CHAPTER - 1

INTRODUCTION

1.1 Metal cutting process

Metal cutting is one of the most significant manufacturing processes in the area of material removal [17]. Metal cutting is the removal of metal from a workpiece in the form of chips in order to obtain a finished product with desired attributes of size, shape, and surface roughness. Drilling, sawing, turning, and milling are some of the processes used to remove material to produce specific products of high quality [13].

The quality of machined components are evaluated by how closely they adhere to set product specifications of length, width, diameter, surface finish, and reflective properties. High speed machining operations, dimensional accuracy, tool wear, and quality of surface finish are three factors that manufacturers must be able to control [69]. Among various process conditions, surface finish is central to determining the quality of a workpiece [24].

1.2 Milling process

Milling process is one of the most widely used process in the machining of metals. It is classified as material removal process. This process and its machine tools are capable of producing complex shapes such as stepped cavity or tapped hole with the use of multitooth, as well as single point cutting tools. In the milling process, a multitooth cutter rotates along various axes with respect to the workpiece [14].

Since milling operations are performed by using different types of cutters and machine configurations, they have been grouped according to two main operations: peripheral and face milling operations.
1.2.1 Peripheral milling

Peripheral milling generates surfaces that are parallel to the cutter axis [120]. When the peripheral velocity is in the opposite direction to the feed, the process is called conventional, or up-milling. In this case, the unreformed chip thickness is zero at the start of the cut and increases to maximum value just before the tooth disengages the workpiece. When the cutter velocity and the feed are moving in the same direction, the process is called climb, or down-milling; the chip thickness will have a maximum value just after the cut is started, and will drop to zero at the end of the cut [111].

1.2.2 Face milling

Face milling is performed by cutting edges on the periphery and the end of the cutter. The surface generated is usually at right angles to the cutter axis. In face milling, the maximum chip thickness is obtained at the center of travel and decreases toward the end of the tooth engagement [111]. Face milling is a very efficient operation because the metal removal rate is high in comparison with single point tool cutting [78].

1.3 End milling

End milling can be considered as a combination of peripheral and face milling where a multiple tooth cutter with straight or helical teeth is used [120]. The end milling process is one of the most fundamental metal removal operations used in the manufacturing industry because of its ability to remove material faster and giving reasonably good surface quality. [74]. It is used in a variety of manufacturing industries including aerospace and automotive sectors, where quality is an important factor in the production of slots, pockets, precision moulds and dies. Greater attention is given to dimensional accuracy and surface roughness of products by the industry these days. Moreover, surface finish influences mechanical properties such as fatigue behaviour, wear, corrosion, lubrication and electrical conductivity. Thus, measuring and characterizing surface finish can be considered for predicting machining performance [114].
1.4 Mechanism of end milling process

End milling process is classified as material removal process. This process and its machine tools are capable of producing complex shapes with the use of multi tooth cutting tools. In the end milling process, a multi tooth cutter rotates along the various axes with respect to the workpiece. It is shown in Figure 1.1.

![End milling process diagram](image)

Figure 1.1 End milling process

1.5 CNC end milling

Intense international competition has focused the attention of manufacturers on automation as means to increase productivity and improve quality. To realize full automation in machining, computer numerically controlled (CNC) machine tools have been implemented during the past decades. CNC machine tools require less operator input, provide greater improvements in productivity, and increase the quality of the machined part.

Among several CNC industrial machining processes, milling is one of the most cutting processes in machining besides turning [11]. End milling is the most common metal removal operation encountered. It is widely used in a variety of manufacturing industries including the aerospace and automotive sectors, where quality is an important factor in the production of slots, pockets, precision moulds and dies [31].
1.6 **End mill cutters**

End mill cutters can be broadly classified into uncoated and coated carbides, ceramic inserts, cermets, and poly crystalline grade inserts. End mill selection is usually based on work piece material, surface finish, machine capability and rigidity, cutting speed and feed, and productivity goals.

In this investigation, three types of commercially available solid carbide end mill cutters were used. They are,

- Uncoated solid carbide end mill cutter
- TiN coated solid carbide end mill cutter
- CBN coated solid carbide end mill cutter

1.6.1 **Uncoated solid carbide end mill cutter**

To meet challenge for increase higher cutting speeds, carbides end mills were introduced in the 1930s. Because of their high hardness over a wide range of temperature, high elastic modulus, high thermal conductivity, and low thermal expansion, carbide are among the most important, versatile, and cost effective tool and die materials for a wide range of application [46].

Uncoated carbides are still used to machine ferrous and non-ferrous material at low speeds, where diffusion of coating material into the work piece is of concern, or for very short runs.

1.6.2 **TiN coated solid carbide end mill cutter**

TiN coating is usually used as an outermost layer. In addition to adding to the total wear resistance of the insert, the golden color of the TiN coating helps in wear detection by allowing the operator to distinguish between a used and a new cutting edge corner [108]. In addition, TiN often reduces the sticking of the work material [8]. Dissolution–diffusion and discrete plastic deformation are the principal wear mechanisms for TiN coating [27]. Coating carbide with TiC, TiN and Al₂O₃ drastically reduces the rate of flank wear [26]. TiN deposited as a mono-layer holds a dominant position in the field of hard coatings to improve the wear resistance of cutting tools [15, 101]. However,
a drawback of TiN coating is its limited oxidation resistance at temperatures above 600 °C. The coating consists of single or multiple layers of physical or chemical vapour deposited coating material like Titanium Carbide (TiC), Titanium Nitride (TiN) or Aluminum Oxide (Al₂O₃). TiN coated end mill able to hold their sharpness at elevated temperatures [64]. They have excellent thermal and chemical resistance and are used for high-speed semi finishing and finishing machining. TiN layer reduces friction during machining thus generating less heat at the tool work piece interface [106].

1.6.3 CBN coated end mill cutter

CBN cutting tools have greater wear resistance than other tool materials due to their high degree of hardness [16]. They found acceptable tool life together with excellent surface finish in the range of 0.1 to 0.2 μm in Ra. It points out that tool life would need to be extended to make the process economically viable. Materials with cubic boron nitride crystals are often used in the tool bits of cutting tools. Though only the use of substrate materials other than silicon leads to an application of CBN coatings on cutting tools. Cubic boron nitride (CBN) coated end mill are expensive compared to uncoated, the cost of the cutter can be recovered by a longer tool life and higher productivity. They are used to machine non-ferrous materials at high speeds and have high thermal conductivity. It has low thermal conductivity but higher compressive strength, which makes them conducive to machine hot at higher speeds.

Schintlmeister et al. [104] had summarized the effect of coatings in the following statements:

1. Reduction in friction, in generation heat, and in cutting forces
2. Reduction in the diffusion between the chip and the surface of the tool, especially at higher speeds (the coating acts as a diffusion barrier)
3. Prevention of galling, especially at lower cutting speeds.
1.6.4 Nomenclature of an end mill cutter

End mill is a milling cutter, which is shank-mounted to the machine tool. It has cutting edges on the face end as well as on the periphery, and may be single or double end construction. End mills are the most common and widely used type of milling cutters. Figure 1.2 shows the nomenclature of an end mill cutter.

Figure 1.2 Nomenclature of an end mill cutter
**Clearance angle**  
The angle, which indicates the inclination of the flank relative to the finish surface.

**Cutting edge**  "One of the elements of the cutting part. It is the intersecting line of the face and flank.

**Flute**  
The indented part between the neighbouring cutting edge and the heel. It becomes the chip space.

**Helix angle**  
The angle made by the axial line and the helix cutting edge.

**Length of cut**  
The length of the cutting part.

**Overall length**  
The overall length (including length of cut and shank) measured parallel to the axis.

**Radial Rake angle**  
The angle made by the inclination of the face relative to the reference plane.

**Shank**  
The part of the tool held by the milling machine.

**Shank diameter**  
The diameter of the straight shank.

**Shank length**  
The length of the shank measured in parallel to axis.

**Straight shank**  
The circular cylindrical shank.

1.7 **Surface roughness (Ra)**

The surface roughness parameter used to evaluate surface roughness in this study is the Roughness average (Ra). This parameter is also known as the arithmetic mean roughness value, Arithmetic Average or Centerline Average. Within the presented research framework, the discussion of surface roughness is focused on the universally recognized Ra. Ra is recognized universally as the commonest international parameter of roughness.
The average roughness is the area between the roughness profile and its centre line, or the integral of the absolute value of the roughness profile height over the evaluation length as shown in Figure 1.3 [123].

![Surface roughness profile](image)

**Figure 1.3** Surface roughness profile

1.8 Tool wear (VBmax)

In manufacturing industries milling is fundamental metal cutting operation and end milling is the most frequent operation encountered, which was employed for making profiles, slots, engraves, contours, pockets in various components. During machining cutting tools are subjected to rubbing process, the friction between cutting tool and workpiece materials results in progressive loss of materials in cutting tool. Tool wear is a change of shape of tool from its original shape resulting from the gradual loss of tool material. Thus tool wear becomes an important parameter in the metal cutting process. The worn tool may cause significant degradation in the work piece quality [20]. The consequence of the tool wear are poor surface finish, increase in cutting force, increase in vibration of the machine tool, increase in tool-work piece temperature during machining, decrease in dimension accuracy, increase in the cost and lowers the production efficiency and component quality. Tool wear can be categorized into several types as crater wear, notch wear, chipping, plastic deformation, ultimate failure and flank wear based on the
tool wear phenomena. In practice flank wear is used to determine the tool life. Wear on the relief face is called flank wear and it occurs due to abrasive wear of the cutting tool against the machined surface. The propagation of the flank wear follows three stages, initial (or preliminary) wear, steady wear and severe (or ultimate or catastrophic) wear. When the flank wear reaches critical value (severe wear) the wear rate increases, cutting force and temperature increase rapidly and the surface roughness of the machined surface decreases [73]. Prediction of tool wear becomes important to increase the maximum utilization of tool and to minimize the machining cost [92].

The tool wear area is considered as the criterion that would affect the results of cutting process. The measurement of the width of the flank wear land of the cutting tool was used to evaluate the tool wear as shown in Figure 1.4. The maximum value of flank wear ($V_{B_{\text{max}}}$) was adopted as the machinability evaluation of machining MMC. Here, the tool flank wear ($V_{B_{\text{max}}}$) was measured by using Metzer tool maker’s microscope.

![Figure 1.4 Measurement of flank wear](image)

**Figure 1.4 Measurement of flank wear**

### 1.9 Composite materials

A composite material is a material consisting of two or more physically and/or chemically distinct phases. The composite generally has superior characteristics than those of each of the individual components. One of the constituent material acts as the matrix and at least one other constituent material acts as the reinforcement in the composite. With the advent of new processing techniques, the technological interest and research activity in the development of metal matrix composites have increased rapidly in
recent years [23]. In comparison with unreinforced monolithic alloys and resin matrix composites, MMCs offer higher stiffness and strength values, lower coefficient of thermal expansion and the ability to be used at higher temperatures [82]. Metal matrix composites (MMCs) are materials, which combine a tough metallic matrix with a hard ceramic reinforcement to produce composite materials with superior properties to conventional metallic alloys [9]. The most popular reinforcements are silicon carbide and alumina. Aluminum, titanium and magnesium alloys are commonly used as the matrix phase. The density of most MMCs is approximately one third that of steel, resulting in high specific strength and stiffness. Due to these potentially attractive properties coupled with the ability to operate at high temperatures, MMCs compete with super alloys, ceramics, plastics and re-designed steel parts in several aerospace and automotive applications [44].

1.9.1 Matrix phase

Matrix is a solid which can be processed so as to embed and adherently grip the reinforcement; matrix should not react chemically or metallurgically with the reinforcement.

The role of the matrix material comprises of the following:

- Distribute the stress to the reinforcement material
- Provide the final shape of the composite part
- Binds the reinforcements (fibers/particulates) together
- Mechanically supporting the reinforcements
- Load transfer to the reinforcements
- Protect the reinforcements from surface damage due to abrasion
- High bonding strength between fiber and matrix is important

1.9.2 Reinforcement phase

Reinforcement is the strong, stiff integral component which is incorporated into the matrix to achieve desired properties. The term ‘reinforcement’ implies some property enhancement. Reinforcement may be particle, whisker and fiber.
1.10 Aluminum matrix composites (AMCs)

Aluminium alloys have a high machinability index and have been enormously used in aerospace and automobile industries due to their superior properties such as higher strength to weight ratio, excellent low-temperature performance, exceptional corrosion resistance, chemical inertness to commonly used cutting tools, etc. However, the main weaknesses of aluminium alloys are their poor high-temperature performance and wear resistance. To overcome these problems, aluminium alloys reinforced by ceramic particles, known as metal matrix composites (MMCs), have been developed [95]. A composite material offer designers and engineers the advantage of tailoring structures and materials to meet a variety of property and performance requirements in the changing and demanding environments. This flexibility in design combined with superior property-to-weight ratio makes the composite materials an attractive candidate for the use in diverse high performance and energy effective applications in several industries ranging from aerospace and defense to automotive, recreation and other commercial products [38]. In practice, most composites consist of a bulk material (the matrix) and reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix [119]. Aluminum is the most popular matrix for the metal matrix composites (MMCs). The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity. Aluminum matrix composites (AMCs) offer superior combination of properties (profile of properties) in such a manner that today no existing monolithic material can rival. Over the years, AMCs have tried and used in numerous structural, non-structural and functional applications in different engineering sectors. The key benefits of AMCs in transportation sector are lower fuel consumption, less noise and lower airborne emissions. With increasing stringent environmental regulations and emphasis on improved fuel economy, use of AMCs in transport sector will be inevitable and desirable in the coming years. AMCs are intended to substitute monolithic materials including aluminium alloys, ferrous alloys, titanium alloys and polymer based composites in several applications. It is now recognized that in order AMCs in substitution for monolithic materials in engineering system to be wide
spread, there is a compelling need to redesign the whole system to gain additional weight and volume savings. Moreover, by utilising near-net shape forming and selective-reinforcement techniques AMCs can offer economically viable solutions for wide variety of commercial applications. Recent successes in commercial and military applications of AMCs are based partly on such innovative changes made in the component design.

1.10.1 Manufacturing of Al/SiCp composites

Stir casting of MMCs involves producing a melt of the selected matrix material, followed by the introduction of a reinforcement material into the melt, obtaining a suitable dispersion through stirring. The next step is the solidification of the melt containing suspended particles under selected conditions to obtain the desired distribution of the dispersed phase in the cast matrix. Here, the crucial thing is to create good wetting between the particulate reinforcement and the liquid aluminium alloy melt. The simplest and most commercially used technique is known as vortex technique or stir-casting technique. The vortex method is one of the better known approaches used to create and maintain a good distribution of the reinforcement material in the matrix alloy. In this method, after the matrix material is melted, it is stirred vigorously to form a vortex at the surface of the melt, and the reinforcement material is then introduced at the side of the vortex. The stirring is continued for a few minutes before the slurry is cast. The development of the vortex during stirring is observed to be helpful for transferring the

![Figure 1.5 Stir casting](image_url)
particles into the matrix melt as the pressure difference between the inner and the outer surface of the melt sucks the particles into the liquid [50]. The vortex technique involves the introduction of pre-heated ceramic particles into the vortex of molten alloy created by the rotating impeller. Generally it is possible to incorporate up to 30% ceramic particles in the size range 5 to 100 µm in a variety of molten aluminium alloys. SiC particles peroxidised at 900°C were added to the semi-solid matrix alloy at 600°C. An argon atmosphere was maintained over the melt to reduce oxidation. The mixture was rapidly heated to 750°C and the composite slurry was poured into a preheated permanent iron die (150°C) [49]. Figure 1.5 shows the schematic operational sequence of this procedure.

1.10.2 Properties

The attractive physical and mechanical properties that can be obtained with metal matrix composites, such as high specific modulus, strength and thermal stability, have been documented extensively. The various factors controlling the properties of particulate MMCs and the influence of the manufacturing route on the MMC properties has also been reviewed by several investigators. Improvement in modulus, strength, fatigue, creep and wear resistance depends upon the volume fraction of reinforcements. Of these properties; the tensile strength is the most convenient and widely quoted measurement and is of central importance in many applications [86]. The addition of reinforcement into the metal matrix increases the yield strength of the composite. Compressive and tensile strengths, as well as the hardness at room and elevated temperatures, are also increased significantly, resulting in an improvement in the wear resistance of the composite material. With the addition of the SiC reinforcement the Young’s modulus of elasticity and the thermal expansion coefficient are also improved [79]. The SiCp/Al composites exhibit higher 0.2% proof stress, tensile strength and Young’s modulus and lower elongation and reduction of area than the casting aluminum alloy [125].

1.10.3 Applications of Al/SiCp composites

There have been tremendous strides in engineering materials since 1950s. Several super alloys and heat resistance materials have been developed for various industrial
applications, especially aerospace/aircraft and defense. Automotive, medical and sport equipment industries pushed advances in materials further to introduce new generation materials particularly having low density and very light weight with high strength, hardness and stiffness. One of the important of these advanced materials is composites. Composite materials are important engineering materials due to their outstanding mechanical properties. As advanced engineering materials, metal matrix composites are used in many applications that require high wear resistance such as cylinder liners, helicopter blades, ventral fins and lower drag brace landing gears in modern fighter planes. Compared to the monolithic alloys, the wear resistance of MMCs is greatly enhanced by the introduction of a secondary phase in the form of abrasive ceramics into the ductile aluminium matrix. Silicon carbide particle (SiCp) reinforced aluminium-based MMCs are among the most common MMC and commercially available ones due to their economical production [118]. Aluminum matrix composites (AMCs) have been widely studied since the 1920s and are now used in sporting goods, electronic packaging, armours and automotive industries. They offer a large variety of mechanical properties depending on the chemical composition of the Al-matrix. Aluminium composites are widely employed in the aerospace industry. Hyper-eutectic Al-Si based composites such as A356 (Al, 7Si, 0.3Mg) that contain Al2O3, ZrO, particles or SiC particles’ are used in the fabrication of automotive engine components. Wear resistance and operating properties of aluminium cast diesel pistons are enhanced by the use of aluminium-based composite piston ring inserts.” Aluminium-based composites have also been considered as substitute materials for use in the fabrication of brake rotors, pistons, cylinder liners and cylinder heads [28]. A356Al–SiC composites are better wear resistance than the base alloy [10].

1.11 Design of experiments (DOE)

Design of Experiment (DOE) is a structured, organized method for determining the relationship between different factors that affect the process and the output of that process, with minimum number of experiments. This method was first developed in the 1920s and 1930, by Sir Ronald A. Fisher, the renowned mathematician and geneticist. DOE is a method for systematic planning and conducting experiments in which multiple
input variables are systematically changed to observe changes in the outputs of a process [67]. Historically, both science and engineering curricula have emphasized one-factor-at-a-time experiments where one variable (factor) is changed while the others are held fixed. This approach is wasteful and the results can be misleading. However, statistically designed experiments provide a more effective and efficient way to learn about and optimize a process. By combining the settings of several factors simultaneously in design arrays, it is possible to isolate the effects of each factor individually. A designed experiment usually requires fewer resources for the amount of information obtained, and the results are more precise since more measurements are used to determine the effect of a given factor. Moreover, the interactions between the factors, i.e., the effect of one factor on another can be quantified.

1.12 Response surface methodology (RSM)

Response surface methodology (RSM) has been used to plan and analyze the experiments. It is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response. It is a sequential experimentation strategy for empirical model building and optimization. By conducting experiments and applying regression analysis, a model of the response to some independent input variables can be obtained. Based on the model of the response, a near optimal point can then be deduced. RSM is often applied in the characterization and optimization of processes [62]. The objective of using RSM is not only to investigate the response over the entire factor space, but also to locate the region of interest where the response reaches its optimum or near optimal value. By studying carefully the response surface model, the combination of factors, which gives the best response, can then be established [61].

1.12.1 Central composite design (CCD)

The statistical experiment designs most widely used in optimization experiments are termed "response surface designs." In addition to trials at the extreme level settings of
the variables, response surface designs contain trials in which one or more of the variables is set at the midpoint of the study range (other levels in the interior of the range may also be represented). Thus, these designs provide information on direct effects, pairwise interaction effects and curvilinear variable effects. Response surface methodology, one approach to product and process optimization work, derives its name from the use of these widely used optimization experiment designs. Most practitioners of RSM now generate their experiment designs and analyze their data using a statistical software program running on a personal computer. Many of these software programs can generate many classes of RSM designs and, in some cases, offer several varieties of each class. However, the central composite design is the most popular of the many classes of RSM designs due to the following three properties:

- A CCD can be run sequentially. It can be naturally partitioned into two subsets of points; the first subset estimates linear and two-factor interaction effects while the second subset estimates curvature effects. The second subset need not be run when analysis of the data from the first subset points indicates the absence of significant curvature effects.
- CCDs are very efficient, providing much information on experiment variable effects and overall experimental error in a minimum number of required runs.
- CCDs are very flexible. The availability of several varieties of CCDs enables their use under different experimental regions of interest and operability.

1.13 Multi Objective Optimization using Genetic Algorithm

In single objective optimization, one attempts to obtain the best design or decision, which is usually the global minimum or maximum depending on the optimization problem. In case of multiple objectives, there may not exist one solution, which is the best with respect to all objectives. Various classical methods of obtaining the solutions to multi-objective problems are available. Some examples are Min–Max, Weighted Sum and Distance Function methods. These methods change the multi-objective problem into a single objective, with the corresponding weights based on their relative importance. These methods suffer from a drawback that the decision maker must have a thorough knowledge of ranking of objective functions. Also, these methods fail
when the objective functions become discontinuous [68]. Genetic Algorithm (GA) as a kind of multi point search potentially has an advantage for optimization problems with multiple objectives. However, GA has been mainly applied to optimization problems with a single objective. The extensions of GAs to multi objective optimization are proposed in several manners [47]. Genetic algorithm (GA) possesses advantages that it does not require any gradient information and inherent parallelism in searching the design space, thus making it a robust adaptive optimization technique [100]. For multi-objective optimization methods, some modification to simple GA is necessary. Multi-Objective Genetic Algorithm (MOGA), Vector Evaluated Genetic Algorithm (VEGA) and Non-Dominated Sorting Genetic Algorithm (NSGA) are some of GA based multi-objective solution methods. In general, an optimization problem to be addressed has several objectives to be optimized. The complexity of the problem increases as the number of objectives to be optimized because the objectives considered are often contradictory to one another. Such complex optimization problems have a lot of feasible solutions. However, only a few solutions among them are desirable [116]. That is, a set of candidate solutions called non dominated solutions is to be obtained for the problem. Since multiple solutions are to be obtained as candidate solutions of the problem, The two objective genetic algorithm optimization method used in this study is an elitist, Non dominated Sorting Genetic Algorithm (NSGA-II) developed by Deb [57]. This algorithm uses the elite preserving operator, which favors the elites of a population by giving them an opportunity to be directly carried over to the next generation. After two offspring’s are created using the crossover and mutation operators, they are compared with both of their parents to select the two best solutions among the four parent offspring solutions [84, 60].