Investigation of Cutting Forces and Surface Roughness in Face Milling (Down Milling) Operation on AlSiC MMC with HSS Tool

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of his **Master of Engineering in Mechanical Engineering (Production)** studies during academic session 2021- 2023.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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CERTIFICATE OF RECOMMENDATION

This is to certify that **Mr. Brajesh Kumar** has completed his thesis entitled **"Investigation of Cutting forces and Surface Roughness in Face milling (Down milling) operation on AlSiC MMC with HSS tool"**, under the supervision and guidance of **Dr. Suswagata Poria** and **Dr. Titas Nandi**, Jadavpur University, Kolkata. We are satisfied with his work, which is being presented for the partial fulfillment of the degree of **Master of Mechanical Engineering**, Jadavpur University, Kolkata-700032.

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The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner of satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but thesis only for the purpose for which it has been submitted.

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BRAJESH KUMAR

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List of Abbreviation

MMC	Metal matrix composite
HSS	High Speed Steel
OVAT	One Variable At a Time
AlSiC	Aluminium Silicon carbide
C.F.	Cutting force
F_x	Normal force
F_y	Feed force
F_z	Axial force
S.R.	Surface roughness
a_p	Width of cut
a_e	Depth of cut
f	Feed
V_c	Cutting speed
N	Spindle speed in RPM
WoC	Width of cut
DoC	Depth of cut
C.S.	Cutting speed
RPM	Revolution per minute
R_a	Average surface roughness
R_{rms}	Root mean square surface roughness

ABSTRACT

This thesis investigates the cutting forces and surface roughness in the face milling operation on AlSiC Metal Matrix Composite (MMC) using an HSS tool. The effects of cutting parameters (cutting speed, feed rate, and depth of cut) on cutting forces and surface roughness are examined. The experiments are conducted on a horizontal milling machine with an HSS side and face milling cutter. Unlike traditional choices such as carbide or PCD tools, HSS tools, which are primarily designed for machining metals and alloys, are utilized in this study. In this experiment, force measurement is done by Kistler tool dynamometer and surface roughness is measured using a stylus-type profilometer called Talysurf.

The results show that increasing cutting speed initially leads to an increase in cutting forces, but after a certain point, the forces start to decrease due to reduced tool-workpiece interaction and workpiece softening caused by elevated temperatures. Higher feed rates and depth of cut result in increased cutting forces.

Regarding surface roughness, an increase in cutting speed generally results in decreased roughness, indicating a smoother surface finish. However, an increase in feed rate and depth of cut shows an inverse relationship with surface roughness, leading to increased roughness values.

The findings emphasize the importance of selecting appropriate cutting parameters to optimize cutting forces and surface roughness in face milling of AlSiC MMC. The use of HSS tools provides insights into their performance in machining MMCs. Future research can explore advanced tool materials or coatings to further improve the machining process and surface quality of AlSiC MMCs.

CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

The field of machining processes has witnessed significant advancements in recent years, driven by the ever-increasing demand for superior machining performance and improved product quality. Among various machining operations, face milling holds immense significance in the manufacturing industry, as it enables the removal of large amounts of material from a workpiece to achieve the desired shape and surface finish. In the context of face milling, understanding the cutting forces and surface roughness becomes crucial for optimizing machining parameters and ensuring the desired product quality.

This thesis aims to investigate the cutting forces and surface roughness in the face milling (down milling) operation on Aluminum Silicon Carbide (AlSiC) Metal Matrix Composite (MMC). The utilization of these materials is prevalent in various industrial sectors due to their desirable properties, such as lightweight, high strength-to-weight ratio, thermal conductivity, and wear resistance. The choice of High-Speed Steel (HSS) tool as the cutting tool further adds simplicity to the machining process due to its unique characteristics.

The primary objective of this research is to explore the relationship between cutting forces and surface roughness in the face milling operation of Al alloy and AlSiC MMC, with specific emphasis on down milling. The investigation will involve comprehensive experimental studies, where a range of machining parameters, including cutting speed, feed rate, and depth of cut, will be systematically varied to observe their effects on cutting forces and surface roughness. The collected data has been analyzed and interpreted to identify the key factors influencing the machining performance and surface quality.

The outcomes of this research will provide valuable insights into the machining behavior of AlSiC MMC in face milling operations, thereby aiding in the optimization of machining parameters for enhanced productivity and quality. Furthermore, the findings will contribute to the existing body of knowledge concerning the application of HSS tools in the machining of these materials.

This thesis seeks to bridge the gap in understanding the relationship between cutting forces, surface roughness, and machining parameters in the face milling operation on AlSiC MMC. The research findings will benefit manufacturing industries, particularly those involved in the production of components using these materials, by facilitating the development of efficient machining strategies and improving overall product quality.

1.1 Composite and Metal Matrix Composite

1.1.1 composite

Composites are materials that consist of two or more distinct components that are combined to create a new material with unique properties. The components can be any combination of materials, but are typically composed of a **matrix material** and a **reinforcement material**. The matrix material serves as a bonding agent that holds the reinforcement material

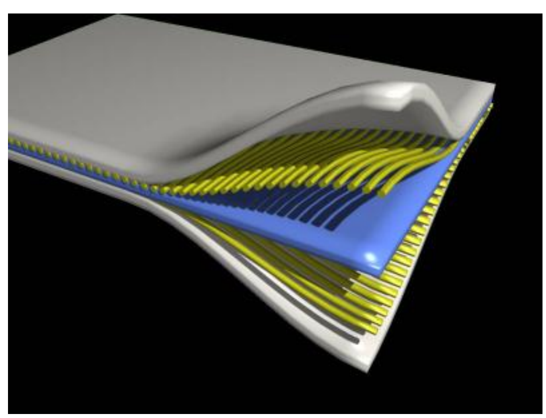

Figure 1.1: composite

together, while the reinforcement material provides additional strength, stiffness, and other desirable properties to the composite material [1].

1.1.2 How to make composite ?

Composite materials are typically made by combining two or more different materials to create a new material with improved properties.The basic process for making a composite material involves the following steps :

1. **Material Selection**: The first step in making a composite material is to select the materials that will be combined to create the composite. The materials can be of different types, such as fibers, matrix materials, and additives, and are selected based on their properties, such as strength, stiffness, toughness, weight, and cost.

2. **Preparation**: The next step is to prepare the materials for the manufacturing process. The fibers, which provide the strength and stiffness, may need to be cut or chopped to the desired length, while the matrix material, which binds the fibers together, may need to be liquefied or dissolved to a specific viscosity. Additives, such as pigments or flame retardants, may also be mixed in at this stage.

3. **Mixing**: The prepared materials are then mixed together to create a uniform blend. The mixing process can vary depending on the materials being used and the desired properties of the final composite. For example, for fiber-reinforced composites, the fibers are typically mixed with the matrix material to create a resin system that wets out the fibers.

4. **Molding**: Once the composite material has been mixed, it is molded into the desired shape. There are several different molding techniques that can be used, such as compression molding, injection molding, and filament winding,

depending on the properties and geometry of the final composite. In compression molding, the material is placed in a mold and heated and compressed to create the desired shape. In injection molding, the material is injected into a mold under high pressure. In filament winding, fibers are wound around a mandrel in a specific pattern to create a hollow structure.

5. **Curing**: After molding, the composite material is cured to harden the material and create the desired properties. Curing can be done through a variety of methods, such as heat, pressure, or chemical reactions, depending on the materials being used and the desired properties of the final composite. The curing process may also involve post-curing, which can further improve the mechanical properties of the composite.

6. **Finishing**: Finally, the composite material may be finished with surface treatments, coatings, or other enhancements to further improve its properties and appearance. For example, the surface of the composite may be polished or painted, or a protective coating may be applied to improve durability and resistance to damage.

The process for making a composite material can be complex and involves several different steps, each of which is critical to creating a final product with the desired properties. The specific process used will depend on the materials being used, the desired properties of the final product, and the intended application of the composite material

1.1.3 Types of Composites

There are several types of composites, each with their own unique properties and applications. Here are some common types of composites:

1. **Metal Matrix Composites (MMCs)**: MMCs consist of a metal matrix reinforced with fibers or particles of materials such as ceramic or carbon. They are strong, stiff, and have good thermal conductivity, making them useful for high-temperature applications such as automotive and aerospace.

2. **Polymer Matrix Composites (PMCs)**: PMCs are the most widely used type of composite, and consist of a polymer matrix reinforced with fibers such as carbon, glass, or aramid. They are lightweight, strong, and have good resistance to corrosion and fatigue. PMCs are used in a wide range of applications, including aerospace, automotive, and sports equipment.

3. **Ceramic Matrix Composites (CMCs)**: CMCs consist of a ceramic matrix reinforced with fibers such as carbon or ceramic. They are lightweight, strong, and have good resistance to high temperatures and wear. CMCs are used in applications such as aerospace, defense, and energy.

4. **Natural Fiber Composites (NFCs)**: NFCs are composites made from natural fibers such as bamboo, hemp, or flax, and a polymer matrix. They are biodegradable, renewable, and have a low carbon footprint, making them a sustainable alternative to traditional composites. NFCs are used in applications such as furniture, construction, and automotive.

5. **Sandwich Composites**: Sandwich composites consist of a lightweight core material sandwiched between two face sheets made of materials such as aluminum or carbon fiber. They are lightweight, stiff, and have good resistance to impact and fatigue. Sandwich composites are used in applications such as marine, aerospace, and wind energy.

1.1.4 Advantages and Disadvantages of Composite

Advantages

1. **High Strength to Weight Ratio**: Composite materials are made by combining two or more materials with different properties to create a new material that has improved properties. For example, carbon fiber reinforced polymer (CFRP) composites are made by combining carbon fiber and a polymer resin. The resulting material has a much higher strength-to-weight ratio than either carbon fiber or polymer resin alone. This makes it ideal for use in lightweight structures that require high strength, such as aircraft components, sports equipment, and racing cars.

2. **Corrosion Resistance**: Composite materials are highly resistant to corrosion because they do not contain metal. Metals can corrode when they come into contact with moisture and oxygen in the air, but composites do not have this problem. This makes them ideal for use in marine and offshore applications, as well as in corrosive industrial environments.

3. **Design Flexibility**: Composite materials offer designers a high degree of flexibility in terms of shaping and forming. They can be molded into complex shapes and structures using a variety of manufacturing techniques, such as filament winding, pultrusion, and resin infusion. This allows designers to create components that are both lightweight and strong, while also being aerodynamic and aesthetically pleasing.

4. **Fatigue Resistance**: Composite materials have excellent fatigue resistance because they are made up of multiple layers or plies of material. Each layer is oriented in a different direction, which helps to distribute stress evenly

throughout the material. This makes it much more resistant to fatigue than traditional materials like metals, which tend to fail after repeated stress cycles.

5. **Thermal Resistance**: Composite materials have excellent thermal resistance because they are made up of materials that have different thermal expansion coefficients. This means that they do not expand or contract as much as metals when exposed to high temperatures. This makes them ideal for use in high-temperature applications such as engine components, exhaust systems, and industrial machinery.

composite materials offer a range of advantages that make them ideal for a wide variety of applications. Their high strength-to-weight ratio, corrosion resistance, design flexibility, fatigue resistance, and thermal resistance make them an attractive alternative to traditional materials in many industries.

Disadvantages

While composite materials offer a number of advantages, there are also some disadvantages to consider. Here are some of the main disadvantages of composite materials:

1. **Cost**: Composite materials can be more expensive than traditional materials such as metals and wood. The manufacturing process for composites can be complex and require specialized equipment and techniques, which can drive up the cost of production.

2. **Brittle**: While composites are generally strong, they can be brittle and prone to cracking or breaking under impact or other high-stress conditions. This can make them less suitable for applications where impact resistance is critical.

3. **Environmental Impact**: The production of composite materials can have a negative environmental impact. The use of resins and other chemicals can

release harmful pollutants into the air and water, and the disposal of composite waste can also be a challenge.

4. **Limited Repairability**: Unlike traditional materials such as wood or metals, composite materials can be difficult to repair if they become damaged. Repairs often require specialized skills and equipment, which can be expensive.

5. **Susceptibility to UV Light**: Some composite materials can be susceptible to damage from UV light. This can cause them to degrade and become discolored over time, particularly when exposed to sunlight or other sources of UV radiation.

Overall, while composite materials offer many advantages, there are also some limitations to consider. The cost of production, brittleness, environmental impact, limited repairability, and susceptibility to UV light are all factors that need to be taken into account when considering the use of composites in different applications.

1.1.5 Metal Matrix Composites (MMCs)

Metal matrix composites (MMCs) are composite materials made up of a metal matrix that is reinforced with one or more materials, such as ceramic particles or fibers. The combination of the metal matrix and the reinforcement material gives MMCs unique properties, including high strength, stiffness, and wear resistance. The most common metals used as the **matrix material** in MMCs are aluminum, magnesium, and titanium. These metals are chosen for their ability to form strong bonds with the reinforcement material, good ductility, and good thermal conductivity. The **reinforcement materials** used in MMCs are typically ceramic particles or fibers, such as silicon carbide, alumina, or boron carbide. These materials are chosen for their high strength, high stiffness, and high wear resistance [2].

One of the key advantages of MMCs is their ability to maintain their properties at high temperatures, making them ideal for use in high-temperature environments, such as aerospace and automotive applications. For example, MMCs are used in aircraft engine components, such as turbine blades, and in automotive applications for brake rotors, suspension components, and engine blocks.

1.1.6 Classification of MMC based on matrix and reinforcement

Metal Matrix Composites (MMCs) can be classified based on the type of reinforcement phase and matrix metal used. Some common types of MMCs include:

1. **Fiber-reinforced MMCs**: These composites contain continuous or discontinuous fibers of materials such as carbon, boron, or silicon carbide embedded within a metal matrix.

2. **Particle-reinforced MMCs**: These composites contain small particles of materials such as silicon carbide, aluminum oxide, or titanium carbide embedded within a metal matrix.

3. **Whisker-reinforced MMCs**: These composites contain long, thin, single crystals of materials such as silicon carbide, aluminum oxide, or boron carbide embedded within a metal matrix.

4. **Hybrid MMCs**: These composites contain a combination of different reinforcement phases, such as fibers and particles, embedded within a metal matrix.

The choice of reinforcement phase and matrix metal depends on the desired properties and application of the MMC.

Matrix Phase

In a metal matrix composite (MMC), the matrix refers to the metal component of the composite. The matrix material provides a continuous phase that holds the reinforcement material in place, transfers loads between the reinforcement material, and provides mechanical support to the composite material. The matrix material in MMCs is typically a metal, such as aluminum, titanium, or magnesium. These metals are chosen for their good ductility, good thermal conductivity, and good corrosion resistance. The matrix material must also be able to form a strong bond with the reinforcement material to ensure efficient load transfer between the two materials.

The properties of the matrix material have a significant impact on the overall properties of the MMC so some of the desired properties of the matrix material in MMCs depend on the specific application and the properties of the reinforcement phase. However, in general, the matrix material in MMCs should possess the following properties:

1. High strength and stiffness: The matrix material should have high strength and stiffness to withstand the applied loads and stresses and to provide mechanical support to the reinforcement phase.

2. Good ductility and toughness: The matrix material should have good ductility and toughness to resist cracking and deformation under stress and to prevent the propagation of cracks in the composite.

3. High thermal stability and conductivity: The matrix material should have high thermal stability and conductivity to prevent thermal degradation and to facilitate efficient heat dissipation.

4. Corrosion resistance: The matrix material should have good corrosion resistance to prevent degradation of the composite in harsh environments.

5. Compatibility with the reinforcement phase: The matrix material should be compatible with the reinforcement phase in terms of chemical composition, thermal expansion coefficient, and mechanical properties to ensure good bonding between the two phases and to prevent to divide into layers and cracking of the composite.

Reinforcement Phase

The reinforcement phase in metal matrix composites (MMCs) plays a crucial role in determining the properties and performance of the material. The reinforcement phase is added to the metal matrix to improve its mechanical and thermal properties.

The reinforcement phase in MMCs can take many forms, including fibers, particles, or whiskers. The choice of reinforcement phase depends on the desired properties of the composite. For example,

- Ceramic fibers such as silicon carbide (SiC) or alumina (Al_2O_3) are often used to improve the strength, stiffness, and wear resistance of the MMC, while metallic fibers such as titanium or aluminum can increase its ductility and toughness.
- The volume fraction of the reinforcement phase in the MMC is an important parameter that affects its properties. As the volume fraction of the reinforcement phase increases, the strength, stiffness, and hardness of the composite increase, but its ductility and toughness decrease. However, the optimal volume fraction of the reinforcement phase depends on the specific application of the MMC.
- The orientation of the reinforcement phase also plays a critical role in determining the properties of the MMC. For example, aligning the fibers parallel to the direction of the applied load can significantly improve the strength and stiffness of the composite in that direction.

- The intended application of the MMC also plays a role in determining the choice of reinforcement phase. For example, if the composite will be used in high-temperature environments, ceramic fibers or particles may be preferred due to their excellent thermal stability. Similarly, if the MMC will be subjected to high wear or abrasion, hard and wear-resistant reinforcement materials may be preferred.

Selection of Reinforcement

The selection of the reinforcement phase in metal matrix composites (MMCs) depends on various factors such as the desired properties of the composite, the intended application of the material, and the processing methods used to fabricate the MMC. Some of the factors to consider when selecting the reinforcement phase for MMCs include:

1. **Mechanical properties**: The reinforcement phase should be selected to enhance the mechanical properties of the MMC, such as strength, stiffness, ductility, toughness, and wear resistance. The choice of reinforcement phase may depend on the specific mechanical properties required for the intended application of the MMC.

2. **Thermal properties**: The thermal properties of the reinforcement phase are important for MMCs that will be exposed to high-temperature environments. Ceramic fibers, for example, have excellent thermal stability and may be preferred for high-temperature applications.

3. **Chemical compatibility**: The reinforcement phase should be chemically compatible with the metal matrix to ensure good bonding between the two materials. Poor chemical compatibility can lead to weak bonding and reduced mechanical properties.

4. **Cost**: The cost of the reinforcement phase should be considered, as it can significantly impact the overall cost of the MMC. The cost of the reinforcement phase may depend on factors such as availability, manufacturing cost, and processing methods.

5. **Processing methods**: The choice of reinforcement phase may also depend on the processing methods used to fabricate the MMC. For example, some reinforcement phases may be difficult to uniformly distribute in the matrix using certain processing methods, which may limit their use.

Overall, the selection of the reinforcement phase for MMCs is a critical decision that requires careful consideration of several factors. The optimal reinforcement phase for a specific MMC application depends on balancing the desired properties of the composite with other factors such as cost and processing methods.

1.1.7 Manufacturing of Metal matrix composites (MMCs)

The manufacturing of metal matrix composites (MMC) typically involves several steps, including the selection of matrix and reinforcement materials, the preparation of the reinforcement phase, the mixing of the matrix and reinforcement materials, and the processing of the MMC into its final form. The following are some of the common methods used for manufacturing MMCs:

1. Powder Metallurgy: In this method, the matrix material is melted and then mixed with the reinforcement material in powder form. The mixture is then compacted into a preform shape and sintered at high temperatures to form a solid composite.

2. In-situ Processing: In this method, the reinforcement phase is formed in-situ during the manufacturing process. For example, a ceramic reinforcement phase

can be formed by a chemical reaction between the matrix and a precursor material during solidification.

3. Liquid Metal Infiltration: In this method, the molten matrix material is infiltrated into a preform of the reinforcement phase, which is typically in the form of a porous structure. The composite is then solidified and shaped into its final form.

4. Spray Deposition: In this method, the matrix material is melted and then sprayed onto a substrate surface together with the reinforcement phase, which is also in powder form. The resulting deposit is then processed to form a solid composite.

5. **Stir Casting**: In this method, the matrix material is melted and the reinforcement phase is added to the melt while stirring. The mixture is then cast into a desired shape and solidified to form a solid composite.

The selection of manufacturing method depends on the specific MMC design requirements, the materials being used, and the desired properties of the final composite.

Powder Metallurgy

Powder metallurgy is a manufacturing process that involves the production of metal parts and components by compacting powdered metal and then sintering it in a furnace.Here are the main steps involved in the powder metallurgy process:

1. Powder production: The first step in the powder metallurgy process is to produce the metal powder. This can be done using several methods:

- Atomization: In this method, molten metal is sprayed into a gas or liquid medium, which rapidly cools and solidifies the metal into small particles.

- Mechanical alloying: This method involves blending two or more metals in powder form and then subjecting them to high-energy ball milling. This causes the metals to deform and mix, resulting in a homogeneous blend.
- Electrolysis: In this method, a metal salt is dissolved in a solvent and subjected to an electric current. The current causes the metal ions to be deposited onto a cathode, forming a layer of metal powder.

2. Mixing: Once the metal powder has been produced, it is mixed with other materials, such as binders and lubricants, to enhance its properties and make it easier to work with. Binders are added to help the metal particles stick together during compaction, while lubricants are added to reduce friction and prevent the powder from sticking to the tooling.
3. Compacting: The mixed powder is then compacted into the desired shape using a press or other tool. This step may involve applying pressure to the powder using a die, or using an isostatic press to apply pressure uniformly in all directions. The compacting process can be done at room temperature (cold compaction) or at elevated temperatures (hot compaction).
4. Sintering: The compacted powder is then heated in a furnace to a temperature just below its melting point. This causes the particles to fuse together, forming a solid mass. The sintering process can take several hours, depending on the size and complexity of the part being produced. During sintering, the metal particles bond together to form a solid, porous mass. The porosity of the part can be controlled by adjusting the compaction pressure and the sintering conditions.
5. Finishing: The sintered part is then subjected to various finishing processes, such as machining, grinding, and polishing, to achieve the desired shape and surface finish. The finishing processes can be done using conventional

machining techniques, such as milling and turning, or using specialized processes, such as electrical discharge machining (EDM) or laser cutting.

The powder metallurgy process is a versatile and cost-effective method for producing high-quality metal parts and components with complex shapes and excellent properties.

In-situ Processing

In-situ processing is a method of creating or modifying materials directly within their final application environment. In the case of composites, it can be used to create a reinforcement phase within the matrix material itself. One way to do this is by using a chemical reaction or precipitation during the manufacturing process. For example, in the case of ceramic matrix composites, a precursor material is added to the matrix material, which reacts with it during solidification, forming a ceramic reinforcement phase within the matrix. This technique can result in composite materials with improved properties, such as high strength and stiffness, thermal stability, and resistance to wear and corrosion, making them suitable for high-performance applications.

1.1.8 Stir Casting

Stir casting, also known as stir casting process or mechanical stirring, is a widely used manufacturing process for producing metal matrix composites (MMCs) and metal alloys. This process involves the addition of a reinforcement material (such as ceramic or metallic particles) into a molten metal matrix while simultaneously stirring the mixture [3].

The stir casting process generally involves the following steps:

1. **Material Preparation**: The reinforcement material and the base metal are prepared in their respective forms. The reinforcement material is typically in the form of powders or particles, while the base metal is in the form of ingots or granules.

2. **Charging the Furnace**: The base metal is melted in a furnace at a temperature higher than its melting point. Once the base metal has melted, the reinforcement material is added to the molten metal.

3. **Stirring**: A mechanical stirrer is used to stir the molten metal and the reinforcement material. The stirrer is designed to agitate the mixture at a constant speed and with a controlled amount of turbulence. The stirring process helps in distributing the reinforcement material evenly throughout the molten metal.

4. **Casting**: The molten metal-reinforcement mixture is then poured into a pre-designed mold to form the desired shape of the final product.

5. **Solidification**: The molten metal cools and solidifies inside the mold, forming a solid metal matrix composite or alloy.

Advantages of Stir Casting

Some of the advantages of the stir casting process are:

1. **Versatility**: The stir casting process can produce a wide range of metal matrix composites and alloys with different combinations of reinforcement materials and matrix metals.

2. **Cost-effective**: Stir casting is a relatively low cost process compared to other metal forming techniques, such as casting, forging, and rolling.

3. **Flexibility**: The process can produce complex shapes with high dimensional accuracy and can be easily scaled up or down to suit different production requirements.

4. **Improved properties**: The addition of reinforcement materials can enhance the mechanical, thermal, and electrical properties of the final product, resulting in improved strength, stiffness, wear resistance, and thermal conductivity.

5. **Homogeneity**: The mechanical stirring helps in achieving a homogeneous distribution of the reinforcement material in the final product, leading to improved product quality and consistency.

6. **Reduced porosity**: The mechanical stirring also helps in reducing the porosity of the final product, resulting in better material properties.

7. **Energy efficiency**: The process consumes less energy than other metal forming techniques, making it an energy-efficient manufacturing process.

However, some limitations of the stir casting process include the potential for uneven distribution of the reinforcement material, the potential for oxide formation due to exposure of the molten metal to air during the process, and the difficulty in achieving a homogeneous distribution of the reinforcement material in the final product.

1.1.9 Types of Metal matrix composites (MMCs)

The following are some of the most common types of MMCs:

1. **Aluminum Matrix Composites (AMC)**: These are the most widely used MMCs and are used in a variety of applications such as aerospace, automotive, and sporting goods. They are usually reinforced with ceramic particles such as silicon carbide (SiC) or aluminum oxide (Al_2O_3), or with continuous fibers of silicon carbide or graphite.

2. Magnesium Matrix Composites: These are lightweight MMCs that have high stiffness and good strength at elevated temperatures. They are usually reinforced with ceramic particles such as silicon carbide or aluminum oxide.

3. Titanium Matrix Composites: These are high-strength MMCs that are used in applications such as aerospace and automotive components. They are usually reinforced with continuous fibers of silicon carbide or with ceramic particles such as titanium boride (TiB_2) or titanium carbide (TiC).

4. Copper Matrix Composites: These are MMCs that are usually reinforced with ceramic particles such as silicon carbide or with continuous fibers of carbon or tungsten. They have low coefficient of thermal expansion, high stiffness and good electrical conductivity.

In general, MMCs offer improved mechanical properties, such as high strength and stiffness, good wear resistance, and improved thermal and electrical conductivity, compared to their base metal. They also have good thermal stability and corrosion resistance. However, their manufacturing process can be complex and costly.

1.1.10 **Aluminum Matrix Composites (AMC)**

Aluminum metal matrix composites (AMMCs) are created by combining aluminum with other materials such as ceramic particles or fibers. These materials enhance the properties of the composite, leading to better strength, stiffness, and resistance to wear. AMMCs can be customized for different applications by changing the type, size, and amount of the reinforcement material used. Compared to traditional composites, AMMCs have a lower coefficient of thermal expansion and higher thermal conductivity, which make them useful for applications that require good thermal stability and heat dissipation [4].

Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are among the most commonly used reinforcement materials for AMCs.

Silicon Carbide Reinforced AMCs

Silicon carbide reinforced AMCs refer to a type of aluminum metal matrix composite that is reinforced with silicon carbide (SiC) particles. SiC is a ceramic material that is extremely hard and has excellent strength and stiffness, making it an ideal material for reinforcing AMCs [5].

The addition of SiC particles to the aluminum matrix results in a composite material that has improved mechanical properties, such as higher strength, stiffness, and wear resistance. The SiC particles also help to reduce the coefficient of thermal expansion and improve the thermal conductivity of the composite. adding more SiC reinforcement to an aluminum matrix composite (AMC) can make it stronger and harder, but at the same time, it may also make it more brittle and less able to withstand impacts [6]. This is because the increased amount of SiC reinforcement causes the material to become stiffer, which can lead to a decrease in its ability to deform and absorb energy when subjected to impact or sudden shock. So, there is a trade-off between strength and toughness in AMCs, and this should be taken into account when designing and using them in various applications.

1.2 Milling machining

Milling is a machining process where metal is removed by rotating a milling cutter. A milling machine, which is a type of machine tool, is used to perform this operation. The workpiece is typically secured in a vice or clamped to a table that can move in three perpendicular directions. The milling cutter has multiple cutting edges that rotate at high speed, enabling rapid metal removal.

The milling machine is highly valued in workshops due to its versatility and precision. It can perform a wide range of operations with excellent accuracy. The workpiece can be machined to create different shapes and features by manipulating the movement of the milling cutter and the workpiece.

The cutting edges on the milling cutter swiftly remove metal, allowing for efficient material elimination. The high speed at which the cutting edges rotate contributes to the fast rate of metal removal. This makes the milling machine an indispensable tool for achieving productivity in the workshop.

One of the key advantages of using a milling machine is the ability to carry out operations with exceptional precision. The rigid structure of the machine, coupled with the controlled movement of the workpiece and the cutting tool, ensures accurate results.

Various machining operations can be performed using a milling machine, including face milling, peripheral milling, slot milling, drilling, and tapping. These operations can be executed with precision and repeatability, making the milling machine suitable for a wide range of applications.

In summary, milling machines are essential machines in workshops for their capability to remove metal with the help of a rotating milling cutter. They offer versatility, precision, and the ability to carry out operations with excellent accuracy. With a milling machine, a wide range of machining tasks can be performed efficiently and effectively [7].

In a milling machine, the workpiece is clamped onto the table, and a rotating cutter removes metal to shape it. The cutter spins at a set speed while the workpiece is fed in three directions: longitudinal, vertical, and cross. The cutter's teeth remove metal from the workpiece, creating the desired shape or features. The milling machine provides precision and flexibility for shaping different workpieces.

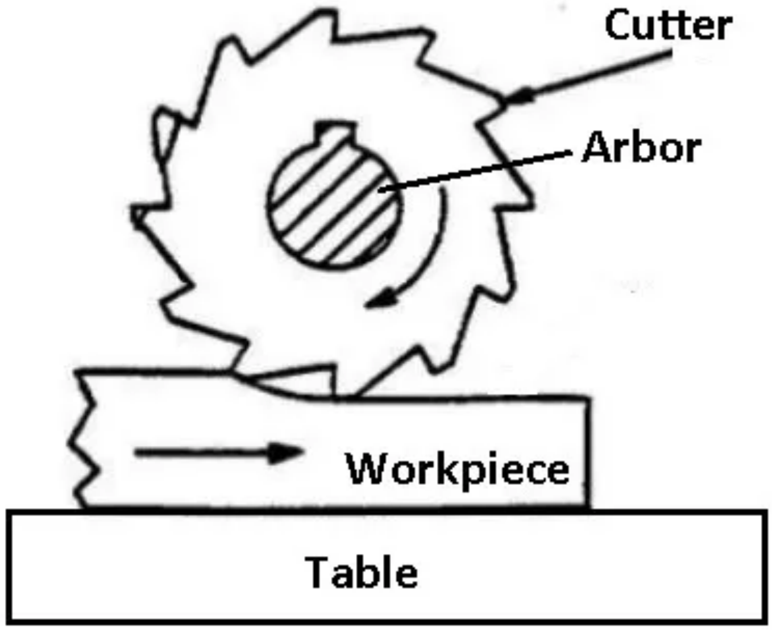

Figure 1.2 : principle of milling machining

1.2.1 Types of milling machine are as follows :

There are several types of milling machines commonly used in machining and manufacturing processes. Here are some of the most common types:

1. Vertical Milling Machine: In a vertical milling machine, the spindle axis is vertically oriented. This type of machine is commonly used for milling operations that require the cutting tool to move vertically.
2. Horizontal Milling Machine: In a horizontal milling machine, the spindle axis is horizontally oriented. This machine is suitable for milling operations that require the cutting tool to move horizontally across the workpiece.

3. Universal Milling Machine: A universal milling machine has the ability to rotate the spindle in multiple directions, allowing for a wide range of cutting angles and orientations. This versatility makes it suitable for various milling tasks.

4. Bed Type Milling Machine: A bed-type milling machine features a worktable that is mounted on a saddle resting on the bed of the machine. This design provides rigidity and stability, making it suitable for heavy-duty milling operations.

5. Knee Type Milling Machine: A knee-type milling machine has a vertically adjustable worktable supported by a knee that can be raised or lowered. This feature allows for precise vertical positioning of the workpiece.

6. CNC Milling Machine: A CNC (Computer Numerical Control) milling machine is controlled by a computer, enabling precise and automated machining operations. CNC milling machines can perform complex tasks with high accuracy and repeatability.

These are just a few examples of milling machine types, and there are other specialized variations available for specific applications. The choice of milling machine depends on the specific machining requirements and the type of workpiece being processed.

1.2.2 Types of milling process

There are various types of milling processes used in machining operations. Here are some common types:

1. **Face Milling**: In face milling, the cutting tool is positioned perpendicular to the workpiece surface. It removes material from the face of the workpiece to create a flat surface.

2. **Peripheral Milling**: In peripheral milling, the cutting tool is positioned parallel to the workpiece surface. It removes material from the periphery of the workpiece, resulting in the desired shape or profile.

3. **Slot Milling**: Slot milling involves milling a narrow groove or slot in the workpiece. The cutting tool moves in a linear path to create the slot, which can be used for various applications such as accommodating fasteners or providing a channel for other components.

4. **End Milling**: End milling is performed using an end mill cutter. The cutter has cutting edges on both the bottom and the sides, allowing it to remove material from the end of the workpiece or create contoured surfaces.

5. **Chamfer Milling**: Chamfer milling is used to create chamfered edges on the workpiece. The cutting tool removes material at an angle, resulting in a beveled edge.

6. **Drilling**: Although drilling is primarily a drilling operation, it is often considered a form of milling. A drill bit is used to create cylindrical holes in the workpiece, providing openings for fasteners or other components.

7. **Tapping**: Tapping is another operation that can be considered a type of milling. It involves cutting threads into a pre-drilled hole using a tap tool, allowing for the insertion of threaded fasteners.

These are some of the common types of milling processes, but there are also specialized milling techniques and operations based on specific requirements. The choice of milling process depends on factors such as the desired shape, surface finish, material properties, and the specific machining goals.

Peripheral milling process

Up milling and down milling are two common types of peripheral milling processes based on the direction of cutter rotation and the relative movement between the cutter and the workpiece.

1. **Up Milling (Conventional Milling)**: In up milling, also known as conventional milling, the cutter rotates against the direction of the workpiece feed. This means that the cutter teeth initially make contact with the workpiece at the thickest point, gradually removing material as it progresses. Up milling typically results in a smoother surface finish and less tool wear compared to down milling.

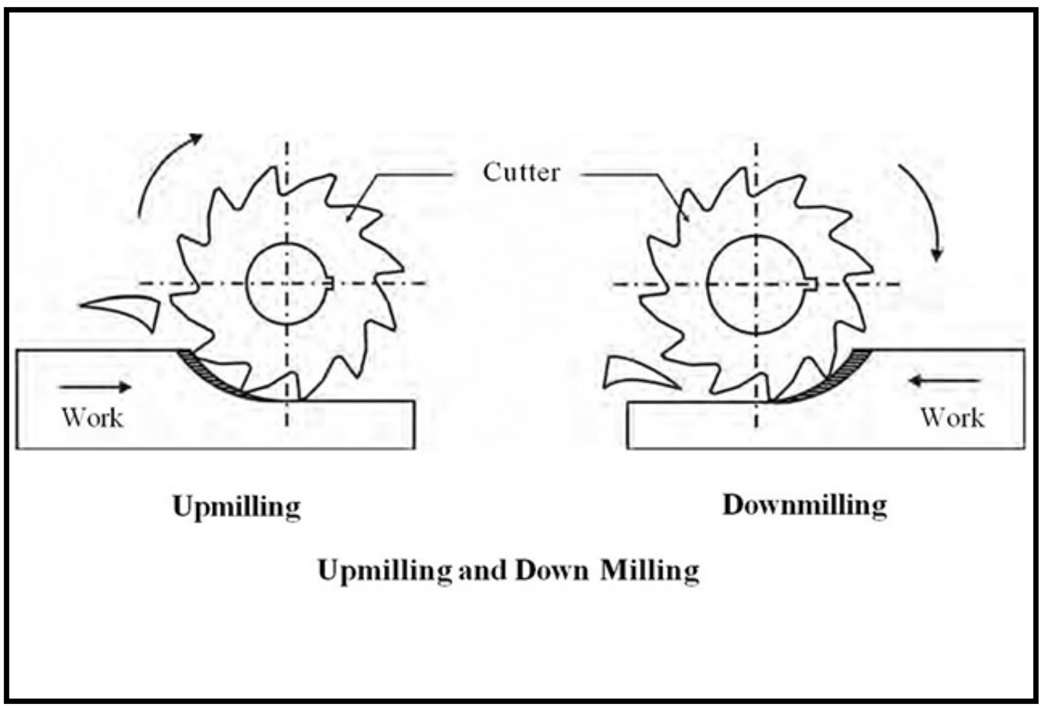

Figure 1.3 : Up milling and Down milling

2. **Down Milling (Climb Milling)**: In down milling, also referred to as climb milling, the cutter rotates in the same direction as the workpiece feed. This means that the cutter teeth initially make contact with the workpiece at the thinnest point, removing material right away. Down milling can provide faster material removal rates but may result in a rougher surface finish and increased tool wear due to the initial high impact forces.

The choice between up milling and down milling depends on various factors, including the type of material being machined, the desired surface finish, and the machine capabilities. Some key considerations are:

- Up milling is generally preferred when there is a need for better surface finish, reduced tool wear, or when working with delicate or thin-walled workpieces.
- Down milling is often chosen for its potential for higher material removal rates and shorter machining times. It can be advantageous for tough materials or when the machine's rigidity and tool holding capabilities allow for smooth and stable cutting action.

It is important to note that the specific conditions and machine setup can affect the performance of both up milling and down milling. Machinists need to carefully evaluate the requirements of each machining operation to determine the most suitable milling method.

1.2.3 Types of milling cutter

There are several types of milling cutters available, each designed for specific milling operations and materials. Here are some common types of milling cutters:

1. End Mill: An end mill is a versatile milling cutter with cutting edges on the bottom and sides. It is used for a wide range of milling operations, including contouring, profiling, slotting, and pocketing.

2. Face Mill: A face mill has a large cutting surface on its end and is primarily used for facing operations to create flat surfaces on the workpiece.

3. Ball Nose Cutter: A ball nose cutter has a rounded tip and is used for 3D contouring and sculpting. It is effective for creating smooth curves and surfaces.

4. Slab Milling Cutter: A slab milling cutter is a wide cylindrical cutter with multiple cutting teeth. It is used for removing material from the periphery or edges of the workpiece.

5. T-Slot Cutter: A T-slot cutter is designed specifically for creating T-shaped grooves or slots, commonly used for work holding and fixturing.

Figure 1.4 : Types of different milling cutter [7]

6. Side and Face Cutter: A side and face cutter has cutting edges on both the side and periphery. It is versatile and used for both side milling and face milling operations.

7. Shell Mill: A shell mill is a large diameter cutter with multiple cutting teeth. It is often used for high-speed milling operations and heavy material removal.

8. Woodruff Cutter: A Woodruff cutter is used for cutting keyways in workpieces. It has a disc-like shape with a profiled cutting edge.

9. Fly Cutter: A fly cutter is a single-point cutting tool that rotates on its axis. It is typically used for facing operations on large flat surfaces.

10. Thread Mill: A thread mill is used for milling threads in a workpiece. It is available in various sizes and thread profiles.

These are just a few examples of milling cutters, and there are many more specialized designs available for specific applications. The choice of milling cutter depends on factors such as the desired operation, material being machined, surface finish requirements, and machine capabilities.

1.2.4 Side and face cutter and its types

A side and face cutter is a specific type of milling cutter that is designed with cutting edges on both the side and periphery of the cutter. It allows for versatile milling operations, including side milling and face milling. The cutting edges on the side of the cutter are used for side milling, while the cutting edges on the periphery are used for face milling.

Side and face cutters typically have a cylindrical shape with teeth distributed along the side and periphery. The number of teeth can vary based on the cutter size and design.

Figure 1.5 : side and face cutter [7]

They are available in various diameters and lengths to accommodate different machining requirements.

The design and configuration of side and face cutters can vary among manufacturers, but they generally feature multiple cutting teeth or inserts. The cutting edges may have different geometries, such as square, rectangular, or helical, depending on the specific application.

The choice of side and face cutter depends on factors such as the material being machined, the desired surface finish, the depth of cut, and the machine's capabilities. It is important to select the appropriate cutter size and geometry based on the specific milling operation to achieve optimal results.

Types of side and face cutter

There are several types of side and face cutters available, each designed for specific machining applications. Here are some common types: [7]

1. Plain Side and Face Cutter: This type of cutter has straight cutting edges on the circumference and one or both faces. It is used for general-purpose milling operations, such as slotting, facing, and profiling.

Fig.1.6 : Plain side and face cutter

Fig1.7: Staggered tooth side and face cutter

2. Staggered Tooth Side and Face Cutter: Staggered tooth cutters have cutting teeth arranged in a staggered pattern on the circumference. This design helps to reduce chatter and improves chip evacuation. It is commonly used for roughing operations and machining large areas.

3. Shell End Mill Cutter: Shell end mills are similar to side and face cutters but have a larger diameter. They typically have a larger number of teeth and are

Fig 1.8 : Shell End Mill Cutter

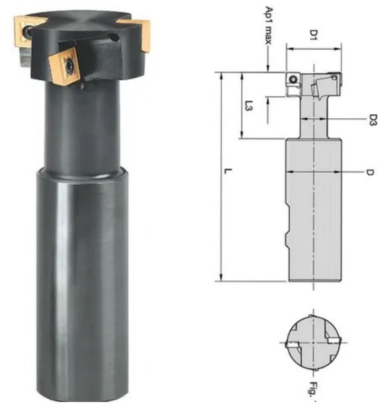

Fig 1.9 : T-Slot Cutter

Fig.1.10 : Woodruff Cutter

Fig.1.11 : Indexable Side and Face Cutter

used for heavy-duty milling operations, such as facing large surfaces or machining deep slots.

4. T-Slot Cutter: T-slot cutters are specialized side and face cutters used for machining T-shaped slots in workpieces. They have a straight cutting edge along

with a T-shaped slot on the face of the cutter, which matches the desired T-slot profile.

5. Woodruff Cutter: Woodruff cutters are specifically designed for machining Woodruff keyways, which are semicircular slots found in shafts. They have a cylindrical body with a half-circle cutting edge on the circumference.

6. Inserted Tooth Side and Face Cutter: Inserted tooth cutters consist of a cutter body with replaceable inserts. These inserts have the cutting edges and can be easily replaced when worn out. This type of cutter offers versatility and cost-effectiveness, as only the inserts need to be replaced.

7. Indexable Side and Face Cutter: Indexable cutters have multiple cutting edges on inserts that can be indexed or rotated when one edge becomes dull. This allows for continuous machining without the need for frequent tool changes.

1.2.5 Terminology of side and face cutter

When discussing side and face cutters, there are several important terminologies to understand:

1. Cutting Edges: Side and face cutters have cutting edges located on both the side and periphery of the cutter. These cutting edges come into contact with the workpiece to remove material during milling operations.

2. Teeth: The cutting edges of the side and face cutter are formed by individual teeth. These teeth are evenly spaced around the circumference of the cutter and can vary in number depending on the size and design of the cutter.

3. Flutes: Flutes are the helical or straight channels that run along the length of the cutter. They provide space for chip evacuation during the milling process. Side and face cutters can have multiple flutes, typically two or more.

4. Helix Angle: The helix angle refers to the angle between the cutting edge of a tooth and a plane perpendicular to the axis of the cutter. It affects the chip formation and evacuation, as well as the cutting forces during milling.

5. Diameter: The diameter of the side and face cutter refers to the size of the cutter across its widest point. It determines the maximum depth of cut and the size of the milling operation that can be performed.

6. Shank: The shank is the portion of the cutter that is inserted into the milling machine's tool holder or collet. It provides stability and ensures proper alignment of the cutter during operation.

7. Inserts: Some side and face cutters use inserts, which are replaceable cutting tips that are mounted onto the cutter body. These inserts can be easily replaced when they become worn or damaged, providing cost savings and convenience.

8. Rake Angle: The rake angle is the angle between the cutting edge and a reference plane perpendicular to the workpiece surface. It affects the cutting action, chip formation, and the forces acting on the cutter during milling.

Understanding these terminologies will help in selecting the appropriate side and face cutter for specific milling applications and optimizing the milling process.

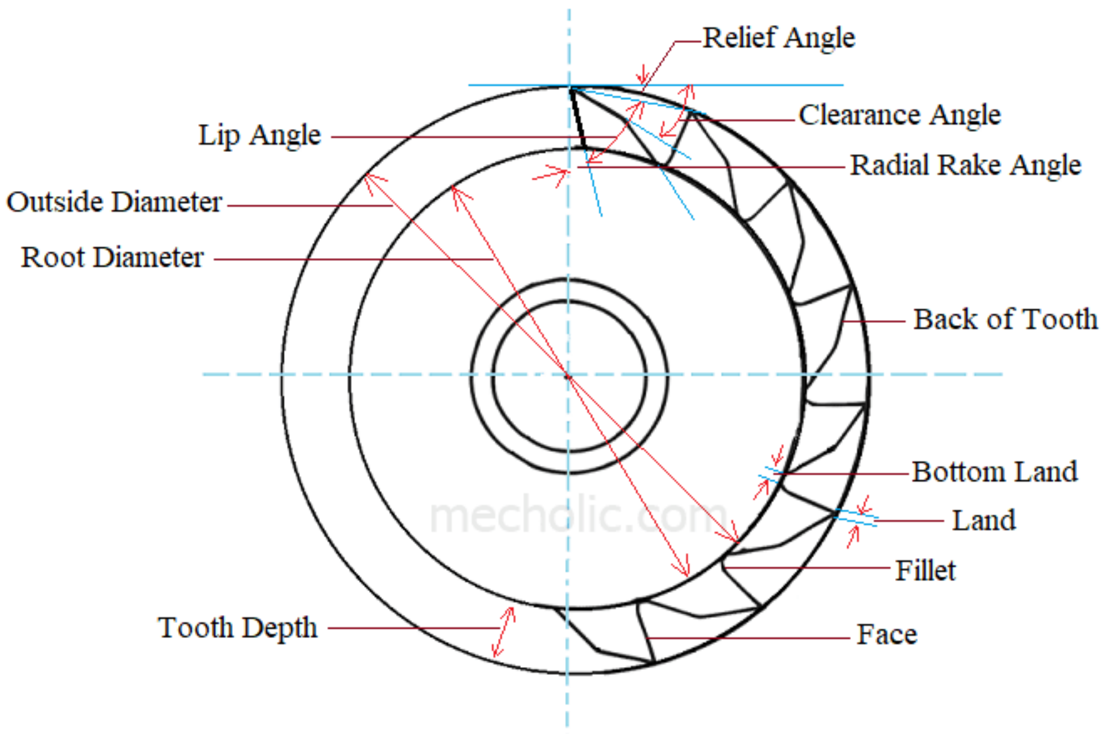

Figure 1.12 : geometry of side and face cutter [8]

Face milling in Metal Matrix Composites (MMC) has received relatively less research attention compared to other milling methods. MMCs, which consist of a metal matrix reinforced with ceramic particles, present unique challenges during machining due to their heterogeneous nature. Face milling, a technique where the cutting edges are located on the face of the milling cutter, holds promise for efficient material removal and surface finishing in MMCs. However, the limited research conducted in this area indicates a lack of understanding regarding the effects of face milling parameters, tool selection, and tool wear in MMCs. It is crucial for future research to focus on optimizing cutting parameters, exploring appropriate cutting tool materials and coatings, and investigating the specific mechanisms of tool wear and chip formation in face milling of MMCs. By addressing these research gaps, the knowledge and understanding of face milling in MMCs can be expanded, leading to the development of improved machining strategies and enhanced performance of MMC components across various industries.

1.2.6 Specific terms in milling process

Cutting Speed (V_c): The cutting speed refers to the velocity at which the cutting edge of the tool interacts with the workpiece surface. It is determined by the rotational speed of the spindle and the size of the cutting tool. A higher cutting speed means that the tool is moving faster across the workpiece.

It is calculated using the formula

$$V_c = (\pi * Dc * n)/1000 \text{ (m/min)}$$

Where, Dc is the cutting diameter at the cutting depth and

n is the spindle speed, both in RPM.

Feed (v_f): The feed rate represents how fast the cutting tool moves relative to the workpiece during machining. It is determined by the feed per tooth (f_z) and the number of effective teeth in the cutter. The feed rate determines how much material is removed per unit of time.It also refers to the rate at which the tool moves in relation to the workpiece. It is calculated as the feed per tooth (f_z) divided by the number of effective teeth in the cutter.

The formula is :

$$V_f = (f_z * n) / Z,$$

where, f_z is the feed per tooth,

n is the spindle speed and

Z is the number of effective teeth.

Depth of Cut: The depth of cut is the measurement of how deeply the cutting tool penetrates into the workpiece surface during a machining operation. It determines the thickness of the material that is removed with each pass of the tool.

Radial Depth of Cut: It refers to the depth of the tool in the workpiece along its radius as it performs a cut. If the radial depth of cut is smaller than the radius of the tool, the tool is only partially engaged, resulting in a peripheral cut. When the radial depth of cut equals the diameter of the tool, the cutting tool is fully engaged and making a slot.

The radial depth of cut refers to the distance between the center of the cutting tool and the surface of the workpiece along its radius. It indicates how deeply the tool engages with the workpiece. A smaller radial depth of cut means that only a portion of the tool's cutting edge is in contact with the workpiece, while a larger radial depth of cut means that the entire cutting edge is engaged.

Importance of milling machining

Milling machining is of significant importance in various industries and manufacturing processes due to several key reasons:

1. Versatility: Milling is a highly versatile machining method that can produce a wide range of complex shapes and features. It allows for the creation of flat, curved, angled, and contoured surfaces, as well as slots, holes, threads, and intricate patterns. This versatility makes milling suitable for diverse applications across different industries.

2. Precision and Accuracy: Milling machines are capable of achieving high levels of precision and accuracy in the machining process. The use of advanced CNC (Computer Numerical Control) technology enables precise control over cutting movements, feed rates, and tool positioning. This results in the production of components with tight tolerances, ensuring proper fit and functionality.

3. Efficiency and Productivity: Milling is a highly efficient machining method. Modern milling machines can remove material quickly and effectively, leading to improved productivity. Multiple cutting edges on the milling cutter allow for simultaneous cutting, reducing the overall machining time. Additionally, the use of CNC automation and programming optimizes workflow and minimizes manual labor.

4. Wide Range of Materials: Milling can be performed on a variety of materials, including metals, plastics, composites, and wood. This versatility allows for the production of components for different industries, such as automotive, aerospace, electronics, and construction. Milling can handle both soft and hard materials, making it suitable for diverse manufacturing needs.

5. Cost-Effectiveness: Despite the initial investment in milling equipment, the cost-effectiveness of the process is evident in high-volume production and repeatable tasks. Once the milling machine is set up and programmed, it can perform repetitive operations with consistent results, reducing labor costs and increasing overall efficiency.

6. Customization and Prototyping: Milling enables the production of customized components and prototypes. It allows manufacturers to create unique designs, iterate quickly, and validate product concepts before mass production. This flexibility and ability to make modifications easily contribute to accelerated product development cycles.

Milling machining plays a vital role in modern manufacturing due to its versatility, precision, efficiency, material compatibility, and cost-effectiveness. It enables the production of complex components with high accuracy, meeting the diverse needs of industries ranging from automotive and aerospace to electronics and beyond.

1.3 Measurement of Responses

1.3.1 Cutting Force

When performing milling machining, it is essential to understand the forces involved in the cutting process and their effects. These forces play a crucial role in determining the efficiency, accuracy, and overall success of the milling operation. Let's delve deeper into the different forces and their implications:

1. Cutting Force: The cutting force is a reaction force that occurs when a cutting tool interacts with the workpiece. It is generated as the tool cuts through the material, removing chips and shaping the workpiece. The magnitude and direction of the cutting force vary depending on several factors, including the cutting conditions such as cutting speed, feed rate, and depth of cut. The cutting force has significant implications for the machining process. It affects tool life and wear, as excessive cutting forces can accelerate tool deterioration. Additionally, the cutting force influences the power required for the cutting operation. Understanding and managing the cutting force is crucial for optimizing tool life, reducing energy consumption, and achieving desired machining results.

2. Feed Force: The feed force is a horizontal force component that acts in the direction of the feed motion. It determines the magnitude of the power required to advance the cutting tool through the workpiece material. The feed force is essential for determining the feed power needed for efficient material removal. Controlling the feed force is crucial for achieving consistent chip formation and preventing issues such as tool breakage, surface finish problems, or excessive power consumption. Optimal control of the feed force ensures efficient material removal while maintaining stability and accuracy during the milling process.

3. Thrust Force: The thrust force is an axial force component that acts along the axis of the cutting tool. It is responsible for deforming both the workpiece and the cutting tool. The magnitude of the thrust force depends on various factors, including the cutting conditions, tool geometry, and workpiece material properties. Excessive thrust force can have detrimental effects on the milling process. It can lead to deflection or vibration, compromising dimensional accuracy and surface finish. Managing the thrust force is critical for maintaining stability, preventing tool deflection, and ensuring the desired machining accuracy.

4. Power Requirements: The power requirements for milling operations are directly influenced by the magnitude of the cutting force. Calculating and understanding the cutting force allows for the estimation of the power needed for the milling machine to perform the cutting operation effectively. Proper power estimation helps in selecting suitable milling machines, tools, and determining appropriate cutting parameters.

By monitoring and optimizing these forces during milling operations, machinists can enhance productivity, prolong tool life, improve dimensional accuracy, and achieve desired surface finish. Adjusting cutting parameters and techniques to control the cutting, feed, and thrust forces enables efficient material removal and ensures the desired machining outcomes.

1.3.2 Surface Roughness

Surface roughness is a measure of the irregularities or deviations on the surface of a material. It is specified using various parameters, including Ra (arithmetical mean roughness), Ry (maximum height), and Rz (ten-point mean roughness).[9]

1. **Arithmetical Mean Roughness (Ra)**: Ra is the average of the absolute values of the surface deviations from the mean line within a sampling length. It provides a measure of the average roughness over the entire surface. Ra is commonly used as a general indicator of surface roughness.

- A standard length section is taken from the mean line on the roughness chart, depicted in Figure 1.18. The mean line is positioned on a Cartesian coordinate system, where it aligns with the x-axis representing the direction, while the y-axis represents the magnification. The value obtained using the formula below is expressed in micrometers (µm) when y is equal to f(x).

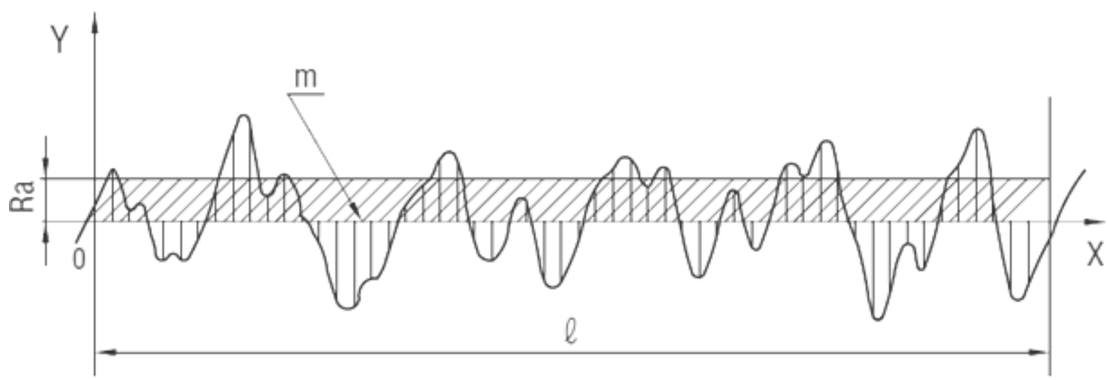

Figure 1.13 : Arithmetical Mean Roughness (Ra) [9].

$$R_a = \int_0^L |f(x)|dx$$

2. **Maximum Height (R_y)**: R_y represents the maximum height of surface irregularities within the sampled length. It measures the largest deviation from the mean line on the surface. Ry is useful in applications where the presence of isolated peaks or valleys on the surface is critical.

- A standard length section is sampled from the mean line on the roughness chart. In Figure 1.19, the distance between the peaks is measured as R_p, and the distance between the valleys is measured as R_v in the y-direction. Both R_p and R_v are expressed in micrometers (μm).

$$R_y = R_p + R_v$$

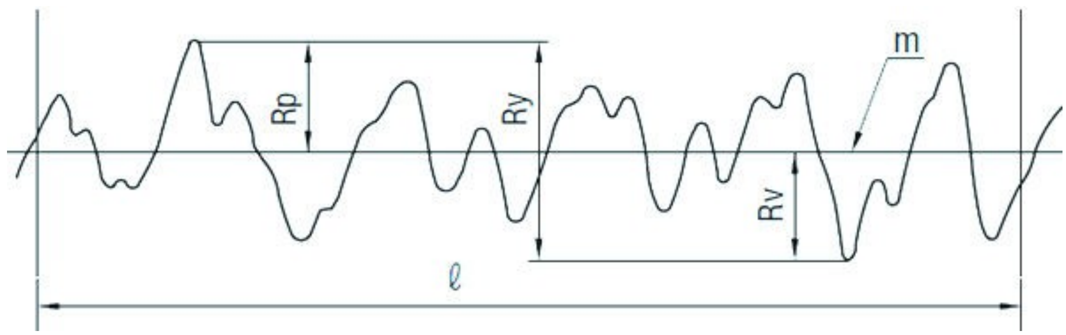

Figure 1.14 : Maximum height roughness [9].

3. **Ten Point Mean Roughness (R_z)**: R_z is calculated by averaging the difference between the heights of the five highest peaks and the five lowest valleys within the sampling length. It provides a measure of the mean roughness of the extreme irregularities on the surface. R_z is particularly useful when evaluating surfaces that may have a few prominent peaks or deep valleys.

- A section of standard length is sampled from the mean line on the roughness chart. The distances between the peaks and valleys of the sampled line in the y-direction are measured, as shown in Figure 1.20. Then, the average peak is obtained by calculating the average value among the five tallest peaks (YP1, YP2, YP3, YP4, YP5). Similarly, the average valley is obtained by calculating the average value among the five lowest valleys (YV1, YV2, YV3, YV4, YV5). The sum of these two values is expressed in micrometers (µm) using the following equation:

$$R_z = \frac{|Y_{P1}+Y_{P2}+Y_{P3}+Y_{P4}+Y_{P5}|+|Y_{V1}+Y_{V2}+Y_{V3}+Y_{V4}+Y_{V5}|}{5}$$

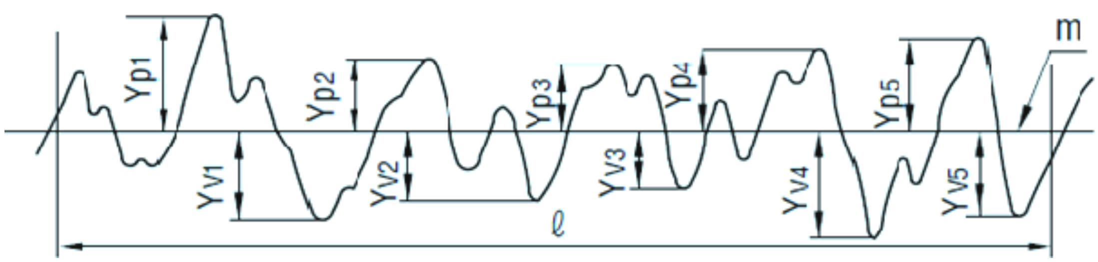

Figure : 1.15 Ten-Point Mean Roughness (R_z) [9]

To determine surface roughness, various techniques and instruments are employed, including:

- Profilometer : These instruments use a stylus or a non-contact method to measure the vertical deviations of the surface profile. They provide detailed information on the surface roughness parameters.
- Surface Roughness Comparators: These are visual or tactile reference standards with known roughness values. They are used to visually or manually compare the roughness of a surface.
- Optical Profilometer : This method uses optical interference or focus variation techniques to measure surface roughness non-destructively. It provides high-resolution 3D surface topography data.

- Atomic Force Microscopy (AFM): AFM utilizes a sharp tip to scan the surface, providing nanoscale resolution and detailed information about surface roughness and topography.

The choice of technique depends on the required accuracy, surface finish characteristics, and the nature of the material being measured.

CHAPTER 2

LITERATURE REVIEW

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2.1 INTRODUCTION

Among the various milling methods available, such as end milling and face milling, the majority of research studies on machining SiCp/Al composites have primarily concentrated on end milling. This indicates that end milling has received the most attention and investigation in the literature when it comes to machining SiCp/Al composites.

End milling involves the use of a cylindrical cutting tool with multiple cutting edges, while face milling utilizes a milling cutter with cutting edges on its face. In the case of SiCp/Al composite machining, researchers have predominantly directed their efforts towards studying the effects of end milling. The focus of these investigations is to understand the impact of various factors, such as cutting parameters, tool wear, surface quality, and cutting conditions, on the machining of SiCp/Al composites using the end milling technique. By concentrating on end milling, researchers aim to optimize the selection of cutting tools and parameters to improve the efficiency, accuracy, and surface finish of the machined SiCp/Al composites. They also aim to gain insights into the mechanisms of tool wear, chip formation, cutting forces, and overall machining performance. While face milling is another milling method that can be used for machining SiCp/Al composites, the existing literature places greater emphasis on end milling. Studies specifically dedicated to face milling in the context of SiCp/Al composite machining are relatively limited compared to end milling.

2.2 Literature review on tool wear

Milling of SiCp/Al composites can be carried out using a range of cutting tools, including uncoated cemented carbide inserts, tools with nano TiAlN coatings, and carbide-coated cutting tools.

The research conducted by Bian et al. [11] was focused on the precise milling of SiCp/Al composites with a higher volume fraction of approximately 65%. These composites were manufactured using the pressure-less infiltration fabrication technology. The milling process was involved with the use of a single flute monocrystalline diamond end mill. The researchers investigated the impact of various input parameters such as spindle speed, feed per tooth, and depth of cut on the quality of the machined surface, surface topography, surface roughness, cutting mechanisms of SiC particles, and tool wear characteristics. They employed scanning electron microscopy (SEM) to analyze the results.

During the precision milling, the researchers were able to achieve a highly polished surface finish with a surface roughness of around R_a 0.1 μm. They observed that increasing the depth of cut led to an increase in surface roughness. However, they also noted the presence of some cracks on the machined surface. These cracks were attributed to the ductile cutting of SiC reinforcements, resulting in partial microfractures. The SEM images revealed that the tool wear predominantly manifested as flank wear on the bottom face of the tool. Additionally, chipping and cleavage were observed on the monocrystalline diamond edge of the tool.

The study conducted by Benjamin et al. [12] examined the side milling of an aluminum alloy matrix reinforced with 10% volume fraction of SiC particles. The composite material was fabricated using a powder metallurgical method. The researchers used a double-edged chemical vapor deposition (CVD) diamond-tipped tool with a diameter of 3mm for the milling tests. The main focus of the research was to investigate the surface characteristics, including roughness and imperfections, as well as residual stress. Additionally, the influence of cutting parameters such as cutting speed and feed rate was analyzed.

To evaluate the surface roughness and imperfections, advanced imaging techniques such as 3D laser scanning microscopy and scanning electron microscopy (SEM) were employed. The results indicate that changes in cutting speed had minimal impact on the depth of surface roughness. However, increasing the cutting speed led to reduced void formation on the machined surface and higher absolute values of compressive residual stresses.

Study go through into the side milling of an aluminum alloy matrix reinforced with SiC particles. The use of a CVD diamond-tipped tool allows for an investigation of the surface characteristics and residual stress. The research findings suggest that while cutting speed variations have limited influence on surface roughness, they do affect void formation and residual stress levels. This study enhances our understanding of the machining behavior and surface properties of SiC-reinforced aluminum alloy composites.

In the research conducted by Shen et al. [13], it was observed that the uncoated WC-Co milling tool experienced the most significant wear on its circumferential cutting edge when milling of SiCp/Al composites were performed. In comparison, the diamond-like carbon (DLC)-coated milling tool exhibited slightly lower wear. However, the milling tool coated with chemical vapor deposition (CVD) diamond demonstrated remarkably superior wear resistance. At the end of the milling tests, the wear on the circumferential cutting edge of the CVD diamond-coated tool was less than 0.07 mm, which was only half of the wear observed in the DLC-coated tool. These findings highlight the importance of tool coating selection for achieving enhanced wear resistance and prolonged tool life in the milling of SiCp/Al composites.

Huang et al. [14] conducted high-speed milling experiments on SiCp/Al composites with a higher volume fraction (56%) and larger particles. Polycrystalline diamond (PCD) tools were used under both dry and wet machining conditions. The aim of the research was to analyze the effects of cutting speed, feed rate, and depth of cut on the machining process. The results showed that the primary form of tool wear observed during milling was abrasion on the flank face of the tools. Furthermore, it was found that the TiC-based cermet tool was not suitable for machining SiCp/Al composites with higher volume fractions and larger particles due to the intense abrasive nature of the reinforcement material. These findings underscore the importance of carefully selecting appropriate tool materials when machining SiCp/Al composites with different particle sizes and volume fractions, in order to optimize machining performance and extend tool life.

Shutao et al. [15] conducted a study focusing on the use of polycrystalline diamond (PCD) tools in high-speed milling of SiCp/Al composites with a higher volume fraction (65%) and larger SiC particle sizes. Their research was aimed to explore the wear resistance and wear mechanisms of PCD tools with varying diamond particle sizes (5, 10, 25, and 32 μm). The cutting conditions employed were a cutting speed of 352 m/min and a feed rate of 0.02 mm.

The results revealed an interesting relationship between diamond particle size and tool performance. It was observed that as the diamond particle size increased, the wear resistance of the PCD tools diminished. This was evidenced by increased flank wear and slight deepening of micro-chipping on the cutting edge. Notably, when PCD tools with a 5 μm particle size were used, both the cutting force and surface roughness were reduced. Moreover, throughout the cutting process, the machined surface roughness remained relatively stable, indicating that tool wear had minimal impact on surface roughness.

These findings emphasize the significance of diamond particle size in determining the wear resistance and overall effectiveness of PCD tools during SiCp/Al composite milling. Smaller diamond particles exhibited superior wear resistance and resulted in lower cutting forces and improved surface roughness. Understanding the relationship between tool parameters and machining performance enables the optimization of tool selection and enhances the quality of machined surfaces in SiCp/Al composite milling applications.

Wang et al. [16] investigated the performance of cutting tools in dry high-speed milling of SiCp/Al composites with a volume fraction of 45%. Two types of tools were used: CVD diamond coated tools and PCD tools. The focus of the study was on analyzing the wear patterns exhibited by the tools.

The results indicated that the wear pattern observed in PCD tools was predominantly flank wear, which was caused by the abrasion of SiC particles. This wear phenomenon was more prominent at relatively low cutting speeds. It is worth noting that graphitization, a potential wear mechanism for PCD tools, did not occur due to the low cutting temperatures experienced during the milling process.

Overall, the wear mechanism observed in PCD tools was primarily characterized by abrasive and adhesive wear. These findings provide valuable insights into the tool wear behavior during dry high-speed milling of SiCp/Al composites and can aid in optimizing tool selection, improving tool life, and enhancing the overall machining process.

In their research, Huang and Zhou [17] investigated the suitability of three different cutting tools, namely the TiN-coated tool, cermet tool, and cemented carbide tool, for machining silicon carbide particle reinforced aluminum matrix composites (SiCp/Al) with a volume fraction of 56%. The experiments were conducted at two different milling speeds: a higher speed of 314 m/min and a lower speed.

The main focus of the study was to analyze the wear behavior of these tools during the machining process. It was observed that flank wear, which occurs on the side of the tool, was the predominant mode of wear for all three types of tools. Interestingly, the wear resistance was found to be similar among the TiN-coated tool, cermet tool, and cemented carbide tool, indicating that they performed comparably in terms of wear resistance. The study revealed that as the milling speed increased, the tool wear also increased. However, the feed rate and depth of cut had a relatively minor impact on the tool wear.

These findings contribute to our understanding of the performance of different cutting tools when machining SiCp/Al composites. They provide valuable insights into the selection of appropriate tools and the optimization of machining parameters to improve the efficiency and effectiveness of the milling process.

Ge et al. [18] investigated the high-speed milling performance of SiCp/2009Al composites using PCD tools at cutting speeds ranging from 600 to 1,200 m/min. They observed that the tool life of PCD tools, defined by a 0.1 mm tool wear criterion, ranged from 25 to 240 minutes. The main causes of tool wear were grain breaking-off, chipping, abrasive wear, micro cracks, and adhesive wear, which resulted from the impact, vibration, and interaction with SiC particles. The cutting force (F_y) varied from 700 to 2,550 N, and the cutting temperature ranged from 240 to 580 degrees Celsius. When the tool flank wear was below 0.09 mm, the achieved surface roughness values were Ra of 0.207-0.542 μm and R_z of 2.02-5.2 μm. The machined surfaces exhibited defects such as pits, voids, grooves, protuberances, and irregularities in the matrix. The depth of the deformation layers was limited to 20-35 μm, and the chip morphology displayed either a semi-flow or saw-toothed pattern.

Ben et al. [19] performed the machining of metal matrix composites containing ceramic particles. It was observed that the wear of cutting tools significantly affected the quality and cost of the produced parts. This research was focused on studying the behavior of tool wear and surface quality during micro milling of 45 vol % SiCp/Al composites under different lubrication conditions : dry and minimum quantity lubrication (MQL). Analysis using scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) revealed that the wear mechanism of diamond-coated micro mills involves adhesive wear, abrasion, oxidation, chipping, and tipping. This was contrast with previous reports that primarily emphasized abrasion as the dominant wear mechanism for machining similar composites. Comparing the two lubrication methods, it was observed that the environmentally friendly MQL technique improved tool life, surface roughness, and significantly reduces cutting forces under the given cutting parameters. Additionally, finite element simulations were utilized to examine the chip formation process during micro orthogonal cutting, providing insights into the impact of reinforced particles on tool wear and surface quality. The simulations indicated that localized high stress, hard reinforced particles within the metal matrix, as well as deboned and cracked particles, played a crucial role in causing severe tool wear and producing an uneven surface morphology.

R. Karthikeyan et al. [20] investigated the face milling characteristics of LM25 A1-SiC particulate composites produced through stir casting. A series of experiments were conducted using an L27 orthogonal array, and mathematical models were developed to analyze the effects of machining on flank wear, specific energy, and surface roughness. The models were evaluated for their accuracy and any insignificant factors were eliminated through a t-test. Additionally, goal programming was applied to optimize the cutting conditions by simultaneously considering multiple objectives such as maximizing metal removal rate and minimizing tool wear, specific energy consumption, and surface roughness.

Ergün et al [21] were focused on the milling process of metal matrix composites created through hot pressing, using a CNC milling machine. The objective was to examine how cutting parameters and different coating types affect the resulting surface roughness. The composites were fabricated through hot pressing, combining aluminum as the matrix material and 10% SiC particles as the reinforcement. During the machining of the composite samples, three types of cutting tools (uncoated, multi-layered, and Nano TiAlN coated) were employed, along with three different cutting speeds (60, 78, and 101 m/min) and three feed rates (0.04, 0.08, and 0.12 mm/rev). To analyze the effects of these cutting parameters and their interactions. The obtained surface roughness data from the experiments were used to develop mathematical models using the response surface method, allowing for optimization of the cutting parameters. The study also included an evaluation of the wear on the cutting tools, and a comparison was made with previous research to gain insights and discuss the observed wear patterns.

2.3 Review on cutting Force

In the literature review on cutting force in metal matrix composites (MMC), several studies have been conducted to investigate the effects of various factors on the cutting forces experienced during machining operations. The cutting force is a crucial parameter that directly impacts the tool life, surface quality, and overall machining performance of MMCs. Researchers have examined factors such as cutting parameters (cutting speed, feed rate, and depth of cut), tool geometry, tool material, reinforcement type and content, and workpiece material properties to understand their influence on cutting forces.

In different milling investigations, the cutting force and its impact factors are often variable; nonetheless, SiC particles and the machining parameters are crucial.

Jayakumar et al. [22] did research on A356 aluminum alloy powder which was reinforced with 10% volume of SiC particles with varying sizes (1 µm, 12.5 µm, and 25 µm). The composites were synthesized using a vacuum hot pressing method, and their mechanical properties and machinability were analyzed. End milling operations were conducted on these composites, and the surface roughness and cutting forces were measured while varying the machining parameters and SiC particle sizes. The results indicated that the composite reinforced with finer particles (1 μm) exhibited lower cutting forces and surface roughness when higher cutting speeds, lower feed rates, and shallower depths of cut were applied. These findings highlight the importance of considering the particle size and machining parameters for optimizing the machinability of composites in milling processes.

Machinability of these composites was investigated using computer numerical control end milling, with cutting speed, feed, and depth of cut as variable parameters. The study measured cutting forces and tool-work interface temperature to analyze the effects of machining parameters and reinforcement on the matrix. The findings provide valuable insights and optimization guidelines for manufacturing industries. Response surface models were developed and compared to experimental results, showing that higher volume percentages of SiCp reinforcement result in increased tool-work interface temperature and require higher cutting forces during the machining process [23].

Vallavi et al. [24] studied the cutting force characteristics of LM6/SiCp composites using the end milling process. The objective was to develop mathematical models that can accurately predict the cutting force based on key parameters such as spindle speed, axial depth of cut, and weight percentage of SiC_p. To achieve this, response surface methodology was employed to create the mathematical models. Experimental tests were conducted on LM6/SiCp composites using a carbide insert, and cutting forces are measured using a milling tool dynamometer. The study examined the individual and combined effects of the machining parameters on the cutting force. Analysis of variance (ANOVA) is utilized to assess the validity and adequacy of the developed models. Ultimately, the research aimed to determine the optimal combination of machining parameters that will result in the most favorable cutting force outcomes.

In the study conducted by Huang et al. [25], it was observed that the milling forces exhibited certain trends in response to variations in the milling parameters. Specifically, an increase in the milling speed was found to correspond to a decrease in the milling forces. Conversely, the milling forces increased as the feed rate and depth of milling were increased. Among the various milling parameters, the milling depth had the most significant influence on the milling forces in the x and y directions, while the feed rate had the greatest impact on the milling forces in the z direction. These findings highlight the importance of carefully selecting and optimizing the milling parameters to achieve desired force levels during the milling process.

Babu et al. [26] observed that the cutting force components were particularly affected by high-speed cutting and full immersion conditions. They found that the cutting force exhibited additional fluctuations due to the unstable chip formation of the composite material and the presence of randomly distributed reinforcement particles. This indicated that the machining process of composites involves complex interactions between the cutting tool, workpiece material, and reinforcement particles, leading to variations in the cutting forces experienced during the operation.

In the report of Ge et al. [27] experimental tests were conducted to study the cutting forces during high-speed milling of SiCp/2009Al composites using PCD tools. The cutting speed ranged from 600 to 1200 m/min. The results showed that the maximum cutting force in the radial direction (Fy) varied between 700 N and 1450 N under the given cutting conditions. Notably, significant vibrations were observed with a maximum amplitude of 700 N in the radial direction of the tool. The cutting forces increased with higher feed rates and radial depths of cut, while they decreased with increasing cutting speeds. It was recommended to use a negative rake angle and a relatively large tool nose radius to minimize cutting forces. Moreover, composites with higher volume fractions or smaller reinforcement particle sizes exhibited higher cutting forces. T6 heat treatment significantly increased the cutting forces, while the use of coolant noticeably reduced them.

Shutao et al. [28] conducted experiment on SiCp/Al composites that is subjected to high-speed milling using polycrystalline diamond (PCD) tools with varying diamond grain sizes. The composites had a volume fraction of 45% and SiC particles with a size of 5 μm. The study aimed to assess the tool wear resistance, cutting forces, and surface roughness. The findings revealed that when machining composites with a volume fraction of 45% and smaller SiC particles (5 μm), the PCD tools exhibited significantly higher wear resistance compared to machining composites with a higher volume fraction (56%) and larger SiC particles (60 μm). PCD tools with larger diamond grain sizes demonstrated superior wear resistance, resulting in lower cutting forces and improved surface roughness. The cutting forces exhibited a consistent trend with tool wear as the cutting distance increased. The machined surface roughness generally decreased, albeit with minimal fluctuations. The predominant wear modes observed were flank wear and slight wear groove marks, while chipping and coarse wear groove marks were absent. Adhesion of machined material on the tool face was observed, but no built-up edge formation occurred.. The cutting forces and torque of PCD tools of larger diamond grain sizes are less than those of smaller diamond grain sizes.

2.4 Review on Surface integrity, machining efficiency, and optimization

Huang et al. [29] did the experiment on Silicon carbide-reinforced aluminum matrix (SiCp/Al) composites with high volume fractions conducted ultrasonic vibration-assisted scratch (UVAS) tests and conventional scratch (CS) tests using a rotary ultrasonic machine. By analyzing the influence of ultrasonic vibration on the machining process, they were able to evaluate the morphologies of the scratching surfaces, scratching forces, and material removal process in detail. The results, both theoretical and experimental, indicated that ultrasonic vibration altered the interaction between the cutting tool and the workpiece. The vibration enhanced the removal of SiC reinforcements by increasing the occurrence of cracks within them, while simultaneously improving the performance of the aluminum matrix. Consequently, the scratching forces in UVAS were smaller and more stable compared to CS. The coefficient of friction (COF) was also reduced, decreasing the adhesion effect of the aluminum matrix during the scratching process. This study highlights the significance of the removal mode of SiC reinforcements in determining the quality of the machined surface. The findings provide valuable insights for selecting appropriate processing parameters to achieve improved machining outcomes for SiCp/Al composites.

Sheng et al. [30] were focused on the machinability of SiCp reinforced aluminum metal matrix composites (MMCs) which gained significant industrial applications. The experimental investigation involved end milling of a composite containing 14 wt. % SiCp using CVD coated carbide tools, with varying cutting parameters. The study examined the relationships between cutting force, surface roughness, cutting speed, and feed. In addition, the study utilizes scanning electron microscopy (SEM) to examine surface defects including ploughed furrows, pits, and matrix tearing. The experimental results provide valuable insights into the machinability of SiCp reinforced aluminum MMCs and shed light on the surface topography defects that may arise during the machining process.

N. Suresh et al. [31] investigated the machinability of Al/SiC particulate metal-matrix composites (PMMCs) through end milling. The focus was on surface integrity and comparing the machinability of Al/SiC PMMC with Al alloy. The experimental results show that the presence of reinforcement enhances machinability, resulting in improved surface roughness and reduced tool clogging. The findings contribute to a better understanding of the end milling process and provide insights for better machining of Al/SiC PMMC. This has potential benefits for industrial applications by replacing Al alloys, leading to technological and economic gains.

G.F. Zhang et al. [32] were aimed to investigate the effect of SiC particle reinforcement on the machining of Aluminum/SiC composite. Experimental milling was conducted on the composite and pure aluminum using a tungsten carbide end mill. Surface observations and roughness measurements revealed that the composite has optimum machining parameters and achieves a smoother surface finish compared to pure aluminum. However, increasing the depth of cut and feed rate beyond certain limits led to the initiation of micro cracks at the SiC-Al interface and periodic formation of macro cracks on the machined surface. The damage mechanism during the machining process is discussed in detail in this paper.

Junwei et al. [33] were focused on improving the surface quality in micro-milling of SiCp/Al composites. The presence of brittle SiC particles and the size effect of the matrix can cause surface defects during the machining process. To address this, a method was proposed that involves achieving ductile regime machining of the particles and diverting away the defects in both the particles and matrix. Cutting parameters are selected based on this method to improve surface quality. The suitable range of feed per tooth for side milling and end milling is determined and validated through micro-experiments. The results demonstrate that the size effect of the matrix and the removal of SiC particles both affect the machined surface. By using the appropriate feed per tooth, the weak size effect of the matrix can be minimized, and the majority of the particles can be removed in the ductile regime, resulting in the best surface quality. Furthermore, this method has a more pronounced effect in end milling compared to side milling.

M. Chandrasekaran et al. [34] performed the end milling of Al-SiCp metal matrix composite components using a carbide end mill cutter. A fuzzy logic-based surface roughness prediction model is developed, taking into account spindle speed, feed rate, depth of cut, and SiCp percentage as input parameters. The model predicts surface roughness, which is then compared with experimental results. The analysis reveals that feed rate, spindle speed, and SiCp percentage have the most significant influence on surface roughness, while depth of cut has the least influence. This model provides a useful tool for optimizing machining parameters and achieving the desired surface roughness in metal matrix composite machining processes.

K. Shekhar et al. [35] performed an experimental investigation on the machinability of silicon carbide particulate metal matrix composites during milling, using multilayered coated carbide tools. The study focuses on the influence of machining parameters such as cutting speed, feed rate, and depth of cut on flank wear and surface finish. The microstructure of the machined surfaces, chip formation, and built-up edge (BUE) were examined using scanning electron microscopy (SEM). By analyzing the test results and SEM images, a suitable range of cutting conditions can be determined for effective machining of Al/SiCp MMC. This research provides valuable insights into optimizing the machining process for metal matrix composites.

Tao WANG et al. [36] wee focused on the surface roughness generated during high-speed milling of silicon carbide particle-reinforced aluminum matrix composites (SiCp/Al) with a high volume fraction (65%). The study examined different surface roughness parameters, including both 2D (Ra and Rz) and 3D (Sa and Sq), to evaluate the impact of milling parameters on surface quality compared to aluminum alloy. Additionally, the 3D topography of the milled surface is analyzed. The results show that the 3D parameters (Sa and Sq) are more effective in describing the influence of milling parameters on surface quality, with Sq being the preferred parameter due to its high sensitivity. Sq decreases with increasing milling speed and increases with higher feed rates. The study also finds that the axial depth of cut has a negligible influence on surface roughness.

R. Ghoreishi et al. [37] researched on investigating the influence of high-speed cutting parameters on the surface roughness and cutting forces of machined AL/SiC composite, a type of Metal Matrix Composite (MMC). The cutting parameters include cutting speed up to 2500 m/min and the use of CO2 cryogenic coolant. The AL/SiC MMC used in the study contains 15% silicon carbide. A design of experiment method utilizing a 5-level central composite design was employed. The results indicate that the use of CO2 cryogenic coolant leads to a 3-8% increase in cutting forces, but improves the surface roughness by 19-23%. Optimal surface roughness is achieved when the cutting speed exceeds 1800 m/min, the feed rate is lower than the particle size per tooth, and the depth of cut ranges between 1 to 1.1 mm.

Shutao et al. [38] investigated the effects of volume fraction of SiC particles on tool wear, cutting force, and surface roughness during high-speed milling of silicon carbide particle-reinforced aluminum matrix (SiCp/Al) composites. A single-tooth milling cutter with a diamond grain size of 5 μm was used. The volume fractions of SiC particles ranged from 15% to 56%. The results showed that the volume fraction had little effect on tool wear morphology but had a significant impact on wear amount and rate. Lower volume fractions resulted in smaller and slower tool wear, while higher volume fractions led to a significant increase in wear with cutting distance. The measured cutting force varied with the volume fraction, with a more pronounced influence observed as cutting distance increased. The initial cutting stage showed larger and fluctuating surface roughness, which gradually decreased and stabilized as the cutting distance increased. Overall, higher volume fractions of SiC particles resulted in larger surface roughness.

Wang et al. [39] performed an experimental investigation on the high-speed milling of particle-reinforced aluminum matrix composites (PRAMCs) using polycrystalline diamond tools (PCD). The focus is on understanding the influence of cutting parameters on surface roughness, surface residual stress, and morphology of the PRAMCs, specifically Al/SiC/65p with a 65% volume fraction. The experiments also compare the surface integrity of the PRAMCs with that of the unreinforced matrix alloy Al 6063. The results reveal that milling speed is the most significant parameter affecting surface roughness, followed by the interaction between feed rate and milling speed, and then the feed rate alone. Axial depth of cut has the highest influence on surface residual stress, followed by milling speed and feed rate. Decreasing the feed rate slightly improves surface roughness, while the effect of milling speed is negligible. Surface residual stress measurements using X-ray diffraction show that the machined Al6063 surface exhibits tensile stress conditions, while the Al/SiC/65p composite surfaces have compressive stress conditions.

The study of Arokiadass et al. [40] was focused on modeling the machinability evaluation of LM25Al/SiCp metal matrix composites (MMCs) using the response surface methodology. The LM25Al/SiCp MMCs were manufactured through the stir cast route. The study investigated the combined effects of four machining parameters: spindle speed (N), feed rate (f), depth of cut (d), and the weight percentage of SiCp, on the performance characteristic of flank wear . Contour plots were generated to analyze the influence of the process parameters and their interactions on the machinability of the MMCs.

S. Jeyakumar et al [41] analyzed the machinability of aluminum (Al6061) silicon carbide particulate (SiCp) metal matrix composite (MMC) during the end milling process. The material's hardness and wear resistance, attributed to the abrasive nature of the reinforcement element, make it challenging to machine. The influence of spindle speed, feed rate, depth of cut, and nose radius on cutting force is investigated.

The study also examines the impact of machining length on tool wear and the relationship between machining parameters and surface finish using a prediction model based on the response surface methodology (RSM). The prediction model was used to determine the combined effect of machining parameters on cutting force, tool wear, and surface roughness. The model's results were compared with experimental data and found to be in good agreement. The prediction model aids in selecting process parameters to minimize cutting force, tool wear, and surface roughness, thereby ensuring high-quality milling processes.

Vamsi et al [42] developed a mathematical models for cutting force (FR), Metal Removal Rate (MRR), and surface roughness (Ra) in order to optimize them. The Response Surface Methodology (RSM) with L31 empirical model was used to conduct trials on Al/SiC composites with different compositions. Various techniques such as XRD, EDS, and optical microscopy were employed to analyze the Al/SiC composites, and the SEM morphology of the machined samples was studied. The developed models for predicting the responses were validated using analysis of variance (ANOVA) to assess their adequacy. The optimal machining configuration was identified, resulting in a MRR reduction of 0.5%, a surface roughness improvement of 14%, and a cutting force reduction of 4% compared to the experimental results.

Rajeshwari et al. [43] focused on determining the optimal combination of geometrical parameters (helix angle, nose radius, rake angle) and machining parameters (cutting speed, feed rate, depth of cut) to minimize surface roughness and tool wear during end milling of Al 356/SiC metal matrix composites (MMCs) using a high-speed steel end mill cutter. The L27 Taguchi orthogonal design and ANOVA analysis are employed to evaluate the influence of each parameter. The grey-fuzzy logic multi-optimization algorithm was used to find the optimal levels for simultaneous reduction of surface roughness and tool wear. The results show the optimal combination and highlight the significance of cutting speed, helix angle, and rake angle. This study contributes to understanding the impact of tool geometry on end milling of MMCs using the Grey-fuzzy logic algorithm.

Sujay et al. [44] examined the impact of speed, feed, depth of cut, and weight fraction on acceleration amplitude in end milling of Al6061-SiC metal matrix composite. Five specimens with different weight fractions were fabricated using the stir casting method. The milling tests were conducted using Taguchi's L25 orthogonal array, and a parametric investigation was performed. The analysis of variance (ANOVA) results revealed that the feed rate had the most significant influence on acceleration amplitude, followed by weight fraction, depth of cut, and speed.

Yingfei et al. [45] investigated the milling of SiCp/2009Al composites using PCD tools. The results showed a tool life of 150 minutes with various types of tool wear. Cutting forces were high, and severe vibrations were observed. The cutting temperature reached 523.7°C. The machined surface exhibited defects and a deformation layer thickness of 20-35μm. Chip formation mechanisms varied depending on the composite's SiC particle volume fraction. Surface generation mechanisms included material swelling, side flow, tool-workpiece vibration, feed rate, and tool nose radius.

In the study conducted by Wang et al. [46] focused on the performance of polycrystalline diamond (PCD) tools during high-speed milling of aluminum reinforced with high volume fraction (65%) and small size (10 μm) SiC particles. The effects of milling parameters (speed and feed rate) and PCD particle size on tool wear were investigated. The results showed that tool wear increased significantly with higher milling speeds, suggesting that speeds above 300 m/min are not suitable for industrial applications. Increasing the feed rate resulted in a larger volume of material removal before the tool wear reached a critical value of 0.6 mm. The optimal PCD particle size was found to be 10 μm. The main wear modes observed were flank wear and crater wear, and wear mechanisms were analyzed using scanning electron microscopy (SEM), laser scanning microscopy (LSM), and Raman spectroscopy.

2.5 Research gap

Although numerous studies have investigated the machining characteristics of aluminum alloys and metal matrix composites (MMCs), there remains a significant research gap in understanding the cutting forces and surface roughness specifically in the face milling (down milling) on AlSiC MMC using a High-Speed Steel (HSS) tool. While face milling is a widely used machining process, the investigation of cutting forces and surface roughness in this specific context is limited, particularly when considering the use of HSS tools.

Existing research on face milling on AlSiC MMC primarily focuses on other cutting tools such as carbide inserts or polycrystalline diamond (PCD) tools. Consequently, there is a lack of comprehensive studies that specifically explore the behavior of HSS tools in face milling operations for these materials. HSS tools are known for their unique characteristics, such as their ability to withstand high temperatures, durability, and cost-effectiveness. Understanding how HSS tools perform in face milling on AlSiC MMC is crucial for practical applications, as it allows for optimized tool selection and improved machining efficiency.

Furthermore, while cutting forces and surface roughness are crucial parameters in evaluating machining performance, there is a lack of research specifically investigating their relationship in the context of face milling on AlSiC MMC. Most studies focus on end milling or utilize different machining processes altogether. Given the distinct characteristics of face milling (down milling) , such as chip thickness variations and the impact of tool engagement, it is essential to investigate the corresponding effects on cutting forces and surface roughness.

Addressing this research gap is critical for both academia and industry. The outcomes of this thesis will provide valuable insights into the behavior of HSS tools in face milling operations on AlSiC MMC, shedding light on the cutting forces exerted during the process and their influence on surface roughness. This knowledge will contribute to the development of optimized machining parameters and tool selection criteria, leading to enhanced productivity and improved product quality in industries utilizing these materials.

In conclusion, the research gap lies in the limited understanding of cutting forces and surface roughness in the face milling (down milling) operation on AlSiC MMC using HSS tools. By investigating this specific context, the thesis aims to bridge this gap and provide valuable insights that can contribute to advancements in machining practices and enable informed decision-making in the selection of cutting tools and machining parameters.

2.6 Scope and Objectives of Research Work

The scope of the research work for the thesis on the investigation of cutting forces and surface roughness in the face milling (down milling) operation on AlSiC MMC with an HSS tool encompasses the following aspects:

1. Experimental Study: The research will involve conducting a series of experimental investigations to analyze the cutting forces and surface roughness during face milling operations. The experiments will be conducted on Al alloy and AlSiC MMC workpieces using an HSS tool.

2. Machining Parameters: The research will focus on studying the influence of various machining parameters on cutting forces and surface roughness. These parameters may include cutting speed, feed rate, depth of cut, tool geometry, and tool wear.

3. Comparative Analysis: The research will involve a comparative analysis of the cutting forces and surface roughness between Al alloy and AlSiC MMC. By examining the differences in machining behavior, the study aims to provide insights into the unique characteristics of these materials and their impact on the machining process.

4. HSS Tool Performance: The research will specifically investigate the performance of the HSS tool in face milling operations. This includes analyzing the tool wear patterns, tool life, and the correlation between tool wear and cutting forces/surface roughness.

5. Data Analysis and Interpretation: The collected experimental data will be thoroughly analyzed and interpreted to understand the relationship between cutting forces, surface roughness, and the machining parameters. Statistical methods and modeling techniques may be employed to extract meaningful insights from the data.

The objectives of the research work can be summarized as follows:

- To investigate the cutting forces and surface roughness in the face milling (down milling) operation on AlSiC MMC using an HSS tool.
- To examine the influence of various machining parameters on cutting forces and surface roughness in the machining process.
- To compare the cutting forces and surface roughness between Al alloy and AlSiC MMC, providing insights into the material-specific machining behavior.
- To evaluate the performance of the HSS tool in face milling operations, including tool wear analysis and its correlation with cutting forces and surface roughness.

- To contribute to the existing body of knowledge on machining processes by providing valuable insights and recommendations for the selection of machining parameters and tools in face milling operations.

By accomplishing these objectives within the defined scope, the research work will advance the understanding of cutting forces and surface roughness in face milling operations, specifically for AlSiC MMC with an HSS tool, and provide practical guidelines for improving the machining performance and product quality in industries working with these materials.

2.7 Summary

Based on the literature review, a significant research gap is identified, which highlights the need for a comprehensive investigation of cutting forces and surface roughness in the face milling (down milling) operation on AlSiC MMC with an HSS tool. By addressing this research gap, the thesis aims to contribute to the existing body of knowledge by providing insights into the behavior of HSS tools in this specific context, elucidating the relationship between cutting forces, surface roughness, and machining parameters, and comment on the machining strategies for improved productivity and product quality.

CHAPTER 3

Methodology and experimental Work

CHAPTER 3

Methodology and Experimental work

3.1 INTRODUCTION

The aim of this study is to examine how cutting speed, feed rate, depth of cut, and width of cut impact cutting force and surface roughness during the face milling (Down milling) operation on AlSiC MMC with HSS tool. In this chapter, we will outline the experimental techniques employed for the research.The ranges of input parameters are selected using the one-variable-at-a-time (OVAT) approach. This means that each parameter is varied individually while keeping the other parameters constant at their default values. By systematically altering one parameter at a time, we are able to observe the isolated effects of each parameter on the cutting force and surface roughness. This approach helps in understanding the individual contributions of the variables and their influence on the machining process.

To ensure efficient and effective experiments, a scientific approach is necessary for planning and conducting them. The process planning involves utilizing statistical design of experiments, which enables the collection of relevant data and its subsequent analysis using statistical methods. This approach ensures that the results obtained are reliable and objective. The design of the experiments and the statistical analysis of the data are interconnected because the chosen method of analysis relies on the experimental design.

By employing the design of experiments, several advantages can be gained. These include improving the performance of existing processes, reducing experimental time, enhancing reliability, achieving product robustness, and minimizing the number of trials required.

In order to draw accurate conclusions from the experimental observations, a well-planned and carefully executed set of experiments is crucial. In this study, the one-variable at a time (OVAT) approach is used for conducting screening experiments, the experiments and analyzing the acquired data.

All the experimental work in this study is performed using by a HMT company horizontal milling machine at **Blue Earth lab , Jadavpur University, Kolkata, India**. Detailed information about the workpiece materials, cutting tools, machine tools, and measuring equipment is provided below.

3.2. Workpiece details

The experimental fabrication process involved in preparing the Aluminum alloy LM6 as the base metal for the Metal Matrix Composite (MMC) with SiC reinforcement is as follows:

1. Melting: The small ingots of the LM6 base metal were melted using an electric melting furnace, ensuring a temperature range of 800-900 ◦C.

Table 3.1 Chemical composition of LM6 alloy

Elements	Si	Cu	Mg	Fe	Mn	Ni	Zn	Pb	Sb	Ti	Al
Percentage	10-13	0.1	0.1	0.6	0.5	0.1	0.1	0.1	0.05	0.2	Rest

2. Preheating of Reinforcement: Simultaneously, the SiC particles of 400 mesh size (37 µm) were preheated in a separate box furnace, maintaining a temperature range of 850-900 ◦C.

3. Reinforcement Addition: Once the LM6 alloy reached its molten state, 2.5 wt.% of preheated SiC particles were carefully added to the liquid metal. Additionally, a small quantity of magnesium (0.5 wt.%) was introduced to enhance the fluidity of

Figure 3.1 : Stir casting machine

the molten metal and improve the bonding between the matrix and the reinforcement.

4. Stirring: The mixture was subjected to vigorous stirring using a mechanical stirrer arrangement driven by a motor. This stirring process occurred within the temperature range of 700-800 °C while maintaining a stirring speed of 400-500 rpm. The purpose of this stirring was to ensure proper distribution and incorporation of the SiC reinforcement throughout the aluminum alloy matrix.

5. Casting: The well-stirred liquid mixture was poured into a mold made of green silica sand. After allowing sufficient time for the material to cool and solidify, the resulting casting was obtained. Cutting: Once the MMC workpiece has solidified, it is removed from the mold. To achieve the desired dimensions and shape, the cylindrical workpiece with diameter 50 mm is cut using a saw cutter. This cutting process ensures that the workpiece is obtained in the desired width and diameter.

6. Cutting : Cutting: Once the MMC workpiece has solidified, it is removed from the mold. To achieve the desired dimensions and shape, the cylindrical workpiece with diameter 50 mm is cut using a saw cutter. This cutting process ensures that the workpiece is obtained in the desired width and diameter

Figure 3.2 : Veekay Cutting machine

Fig. 3.3 : Cylindrical cast cut into piece

Fig 3.4 : after cutting the cylindrical cast

Fig.3.5 : total no. of pieces after cutting

7. Facing: After cutting the workpiece, it may undergo facing operations on a lathe machine. Facing involves removing a thin layer of material from the outer surface of the workpiece to create a smooth and flat surface. This step helps to prepare the workpiece for subsequent machining operations.

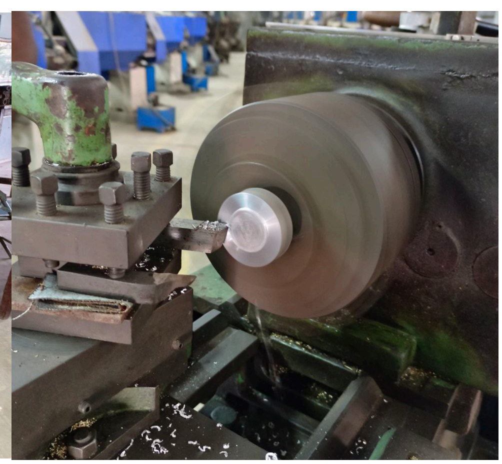

Fig.3.6 : lathe machine used for facing

Fig. 3.7 : facing operation

Figure 3.8 : Final workpiece specimen

Fig. 3.9: Total no. of workpiece

3.3 Cutting tool Details

Tool Specification for Side and Face Cutter (HSS Tool) with the given dimensions:

Manufacturer : Addison & co. Ltd.

Tool Type: Side and Face Cutter

Material: High-Speed Steel (HSS)

- Diameter: 3 inches (Nominal)
- Tolerance: +0.045 inches / 0.000 inches
- Bore Diameter: 1 inch (Nominal)
- Tolerance: +0.00075 inches / +0.00025 inches
- Width: 1/2 inch (Nominal)

Fig.3.10 : HSS side and face cutter

- Tolerance: +0.005 inches / 0.000 inches

Additional Specifications:

1. Number of Teeth: The side and face cutter may have a specific number of teeth depending on the design and application needs. For example, a common configuration 16 teeth.
2. Shank Type: The shank of the tool should match the machine spindle and be compatible with the specific tool holder or arbor used in the machining process.
3. Cutting Edge Geometry: The cutter have the appropriate cutting edge geometry suitable for face milling and side milling operations.
4. Flute Design: The tool features straight flutes for chip evacuation and improved cutting performance. The flute design may vary depending on the manufacturer and the specific application requirements.

It is essential to select a high-quality HSS tool with the appropriate specifications to ensure optimal performance, dimensional accuracy, and longevity during face milling and side milling operations.

3.4 Milling machine

We have used HMT horizontal milling machine to perform the experiment. HMT (Hindustan Machine Tools) is a renowned manufacturer of machine tools i.e horizontal milling machines. The HMT horizontal milling machines are designed for precision machining operations and offer a range of features and capabilities to meet diverse industrial requirements. Here is detailed information on the HMT horizontal milling machine on which we have performed our experiment :

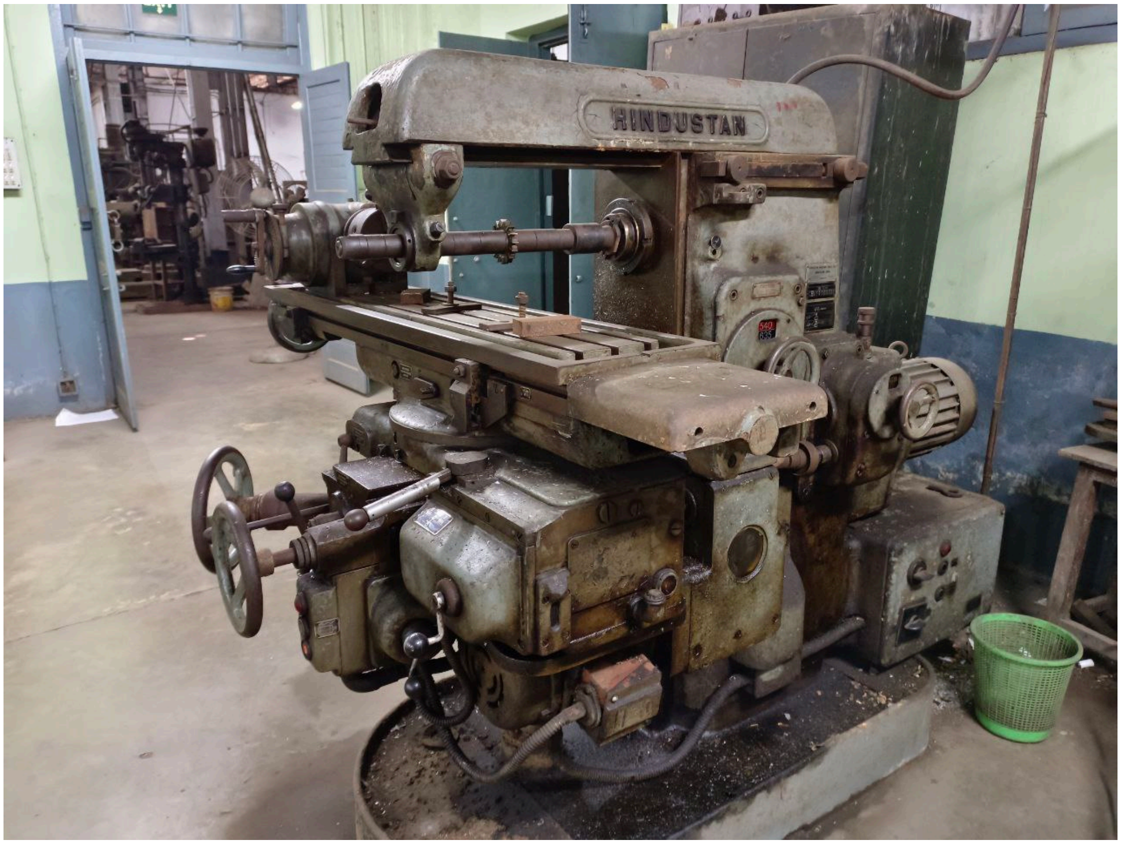

Fig.3.11 : HMT Horizontal Milling Machine

Machine Structure: The HMT horizontal milling machine features a robust and rigid structure to provide stability and support during machining operations. It is constructed using high-quality materials and precision engineering to ensure durability and accuracy.

Bed and Table: The machine consists of a sturdy bed that serves as the foundation for mounting various components. The table is mounted on the bed and provides a flat and stable surface for securing the workpiece. The table can be longitudinally and crosswise moved to facilitate different machining operations.

Spindle: The horizontal milling machine is equipped with a spindle that houses the cutting tool. The spindle is driven by a motor and can rotate at different speeds, allowing for the selection of suitable cutting speeds for various materials and applications. The spindle can also be adjusted vertically for controlling the depth of cut.

Controls and Operation: The HMT horizontal milling machine incorporates user-friendly controls and interfaces for easy operation. It may feature a control panel with buttons, knobs, and digital displays to set and monitor machining parameters such as

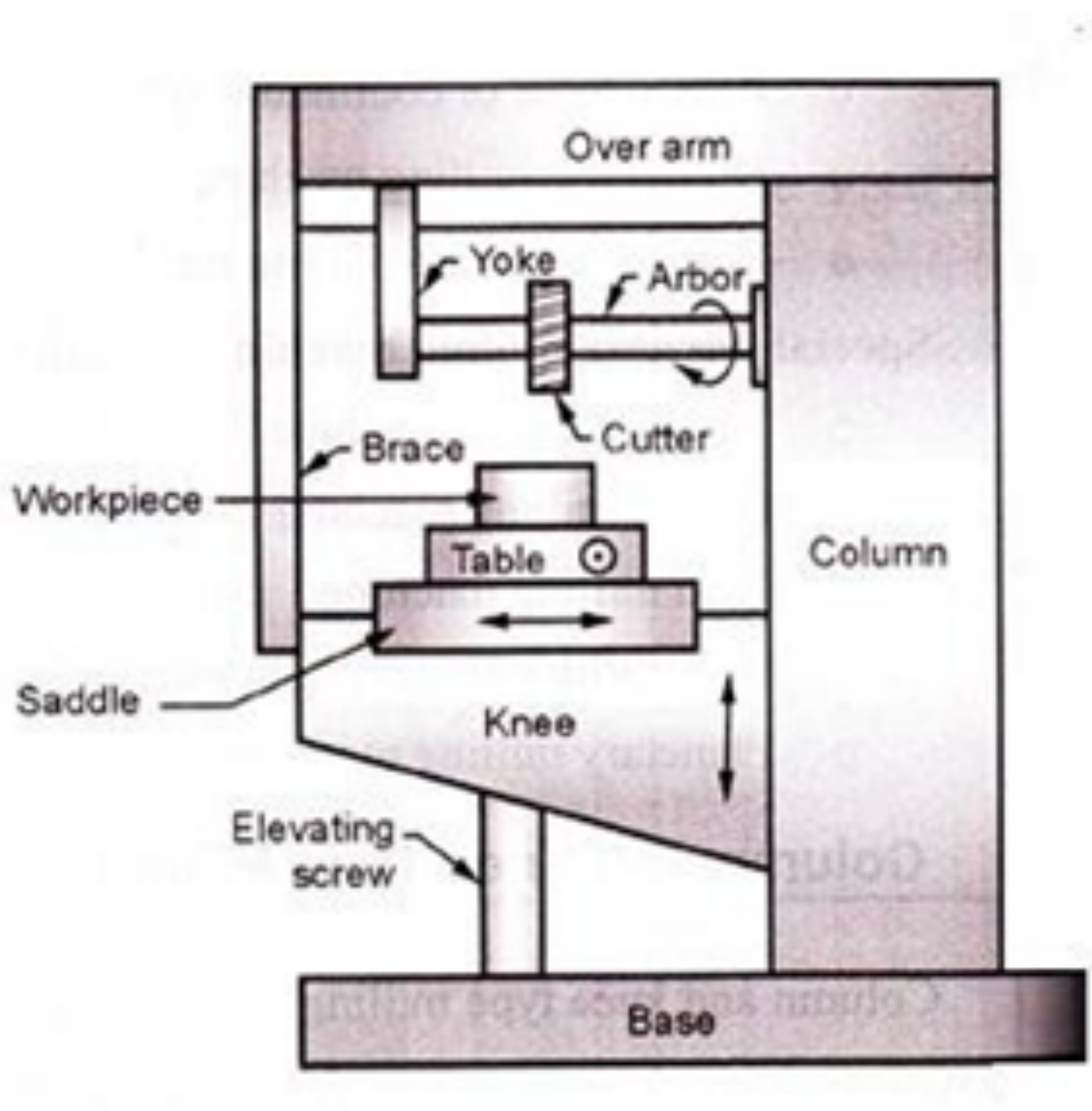

Fig.3.12 : Schematic diagram of Horizontal Milling Machine

spindle speed, feed rate, and tool positioning. Advanced models may include CNC (Computer Numerical Control) capabilities for enhanced automation and precision.

Tooling and Tool Holders: The machine is designed to accommodate a variety of cutting tools and tool holders. Common tooling options include end mills, face mills, and slotting cutters. The tool holders securely hold the cutting tools and allow for quick and efficient tool changes.

Axis Movement: The HMT horizontal milling machine typically offers three primary axes of movement: X-axis (longitudinal movement), Y-axis (crosswise movement), and Z-axis (vertical movement). These axes enable precise positioning and machining of the workpiece.

Workpiece Handling: The machine may feature clamping mechanisms or fixtures to securely hold the workpiece in place during machining. This ensures stability and accuracy during milling operations.

Safety Features: HMT milling machines incorporate various safety features to protect operators and prevent accidents. These may include emergency stop buttons, interlocks, and safety guards to shield operators from rotating parts and flying chips.

Applications: The HMT horizontal milling machines find applications in a wide range of industries, including automotive, aerospace, tool and die making, and general machining. They are suitable for tasks such as face milling, slotting, contouring, and drilling operations on various materials, including metals, plastics, and composites.

HMT horizontal milling machines are known for their reliability, precision, and versatility. They are widely used by manufacturers and machining facilities around the world to produce high-quality components with tight tolerances and superior surface finish.

3.5 Working setup and principle

The HMT horizontal milling machine operates based on the following principles:

1. Setup: The workpiece is securely clamped on the table or held in place with fixtures which is below the dynamometer.
2. Tool Selection: The appropriate cutting tool is selected based on the desired operation and material being machined.
3. Tool Setup: The selected tool is mounted on the arbor or tool holder and secured tightly.
4. Machining Parameters: The operator sets the required spindle speed, feed rate, and depth of cut.

Fig. 3.13 : Experimental setup of machining

5. Operation: The machine is started, and the spindle rotates, driving the cutting tool.

6. Cutting Process: The tool engages with the workpiece, and the table is moved along the desired axes to create the desired shape or size.

3.6 Output response measuring equipments

In this experimental work, cutting force and surface roughness measurements were conducted. The Kistler tool dynamometer was employed to measure the cutting force, while the Surtronic talysurf surface roughness measurement device was used to assess surface roughness.

3.6.1 Cutting force measurement

The Kistler tool dynamometer is a widely used device for measuring cutting forces and torque in end milling and drilling operations. It consists of a four-component dynamometer that accurately determines the torque (Mz) and the three cutting forces. This dynamometer is designed to be extremely rigid, resulting in a high natural frequency and allowing for precise measurement of even the smallest changes in forces and torques.

Figure: 3.14 Kistler tool Dynamometer Type 9272

Fig.: 3.15 workpiece setup on dynamometer

The dynamometer is composed of a four-component sensor that is mounted with a high preload between a base plate and a top plate. It's important to note that coupled and eccentric loads may affect the measuring ranges, potentially reducing their effectiveness. To ensure reliable measurements, the sensor is grounded to avoid any ground loop issues that could interfere with the accuracy of the readings.

When installing the dynamometer, screws can be used to securely attach it to clean, face-ground supporting surfaces such as the table of a machine tool. The cover plate of the dynamometer has eight M8mm threaded holes, which allow for the easy mounting of the workpiece. It's crucial to ensure that the supporting surfaces are face-ground to facilitate proper mechanical interaction between the force introducing elements and

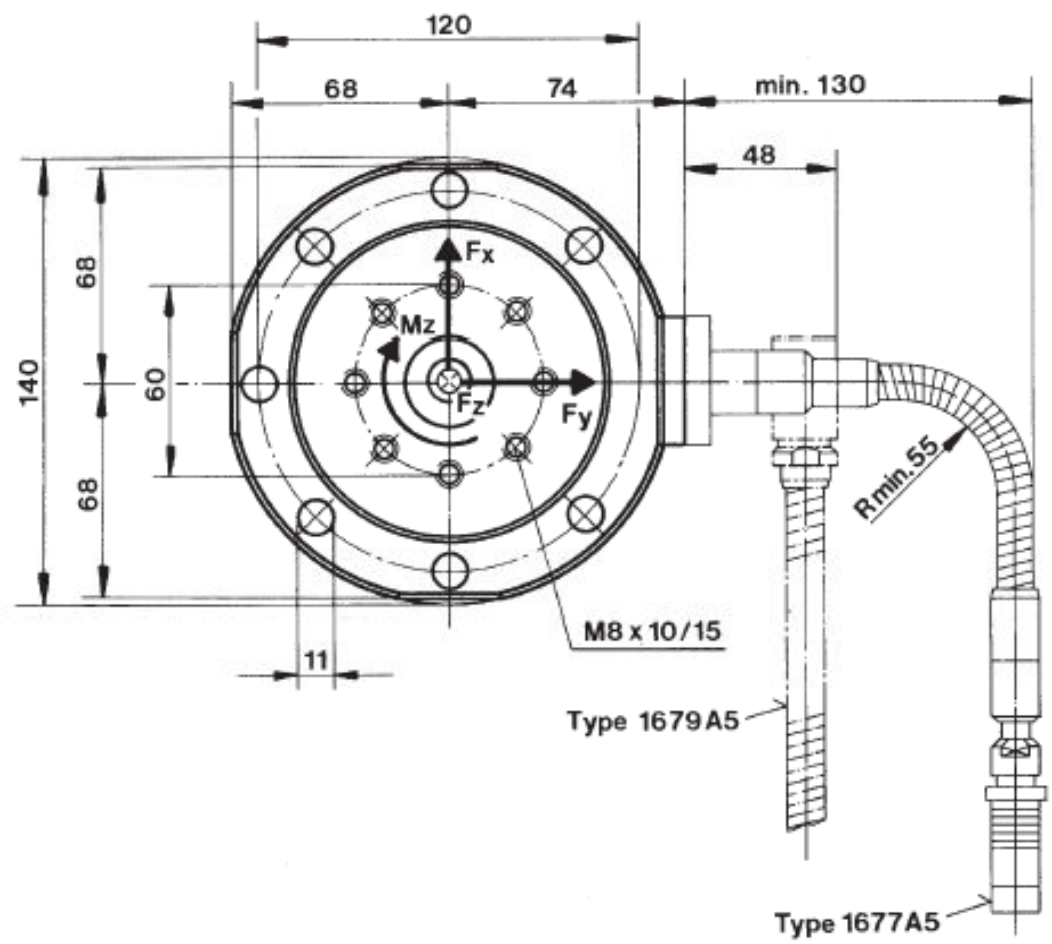

Fig.3.16 : Dimensions of Kistler tool dynamometer

the cover plate. For attaching tools, the recommended tool holder type is 9404, capable of accommodating shank cross-sections up to 20x20mm.

In addition to the dynamometer itself, a multi-core high-insulation connection cable and four charge amplifier channels are required for a four-component measuring system. These components convert the charge signals from the dynamometer into output voltages, which are proportional to the magnitudes of the forces and moments being measured. A multichannel charge amplifier is employed for this purpose.

To facilitate data acquisition during machining, software application Kistler DynoWare are utilized. These programs enable the capture and analysis of data collected by the dynamometer, providing comprehensive insights into the machining process.

For the specific experimental study being conducted, the Kistler 9272 tool dynamometer is employed. It possesses technical specifications that are outlined in figures 3.16 providing a comprehensive overview of its capabilities and performance.

3.6.2 Surface Roughness Measurement

The surface roughness of the sample surfaces is measured using a stylus-type profilometer called Talysurf (Taylor Hobson, Surtronic 3+). The profilometer is configured with specific settings for accurate measurements. These settings include a cut-off length of 0.8 mm, filter 2CR, traverse speed of 1 mm/s, and a 4 mm traverse length.

By employing these settings, the profilometer scans the sample surfaces, collecting data on the roughness parameters. The measured roughness parameter used in this study is CLA (Center Line Average), which provides an average value of the surface roughness over the specified traverse length.

To ensure consistency in the roughness measurements, the samples are selected based on a criteria of having less than 1% variation in the roughness values. This selection criterion helps to ensure that the samples chosen for further analysis exhibit a relatively uniform and consistent surface roughness.

Fig.3.17 : surtronic 3+ device

Overall, the Talysurf profilometer with the specified settings allows for accurate and precise measurement of surface roughness, and the criterion of less than 1% variation in roughness values ensures the selection of suitable samples for subsequent analysis in the investigation.

Figure 3.18 : setup for surface roughness measurement

3.7 Experimental setup

For the design of experiments in the experimental investigation, the ranges of various parameters have been selected using the one-variable-at-a-time method and data provided by the cutting tool supplier. The following parameter ranges have been chosen:

1. Cutting Speed (N): 270-635 RPM

- This parameter represents the speed at which the cutting tool moves across the workpiece. It affects the rate of material removal and can impact tool life and surface finish.

2. Feed Rate (F): 30-75 mm/min

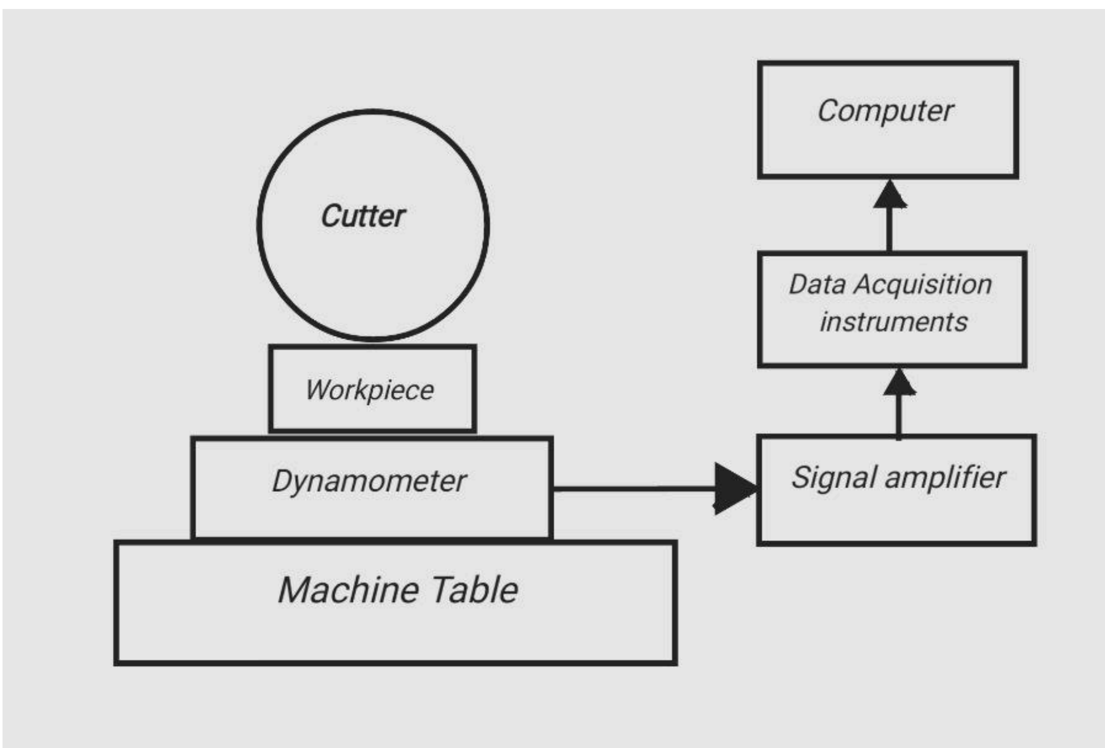

Figure 3.19 : schematic diagram for experimental setup

- The feed rate refers to the rate at which the workpiece is fed into the cutting tool. It determines the amount of material removed per unit of time and affects the chip formation and tool wear.

3. Depth of Cut (DOC) (d): 0.5-1 mm

- The depth of cut is the distance between the original surface of the workpiece and the final cut surface. It determines the thickness of the material removed in each pass and influences cutting forces and surface finish.

4. Width of Cut (WOC) (w): 12.7 mm (0.5 inch)

- The width of cut is the width of the material that is removed during the machining process. It affects the chip formation, cutting forces, and the overall material removal rate.

By selecting these ranges, the experimental investigation aims to explore the effects of different cutting speeds, feed rates, depths of cut, and widths of cut on the cutting forces and surface roughness. This approach allows for a systematic analysis of each parameter's individual impact on the machining process and provides valuable insights for optimizing the cutting conditions for improved performance and efficiency.

The machining process was performed on a workpiece made of AlSiC MMC with a diameter of 50 mm. The experiments were conducted using an HMT horizontal milling machine. For the experimental work, a HSS (High-Speed Steel) side and face cutter with a diameter of 3 inches and a width of 0.5 inch were employed (as shown in Figure).

To measure the cutting forces during the machining process, a tool dynamometer (9272, Kistler make) was mounted on the table of the machine tool. The tool dynamometer is designed to accurately capture and measure the cutting forces exerted on the tool during the operation. These force signals were then amplified through a charge amplifier to enhance their strength and quality.

The amplified force signals were further processed by converting them into analog signals using an A/D (Analog-to-Digital) acquisition card (PCI-6-23E, NI). This acquisition card facilitated the conversion of the analog signals into digital data, which could be easily processed and stored in a computer.

To collect and record the cutting force data, Dynoware software was utilized. Dynoware is a powerful programming environment that enables the acquisition, analysis, and visualization of data in real-time. It provided a user-friendly interface for data acquisition, allowing the researchers to monitor and record the cutting force signals during the machining process accurately

3.8 One Variable at a Time (OVAT)

Initial experiments were conducted using the OVAT method to analyze the relationship between cutting speed, feed rate and axial depth of cut with surface roughness and cutting force. The experiments were performed using a HSS side and face mill cutter tool. The axial depth of cut ranged from 0.5 to 1 mm, the width of cut 25 mm, the feed rate ranged from 30 to 95 mm/min, and the cutting speed ranged from 270 to 635 RPM. Only one parameter was varied at a time while the others were kept constant. The goal was to establish relationships between these parameters and their impact on surface roughness and cutting force providing insights for optimizing the machining process.

Cutting speed, feed rate and depth of cut

Based on the provided information, the cutting speeds were varied while keeping the feed rate, and depth of cut constant at 30 mm/min and 0.5 mm respectively in each set of experiment. The cutting force and surface roughness were measured at different cutting speeds, as shown in Table 3.2 . Same cutting speed again repeated when feed rate becomes 60 or 75 or 96 mm/min. The depth of cut remains 1 mm in that case.

Table:3.2 design of experiment

Sr.	Cutting speed /Spindle	Feed rate (mm/min)	Depth of cut(mm)
1	270	30	0.5
2	317	30	0.5
3	380	30	0.5
4	450	30	0.5
5	540	30	0.5
6	635	30	0.5
7	270	60	0.5
8	317	60	0.5
9	380	60	0.5
10	450	60	0.5
11	540	60	0.5
12	635	60	0.5
13	270	75	0.5
14	317	75	0.5
15	380	75	0.5
16	450	75	0.5
17	540	75	0.5
18	635	75	0.5
19	380	30	1.0
20	450	30	1.0
21	540	30	1.0
22	635	30	1.0
23	380	60	1.0
24	450	60	1.0
25	540	60	1.0
26	635	60	1.0
27	380	75	1.0
28	450	75	1.0
29	540	75	1.0
30	635	75	1.0

In this experimental work, cutting speed Vc is converted into spindle speed N as a machining parameter For conversion cutting speed into spindle speed following equation is used ;

$$Vc = \pi DN/1000 \text{ (m/min)}$$

Where Vc is cutting speed in m/mm, D is the diameter of the cutting tool in mm and N is spindle speed in revolutions/minute.

The diameter of cutting tool is 3 inch (76.2 mm). so the following spindle speeds have been converted from cutting speeds which have been taken during experiment work as shown in the table 3.3.

Table 3.3 : Convert spindle speed into cutting speed

Sr.No.	Spindle speed (rpm)	Cutting speed (m/min)
1	270	64.635
2	317	75.887
3	380	90.967
4	450	107.725
5	540	129.270
6	635	152.012

In milling operation, the cutting operation is always intermittent and the risk of thermal cracking is also caused higher by the coolant. So dry machining is, therefore, the primary choice to increase tool life, especially when cutting with mmc, cast iron and some composite materials. In terms of cutting force and chatter stability, the down face milling mode is more suited for face milling than the up end-milling mode. All experiments have been repeated two times and an average value has been considered. Following process or has been done for experimental work.

1. Cutting tool has been fixed in the spindle of the horizontal milling machine.
2. Tool dynamometer has been mounted on the machine bed and connected with the amplifier and dynoware system properly.
3. Workpiece has been mounted on tool dynamometer with help of clamping.
4. Experimental readings have been taken using HSS tool with cutting parameters such as spindle speed 270, 317, 380, 450, 540 and 635 rpm , feed 30, 60, 75, 96, mm/min, depth of cut 0.5 and 1mm and width of cut 0.5 inch.
5. Total of 30 experiment runs have been done in this way.
6. Cutting forces have been measured during the machining process using a tool dynamometer
7. Surface roughness has been measured using a surface roughness tester after the machining process.

3.9 Summary

This chapter provides a detailed description of the workpiece, including types, designations, and behavior, along with a comprehensive discussion on the cutting tool, including types, designations, and a detailed drawing. The measurement of important responses such as cutting force and surface roughness is explained, supported by illustrations, photographs, and principles of the measuring equipment. The specifications of the tool dynamometer, surface roughness measuring equipment, and horizontal milling machine are tabulated. Initial experiments are analyzed to determine levels of input parameters for the subsequent design of experiments, which are detailed using response surface roughness. The levels of input parameters and measured responses are tabulated, and the significant effects of the input machining parameters on the responses are reported. Overall, this chapter provides a comprehensive foundation for understanding the workpiece, cutting tool, measurement process, and subsequent investigation of input parameters and their effects on the responses.

CHAPTER 4

RESULT AND DISCUSSION

Chapter 4

RESULT AND DISCUSSION

The results and discussion section of this thesis presents a comprehensive analysis of the cutting forces and surface roughness obtained from face milling operations in down milling mode, specifically focusing on Aluminum Silicon Carbide Metal Matrix Composite (AlSiC MMC) using a High-Speed Steel (HSS) tool. This section highlights the findings and their significance in understanding the effects of various cutting parameters on these machining responses. The discussion explores the relationships between cutting forces, surface roughness, and the selected cutting parameters, for improved performance and surface quality. By examining the experimental data and comparing it with existing literature, this section provides valuable insights into the behavior of AlSiC MMC during face milling operations, offering practical implications for the machining industry.

4.1 RESULT AND DISCUSSION ON MILLING FORCE

The effect of spindle speed on cutting force have been presented on Figure 4.1 and Based on the Figure 4.1, the experiment was conducted with a fixed feed rate 30 mm/min and depth of cut 0.5 mm. The results for the cutting forces in the Z-axis (F_z) indicate an initial increase followed by a decrease after reaching a certain cutting speed. Similarly, the cutting forces in the Y-axis (F_y) and X-axis (F_x) exhibit the same pattern.

This pattern suggests that there is an optimal cutting speed at which the cutting forces reach their maximum value and then start to decrease. The initial increase in cutting forces can be attributed to the increase in tool material interaction and material removal rate as the cutting speed increases. However, beyond a certain point, further

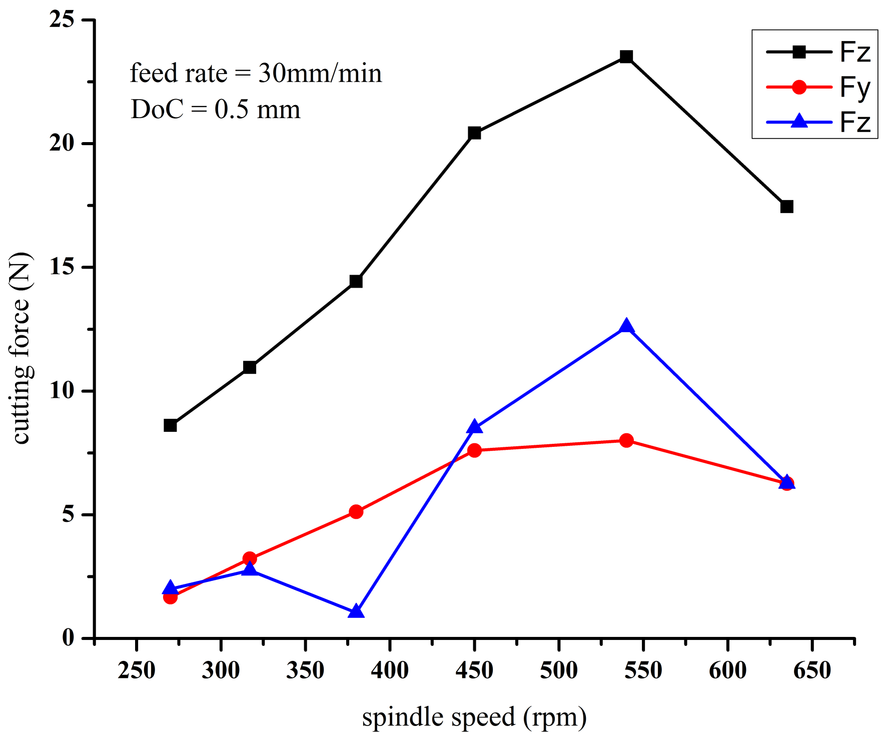

Figure 4.1: cutting force vs spindle speed plot for feed rate 30 mm/min and depth of cut 0.5 mm

increases in cutting speed may lead to reduced tool engagement and less material removal, resulting in a decrease in cutting forces.

Based on Figure 4.2, at 60 mm/min feed rate and depth of cut 0.5 mm are kept constant, the results of the cutting forces indicate specific patterns. The cutting force in the Z-axis (Fz) initially increases sharply as the cutting speed increases, but after reaching a certain speed, it starts to decrease. On the other hand, the cutting force in the Y-axis (Fy) slightly increases with increasing cutting speed, while the cutting force in the X-axis (Fx) shows a slight decrease.

The sharp increase in the cutting force F_z can be attributed to the increased tool-material interaction and higher material removal rates at higher cutting speeds.

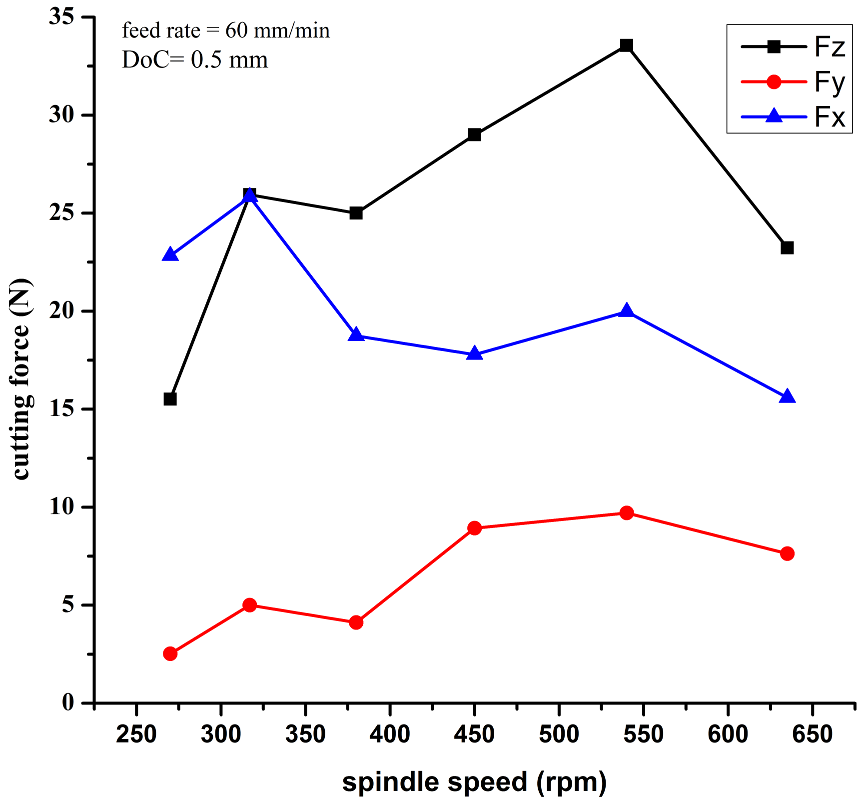

Figure 4.2 cutting force vs spindle speed plot for feed rate 60 mm/min and depth of cut 0.5 mm

However, beyond a certain critical speed, the cutting force starts to decrease. This decrease could be due to factors such as reduced tool engagement, reduced friction, or a change in the chip formation mechanism.

The slight increase in the cutting force F_y suggests that there is a progressive increase in the forces acting perpendicular to the feed direction. This could be due to factors like increased chip thickness or changes in the material behavior at higher cutting speeds.

The slight decrease in the cutting force Fx indicates a reduction in the forces acting in the feed direction. This could be attributed to factors such as reduced tool rubbing or changes in the chip formation process.

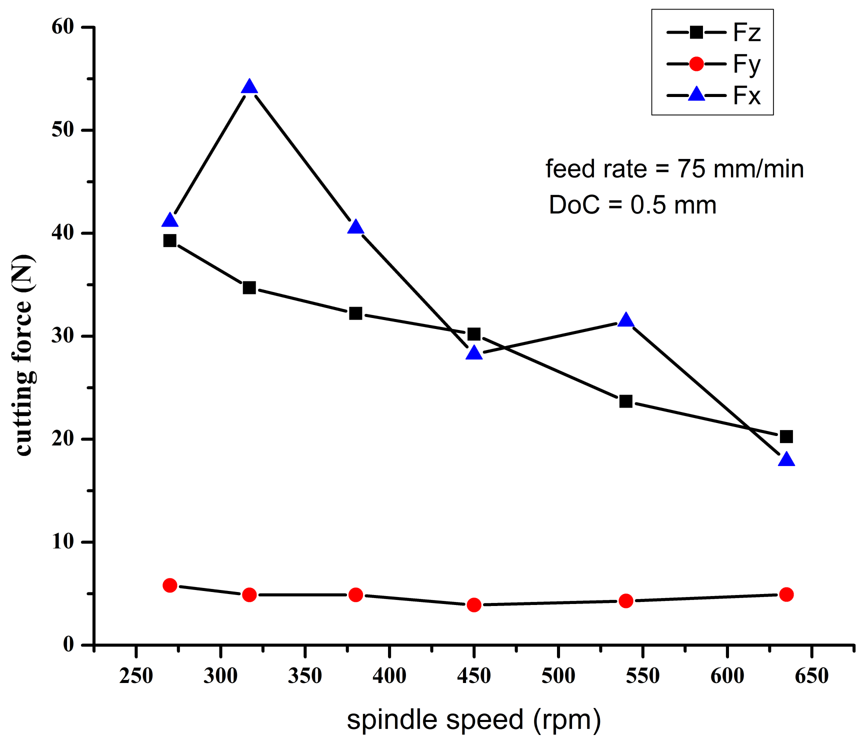

Figure 4.3 : cutting force vs spindle speed plot for feed rate 75mm/min and depth of cut 0.5 mm

Based on Figure 4.3 when the feed rate is 75 mm/min and depth of cut 0.5 mm, the behavior of cutting forces is influenced by various factors, including the impact on each tooth and the temperature generated during the process. As the cutting speed increases, the impact on each tooth decreases. This is because at higher cutting speed, the time available for each tooth to engage with the workpiece is reduced. Consequently, the impact force exerted by each tooth on the material decreases. This can lead to a decrease in the cutting force in the z-direction (Fz) as the cutting speed increases, as observed in the graph. Additionally, the temperature generated during machining may has a significant impact on cutting forces as shown in Figure 4.4, when feed rate is 60 mm/min and depth of cut 1 mm. Higher cutting speeds result in increased friction and heat generation between the tool and the workpiece. This elevated temperature can cause the workpiece material to softening, resulting in reduced cutting forces. However, it is important to note that there is a critical point where the temperature reaches a threshold, beyond which the material's response changes. At this point, the material may harden or exhibit other behaviors that can increase the cutting forces.

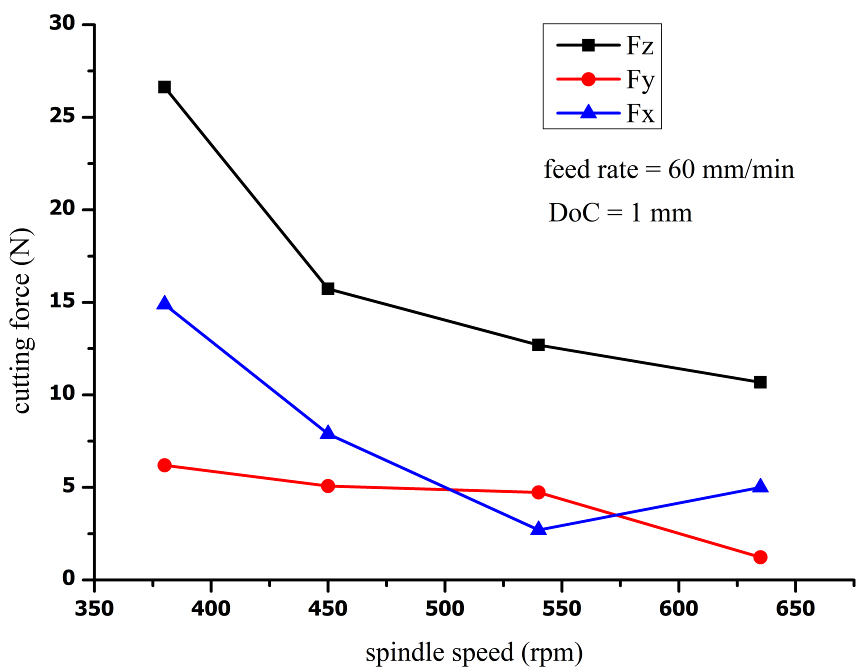

Figure 4.4 : cutting force vs spindle speed plot for feed rate 60 mm/min and depth of cut 1 mm

The interaction between cutting speed, impact on each tooth, and temperature plays a crucial role in the observed trends in cutting forces. It is necessary to carefully optimize the cutting parameters to achieve the desired balance between material removal and minimizing cutting forces. Fine-tuning the cutting speed can help manage the impact on each tooth, ensuring efficient chip formation and evacuation. Controlling the temperature through appropriate cooling strategies or tool coatings can also contribute to maintaining optimal cutting forces.

In the y-direction (F_y), the cutting force exhibits a decreasing trend from the beginning of the machining process. This indicates efficient chip evacuation and reduced friction between the tool and the workpiece. Side and face milling operations typically involve a shearing action that facilitates chip formation and removal. The tool geometry and cutting parameters play a significant role in ensuring smooth chip flow, resulting in lower cutting forces in the y-direction.

In the x-direction (F_x), the cutting force remains relatively constant throughout the machining process. This suggests a balanced distribution of forces acting on the tool in the horizontal direction. The stability of the machining setup, tool design, and cutting conditions contribute to maintaining a consistent cutting force. This is important for achieving uniform material removal and minimizing tool deflection.

In Figure 4.5 and Figure 4.6, it is clearly depicted that the cutting force in the z-direction (Fz) increases as the depth of cut increases when machining is done with a side and face cutter. Moreover, the cutting force also exhibits a positive correlation with the cutting speed.

The increase in cutting force with higher depths of cut can be attributed to the larger chip volume and the increased engagement between the tool and the workpiece. As the depth of cut increases, more material is being removed with each pass, requiring higher cutting forces to overcome the resistance offered by the workpiece. This phenomenon is evident in the graph, where the cutting force in the z-direction rises consistently with an increase in the depth of cut. Furthermore, when the cutting speed is increased, it further influences the cutting force in the z-direction. Higher cutting

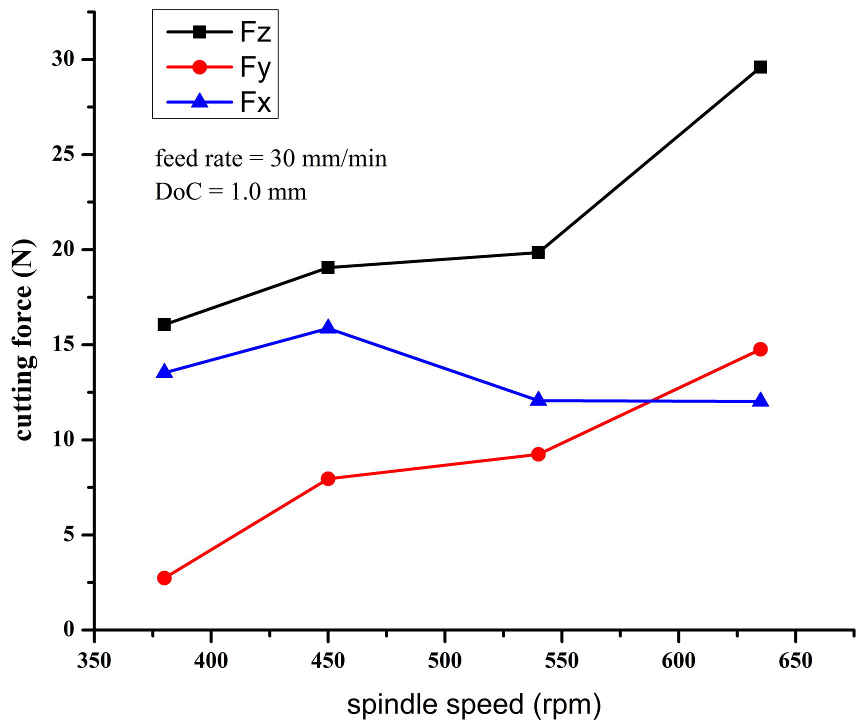

Figure 4.5 : cutting force vs spindle speed plot for feed rate 30 mm/min and depth of cut 1.0 mm

speeds result in a higher rate of material removal, leading to larger chip volumes and increased cutting forces. This effect is observed in the graph, where higher cutting speeds coincide with higher cutting forces.

It is important to consider the limitations of cutting forces when selecting cutting parameters. Excessively high cutting forces can result in tool wear, reduced tool life, and poor surface finish. Therefore, manufacturers must strike a balance between achieving desired material removal rates and ensuring manageable cutting forces to maintain machining efficiency and tool longevity.

The relationship between cutting force in the z-direction, cutting speed, and depth of cut illustrated in Figure 4.5 and 4.6 provides valuable insights for process optimization and selecting appropriate cutting parameters in side and face milling operations. By understanding these relationships, manufacturers can make informed decisions to achieve efficient and productive machining while considering the limitations and requirements of the cutting system and workpiece material.

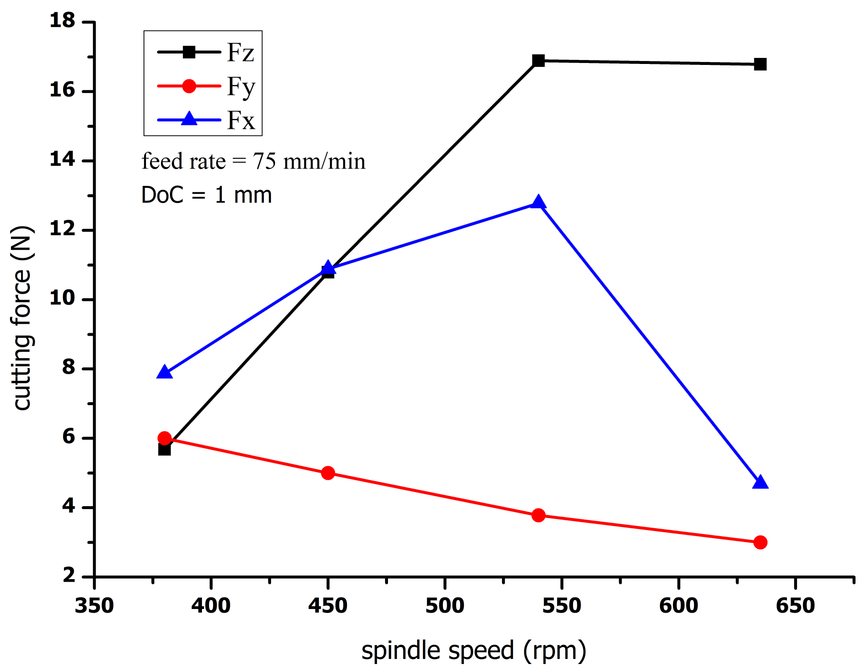

Figure 4.6 : cutting force vs spindle speed plot for feed rate 75mm/min and depth of cut 1 mm

While the cutting force in the x and y-direction may exhibit minor fluctuations due to factors such as tool wear or workpiece material variations, the overall trend remains relatively consistent. This indicates that the cutting force in the x-direction is not significantly influenced by changes in the depth of cut or cutting speed within the range of parameters studied.

4.2 Graphical analysis of cutting force vs cutting speed

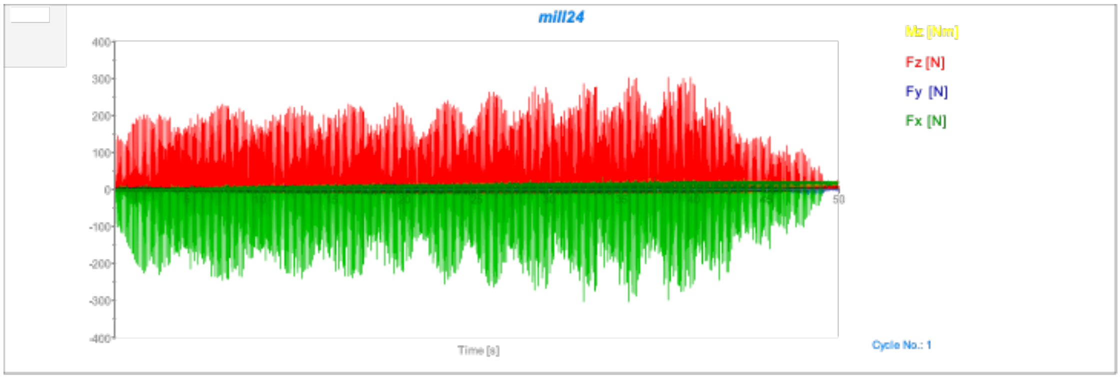

Figure 4.7: when cutting is done at high rpm

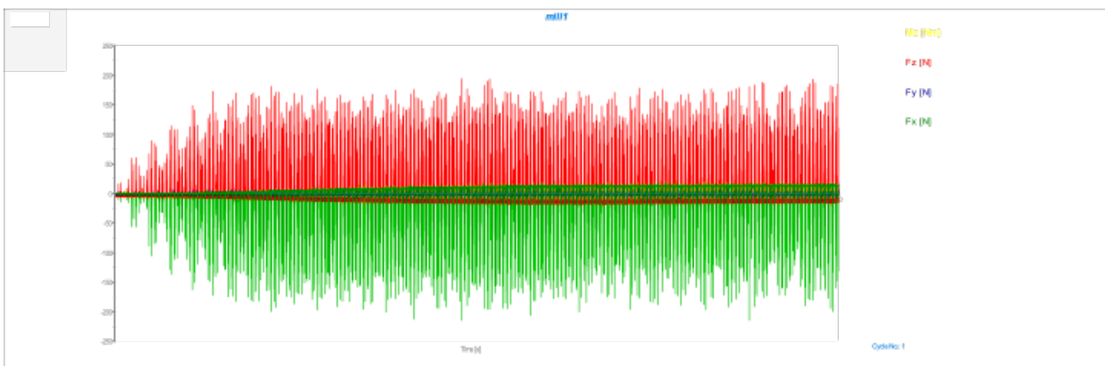

Figure 4.8: when cutting is done at low rpm

In Figures 4.8 and Figure 4.9, a noticeable trend can be observed when analyzing the effect of cutting speed on cutting forces. As the cutting speed increases, there is a reduction in the variation of cutting force. This indicates that at higher cutting speeds, each cutting tooth experiences less thrust force during the machining process.

The reduction in the variation of cutting force can be attributed to several factors. Firstly, at higher cutting speeds, the tool has a reduced engagement time with the workpiece material. This shorter contact time results in a reduced impact force on each cutting tooth, leading to a more consistent cutting force profile.

Additionally, the increased cutting speed can generate higher cutting temperatures. This rise in temperature causes the workpiece material to soften, reducing its resistance to cutting. As a result, the cutting forces experienced by each tooth are decreased.

Furthermore, the reduced variation in cutting force can be associated with improved chip evacuation at higher cutting speeds. The increased chip flow and effective chip removal contribute to smoother cutting operations, resulting in a more consistent cutting force distribution across the cutting tool.

It is important to note that while increasing cutting speed can lead to a reduction in the variation of cutting force, there is a limit to this trend. Beyond a certain cutting speed, other factors such as tool wear, tool deflection, and machine dynamics may come into play and affect the cutting forces differently.

In summary, the analysis of Figures 4.8 and Figure 4.9 indicates that as the cutting speed increases, the variation of cutting force reduces, and each cutting tooth experiences less thrust force. This can be attributed to reduced engagement time, workpiece softening, and improved chip evacuation at higher cutting speeds. Understanding and optimizing the cutting parameters, including cutting speed, can help achieve more stable and efficient machining processes.

4.3 RESULT AND DISCUSSION ON SURFACE ROUGHNESS

In this experiment, the focus is on investigating the surface roughness of the machined components using two key parameters: Ra (average roughness) and R_{rms} (root mean square roughness). The experiment involves varying cutting parameters, including cutting speed, feed rate, and depth of cut, while machining is performed on a horizontal milling machine using a side and face cutter.

The cutting speed is varied within the range of 270 to 635 rpm, allowing for a comprehensive evaluation of its impact on surface roughness. Similarly, the feed rate is varied between 30 to 75 mm/min, while the depth of cut was set at two different levels: 0.5 mm and 1 mm.

To conduct the experiments, the horizontal milling machine is set up with the appropriate tooling, including the side and face cutter. Machining operations are performed on the workpiece, and surface roughness measurements were taken by surtronic 3 + device . The obtained surface roughness data, specifically the Ra and Rrms values, provide valuable insights into the quality and characteristics of the machined surfaces. By analyzing the data in graphical form are as follow.

4.2.1 R_a values observation

In the analysis of the R_a values obtained from the experiments, a noticeable trend can be observed. Figure 4.9 and Figure 4.10 observation indicates that it is evident that the Ra value decreases with an increase in cutting speed when the feed rate and depth of cut are kept constant. This observation suggests that higher cutting speeds have a positive effect on reducing surface roughness, resulting in a smoother machined surface.

On the other hand, when analyzing the effects of feed rate and depth of cut on surface roughness, an inverse relationship is observed. As the feed rate increases, the surface

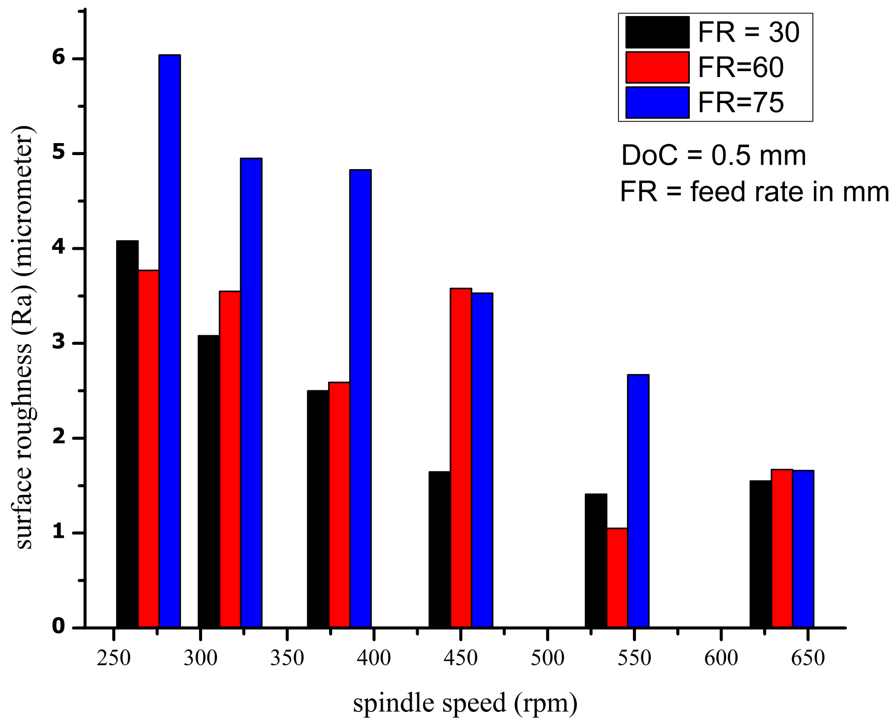

Figure 4.9 : R_a vs spindle speed plot when DoC is 0.5 mm

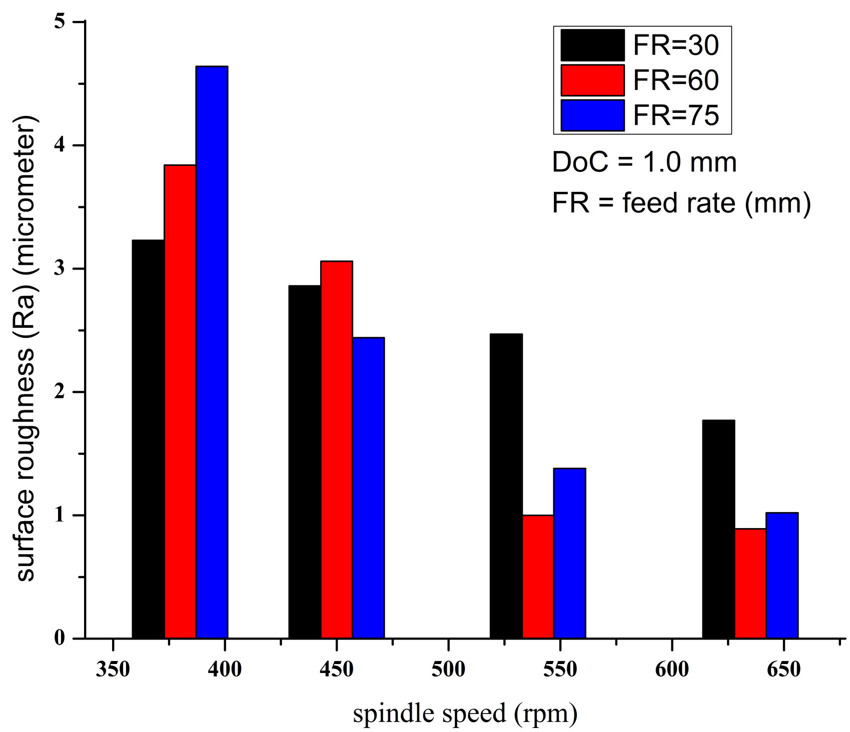

Figure 4.10 : R_a vs spindle speed plot when DoC is 1.0 mm

roughness tends to increase as well. This can be attributed to the fact that a higher feed rate leads to more material being removed per unit of time, potentially causing more tool-workpiece interaction and resulting in a rougher surface finish [47].

Similarly, an increase in the depth of cut also contributes to an increase in surface roughness. A larger depth of cut means a greater volume of material is being removed with each pass, potentially leading to more prominent tool marks and surface irregularities.

4.2.2 R_{rms} value observation

R_{rms} (root mean square roughness) is another important parameter used to characterize surface roughness in machining processes. It provides a measurement of the average deviation of the surface profile from the mean line, taking into account both the amplitude and frequency of roughness variations.

The observation that Rrms follows a similar pattern as R_a when cutting speed increases, resulting in a decrease in surface roughness, is consistent with the findings. Additionally, the impact of feed rate and depth of cut on surface roughness can provide further insights into the behavior of R_{rms}.

When the feed rate increases, it leads to a higher material removal rate, which can result in a rougher surface. This is because a faster feed rate may cause more significant tool-workpiece interaction, leading to increased contact pressure and potential for plowing or tearing of the material. These effects contribute to an increase in surface roughness, as indicated by higher R_{rms} values.

Similarly, an increase in the depth of cut means a greater amount of material is being removed with each pass. This can result in more pronounced tool marks or grooves on the surface, leading to an increase in roughness. The larger chips produced during a higher depth of cut may also contribute to a rougher surface finish. As a result, R_{rms}

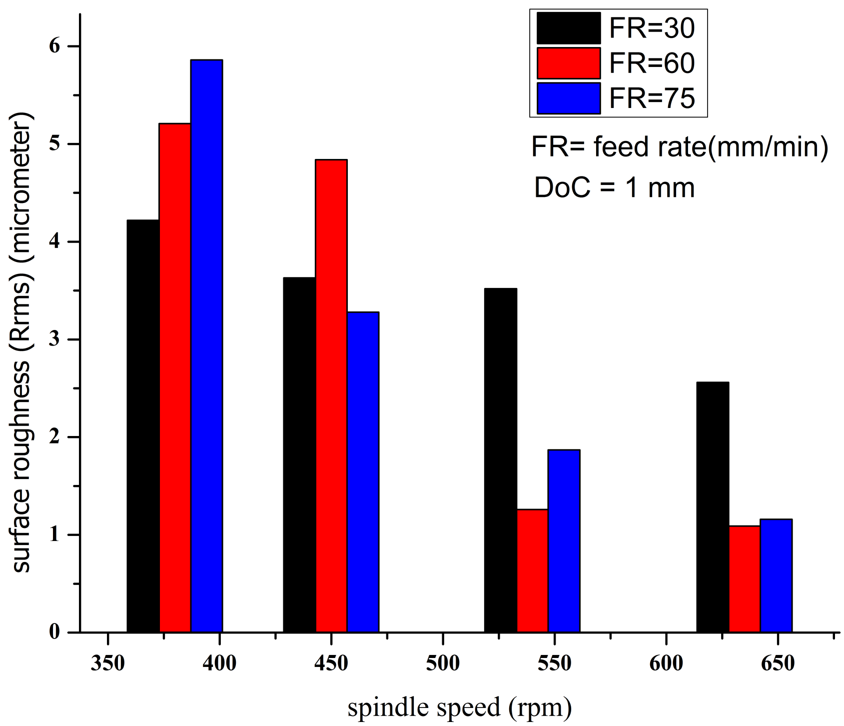

Figure 4.11 : R_{rms} vs spindle speed plot when DoC is 1 mm

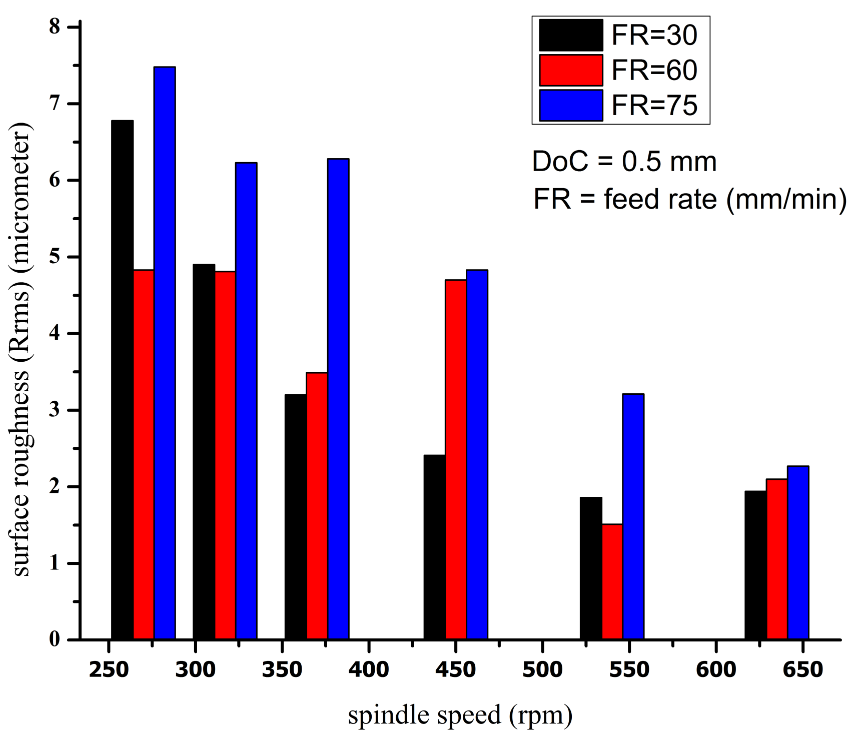

Figure 4.12 : R_{rms} vs spindle speed plot when DoC is 0.5 mm

values tend to increase with an increase in the depth of cut.

It is important to note that while cutting speed generally has a dominant influence on surface roughness, the feed rate and depth of cut can also play significant roles. These parameters should be carefully optimized to achieve the desired surface finish and meet the specific requirements of the machining operation.

Overall, the experimental findings demonstrate that variations in feed rate and depth of cut can affect surface roughness, leading to an increase in Rrms values. However, the influence of cutting speed on Rrms is consistent with its impact on Ra, with higher cutting speeds generally resulting in a decrease in surface roughness [48]. Understanding these relationships and optimizing the cutting parameters can help achieve the desired surface quality and improve the overall performance of the machining process.

Some important reason behind above surface roughness trends

When face milling operations are performed using a side and face milling cutter in a horizontal milling machine, several possible causes can explain why surface roughness decreases with an increase in cutting speed and a decrease in feed rate and depth of cut:

1. Decreased Tool-Workpiece Contact Time: Increasing the cutting speed reduces the contact time between the cutting tool and the workpiece. This shorter interaction time minimizes the chances of tool vibrations, leading to a smoother surface finish.
2. Enhanced Chip Evacuation: Higher cutting speeds facilitate better chip formation and evacuation. The side and face milling cutter effectively removes chips generated during the cutting process. Proper chip evacuation reduces the

chances of chip recutting, tool rubbing, and surface irregularities, resulting in a smoother surface finish.

3. Improved Cutting Edge Penetration: Increasing the cutting speed allows the cutting tool to penetrate the workpiece more efficiently. The side and face milling cutter engages the material more effectively, reducing tool rubbing and resulting in a cleaner and smoother cutting action.

4. Efficient Heat Dissipation: Higher cutting speeds enable better heat dissipation due to increased chip flow and contact with the workpiece. This helps minimize thermal damage such as work hardening and residual stresses, which can contribute to surface roughness.

5. Reduced Built-Up Edge (BUE) Formation: Increasing the cutting speed hinders the formation of built-up edge (BUE) on the cutting tool. BUE can cause erratic cutting forces and result in poor surface finish. By minimizing BUE formation, the surface roughness is improved.

6. Optimized Chip Thickness: Decreasing the feed rate and depth of cut allows for smaller chip thickness. Smaller chips are easier to evacuate and are less likely to cause surface irregularities, resulting in a smoother surface finish.

7. Improved Lubrication and Cooling: Lower feed rates and shallower depths of cut allow for better application and distribution of cutting fluids. Adequate lubrication and cooling help reduce friction and heat generation, leading to improved surface finish and reduced surface roughness.

8. Minimized Cutting Forces: Decreasing the feed rate and depth of cut reduces the cutting forces acting on the tool and workpiece. Lower cutting forces result in reduced tool deflection and improved surface finish.

By carefully optimizing the cutting speed, feed rate, and depth of cut in face milling operations with a side and face milling cutter in a horizontal milling machine, these factors collectively contribute to decreasing surface roughness and achieving the desired surface finish.

CHAPTER 5

CONCLUSION & FUTURE SCOPE

CONCLUSION & FUTURE SCOPE

5.1 CONCLUSION

The results of the investigation on cutting forces and surface roughness in the face milling (down milling) operation on AlSiC MMC with an HSS tool provide valuable insights into the machining process. The study focused on analyzing the variations in cutting forces with respect to cutting speed, feed rate, and depth of cut.

The findings revealed that as the cutting speed is increased, there is a corresponding increase in the cutting forces. This can be attributed to the higher material removal rate at higher cutting speeds, which requires more force to achieve the desired machining outcome. However, beyond a certain point, an interesting phenomenon is observed. The cutting forces started to decrease. This can be attributed to the decreased tool interaction with the workpiece surface at higher cutting speeds. The tool may experience reduced engagement with the workpiece, resulting in lower cutting forces.

Another significant factor influencing cutting forces is the feed rate. The results indicated that as the feed rate increased, the cutting forces also increased. This can be explained by the higher material removal per unit time at higher feed rates, necessitating more force to overcome the resistance of the workpiece.

Furthermore, the depth of cut is found to impact the cutting forces. As the depth of cut increased, the cutting forces are also increased. This is due to the larger volume of material being removed during each pass, requiring greater force to accomplish the machining operation.

In addition to tool interaction and feed rate, the increase in temperature within the workpiece are also get influenced by the cutting forces. As the cutting speed is increased, the temperature within the workpiece start to rise. This rise in temperature can cause the workpiece material to soften, leading to reduced cutting forces. The softened material offers less resistance to the cutting tool, resulting in decreased cutting forces.

In summary, the investigation has demonstrated that cutting forces in the face milling operation on AlSiC MMC with an HSS tool is largely influenced by cutting speed, feed rate, and depth of cut. Cutting forces initially increase with increasing cutting speed and feed rate, but beyond certain thresholds, they start to decrease. The increase in temperature within the workpiece due to higher cutting speeds also affects the cutting forces. Additionally, the depth of cut has a direct impact on cutting forces, with higher depths of cut resulting in increased forces. These findings provide valuable insights for optimizing cutting parameters and improving the machining process for AlSiC MMC.

5.2 FUTURE SCOPE

The investigation on cutting forces and surface roughness in the face milling operation on AlSiC MMC with an HSS tool has provided valuable insights into the machining process. However, there are several potential areas for future exploration that can further enhance our understanding and optimize the machining performance of AlSiC MMC.

One promising direction for future research is the optimization of cutting parameters. While the current study analyzed the effects of cutting speed, feed rate, and depth of cut, there is room for conducting a comprehensive parametric study using advanced optimization techniques. By determining the optimal combination of cutting parameters, researchers can minimize cutting forces and achieve superior surface finish in the machining of AlSiC MMC.

Another area of interest is the investigation of different tool materials and geometries. Comparing the performance of HSS tools with other materials, such as carbide or ceramic, can help identify the most suitable tool for machining AlSiC MMC. Additionally, studying the effects of various tool geometries, such as rake angle and cutting edge geometry, can provide insights into their impact on cutting forces and surface roughness.

The implementation of effective cooling and lubrication techniques is also worth exploring. Advanced cooling and lubrication methods, such as minimum quantity lubrication (MQL) or cryogenic cooling, can significantly influence cutting forces and surface roughness. Investigating the use of these techniques can help reduce tool wear, temperature rise, and cutting forces, ultimately improving surface quality in AlSiC MMC machining.

Further research can also focus on the influence of material properties and reinforcements. Exploring different reinforcement materials, varying reinforcement content, and distribution within the matrix can provide insights into the machinability of AlSiC MMC compositions. Understanding the effects of these factors on cutting forces and surface roughness can aid in optimizing the material composition for improved machining performance.

Advanced machining techniques offer another avenue for future exploration. High-speed machining, vibration-assisted machining, and adaptive control strategies can be investigated to optimize the machining process. These techniques aim to minimize vibrations, control heat generation, and enhance chip evacuation, resulting in improved surface quality in the machining of AlSiC MMC.

Lastly, conducting a comprehensive analysis of the machined surfaces through advanced characterization techniques can provide a deeper understanding of the effects of cutting forces on surface integrity. Analyzing surface morphology, tool-chip interaction, and potential defects or anomalies can help identify areas for improvement and guide future machining strategies.

By addressing these areas, researchers can contribute to the development of optimized machining strategies, improved tool designs, and enhanced surface quality in the face milling operation on AlSiC MMC with an HSS tool. This will ultimately advance the field of machining composite materials and pave the way for their wider application in various industries.

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