CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Composites are normally composed of distinct constituents dispersed in a continuous matrix phase. These materials are designed and engineered to exhibit properties that are most desirable for a given application. This is arrived by selecting the appropriate matrix composition, and reinforcing phase its volume fraction, shape and size. The reinforcement provides a unique feature to the composites and mainly depends on the properties, geometry, architecture and interface of constituents. Based on the physical and chemical characteristics of matrix phase, composites are categorized into polymer matrix, metal matrix and ceramic matrix composites. Metal Matrix Composites (MMCs) have been in existence since 1970s in the aerospace industry. However, they found applications in other industries such as automotive industry during middle of 1980s. The density of most MMCs is approximately one-third of that of steel (Arokiadass et al 2011; Srinivasan et al 2012). Due to these potentially attractive properties MMCs compete with super-alloys, ceramics, plastics and steel parts in several aerospace and automotive applications. The other applications of MMCs include transportation, defence, sports and recreational industries etc, owing to increasing performance requirements (Sikder 2010). In the recent years, the application and development of metal matrix composites have increased in many engineering fields due to arrival of innovative processing methods and research activity in the metal matrix composites.
Though the composites are processed through casting or forming methods, the machining process cannot be eliminated entirely since it gives preferred dimensions, shape and surface texture. Machining of a composite depends on the properties and relative content of the reinforcement and the matrix materials, as well as on its response to the machining process. In addition, the choice of the specific machining process depends upon the following factors: type of machining operation, part geometry and size, finish and accuracy requirements, number of parts, diversity of parts, availability of appropriate machine and cutting tools, current machining practice, manufacturing schedule, capital requirements, environmental and safety considerations, and overall cost.

The manufacturing market of today demands both quality and productivity. Quality of a product can be described by the surface roughness of the machined part and it can be controlled within the desirable limit by controlling the machining parameters. Another important criterion is productivity, which is directly related to the profit level and also to the goodwill of the organization. Every manufacturing industry aims to produce a large number of products within the available time. And also manufacturing industries aspires for better performance characteristics to achieve a high profit and productivity. This necessitates optimisation of the best combination of process parameters for the manufacturing process.

1.2 CLASSIFICATION OF COMPOSITE MATERIALS

Composite materials can be classified on the basis of the matrix material as,

Polymer Matrix Composites (PMCs)
Metal Matrix Composites (MMCs)
Ceramic Matrix Composites (CMCs)
1.2.1 Polymer Matrix Composites

Polymer matrix composites are also referred as Fibre-Reinforced Plastics (FRPs), in which strong and brittle fibres are incorporated into a soft and ductile polymeric matrix. The nature of the reinforcement is glass, carbon or aramid fibres and is in the form of long or short fibres. Long fibres can be unidirectional or woven into a fabric or cloth. Glass Fibre-Reinforced Plastics (GFRPs) are the most commonly used materials in view of their high specific mechanical properties and low cost. Though Carbon Fibre-Reinforced Plastics (CFRPs) and Aramid Fibre-Reinforced Plastics (AFRPs) offer higher specific strength, higher specific stiffness and lighter weight, they are expensive. They are used only for those applications where performance and not cost is the major consideration. AFRP is used instead of CFRP where strength, lightness and toughness are major considerations, but stiffness and high temperature performance are not required.

The common matrix materials for FRP composites are thermoset polymers (e.g. polyester, epoxy) and thermoplastic polymers (e.g. polyamide, peek). Thermoset polymers consist of a highly cross-linked three-dimensional network and remain rigid when heated. They are quite strong and stiff, thus offers poor ductility. Among the thermoset resins, polyester resins are less expensive but they are not strong as epoxy resins. Polyester matrix composites are used in the fabrication of boat hulls, structural parts for automobiles and aircrafts, building panels and beams, electrical appliances, water tanks, pressure vessels, etc. Epoxy resins offer a lower shrinkage after curing and also provide higher fabrication accuracy. Thermoplastic polymers consist of flexible linear molecular chains that are tangled together (Indacochea 2014). They have lesser strength and modulus, but are highly ductile. Among the thermoplastic resins, polyamide and peek resins are used as matrix materials in FRP composites for applications in the aerospace
industry. Maximum service temperatures for FRP composites are relatively low, as the matrix material is prone to softening, chemical decomposition or degradation occurs at moderate temperatures.

1.2.2 Metal Matrix Composites

MMCs are used in those applications which require higher operating temperatures and strength, where PMC cannot be used. Most of MMCs are developed for the aerospace industry, but they are also finding applications in the automotive industry, more specifically in automobile engine parts. The reinforcement materials for MMCs are silicon carbide, alumina and graphite in the form of particles, short fibres (whiskers) or long fibres. Aluminium, magnesium and titanium alloys are the most common matrix materials used in MMC materials. In general, MMCs have higher specific strength and specific modulus over conventional steel, Al, Ti, and Mg alloys, and have properties superior to PMCs composites.

Using continuous fibres in MMCs provides higher stiffness and strength properties. Boron-aluminium composites are one of the earliest developed MMC materials. These are made by hot pressing layers of boron fibres between aluminium foils. The aluminium foils deform around the fibres and bond with each other. By reinforcing boron with aluminium, the tensile strength can be increased by a factor of three to five times, while the elastic modulus can be tripled.

Discontinuous fibre and particle reinforced MMCs are low cost MMCs that provide better properties over the corresponding unreinforced alloys. The fabrication of Particulate Metal Matrix Composites (PMMCs) is more common due to the easy availability, large volume production and is inexpensive than the fibre-reinforced MMCs. PMMCs are of special interest since they exhibit higher ductility, superior wear resistance and lower
anisotropy than fibre-reinforced MMCs. Small additions of reinforcement moderately increase the base alloy strength and stiffness. It also increases the wear resistance of the composite and contributes toward the difficulty in machining because of hard ceramic particles.

1.2.3 Ceramic Matrix Composites

Generally, CMC materials possess higher specific modulus and mechanical properties at high temperature and so are superior to the metals (Butkus 1992). In order to enhance the fracture toughness of unreinforced ceramics, reinforcing constituents are used. The common reinforcement materials used in CMCs are alumina and silicon carbide. A volume fraction 20% of SiC whiskers added to alumina can increase the fracture toughness from 25 to 50MPa. Such an increase in toughness of a ceramic cutting tool would enable it to take heavy cuts or to perform without fracture in case of interrupted cutting. Conventional hot iso-static pressing techniques can be used to consolidate CMCs.

1.3 ALUMINIUM METAL MATRIX COMPOSITES

The most popular type of MMCs is aluminium alloys reinforced with ceramic particles (Muthukrishnan & Davim 2009). In Aluminium Metal Matrix Composites (AMCs), the matrix phase is aluminium / aluminium alloy and the other constituent is reinforcement which is generally non-metallic or ceramic such as SiC, Al₂O₃, B₄C, Gr etc. The foremost benefits of AMCs when compared with conventional alloys are as follows: low density, higher strength and elastic modulus, better stiffness, superior high temperature properties, good damping characteristics, decreased part weight, low thermal shock and low coefficient of thermal expansion, and improved performances in electrical, abrasion and wear resistance. AMCs withstand high tensile and compressive stresses by transferring and distributing the applied load from the
ductile matrix to the reinforcement phase. This load transfer occurs through the interfacial bond, which is formed between the particulate reinforcement and the matrix. AMCs are fabricated by the addition of a reinforcement phase to the matrix, using one of the following techniques: powder metallurgy processing, spray atomization and co-deposition, plasma spraying, stir casting, compo-casting and squeeze casting.

1.4 MACHINING OF COMPOSITES

Machining of composite materials differs significantly in many aspects from machining of conventional metals and their alloys (Phadnis et al 2013). In the machining of composites, the material behaviour depends on reinforcement and matrix properties, the volume fraction of reinforcement and distribution of reinforcement phase. The extensive tool wear is caused during machining by hard and abrasive reinforcements. The machining of composite materials imposes special demands on the geometry and wear resistance of the cutting tools. The main reason for wear is the direct contact between the reinforcing particles or fibres and the cutting edge, which causes both a mechanical and a thermal load on the cutting edge. The dominant wear mechanism on the cutting tool is abrasion, which is generated by impacts at the cutting edge and by the sliding of the particles relative to tool face. Additionally, a thermal load is generated by micro-contacts between the cutting edge and the reinforcement which stresses the cutting edge. This thermal load is limited through a relatively low process temperature.

1.5 ADJUSTABLE PARAMETERS IN TURNING

Turning is the removal of metal from the outer diameter of a rotating cylindrical workpiece, thus reducing the diameter of the workpiece to a specified dimension. It is a machining operation that produces cylindrical parts and the primary factors involved are cutting speed, feed, and depth of
Other factors such as material and tool type also have a significant influence, but the controllable factors such as cutting speed, feed, and depth of cut depend on the operator’s choice.

In dealing with cutting speed, it always refers to the spindle and the workpiece. In turning operations, the surface speed, otherwise known as the speed at which the workpiece rotates over the cutting tool. This may be viewed as the product of the rotating speed and the circumference of the workpiece before the commencement of the cutting action. Usually, it is expressed in terms of meter per minute (m/min), and this only refers to the workpiece. Anytime reference is made to feed, it is always associated to the cutting tool, and this is described as the rate at which the tool moves along its cutting path. It is expressed in mm (of tool advance) per revolution (of the spindle), or mm/rev. Depth of cut is the thickness of the layer removed in a single pass from the workpiece or the distance from the uncut surface of the work to the cut surface. It is expressed in mm (TRG 2014).

1.6 RESPONSES CONSIDERED DURING TURNING

The outermost layers of the machined surfaces display a great number of both macro- and micro-geometrical deviations from the ideal geometrical surface (Khandey 2009). These deviations are referred to as surface roughness and range up to the sixth order (Barik & Mandal 2012; Vakondios et al 2012). The material removal rate in turning operations is the volume or amount of material/metal that is removed per unit time (Kumar et al 2011). It is expressed in mm$^3$/min or g/min.

Tool wear in machining is defined as the amount of volume loss of tool material on the contact surface due to the interaction between the tool and workpiece (Khandey 2009). Generally, tool wear is represented as wear rate
and is strongly determined by material, temperature and relative sliding velocity generated at the contact interface.

At high cutting speed, the tools are subjected to an extremely severe rubbing process resulting in metal-to-metal contact, inducing very high stresses at high temperature. In machining, cutting tools remove material from the component to achieve the required shape, dimension and surface roughness. However, wear occurs during the cutting action ultimately resulting in the failure of the cutting tool. When the tool wear reaches a certain extent, the tool or active edge has to be replaced in order to obtain the desired cutting action.

1.7 NEED FOR THE PRESENT STUDY

Even though particulate metal matrix composites having excellent mechanical and thermal properties, these materials are very much complicated to machine. The hard reinforcement particles like SiC, Al$_2$O$_3$ acts as an abrasive medium between the cutting tool and the workpiece, finally ensuing in high tool wear, poor surface finish and more power consumption. The machinability of Particulate Metal Matrix Composites (PMMCs) is improved by reinforcing the soft particles like graphite along with hard ceramic particles.

Severe lubrication problems occurred at high temperature environments where oils and greases cannot be used. In this extreme condition, the need for solid lubricants extensively arises. Gr particles are well suited for this condition. However, a high amount of Gr may result in decreased in fracture toughness of the material. The percentage reinforcement of Gr and SiC particles in aluminium matrix is limited to certain level beyond which adding either Gr or SiC is not desirable. Al–SiC–Gr hybrid composite is self-lubricating material due to existence of graphite particles and on the
other side, their strength is enhanced from the presence of SiC ceramic phase. These hybrids composite substitute the materials for automotive and aerospace fields due to enhanced properties.

Al-SiC-Gr hybrid composite provides improved tribological, mechanical and machinability properties over those composite with single reinforcement, either SiC or Gr. Therefore, investigations on the influence of reinforcements, machining characteristics and optimisation of machining process parameters are required in the area of Al-SiC-Gr composites.

The need for precise machining of composites is increasing in many fields. Therefore, it is necessary to select the most appropriate machining conditions to reduce manufacturing cost, produce high quality parts and to improve efficiency. It is also essential to analyse and optimise the influence of process parameter during machining of Al-SiC-Gr hybrid composites. This provides the chance to further analyse and optimise the machining parameters for effective turning process using different optimisation techniques.

1.8 PROBLEM DEFINITION

The addition of silicon carbide to aluminium alloy matrix, improve both strength and wear resistance of the composites. However, a high amount of SiC makes machining difficult. Thus, it is essential to retain the advantageous influence of SiC while simultaneously attending to the problem of machining of composites reinforced with SiC. Addition of graphite particles improves both the machining properties and the wear resistance of Al–SiC composites. In machining operations, the economics of machining and rate of production is based on the performance characteristics such as surface roughness, material removal rate, tool wear, etc (Subramanyan & Sarcar 2013). The machining parameters setting mainly depend on the
experience of operators or charts developed by machine tool builders. Obviously, the “trial and error” method is time consuming, ineffective and the achievement of a desirable value is not repetitive. Several studies have focused on tribological aspects of Al-SiC-Gr composites but machining related studies are limited. This opens the chance in optimisation of machining parameters for effective turning process.

1.9 OBJECTIVES OF THE PRESENT WORK

The present work deals with production of Al-SiC-Gr hybrid composites, machining characteristics, and optimisation of machining parameters. The objectives of the present work are:

1. a) To produce Al-SiC-Gr hybrid composite specimens with 5, 7.5 and 10% of combined equal weight fraction of SiC-Gr particles using compo-casting technique or semi-solid state processing.

b) To do a microstructure analysis for the distribution of silicon carbide and graphite particles in aluminium matrix.

c) To determine some of the mechanical properties of Al-SiC-Gr hybrid composites.

2. To study the machinability of Al-SiC-Gr hybrid composites and to develop the mathematical models for the responses to analyse the influence of process parameters.

3. To conduct machining experiments on Aluminium hybrid composites using conventional lathe in order to determine optimal level of process parameters setting for individual and multi-performance characteristics.
4. a) To develop a predictive model for surface roughness of machined surface during turning of Al-10%SiC composite and Al-10%(SiC-Gr) hybrid composite using an artificial neural network and response surface models.

b) To compare and evaluate the surface roughness values of both Al-10%SiC composite and Al-10%(SiC-Gr) hybrid composite.

5. To carry out turning experiments on CNC lathe and determine the optimal level of parameters for multi-performance characteristics using grey-fuzzy logic approach.

1.10 OUTLINE OF THE THESIS

This research work attempts to develop Al-SiC-Gr hybrid composite with 5, 7.5 and 10% of combined equal weight fraction of SiC-Gr particles. Also, machining operations are performed on this hybrid composite to analyse the performance characteristics.

Using an appropriate design of experiments, the turning experiments are conducted on Al-SiC-Gr composite specimens with different levels of input parameters and the corresponding responses are determined. The process parameters include cutting speed, feed rate, depth of cut and weight fraction of SiC-Gr. The influence of these process parameters and their level of significance on the performance characteristics of Surface Roughness ($R_a$), Material Removal Rate (MMR) and Flank Wear ($F_b$) of the tool has been evaluated. The optimal parameters setting for turning in conventional lathe is found out for individual and multi-performance characteristics using response table and Grey relational approach.
In CNC machining, the surface roughness of the machined surface of Al-10\%SiC and Al-10\%(SiC-Gr) composites is compared with the predicted value of ANN and RSM approach. Fuzzylogic approach is also incorporated with grey relational analysis, in order to reduce the uncertainties in grey relational grade. Thereby, a fuzzy reasoning of multiple performance characteristics has been developed and the optimal turning condition is determined.

The details about the individual chapters are given below,

**Chapter 1:** This chapter deals with the introduction part of the thesis, which includes types of composite materials and its application, parameters and responses considered during machining, and the main objectives of the present work.

**Chapter 2:** In this chapter, the literature review has been carried out in-depth to analyse the work carried out on metal matrix composite materials. The review has been summarised as follows: types and processing methods of composites, characteristics and properties of MMCs, machinability of AMCs and optimisation methods used for optimising the process parameters during machining.

**Chapter 3:** This chapter discusses the various steps followed in the production of Al-SiC-Gr hybrid composites. The steps described include selecting the aluminium alloy and reinforcement materials, preheating of reinforcement materials, mixing of reinforcements with matrix alloy and production of composite castings. Also, the characterisation of composite material is analysed in terms of the microstructure and mechanical properties.

**Chapter 4:** This chapter describes the machinability of Al-SiC-Gr hybrid composites by performing the turning operation in a conventional lathe. In addition, the effect of process parameters on the performance characteristics
such as surface roughness and material removal rate are also modelled and analysed using Response Surface Methodology (RSM).

**Chapter 5:** This chapter presents the details related to the optimisation of process parameters in machining Al-SiC-Gr hybrid composites for individual and multi-response characteristics. The experiments are performed based on Taguchi $L_{18}$ orthogonal array in all gear lathe using tungsten carbide tool by varying the process parameters such as cutting speed, feed rate, depth of cut and combined equal weight fraction of SiC-Gr. The optimum process parameters level for individual performance characteristic is found out using Taguchi’s response table of signal-to-noise ratio values of responses. The multi-performance characteristics are also analysed using grey relational approach by determining the grey relational coefficients and grades.

**Chapter 6:** This chapter discusses the surface roughness obtained during turning of Al–10%SiC and Al-10%(SiC-Gr) composites under different cutting conditions in a CNC lathe. An Artificial Neural Network (ANN) and Response Surface Model (RSM) are developed to predict the surface roughness of the machined surface of both composites. The experimental results have been compared with the predicted models of ANN and RSM approaches.

**Chapter 7:** This chapter deals with the experimental investigation carried out for optimisation of machining parameters in the turning of hybrid metal matrix composites. Using grey-fuzzy logic approach, optimum turning parameters is determined for the multi-performance characteristics of minimum surface roughness, flank wear of the tool and maximum material removal rate.

**Chapter 8:** The conclusion of the overall work is summarised in this chapter. Scope for further study on this work is also highlighted.