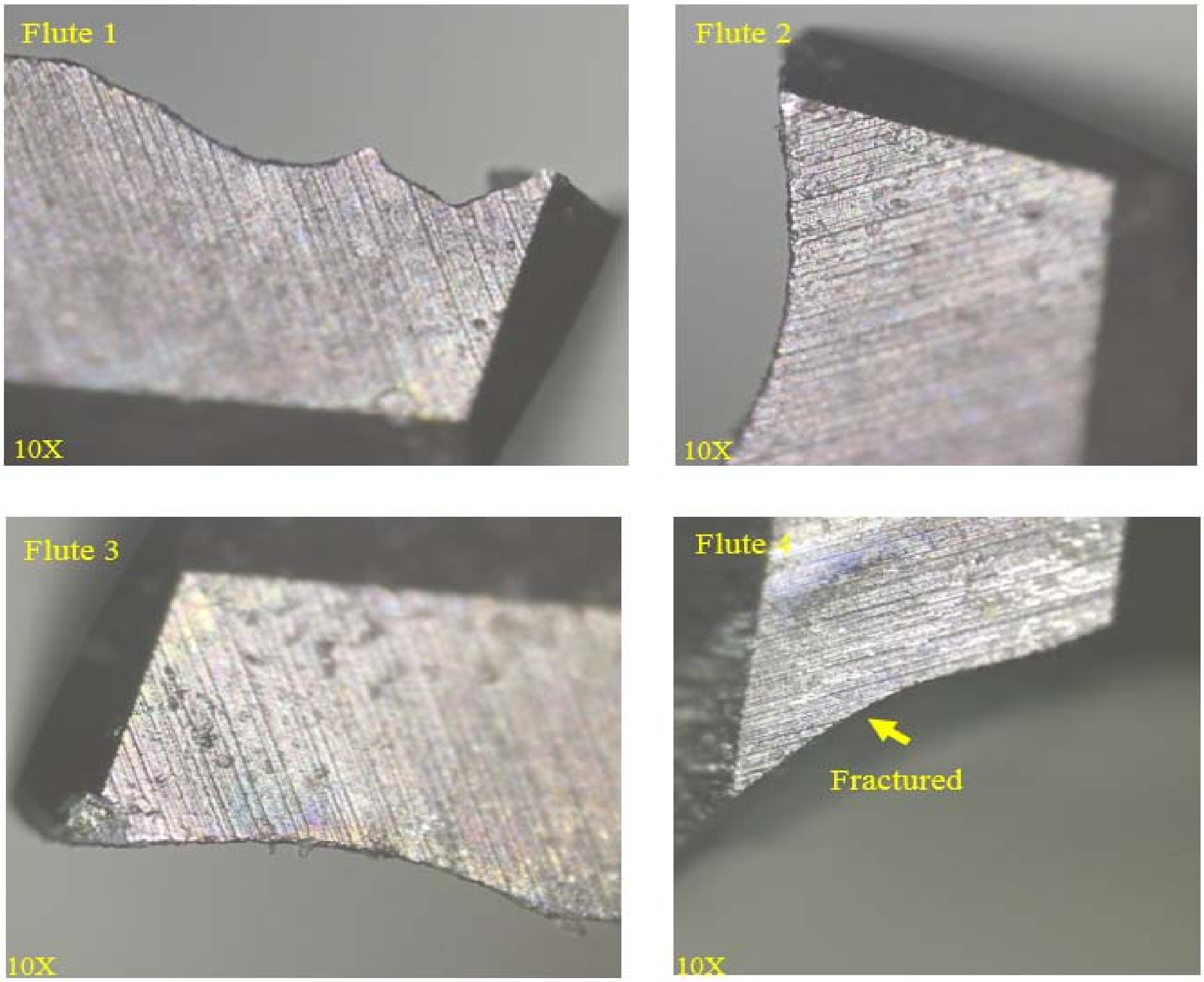
g) Tool 7: VA= 0.185929mm/min, F = 400mm/min, A_p = 0.2mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



h) Tool 8: VA= 0.185929mm/min, F = 500mm/min, A_p = 0.1mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9 (Continued)



i) Tool 9: VA= 0.185929mm/min, F = 600mm/min, A_p = 0.15mm

Figure 5.12: Optical micrographs of end mill cutter indicating different types of tool wear (a) Tool1 (b) Tool2 (c) Tool3 (d) Tool4 (e) Tool5 (f) Tool6 (g) Tool7 (h) Tool8 (i) Tool9

It is observed from the Figure 5.12 that tool wear propagates as the level of vibration amplitudes increases. This can be explained in such a way that high spindle vibration amplitude and feed rate enhance the contact area between cutter and new surface of workpiece, thus increasing the flank wear. It is also evident that the 36% increment in vibration amplitude from level 1 to level 2 produces 14.74% increment in flank wear (VB_{max}) on the end mill cutter. It can also be observed from Figure 5.12(i) that as the vibration amplitude increases from level 2 to level 3, the tool experiences fracture.

In order to investigate the chance of any human error during the course of experimentation, the experiment is performed twice wherein it experiences the fracture confirming that cutter undergoes tool failure which confirms the result that high level of spindle vibration amplitudes has deteriorating effects on the end mill cutter.

To find out the possible reasons of tool fracture, SEM micrographs are taken for fractured end mill. Micrographs of SEM are shown in Figure 5.13 (a-d).

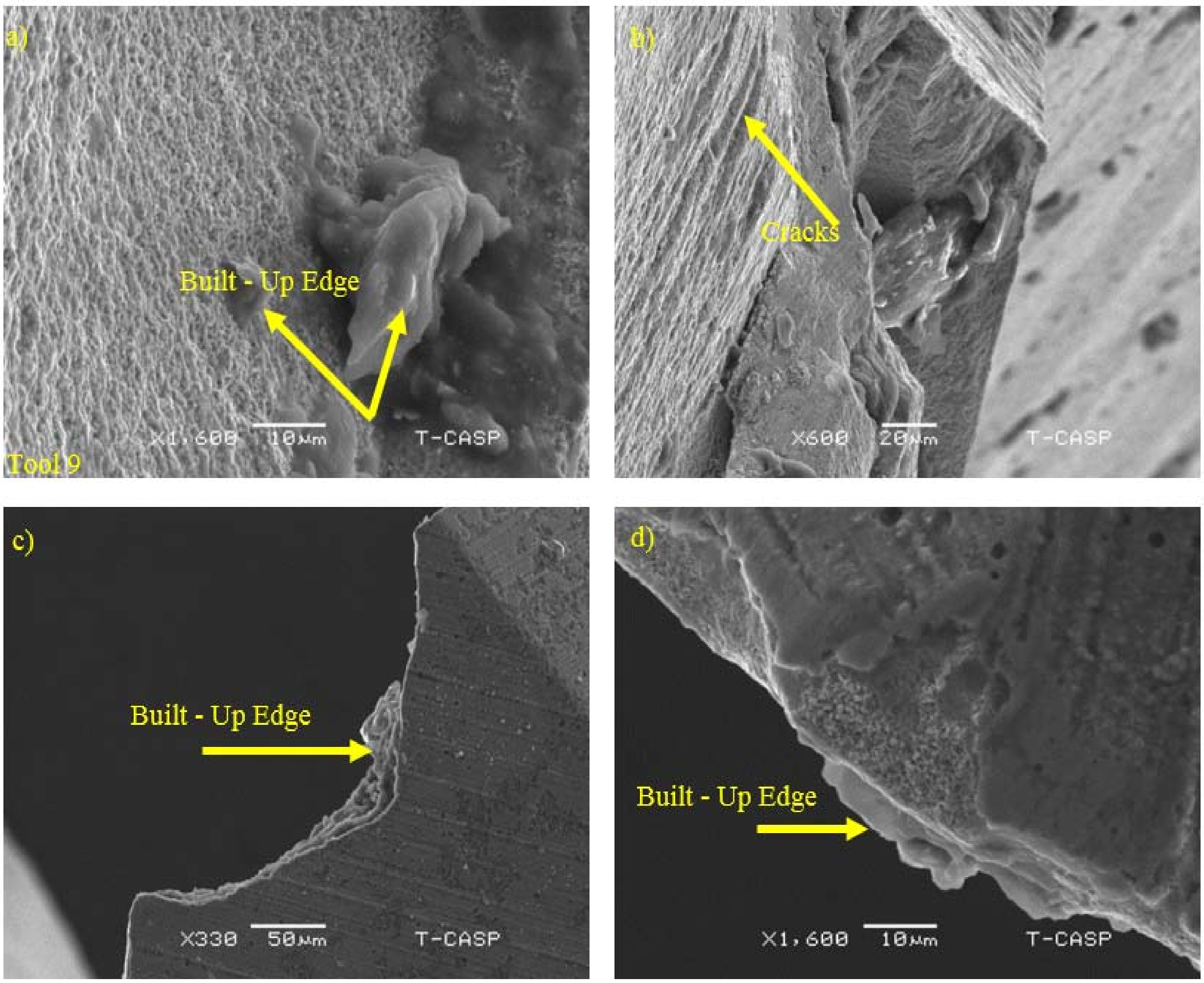


Figure 5.13: SEM micrographs of fractured tool VA= 0.185929mm/min, F = 600mm/min, A_p = 0.15mm

It is revealed from the SEM micrographs that tool failure may be occurred due to the excessive formation of BUE and grooving wear. The intermittent type of cutter interaction with the workpiece in case of milling operation would be one reason of the of tool failure. The intermittent machining involves in engagement and disengagement of cutting edge with respect to workpiece during the machining. This sudden disengagement of the cutting edge of the tool produces BUE i.e. welding of chips material on the tip of the cutter. The torn off the BUE results tool material damage on the tool face. The formation of cracks would be another reasons ensuing failure to the cutting tool. The possible reason of formation of cracks is the coefficient of linear expansion. As coefficient of linear expansion for workpiece material (steel) would be twice of the cutting tool material (carbide), causes the cracks as a result of contraction due to cooling [121].

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The scope of this chapter is limited to the conclusions drawn on the basis of previous discussed experimentation. It also includes some future recommendation related to this research.

6.1 Conclusions Extracted from Literature Review

- Literature suggests that machine tool condition is directly related to vibration amplitudes of machine spindle.

- It is concluded that spindle forced vibrations need to observe carefully during milling operations in order to obtained better surface quality of the machined parts and tool life.

- Forced vibrations effects are assessed during turning operations. It is concluded from the study that spindle vibrations have moderate effect on surface roughness.

- Literature also draws following conclusions for end milling operations
    - ➢ The cutting speed and fee rate are reported to influence the surface quality of the workpiece. High cutting speeds and feed rates improve the surface finish.

    - ➢ Depth of cut is reported insignificant for the surface finish.

6.2 Conclusions Drawn from Present Experimental Work

The following conclusions have been made from the present experimental work.

- The induced vibration levels of CNC machining center by using external weights simulate the default vibration amplitudes of old industrial machines with different machine tool conditions to a fair degree.

- It is also confirmed from the present research that vibration amplitude level has a linear relationship with machine tool condition which is in agreement with the literature.

- The first natural frequency of machine spindle under study is found at 900 RPM. This can be helpful to select safe machining parameters for better surface quality of the machined parts.

- This setup can be used to investigate forced vibrations effects on dimensional surface quality of the machined part.

The conclusions based on the experimentation using cobalt coated high speed steel end mill cutters are listed below:

- Set I experimentation based on maximum level of machining parameters reveals that the end mill cutters experience fracture during machining which leads to the conclusion that maximum levels of machining parameters may be unfavorable for milling of AISI P20.
- For set II experimentation, feed rate is ranked the most influencing parameter by S/N ratios analysis for surface roughness.This conclusion is in agreement with the literature. This is also revealed from the analysis that vibration amplitude is the least affecting parameter with the smallest delta value.

- ANOVA analysis reveals that all the three input parameters are statistically insignificant at 95% confidence level in case of surface roughness.

- Random trends are observed in case of dimensional accuracy from S/N ratio and ANOVA analysis. It is concluded that initial wear of the tool is responsible for dimensional inaccuracy of the milled slot.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The conclusions have been made based on experimentation carried out for TiAlN coated solid carbide end mill cutters. A list of conclusions is given below:

- Vibration amplitude is ranked as the most affecting parameter followed by axial depth of cut as revealed by S/N ratio analysis in case of surface roughness. This conclusion is further validated by main effects plot which indicates that vibration amplitude and axial depth of cut has a near linear relationship with surface roughness.

- Vibration amplitude and axial depth of cut is found statistically significant at 95% confidence level for surface roughness with PCR 83.4% and 12.39% respectively.

- The results of vibration amplitude in case of milling operations are not in agreement with the conclusion draws from literature in case of turning operations. The conclusion related to axial depth of cut also holds the disagreement with the literature in the case of milling operations.

- Dimensional accuracy at 95% confidence level is found insensitive to all the three input parameters. Initial wear in the end mill cutter is considered one of the reasons for dimensional inaccuracy of milled slots.

Conclusions related to the tool wear for both HSSco and solid carbide end mill cutters are mentioned below:

- Higher levels of vibration amplitude and feed rate accelerate different type of tool wear in case of HSSco and solid carbide end mill cutter.

- A tool fracture is experienced at 0.185929 mm/min value of vibration amplitude, 600mm/min feed rate and 0.15 mm axial depth of cut concluding that machining parameters should be kept at lower values than stated values while milling AISI P20 tool steel with solid carbide cutter.

- The excessive formation of BUE and crater wear is found the likely reason for end mill cutter fracture.

Table 6.1 shows the recommended machining parameters for the optimization of machine vibrations for dimensional surface quality in milling of AISI P20 tool steal using TiAlN coated solid carbide end mill cutter for finishing operations. The optimization is carried out using default level of machine vibrations.

Table 6.1: Recommended machining parameters

Parameters	**Values**
Cutting speed	30m/min
Axial depth of cut	0.1mm
Feed rate	500mm/min
Tool hang	32mm

- At these operating parameters, the surface roughness of work piece is 1.4 µm with crater wear KT 45.58 µm.

- It is further concluded from present research that effect of machine tool spindle vibration may not be applicable across the board for all type of tool materials.

The present research also concludes the industrial applications of the research which are listed below:

- Research gives a methodology to simulate different machine tool conditions for research work.

- It provides a guide line to select cutting tool material in combination with machine tool spindle vibrations for finishing operations.

- It enables the machinist to estimate the surface roughness values due to spindle vibrations for old machines running in the industries.

6.3 Future Recommendations

On the basis of the results drawn from the present study, following areas are recommended for the future investigations.

- Evaluation of surface integrity to investigate the effects of spindle forced vibrations.

- In depth investigation of tool wear in order to evaluate the tool life while incorporating the machine spindle forced vibrations.

- Assessment of the effects of spindle forced vibration on composite materials in case of milling operations.

- Investigation of effect of forced vibrations in boring operations.

- Evaluation of performance of coated and uncoated end mill cutters incorporating the machine tool condition.

- To investigate the effects of cutting environment taking the effect of forced vibrations on the machining characteristics

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APPENDIX A

S/N ratio analysis main effect plots and interaction plot of surface roughness and dimensional accuracy for cobalt coated high speed steel end mill cutter of Phase IIA

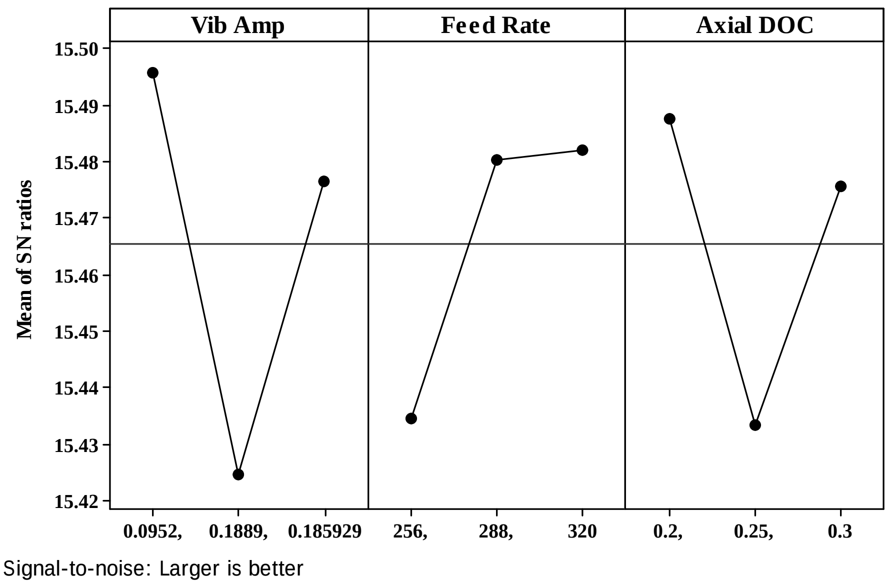

Figure B1: S/N ratio analysis main effects plot for surface roughness

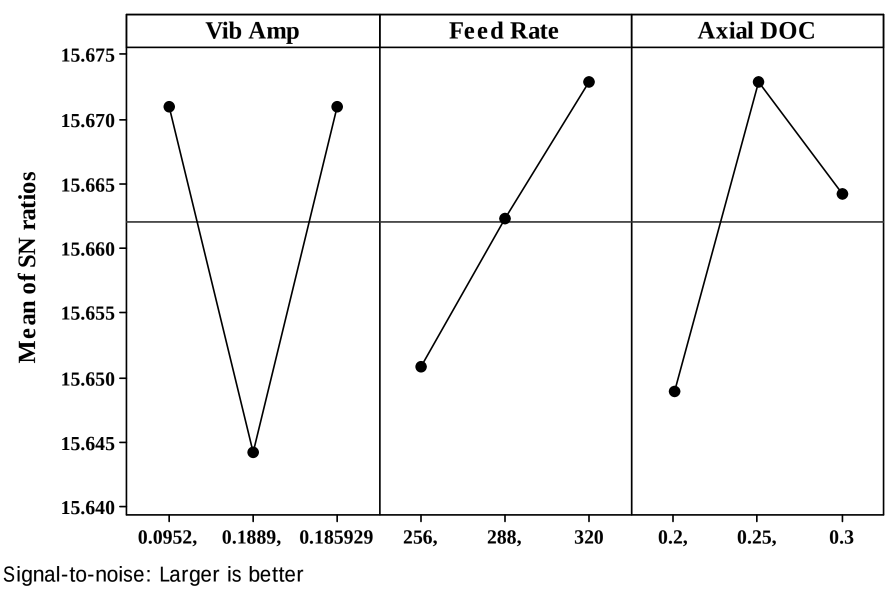

Figure B2: S/N ratio analysis main effects plot for surface roughness

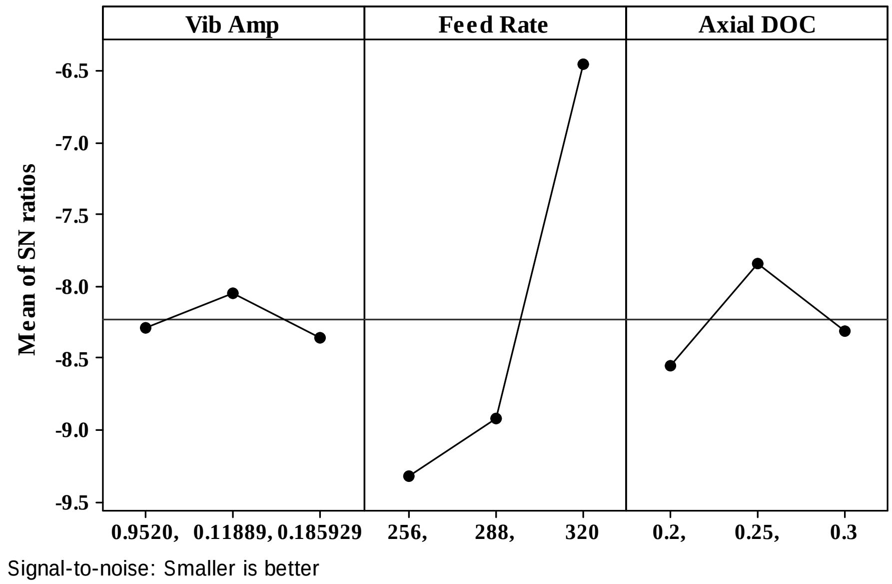

Figure B3: S/N ratio analysis main effects plot for width

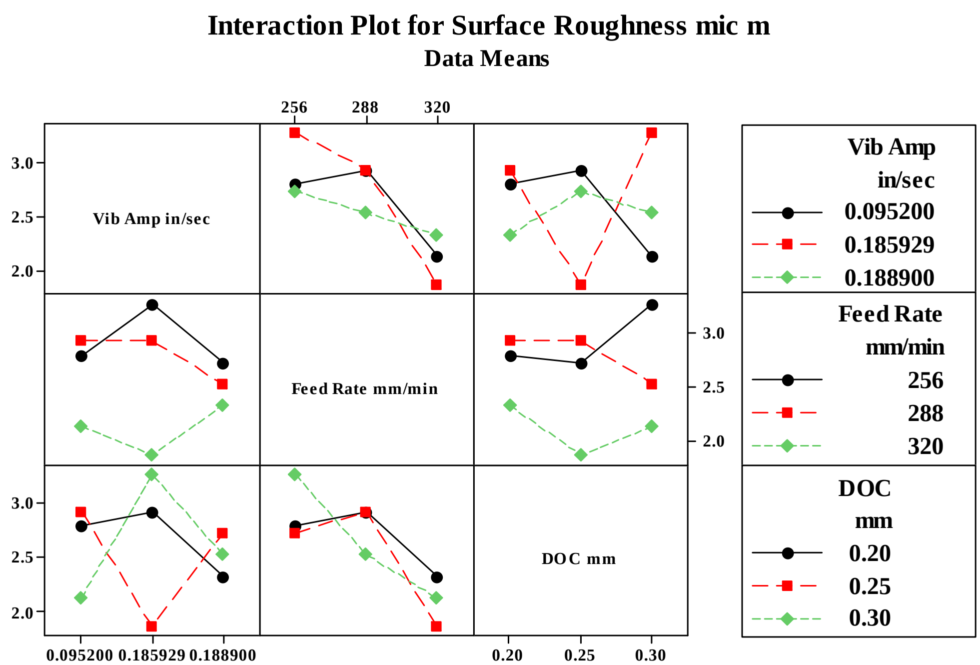

Figure B4: Interaction plots for surface roughness

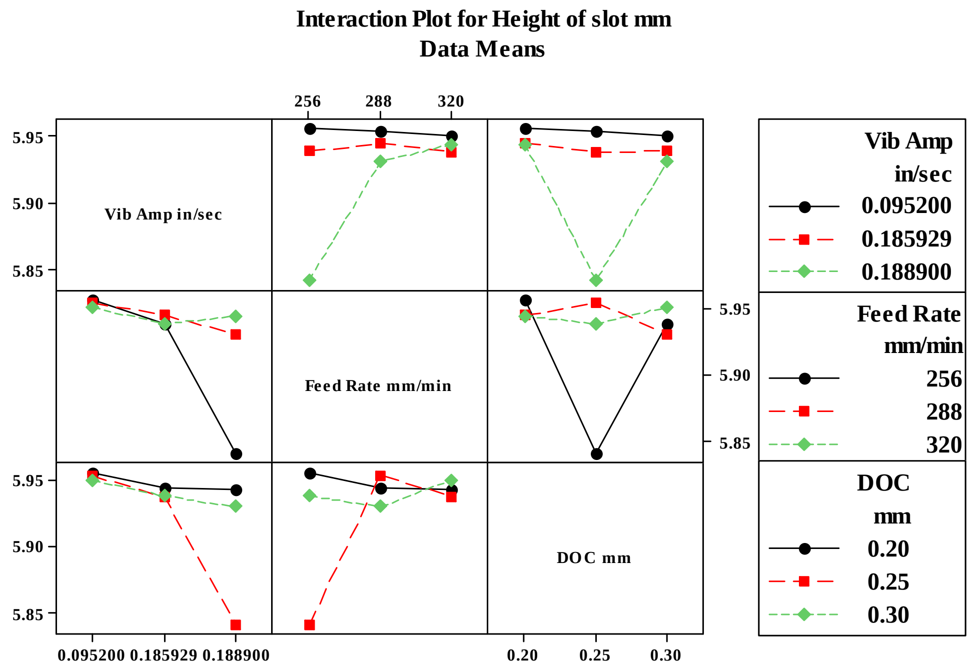

Figure B5: Interaction plots for height

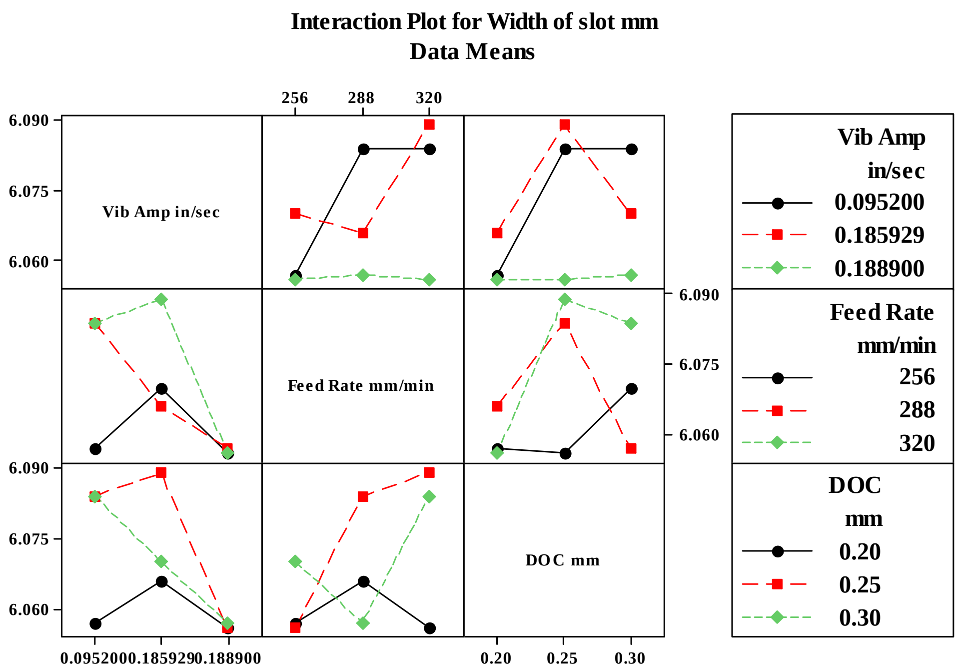

Figure B6: Interaction plots for width

S/N ratio analysis main effect plots and interaction plot of surface roughness and dimensional accuracy for TiAlN coated solid carbide end mill cutters of Phase IIA

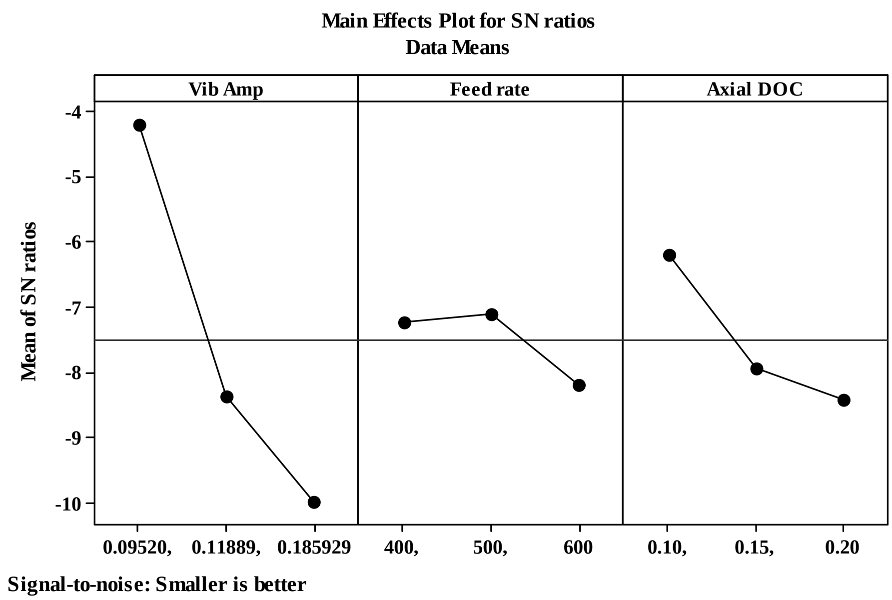

Figure B7: S/N ratio analysis main effects plot for surface roughness

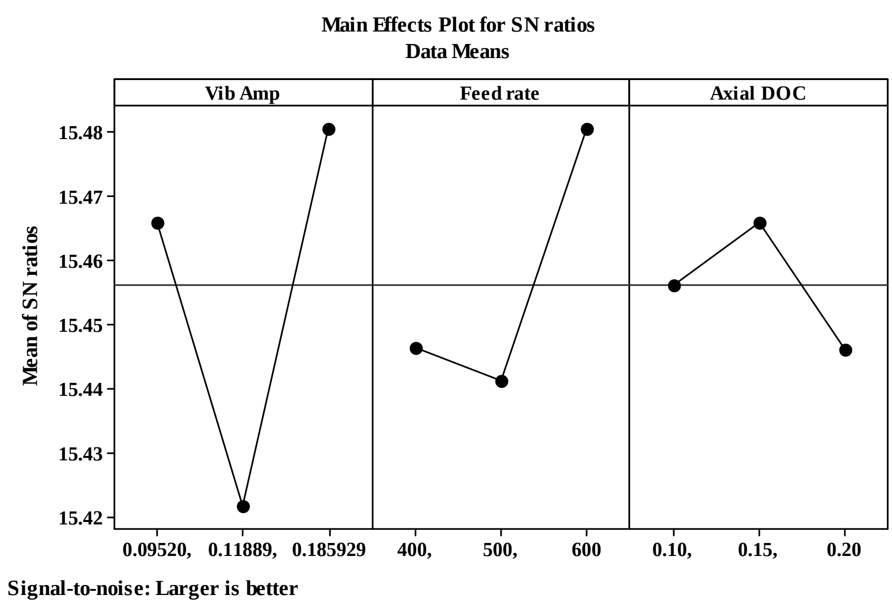

Figure B8: S/N ratio analysis main effects plot for height

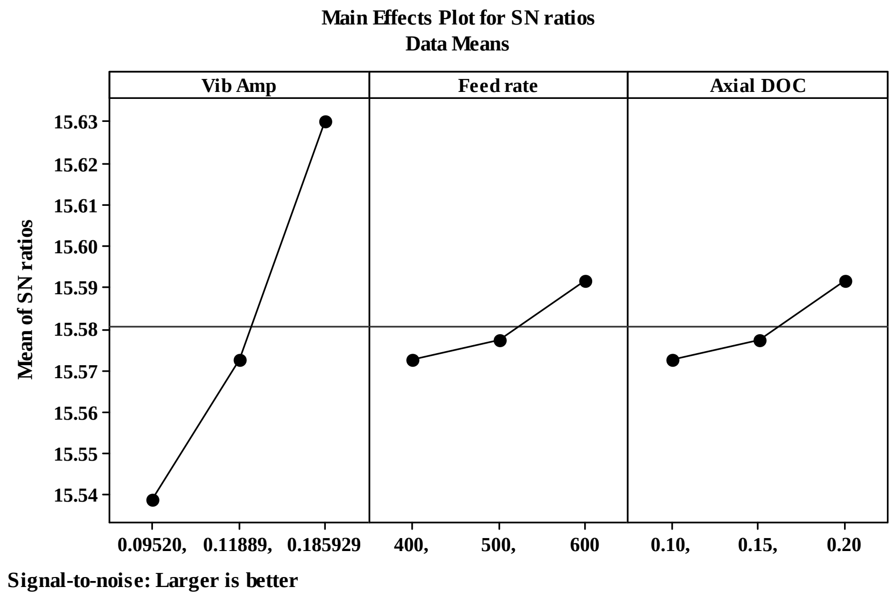

Figure B9: S/N ratio analysis main effects plot for width

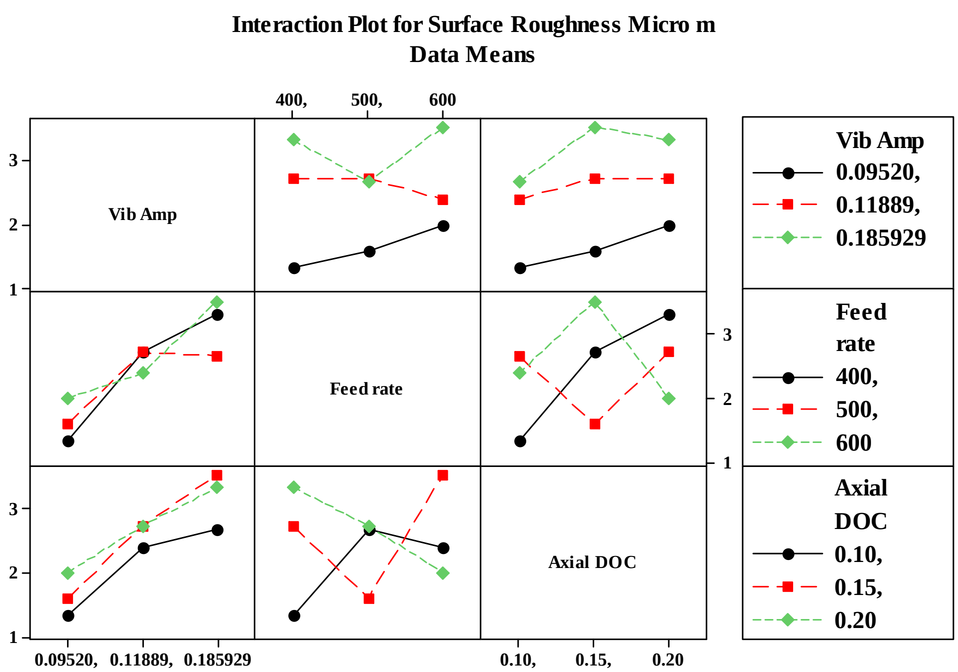

Figure B10: Interaction plots for surface roughness

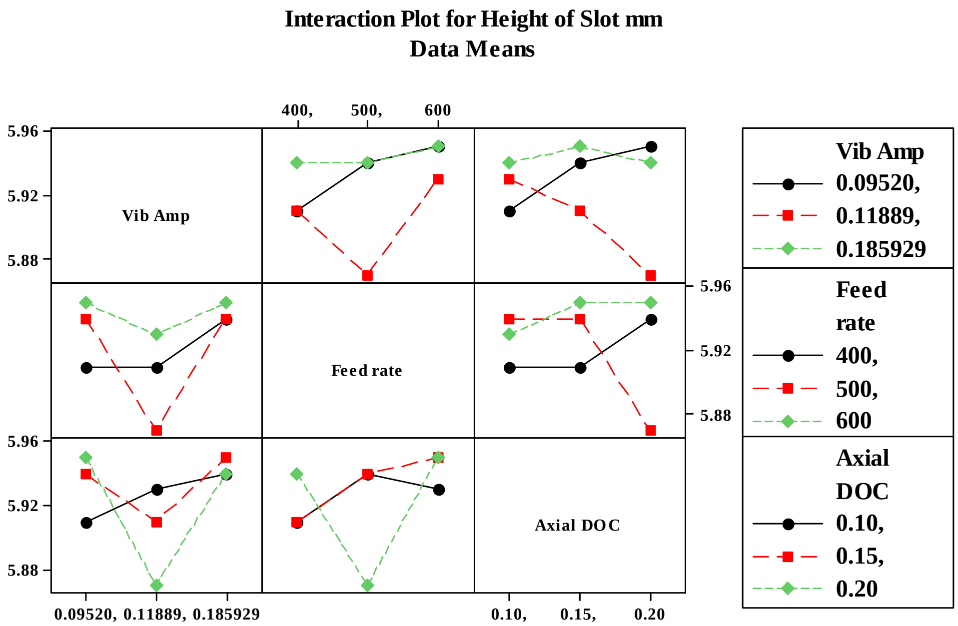

Figure B11: Interaction plots for height

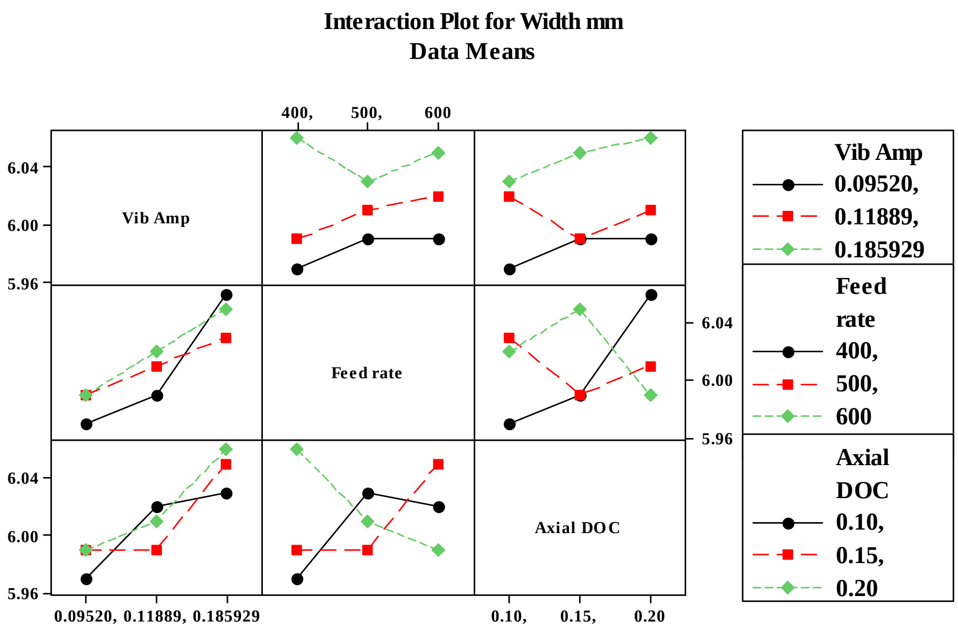

Figure B12: Interaction plots for width

APPENDIX B

List of publications

Paper published

Zahoor S, Mufti NA, Saleem MQ, Mughal MP, Qureshi MAM. (2016) "Effect of machine tool's spindle forced vibrations on surface roughness, dimensional accuracy and tool wear in vertical milling of AISI P20". The International Journal of Advanced manufacturing Technology.

Paper under submission

Sadaf Zahoor, Nadeem Ahmad Mufti, Mohammad Pervez Mughal, Muhammad Qaiser Saleem and Muhammad Asif Mehmood Qureshi, "Experimental simulation of forced vibrations in spindle of CNC machining center".