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BSc in Mechanical Engineering Sciences

STUDY OF MACHINABILITY OF METAL MATRIX COMPOSITES PRODUCED BY UPWARD FRICTION STIR PROCESSING

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Study of machinability of metal matrix composites produced by upward friction stir processing

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To all my family and friends and specially to myself.

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ABSTRACT

Metal matrix composites (MMC) are materials that have attracted a lot of attention in several industries such as aerospace and automotive due to their excellent mechanical properties. Nowadays, one of the most used process to produce MMC is the Friction Stir Processing (FSP), which modifies the microstructure of the metal and allows the addition of reinforcement particles.

Most of these materials require machining operations to obtain the desired shape, size and surface quality. However, machining of MMC is usually associated with high cutting forces, severe tool wear and poor surface quality.

In this investigation, MMC were produced via an innovant variant known as Upward Friction Stir Processing (UFSP), by adding SiC particles to the aluminium matrix. Subsequently, several milling operations were performed, where the cutting speed and feed rate were varied in order to analyse the evolution of cutting forces as well as tool wear and surface roughness. Thus, it was possible to have a perception of the most suitable parameters for machining these materials.

The results achieved demonstrate that these three indicators are interrelated, and that tool wear is the most critical parameter in the milling of MMC. Additionally, also the particle distribution in the matrix had influence on the results.

Keywords: Metal matrix composites, Milling, Cutting force, Tool wear, Surface quality

RESUMO

Os compósitos de matriz metálica são materiais que têm atraído muita atenção em várias indústrias, tais como a aeroespacial e automóvel, devido às suas excelentes propriedades mecânicas. Atualmente, um dos processos mais utilizados para produzir compósitos de matriz metálica é o *Friction Stir Processing* (FSP), que modifica a microestrutura do metal e permite a adição de partículas de reforço.

A maioria destes materiais requer operações de maquinação para obter a forma, tamanho e qualidade de superfície desejada. Contudo, a maquinação de compósitos de matriz metálica está normalmente associada a elevadas forças de corte, desgaste severo da ferramenta e má qualidade superficial.

Nesta investigação, os compósitos de matriz metálica foram produzidos através de uma variante inovadora conhecida como *Upward Friction Stir Processing* (UFSP), adicionando partículas de SiC à matriz de alumínio. Seguidamente, foram realizadas várias operações de fresagem, onde a velocidade de corte e o avanço foram variados de modo a analisar a evolução das forças de corte, bem como o desgaste da ferramenta e a rugosidade da superfície. Assim, foi possível ter uma perceção dos parâmetros mais adequados para a maquinação destes materiais.

Os resultados obtidos demonstram que estes três indicadores estão inter-relacionados, e que o desgaste da ferramenta é o parâmetro mais crítico na fresagem de compósitos de matriz metálica. Além disso, também a distribuição de partículas na matriz teve influência nos resultados.

Palavas chave: Compósitos de matriz metálica, Fresagem, Força de corte, Desgaste da ferramenta, Qualidade superficial

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NOMENCLATURE AND SYMBOLS

BUE	Build-up edge
CNC	Computer Numerical Control
FSP	Friction Stir Processing
FSW	Friction Stir Welding
<i>F_x</i>	Cutting force component according to the <i>x</i> direction
MMC	Metal Matrix Composites
SEM	Scanning Electron Microscope
SiC	Silicon Carbide
UFSP	Upward Friction Stir Processing

1 INTRODUCTION

1.1 Motivation

The use of lightweight metals such as aluminium has gained great importance in many industries, like aerospace and automotive. However, these materials are still not suitable in some areas where a lightweight material with high strength is needed. In order to improve the mechanical properties of metals, a microstructural modification and addition of reinforced material is required [1]. Friction Stir Processing (FSP) is one of the methods that allows to do that by including reinforced particles in the metal matrix.

Machining is one of the oldest methods to get the desired size, shape with specific quality and surface finish of the component. Hence, about 80% of manufactured parts need machining before they are ready to use [2]. Additionally, Metal Matrix Composites (MMC) have gained great relevance in several industrial applications and have been replacing the conventionally used metals [3] due to their excellent mechanical properties. However, machining this type of material is not an easy process. MMC are inhomogeneous materials and their machining is normally associated with high tool wear and damage of work piece, due to the hard and abrasive nature of reinforcement [4]. Thereby, alternating machining of matrix and reinforcement materials causes fluctuating tool load and therefore fatigue failure. So, the separation of material is achieved by brittle fracture instead of plastic deformation [5]. Hence, the selection of tool material is crucial for the good functioning of the process. Thus, a key point is that the tool material has to be harder than the work piece material. However, the tool selection also depends on other parameters, such as: MMC composition, environmental stimuli, type of reinforcement (particle dimension) [6], type of machining operation (dry, wet or flood cutting) [7] and roughing or finishing operation [3]. Therefore, because of the high costs associated with cutting tools, machinability of MMC and optimization of cutting parameters are still an area of great interest and research [3].

1.2 Objectives

The objective of this research work is to develop systemic analysis of the variables that define the machinability of aluminium alloys with reinforcement particles produced by upward friction stir

processing (UFSP). So, it is crucial to investigate the influence of cutting parameters and reinforcement material on the forces, tool wear and surface quality.

In order to achieve the goals mentioned above, metal matrix composites produced by UFSP were machined through milling tests. During the tests the cutting forces were recorded using a dynamometer and a charge amplifier. Tool wear was analysed through a microscopic analysis at the end of each experiment and through Scanning Electron Microscope (SEM). Finally, surface roughness values of the machined surfaces were measured with a rugosimeter.

1.3 Document structure

This document is divided into five chapters to allow a better organisation and understanding of the dissertation.

Chapter one provides a brief initial introduction to the theme of the dissertation. That includes the motivations for the choice of this theme, the objectives which are intended to be reached during this period and the structure of the document.

In chapter two, it is presented the revision of the state of the art about MMC, FSP and machining of MMC. In the machining part the influence of cutting parameters, reinforcement material and type of tool on tool wear, surface quality and cutting forces is discussed.

Chapter three describes the experimental methodology, which includes the production of MMC by UFSP, milling tests of the produced samples and evaluation of cutting forces, tool wear and surface quality.

In chapter four, the results obtained on the milling tests are presented and discussed.

Chapter five gives conclusions about the developed work, as well as suggestions and improvements about the machining process of MMC.

2 STATE OF THE ART

2.1 Metal Matrix Composites

Metal Matrix Composites (MMC) are inhomogeneous materials [4] that have attracted attention and are being increasingly used in several industries, like aerospace and automotive, due to their exciting properties, such as: low density, high fatigue strength and specific modulus, good thermal conductivity and wear resistance [8]. The selection of both matrix and reinforcement material is crucial to obtain the desired properties for a specific application [9]. MMC are composed by a metal, matrix material, and one or more reinforcement materials.

The most used metal matrix materials in preparation of the composite are aluminium, manganese, titanium, copper and their alloys. Figure 2.1 shows the distribution of published articles based on the type of matrix material. As can be seen, aluminium is the most commonly used material for this purpose [3], being also used as matrix material in the work under development.

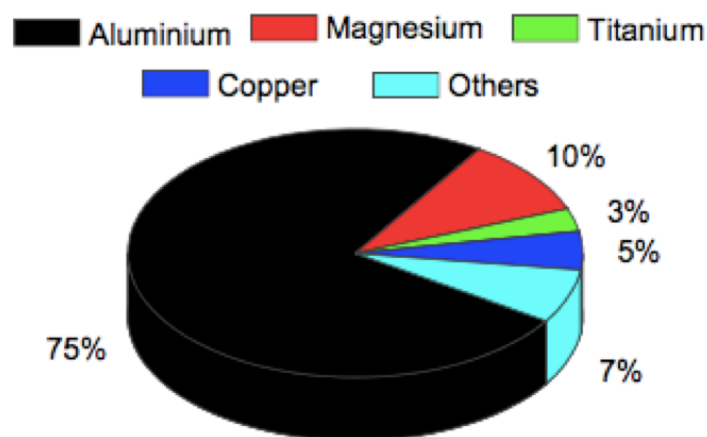


Figure 2.1 - Distribution of published articles based on the type of matrix material [3].

Reinforcement helps to improve the mechanical properties of the matrix by offering, for example, high tensile strength, improved wear resistance, high or low thermal conductivity, good fatigue strength,

corrosion resistance, high hardness and high strength to weight ratio [3]. Therefore the selection of reinforcement material is crucial to achieve certain properties and it is necessary to take into consideration factors like price, mechanical properties, thermal and electrical conductivity, melting point, among others [9]. The reinforcement materials normally used to reinforce the metal matrix are oxides, carbides, nitrides, borides or combination of any two [10]. Additionally, it is important to mention that, of all reinforcement methods, particulate reinforced MMC present several advantages such as: low cost, easy to fabricate, good isotropic properties and good machinability [8].

2.2 Friction stir processing

Friction Stir Processing (FSP) is a solid-state process derived from the basic principles of Friction Stir Welding (FSW) where the objective is to modify the base material (matrix) microstructure and properties. During the process the material is subject to intense plastic deformation allowing its properties to be modified. In composite fabrication FSP presents several advantages when compared with other processes, like energy saving, environmental friendly, high efficiency and low cost [11]. This process involves a rotating tool, composed by a shoulder and a probe/pin, that plunges with pressure into the workpiece and moves in the processing direction, as shown in Figure 2.2. The tool is responsible for the generated heat, caused by the friction between the rotating tool shoulder and the workpiece, and the plastic deformation in the material [12].

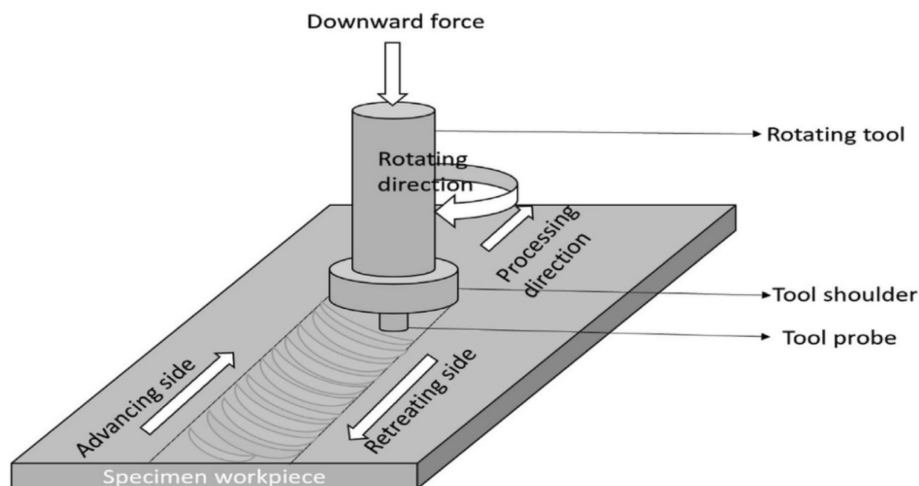


Figure 2.2 - Schematic illustration of FSP Technique [12].

Nowadays, FSP is one of the most employed processes to produce MMC, by modifying the microstructure of metals through the addition of reinforcement materials. The manufacture of this type

of material using this process is divided into preparation of substrate, preparation of the holes or grooves on the substrate to reinforcement insertion, capping of reinforcement using pinless tool, fabrication of MMC using FSP procedure with optimized parameters and preparation of specimens for different tests. The efficiency of FSP is dependent on tool/process variables. So, through optimization of these parameters, the desired material properties can be obtained. [13].

In this research work, the technique used to produce the MMC is an innovate variant known as Upward Friction Stir Processing (UFSP). In contrast with FSP, this technique promotes an upward flow of material. This flow is reached, for right-hand thread, by a clockwise rotation of the tool and allows to introduce more particles with a more uniform distribution over the processed volume. The particles are confined between two plates and a spacer is used to ensure the desire quantity and the uniform distribution of this particles, as shown in Figure 2.3 [14]. However, these composites still need to be machined to get the desire size, shape and surface quality. The study of the machinability of this type of materials is the main purpose of this work and will be approach next.

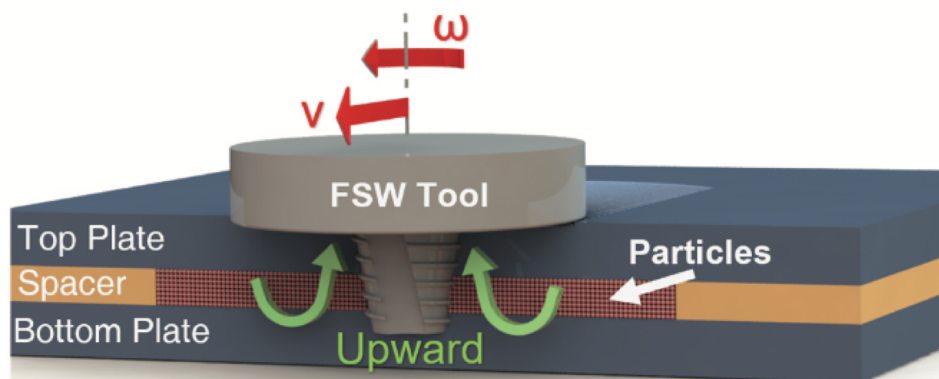


Figure 2.3 - Schematic representation of the Upward Friction Stir Processing [14].

2.3 Machining of Metal Matrix composites

Generally speaking, machining operations are understood as those that give the workpiece the desired shape, dimension, finish or any combination of these three. Such operations are based on the material removal and the portion of material removed is referred to as chip. During this process the movements between the workpiece and the tool are relative movements [15]

In order to achieve high dimensional accuracy and the required surface quality of the MMC produced by FSP, machining processes are essential. However this process presents some difficulties because of the hardness and abrasiveness of reinforcement material [4]. Therefore, it is important to study the variables that define this process. The machinability of this type of material is determined by

a combination of factors, which are: reinforcement material, type and size of reinforcement, volume fraction of reinforcement, matrix properties and distribution of particles in the matrix [5]. Surface quality and evolution of tool wear are key aspects and can be affected during machining of MMC. Moreover, characteristics such as cutting forces, energy consumption and specific cutting energy are also crucial to investigate this operation. These characteristics will be discussed below according to the results achieved in different studies.

2.3.1 Milling process

The milling process is a machining operation where the tool is usually multi-cutting, which means that possesses more than one cutting tooth. In this process the tool rotates and the workpiece or tool moves according to a specific path. Basically, two types of milling are distinguished: [15]

- Tangential milling
- Frontal milling

Tangential milling, represented in Figure 2.4, is characterized by the fact that the flat surface obtained is parallel to the tool rotation axis. This type of milling also has two variants according to the tool rotation direction and the feed direction. Down milling when the rotation direction coincides with the feed direction and up milling when the rotation direction is opposite to the feed direction. On the other hand, in frontal milling the flat surface obtained is perpendicular to the tool rotation axis, as can be seen in Figure 2.5 [15].

In order to study this process, it is important to have some basic concepts. Among all the concepts stand out the cutting parameters, namely the feed rate, the cutting speed, the axial depth of cut and the radial depth of cut. Feed rate is the progression of the tool made in one revolution or one cycle. Regarding the cutting speed, it corresponds to the instantaneous speed of the reference point of the cutting edge, according to the cutting direction. Axial depth of cut is the distance between the tool tip and the unmachined surface, measured perpendicularly to the working plane. On the other hand, radial depth of cut corresponds to the size of the cutting area measured in the working plane and in perpendicular direction to the feed direction. Both axial and radial depth of cut are shown in Figures 2.4 and 2.5 [15].

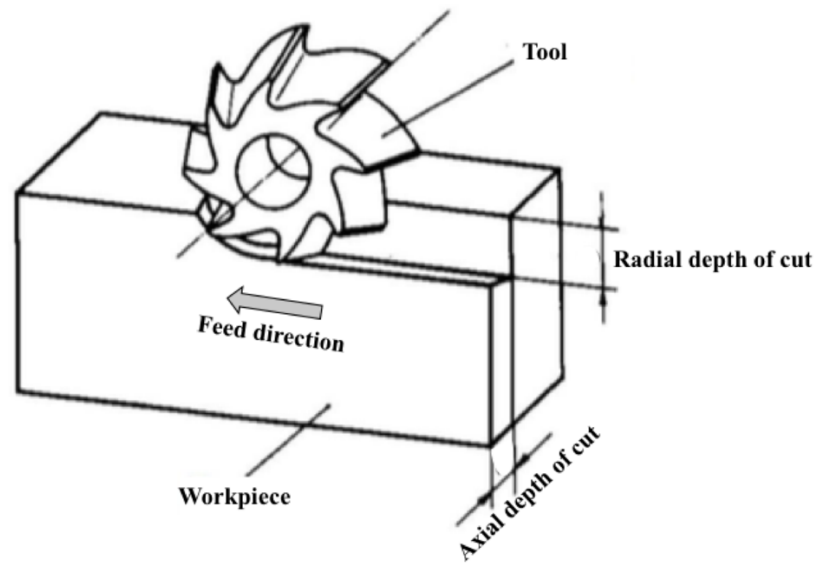


Figure 2.4 - Tangential milling [15].

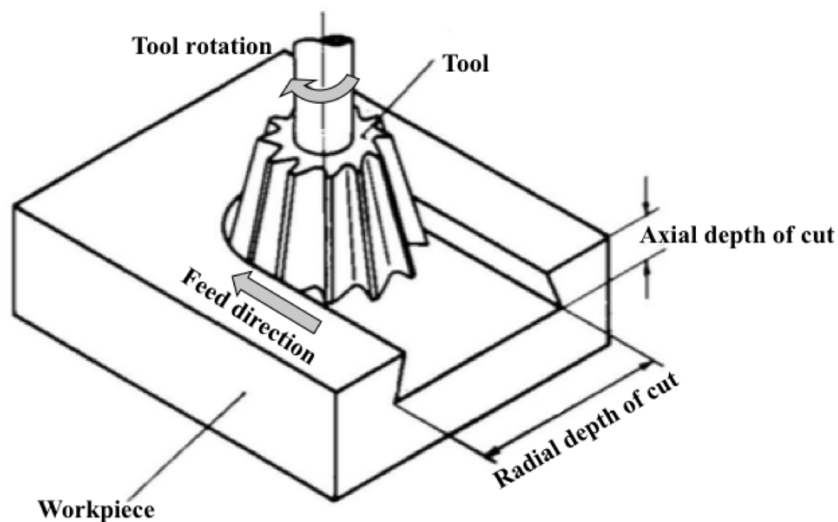


Figure 2.5 - Frontal milling [15].

2.3.2 Cutting forces

The analysis of cutting forces is another key factor to define the machinability of MMC. Cutting forces are associated with energy transformed into heat and so, can be related with tool wear and surface quality. The evolution of this aspect depends on both the machining parameters and material properties. Hence, the investigation of factors such as cutting parameters, volume fraction of reinforcement and particle size is crucial to optimise this factor.

- Cutting parameters

In the research work realized by Mahanta et al. [16], the influence of cutting speed and feed rate on cutting forces during turning of Al6063 reinforced with SiC particles was studied. By the achieved results it was concluded that the increase of cutting speed leads to the decrease of cutting forces. This can be explained by the consequent increase of the generated heat in the cutting zone, which decreases the shear stress and resistance of the material against the moving cutting edge. So, the forces needed to cut the material are lower. With regard to the feed rate, it was seen that its increase implies the increase of cutting forces. Contrary to cutting speed, the increase in feed rate is related to higher shear stress in the cutting zone and higher resistance of the material against the moving cutting edge, resulting in increased cutting forces.

Shoba et al. [17] analysed the effect of cutting parameters on the evolution of cutting forces while machining hybrid MMC. They found out that increasing the cutting speed contributes to a decrease in cutting forces, as shown in Figure 2.6, due to thermal softening of the work piece. On the other hand, an increase in cutting forces was observed when the feed rate increased, as illustrated in Figure 2.7, because of the higher friction between the cutting edge and the workpiece. Additionally, it was verified that the increase of the depth of cut leads to higher cutting forces. This event is related to the associated increase of contact area between the cutting edge and the work piece.

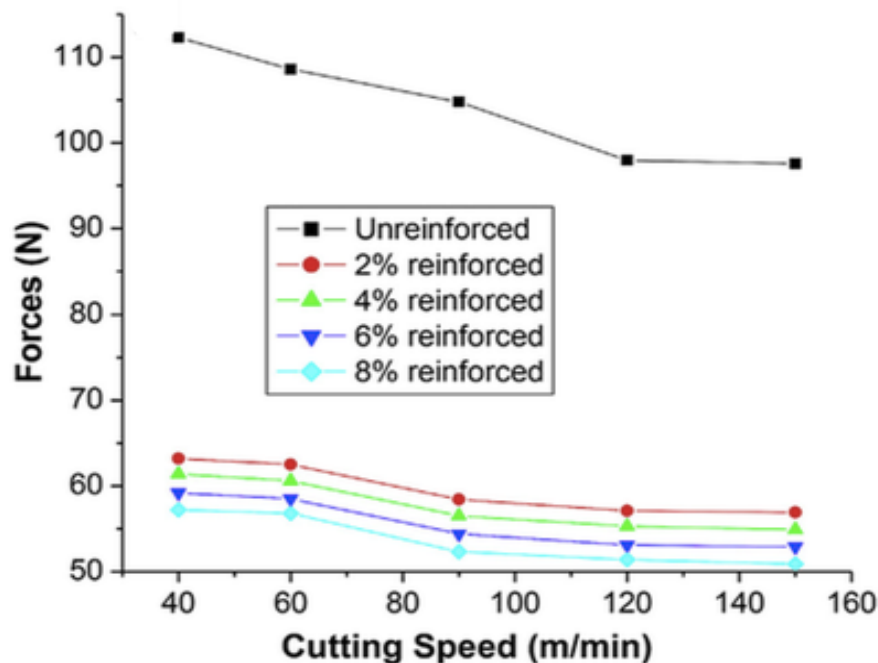


Figure 2.6 - Variation of cutting force with cutting speed at constant feed 0.14 mm/rev and depth of cut 0.5 mm [17].

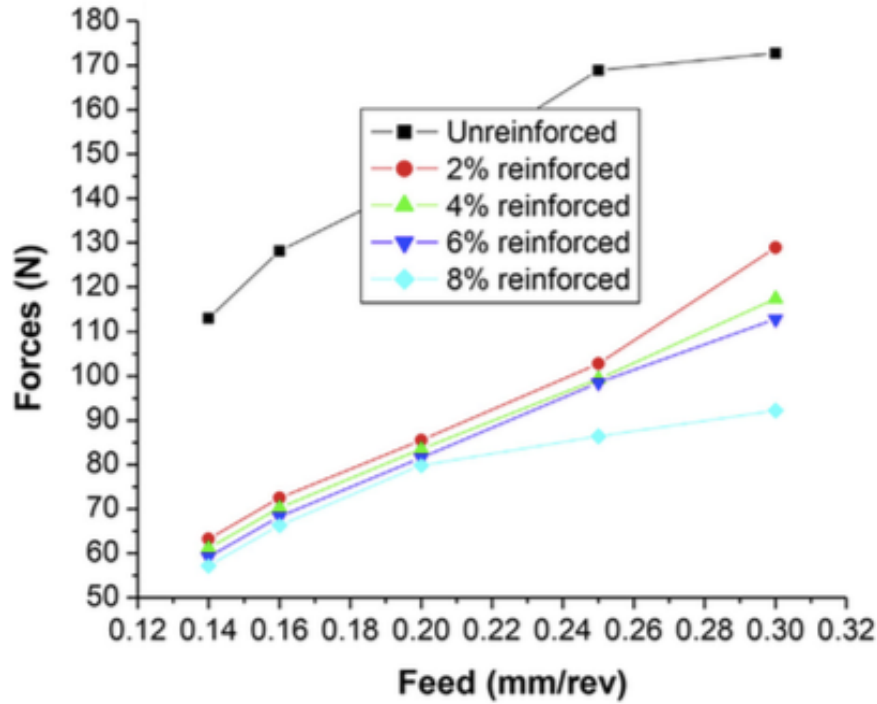


Figure 2.7 - Variation of cutting force with feed at constant cutting speed 150 m/min and depth of cut 0.5 mm [17].

The impact of varying the cutting parameters on the cutting forces achieved was further investigated by Anandakrishnan et al. [18]. During turning of Al-6061/TiB₂, the results were similar to those obtained in [16,17]. So, it was observed that the increase of cutting speed contributes to a reduction of cutting forces. Furthermore, higher cutting forces were recorded when the feed rate and depth of cut were increased.

Gaitonde et al. [19] studied the effect of feed rate and cutting speed on machining force, cutting power and specific cutting force by creating second-order mathematical models using response surface methodology (RSM). To validate the mathematical models these parameters were analysed during the turning of aluminum alloy reinforced with SiC particles using a polycrystalline diamond (PCD) tool. Regarding the cutting force, the results were similar to those obtained in [16]–[18]. In what concerns the cutting power and the specific cutting force, the outcomes are represented in Figure 2.8 and 2.9, respectively. As can be seen in Figure 8, cutting power increase with both feed rate and cutting speed, being highly sensitive to variations in cutting speed at higher values of feed rate. By the observation of Figure 9 it is possible to conclude that the specific cutting force decrease with both feed rate and cutting speed, being more sensitive to the feed variation than to the speed variation.

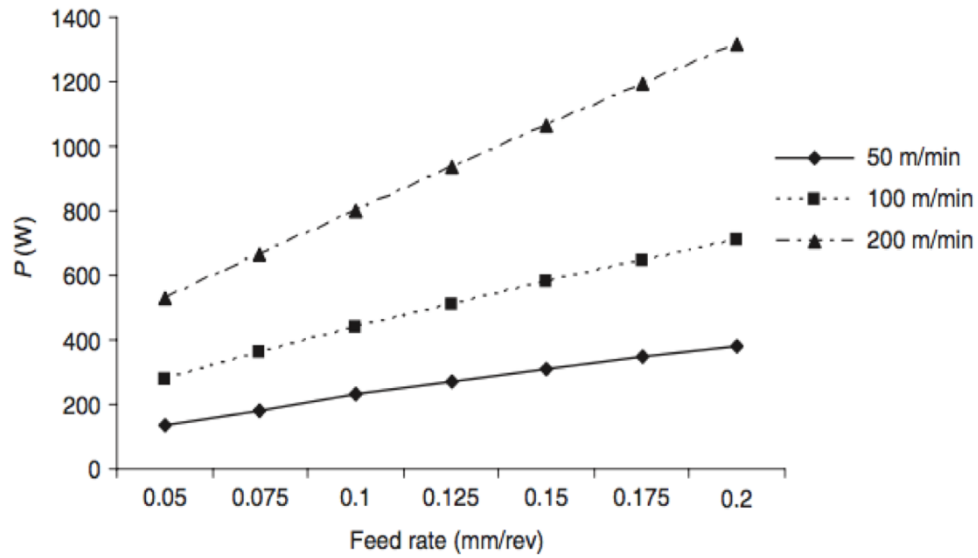


Figure 2.8 - Effect of cutting speed and feed rate on cutting power [19].

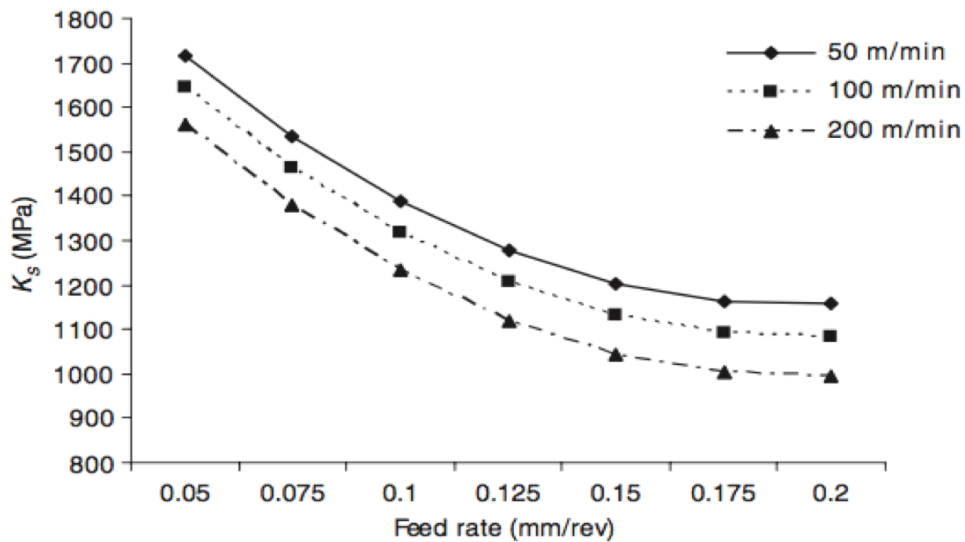


Figure 2.9 - Effect of cutting speed and feed rate on specific cutting force [19].

- Reinforcement material

Mahanta et al. [16] further investigated the impact of the amount of reinforcement particles on cutting forces. They observed that a higher percentage of SiC particles leads to higher cutting forces. This phenomenon is explained by the consequent increase of the resistance of the material to plastic deformation during the cutting process.

In the study carried out by Shoba et al. [17], it was found that the increase of volume fraction of reinforcement originates the decrease of cutting forces. This can be explained by 3 factors. First of all, as the volume fraction increases, hardness also increases, which results in the chip formation by large

plastic shear. On the other hand, this reduction can be caused by the increase in porosity, which results in lower forces to cut the composite in the areas with pores. Finally, it can be associated with BUE formation at lower volume fractions, that is caused by the adherence of the chips to the cutting tool. The evolution of cutting forces with the percentage of reinforcement particles is represent in Figures 2.6 and 2.7, presented before.

Teng et al. [20] performed a cutting mechanism comparison of Al/SiC MMC reinforced with micro and nano particles using finite element method. To validate this model a comparison was made between the results obtained from simulation model and micro milling experiments. Cutting force was evaluated and it was possible to establish that in micro MMC there is a larger cutting force fluctuation when compared to that in nano MMC. The greater fluctuation of cutting force observed during machining of micro MMC is related to fragmented chip formation and to increased kinetic energy of micro particles during tool-particles interaction.

In order to verify an analytical model developed for force prediction when machining MMC, Sikder et al. [21] performed cutting tests on aluminium MMC reinforced with alumina particles and analysed the effect of volume fraction and particle size of reinforcement on cutting forces. The resulting cutting forces generated during the machining of this type of material are mostly produced by cutting and ploughing of the metal matrix and debonding and fracture of the reinforcement particles. In that sense, it was observed that the increase of volume fraction of alumina particles results in higher cutting forces because of the increase in the frictional force along the chip-tool interface and the debonding force. In relation to the particle size, it is expected that the increase of this parameter contributes to increased cutting forces. This can be explained by the greater calculated debonding energy per particle, shown in Figure 2.10 and which is related to an increase in the contact surface during this event, and by the higher frictional force on the chip-tool interface.

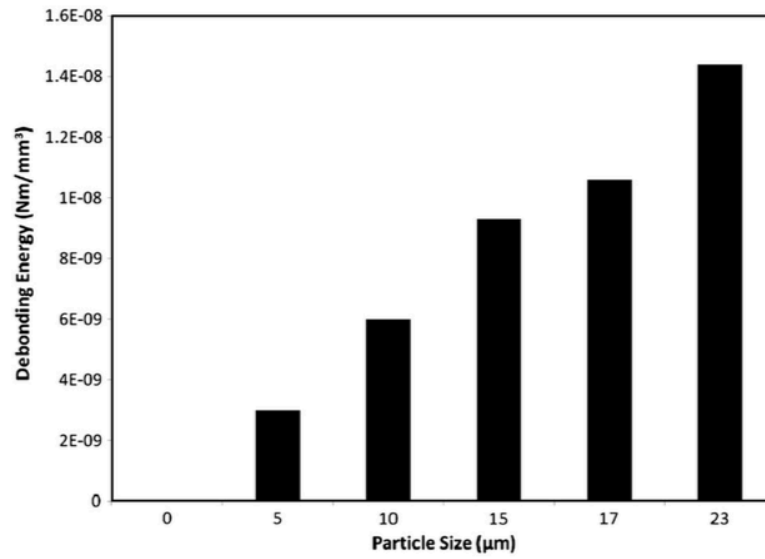


Figure 2.10 - Debonding energy per particle [21].

Anandakrishnan et al. [18] also investigated the influence of percentage of reinforcement particles on cutting forces and the results are in agreement with those obtained in [17]. Therefore, cutting force reduces with the increase of percentage of reinforcement material. This is mainly justified by the consequent minimization of BUE formation, which contributes to decrease the cutting force.

2.3.3 Tool wear

The machining of MMC is typically linked with high tool wear, which is a critical point in this process. Hence, it is important to try to minimise this wear, in order to increase tool life. Thus, the analysis of factors like cutting parameters, type of tool, volume fraction of reinforcement and particle size is fundamental to improve this aspect.

- Cutting parameters

Ozben et al. [22] analysed the influence of cutting parameters on tool wear during turning of AlSi7Mg2-MMC reinforced with SiC particles. To this purpose, a TiN coated WC (K10) tool was used and several tests were performed, varying the values of cutting speed, and feed rate, as illustrated in Figures 2.11 and 2.12. The increase of cutting speed when feed rate and cutting depth are constants, causes increased tool wear. In terms of feed rate, it was also found that the increase of feed rate implies the increase of tool wear. However, it was observed that cutting speed has more influence than feed rate on this aspect.

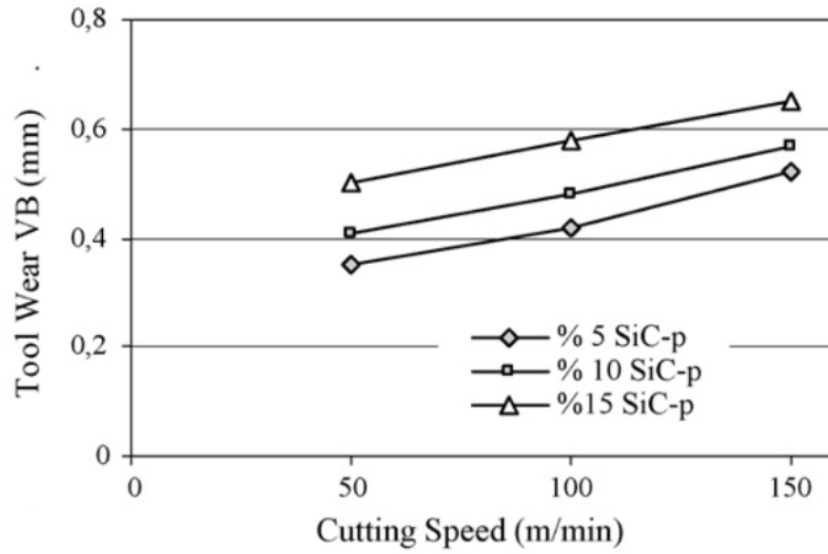


Figure 2.11 – Effect of cutting speed on tool wear (feed rate = 0.1 mm/rev) [22].

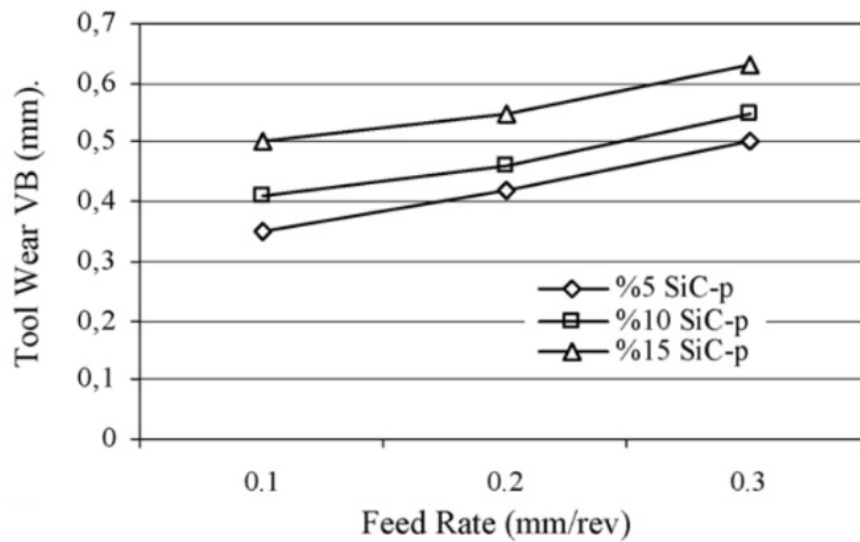


Figure 2.12 – Effect of feed rate on tool wear (cutting speed = 50 m/min) [22].

Kilickap et al. [23] investigated the effect of cutting parameters on tool wear. The selected machining process was turning method and the selected tool was titanium carbide K10 grade. In accordance with the achieved results on [22], it was noticed that increase of cutting speed and feed rate increased tool wear. Additionally, the increase in depth of cut resulted in a slightly increased tool wear.

In the study conducted by Manna et al. [24], the influence of cutting parameters on tool wear was again evaluated. To this end, turning operations of silicon carbide particulate aluminium MMC without use of coolant were performed using an uncoated tungsten carbide tool. The obtained results show that the increase of cutting speed and feed rate is linked with increased tool wear. It was also established

that, for this material, the best suitable cutting speed range for low tool wear and consequently lower machining cost is 60-100 m/min.

Rao et al. [25] studied the impact of cutting speed and feed rate on tool life during turning of Al6061 reinforced with fly ash containing ceramic particles. For this purpose, it was used a K10 Grade carbide inserts and the criteria for changing cutting edge was failure of cutting tools due to built up edge formation followed by micro chipping, chipping of the cutting edge and notch wear. As expected, it was found that tool life decreases with the increase of cutting speed and feed rate. It was also found that the failure of cutting tools are mainly due to notch wear, which occurs at the end of radial depth, intersection of rake and flank surface.

Übeyli et al. [26] analysed the effect of feed rate on tool wear in Milling of Al-4% Cu/B₄C_p Composite and found out that, unlike the results obtained in [22]–[25], the flank wear decreases with an increase in the feed rate at a modest rate, as demonstrated in Figure 2.13. The most likely justification for this trend is related to the decrease in the contact between the cutting tool and the hard particles of the composite at higher feeds. In addition, they also concluded that in milling of aluminium matrix composite the use of lower cutting speeds and higher feed rates is beneficial to decrease the flank wear.

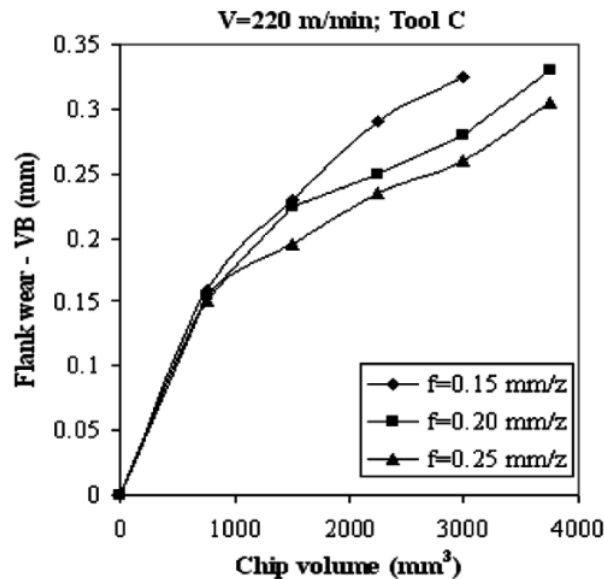


Figure 2.13 - Flank wear variation at various feed rates and for cutting speed of 220 m/min [26].

In general, it was found that the increase of cutting parameters is related with increased tool wear. Furthermore, cutting speed is the most influential parameter and its effect is similar to machining any material, since cutting tool wears out faster with the use of higher cutting speed [23]. This is due to the consequent increase of heat generated by the contact between the tool and the workpiece. Therefore, the selection of an appropriate value for this parameter is essential to improve the tool life.

- Reinforcement material

Ozben et al. [22] also investigated the effect of volume fraction of SiC-p on tool wear and the achieved results are also shown in Figures 2.11 and 2.12. As can be seen, tool wear increases with increasing volume fraction of reinforcement material. This is because of the abrasive nature of reinforcement elements that causes higher wear on cutting tools.

Rao et al. [25] further analysed the impact of the percentage of reinforcement material on cutting tool life. Firstly, it was verified that increasing this percentage results in an increase of hardness of the composite. Then, it was noted that the increase of volume fraction of fly ash results in a decrease of tool life. This decrease is related to the increase of the hardness of the material, which leads to a higher tool wear.

Li et al. [27] studied the influence of the percentage of reinforcement and the size of particles in cutting tool wear during turning of aluminium- silicon carbide metal matrix composite (Al-SiC MMC) using tungsten carbide tools. They realized that both parameters are important for the machinability of MMC in terms of tool life. In general, the increase of these parameters leads to increased tool wear, as shown in Figure 2.14. This happens due to the tendency of the cutting tool to move this hard and brittle particles, instead of cutting or breaking them. Hence, the particle can be dislodged from the workpiece or embedded into the matrix. During this process, if the particle hits a neighbouring particle its movement will be impeded, as represented in Figure 2.15. Consequently, the particle will receive additional resistant forces from the interference and damage the tool due to the higher hardness of the reinforcement material compared to the cutting tool.

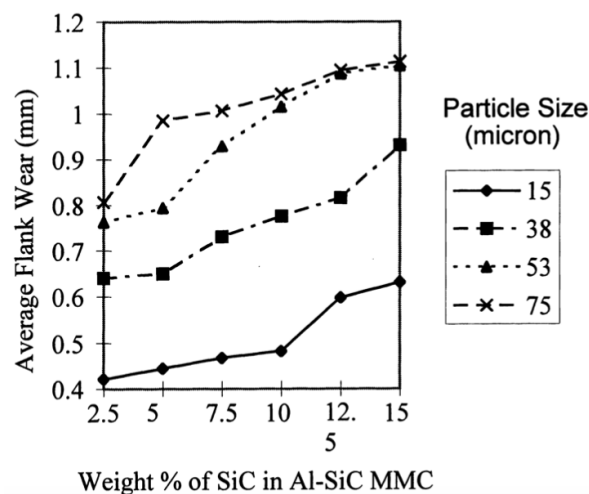


Figure 2.14 – Effect of the percentage of reinforcement and size of the particles on tool wear (cutting speed = 39.27 m/min; feed rate = 0.1 mm/rev; depth of cut = 1 mm) [27].

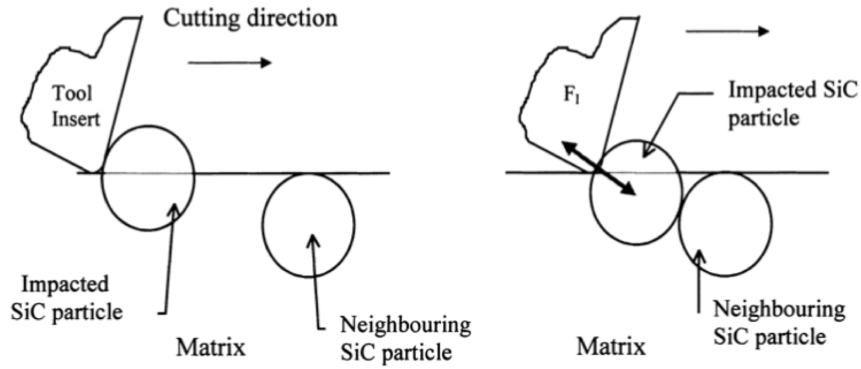


Figure 2.15 – Particle impacted by tool cutting edge hits a neighbouring particle [27].

In this research work it was also found that there is a critical value of reinforcement percentage above which the flank wear rate increases quickly. When this value is reached, the inter-particle spacing in the MMC is not large enough for the particle to be dislodged or embedded without interfering with a neighbouring particle. As can be seen in Figure 2.15, the size of the particle also influences the critical value of reinforcement percentage. The increase of the size results in a decrease of the critical percentage, as larger particles need longer paths when they are dislodged or embedded. Figure 2.16 shows the effect of particle size on theoretical and experimental critical SiC weight percentage [27].

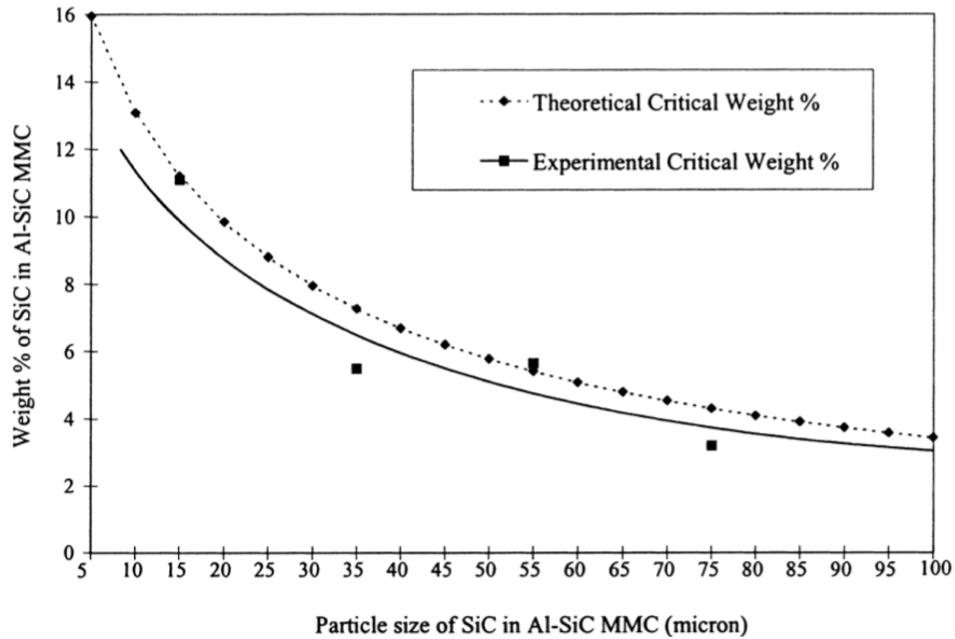


Figure 2.16 – Theoretically predicted values and the average values of experimental value bands of the critical SiC weight percentage varying against the size of SiC particle [27].

Ciftci et al. [28] conducted machining tests performed by continuous turning of 2014 Al alloy reinforced with SiC particles using coated and uncoated grade cemented carbide tools. They also

investigated the impact of the percentage of reinforcement and the size of particles in tool wear. In agreement with the results obtained previously, tool wear increased with increasing particulate weight percentage and size. Additionally, it was found that flank wear was the main wear mode and the primary reason for this wear was the abrasive nature of the reinforcement material. Moreover, it was observed that it was inappropriate to machine this composite with this cutting tool when the size of the particles increased to 110 μm due to the heavy fractures of the cutting edge.

Teng et al. [20] evaluated the difference on tool wear while machining MMC reinforced with micro and nano particles and it was observed that the high contact stress at tool-particle interface is the main reason for this phenomenon. More specifically, the particle embedded in the fragmented chips slides along the tool rake face and causes a high localised contact region, which accelerates the tool wear. Additionally, as illustrated in Figure 2.17, a scanning electron microscope (SEM) analysis was performed for both micro and nano particles reinforced MMC and it was found that the flank face of the tool used in machining nano particles presented a rounded tool tip and smooth abrasive wear. On the other hand, the machining of micro particles caused severe cutting edge chipping and fracture of tool tip. The noted difference on tool wear is linked with the good mobility with the matrix deformation and the small kinematic energy of nano particles when compared to micro particles. Hence, it can be concluded that the smaller particle size is beneficial to improve tool life.

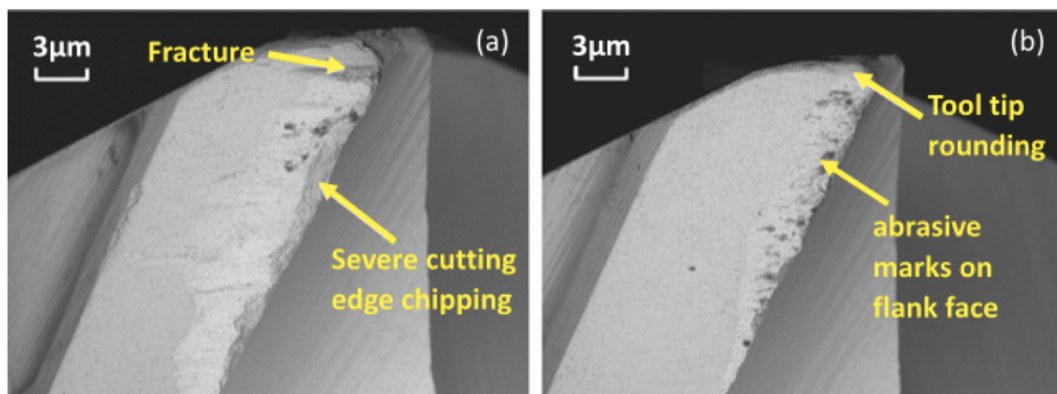


Figure 2.17 - SEM micrographs of main cutting edge wear of micro endmill obtained from machining Al/SiC MMCs reinforced with (a) micro-sized particles; (b) nano sized particles under feed per tooth 4 $\mu\text{m}/\text{tooth}$, cutting speed of 125.64 m/min and depth of cut of 30 μm [20].

- Type of tool

In the study conducted by Kilickap et al. [23], the difference between the use of coated and uncoated carbide tools on tool wear was evaluated. It was seen that the coating of cutting tool provided a lower tool wear, because it made the tool surface harder than normal surface.

Ciftci et al. [28] also analysed the impact of using coated cutting tools on tool wear. For all the materials machined, coated cutting tools provided less flank wear than uncoated cutting tools. However, the better performance of coated tools is not entirely due to the coating, as microscopic evaluation showed that the coating was worn away completely in the cutting zone. Therefore, it can also be related with a larger and more stable BUE formation, which under certain conditions can protect the flank face.

2.3.4 Surface quality

Alongside tool wear, surface quality is another crucial point for analysing the machinability of a material. This aspect provides information about the quality of the cutting process and in the machining of MMC it is dependent on the materials used and working conditions. Therefore, the analysis of factors such as cutting parameters, type of tool, volume fraction of reinforcement and particle size is essential to improve the quality of the surface.

- Cutting parameters

In the research work carried out by Manna et al. [24] the evolution of surface roughness with the variation of cutting parameters was also analysed. For this purpose, it was evaluated the values of the arithmetic average roughness height, R_a [μm], and the maximum peak to valley of surface roughness height, R_t [μm]. In general, it was observed that R_a and R_t decreased with the increase of cutting speed and increased with the increase of feed rate and depth of cut, as shown in Figures 2.18, 2.19 and 2.20.

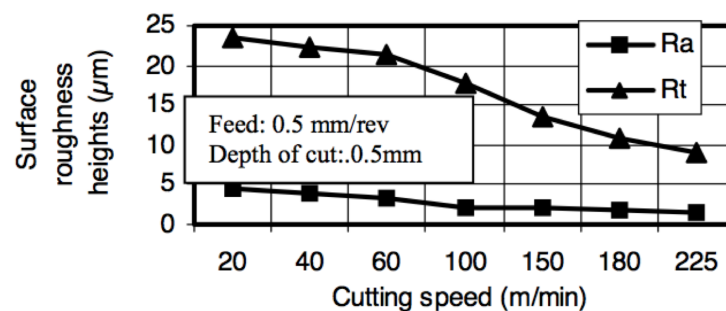


Figure 2.18 – Influence of cutting speed on surface roughness [24].

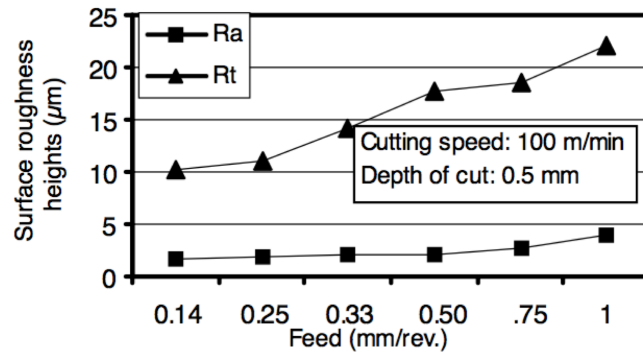


Figure 2.19 – Influence of feed rate on surface roughness [24].

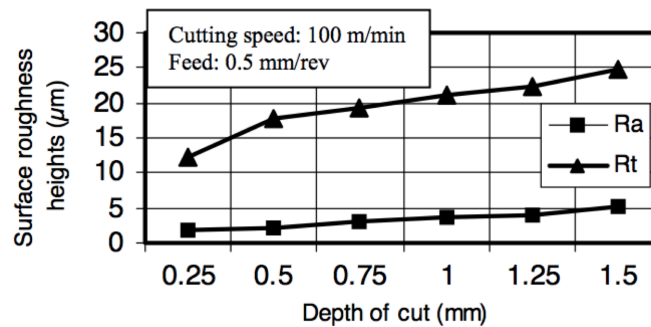


Figure 2.20 - Influence of depth of cut on surface roughness [24].

One of the factors that may be at the origin of poor surface quality is the formation of the built-up edge due to the adherence of reinforcement particles to the cutting tool materials during machining. It was also found that the formation of BUE is more likely at lower cutting speed and the increase of depth of cut implies an increase of the BUE. These results are in agreement with those obtained regarding the effect of cutting speed and depth of cut on surface quality [24].

Ajithkumar et al. [29] also analysed the effect of cutting parameters on surface roughness during turning of Al 7075 based hybrid composites. In the experimental procedure it was used uncoated and Diamond Like Carbon (DLC) coated carbide tool inserts. It was verified that surface roughness decreased with the increase of cutting speed and increased with the increase of feed rate and depth of cut. The impact of feed rate can be explained by the higher vibration of the tool while machining with increased feed rate.

- Reinforcement material

Cheung et al. [30] investigated the effect of reinforcement on surface generation in turning of Al/SiC MMC. It was established that to remove the reinforcement material in this process the particles can be cut through or pulled out. Cut through consists in the direct cutting of the particles and results in a

machined surface without pits and cracks. On the other hand, when the reinforcement is pulled out, the cutting surface presents cracks and pits. Therefore, in order to produce a better surface finish, it is favourable that the removal of reinforcement material is performed by the cut through mechanism. Figure 2.21 illustrates the mechanisms presented before and the respective surfaces obtained after cutting.

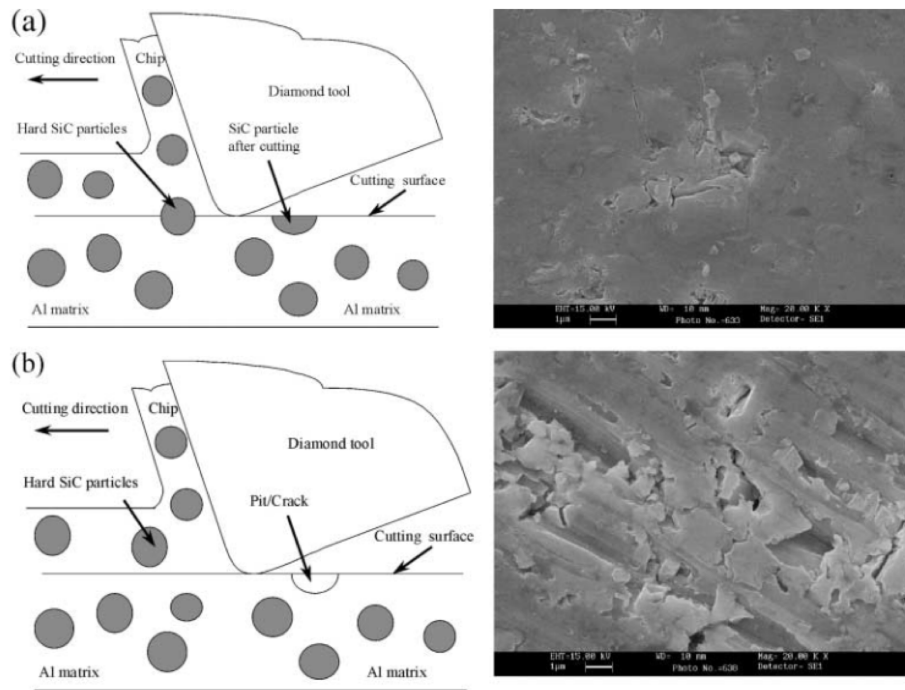


Figure 2.21 – Illustration of the a) cut through and b) pulled out mechanisms in cutting SiC particles [31].

In the study conducted by Ozben et al. [22] the effect of volume fraction of reinforcement on the surface roughness was also analysed. Thus, it was concluded that samples with higher percentage of SiC particles presented higher values of surface roughness. The reason for this occurrence is that some reinforcement particles are pulled out instead of being cut, causing small gaps in the machined surface. So, the higher the percentage of reinforcement, the higher the number of gaps in the surface.

Teng et al. [20] also investigated the influence of particle size in the surface quality. In general, this aspect can be affected by defects related to the reinforcement particles such as fragmented particles embedded within the machined surface, particles pressed into the matrix and cavities caused by particle detachment from the machined surface. The simulation of the effect of these defects on the surface after machining of micro and nano MMC is shown in Figure 2.22. As can be seen, the simulated surface morphology is identical for both micro and nano MMC.

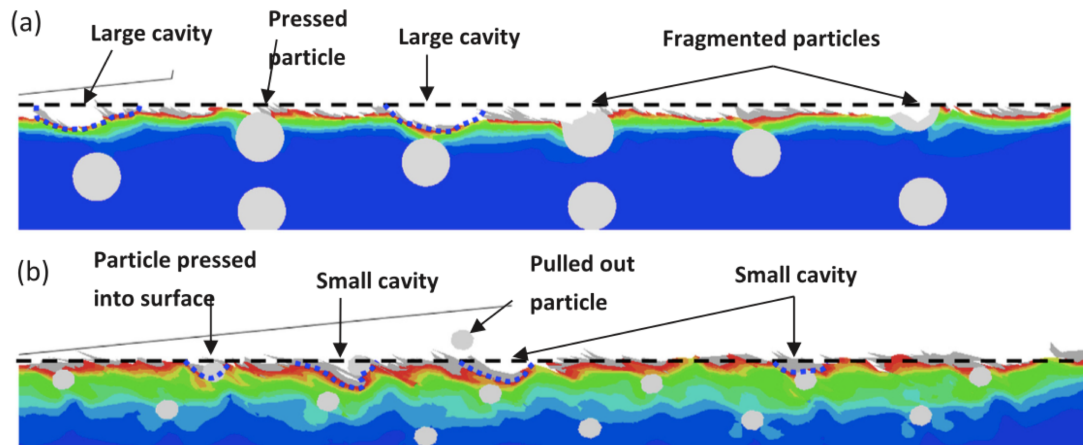


Figure 2.22 – Simulated surface morphology from machining a) micro MMC and b) nano MMC [20].

The results achieved by micro milling experiments of micro MMC were similar to those of the simulation. Large cavities, scratch marks and fragmented particles embedded within matrix were observed after cutting procedure. However, the surface morphology obtained after micro milling tests of nano MMC was not similar to that observed in the simulation. After cutting process, the distinct milling tool path is visible and there were only some micro defects that can be caused by the scratching of residual chips containing nano particles at the tool-matrix interface. Therefore, it can be said that the use of smaller particles is convenient to improve surface quality [20].

- Type of tool

Kilickap et al. [23] also investigated the difference between the use of coated and uncoated carbide tools on surface quality and the results were similar to those obtained for tool wear. This means that surface quality increased with using coated cutting tool.

During the experimental work performed by Ciftci et al. [28] the impact of using coated cutting tools on surface roughness was also evaluated. It was observed that the influence of the coating is related to the cutting speed. In general, contrary to what was observed in [23], uncoated carbides produced better surface finish. This can be explained by the larger BUE formation of coated cutting tools, which can be an indicator of poor surface finish. However, at higher cutting speeds coated cutting tools presented lower values of surface roughness than uncoated cutting tools. This can be attributed to edge chipping of uncoated tools at higher cutting speed.

3 EXPERIMENTAL METHODOLOGY

3.1 Characterization of the Base Material

The base material used in this work was the aluminium alloy AA7075-T651 in sheet form, with dimensions of 200 x 100 x 3 mm. In order to obtain mechanical properties such as ultimate tensile strength, fracture strength and elongation at fracture, uniaxial tensile tests were performed using standard specimens according to ASTM E8/E8M – 13a, as shown in Figure 3.1. The most relevant mechanical properties for machining operations and the chemical composition of this alloy are shown in Table 3.1 and 3.2, respectively.

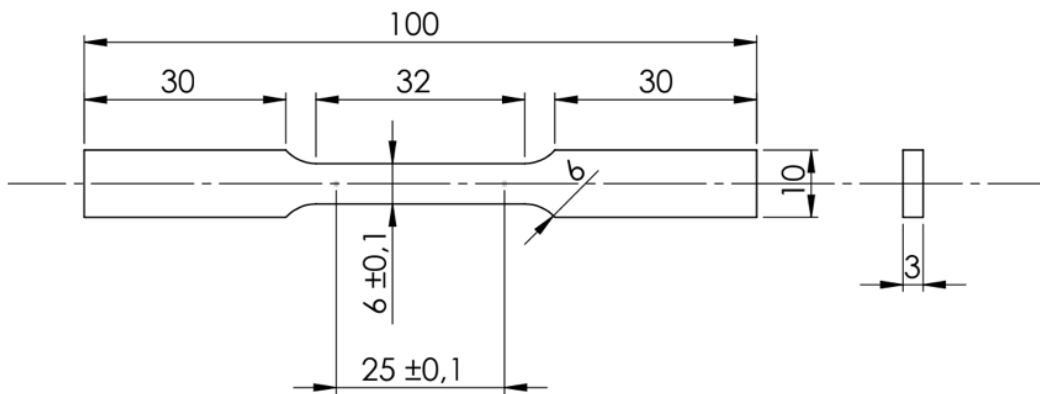


Figure 3.1 - 2D drawing of the standard specimen according to ASTM E8/E8M – 13a.

Table 3.1 – Average values and standard deviation of ultimate tensile strength, fracture strength and elongation at fracture obtained in the uniaxial tensile tests for the aluminium alloy AA7075-T651.

	Ultimate tensile strength [MPa]	Fracture strength [MPa]	Elongation at fracture [%]
Average	568	534	11.7
Standard deviation	8.9	16.3	0.7

Table 3.2 - Chemical composition of the aluminium alloy AA7075-T651 [32].

Elements	Weight (%)
Si	≤ 0.4
Fe	≤ 0.5
Cu	1.2 - 2
Mn	≤ 0.3
Mg	2.1 – 2.9
Cr	0.18 – 0.28
Zn	5.1 – 6.1
Ti	≤ 0.2
Al	87.32 – 91.42

3.2 Samples production via Upward Friction Stir Processing

In the first instance it was necessary to produce the samples to be machined. The production of these composites was performed by adding particles to the base material using the variant UFSP in the conventional 3-axis milling machine present in the laboratory of Mechanical Processes of NTI. During this process, a tool with a concave shoulder of 16 mm diameter and a triflute probe of 6 mm of diameter and length was used. The particles are confined between two plates and a spacer (Kapton® tape) was used to ensure the desire quantity and the uniform distribution. Therefore, SiC particles with a size between 6 and 8 μm were added to the base material. Figure 3.2 shows the top and transversal view of the setup used to produce the composites via UFSP.

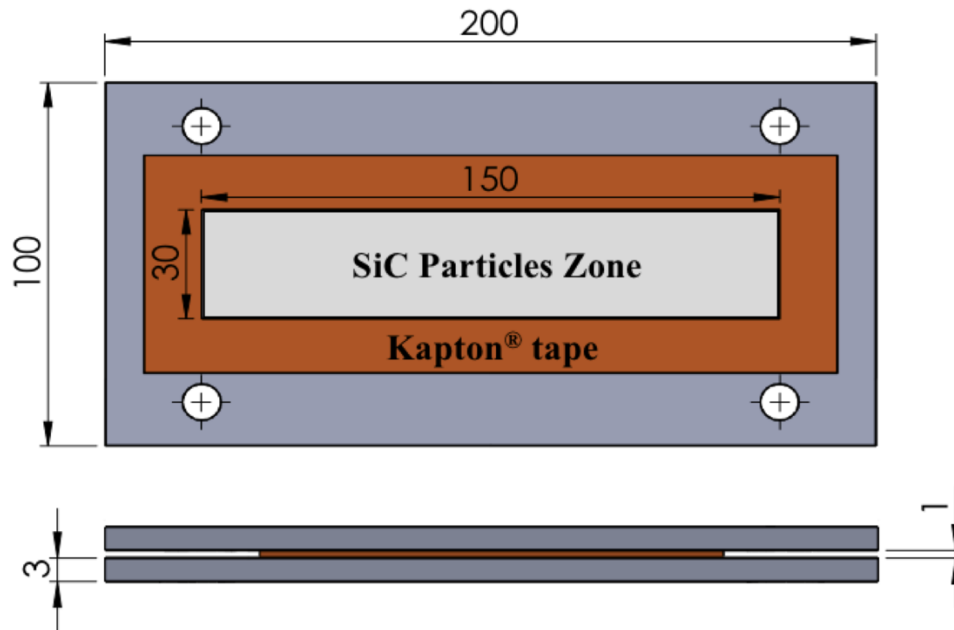


Figure 3.2 – Top and transversal view of the setup used to produce the composites via UFSP.

The selection of the process parameters is crucial to obtain composites with a good homogeneity within the processed zone and a reduced and well positioned defect. The selected parameters are in agreement with the ones used in [14] and are presented in Table 3.3. Figure 3.3 represents one of the composites produced by UFSP with 6 passes spaced by 1 mm offset.

Table 3.3 – Selected parameters for the Upward Friction Stir Processing trials.

Parameters	Value
Tool travel speed	180 mm/min
Tool rotation	900 rev/min
Tool rotation direction	CCW
Number of passes	6 and 8
Tool tilt angle	1°
Offset	1 mm
Spacer's thickness	1 mm

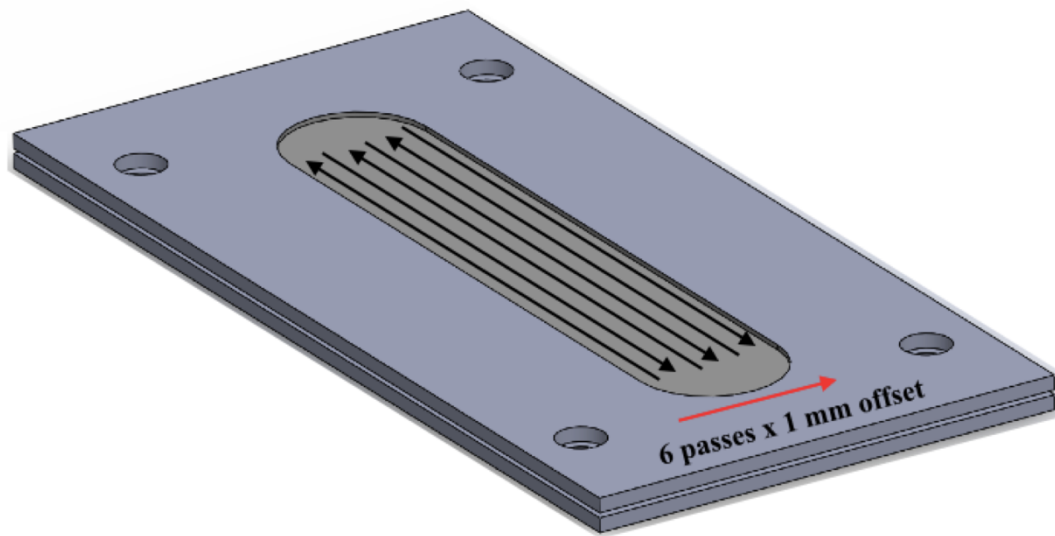


Figure 3.3 - One of the composites produced by UFSP with 6 passes spaced by 1 mm offset.

In total 5 UFSP sets of aluminium sheets were processed via UFSP to produce the necessary MMC and, as mentioned before, it was used the aluminium alloy AA7075-T651 as matrix and SiC particles as reinforcement material. As can be seen in Table 3.4, the only different parameter in some samples was the number of passes used, which is related to the bead width. Thus, the higher the number of passes, the wider the bead, allowing more cutting tests on the sample.

Table 3.4 -Number of passes of each sample of MMC produced.

Samples	Number of passes	Particles
1	8	SiC
2		
3	6	
4		
5	8	

3.3 Analysis of the composites produced

After the production of the composites, the eddy currents method was used to evaluate the particle distribution in the matrix. The working principle of this method is the electromagnetic induction phenomenon and the surface or sub-surface defects/discontinuities are detected through the variation of the electrical impedance. To perform this evaluation a 3D printer and an Olympus NORTEC 600 eddy current flaw detector were used. In this particular case, the SiC particles have a lower electrical conductivity than the aluminium matrix, which means that the induced current has greater difficulty to circulate in the area containing particles. Figure 3.4 presents the setup used to perform this analysis.

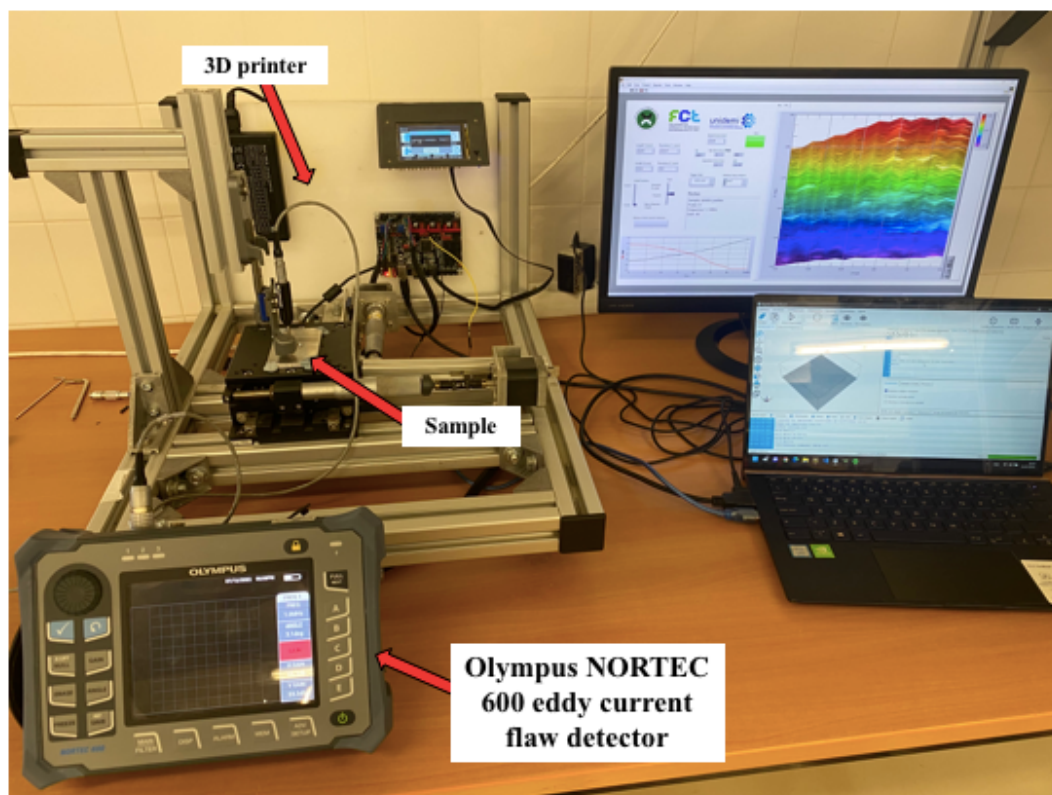


Figure 3.4 – Setup used to perform the eddy currents method.

Before performing this evaluation, it was necessary to cut the samples to obtain an area without defects and then milling and polishing processes were used to make the processed surface smooth and polished. Thus, all the necessary conditions to realize this analysis were fulfilled and 48 mm length scans were performed on the surface where the UFSP trials were executed.

3.4 Cutting tests

The experimental procedure of this research work aims to investigate the machinability of MMC by analysing the influence of cutting parameters on the evolution of cutting forces, tool wear and surface quality. This chapter presents several important factors to understand the tests performed and their preparation. Therefore, it is crucial to approach the tests planning, the equipment and tools used, the selection of the cutting parameters, the material preparation and fixture design, the cutting forces acquisition and the tool wear and surface roughness measurements.

3.4.1 Milling tests planification

The planning of the milling tests carried out was essential to determine the amount of material needed and the cutting tool to be used. In order to achieve the intended goals, it was decided to perform an operation that would guarantee the surface quality, that is, a finishing operation. This choice is justified by the high tendency to pull out the reinforcement particles instead of cutting them, resulting in a poor surface quality.

Additionally, it was chosen to perform end milling of 3 mm wide and 20 mm length slots. So, an end mill with 3 mm diameter would have to be chosen and the minimum distance between slots had to be half the diameter of the cutting tool, which is 1.5 mm. Then, it was defined the use of 5 different values for the cutting speed and feed rate, keeping constant the value of the depth of cut. In this way, a total of 25 tests were performed. The number of tests performed on each sample was dependent on the width, length and depth of the particle reinforced zone. Thus, it was not possible to execute the same number of tests in all specimens, as shown in Table 3.5. Figure 3.5 represents, as an example, the slots made in the sample 1, as well as their dimensions and the distance between them. Finally, it was also decided to perform a dry machining so that the results would not be influenced by the use of coolant.

Table 3.5 -Number of cutting tests per sample.

Samples	Number of tests
1	12
2	4
3	4
4	3
5	2

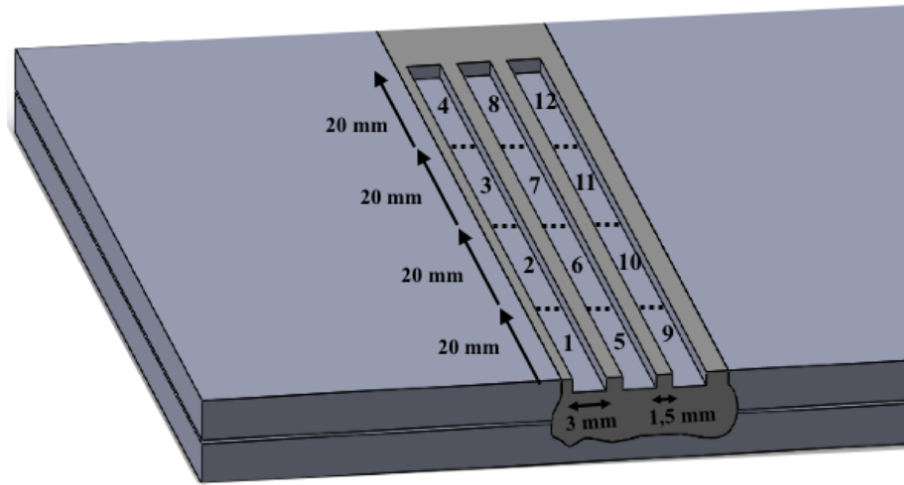


Figure 3.5 - Slots made in the sample 1, as well as their dimensions (20 mm length and 3 mm wide) and the distance between them (1.5 mm).

All the cutting tests were performed in the laboratory of Mechanical Processes of NTI using CNC (Computer Numerical Control) equipment. More specifically, the vertical machining centre HAAS Super Mini Mill 2, shown in Figure 3.6, was used.



Figure 3.6 - Vertical machining centre HAAS Super Mini Mill [33].

3.4.2 Cutting tools

When machining composites, one of the fundamental aspects is the selection of the cutting tool. In this particular case, it was intended to select a finishing end mill with 3 mm diameter and that would allow machining composite materials. Thus, a solid carbide tool with TiAlN coating was selected. More specifically, a Dormer S9223.0, represented in Figure 3.7. The geometric characteristics of the cutting tool are represented in Figure 3.7 and detailed in Table 3.6.

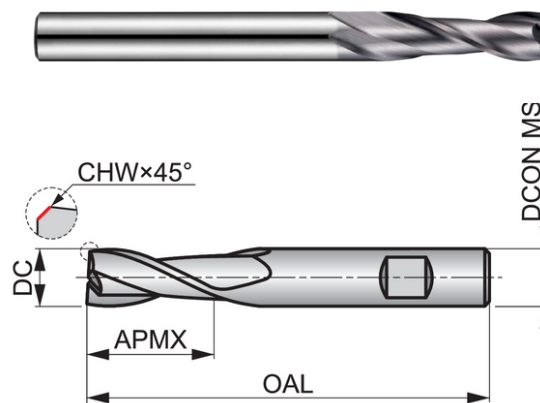


Figure 3.7 – Dormer S9223.0 and the respective geometric characteristics [34].

Table 3.6 - Geometric characteristics of Dormer S9223.0 [34].

Geometric characteristics	Dormer S922
Cutting diameter (DC) [mm]	3
Corner chamfer width (CHW) [mm]	0.08
Connection diameter (DCON MS) [mm]	3
Maximum depth of cut (APMX) [mm]	12
Overall length (OAL) [mm]	38
Number of teeth	2
Helix angle [°]	30
Radial rake angle [°]	12

3.4.3 Cutting parameters

As seen in the literature review, the cutting parameters have a major importance in the study of the machinability of MMC. Hence, it is relevant to analyse the influence of these parameters on the cutting forces, tool wear and machined surface quality, in order to optimise the machining process of these materials. For this purpose, and as mentioned before, five different values for cutting speed and feed rate were used in the tests. The values for these parameters were adjusted using the recommended values for machining composites with a 3 mm diameter Dormer S922, shown in Table 3.7. More specifically, values 15% and 30% lower and higher than recommended were used. On the other hand, the depth of cut was kept constant in all the experiments performed. The Appendix A and B presents, respectively, the cutting parameters applied in the tests and the G-code used to automatize the production process.

Table 3.7 – Recommended values for machining composites with a Dormer S9223.0 [34].

Material	Recommended value	
	Cutting speed [m/min]	Feed [mm/rev]
N4.3 – Reinforced polymers or composites	64	0.017

3.4.4 Material preparation and fixture design

One of the key aspects to obtain trustworthy results is to carry out a good experimental setup. Therefore, in cutting processes, it is fundamental to guarantee the correct fixation of the sample in order to avoid possible vibrations that may affect the obtained cutting forces, the tool wear and the surface quality. To avoid vibrations, four holes were drilled in the specimens and in an aluminium block and four class 8.8 M4 screws and nuts were used to fix them. Additionally, two steel blocks were placed to ensure the fixation at the desired height. Figure 3.8 presents the used experimental setup.

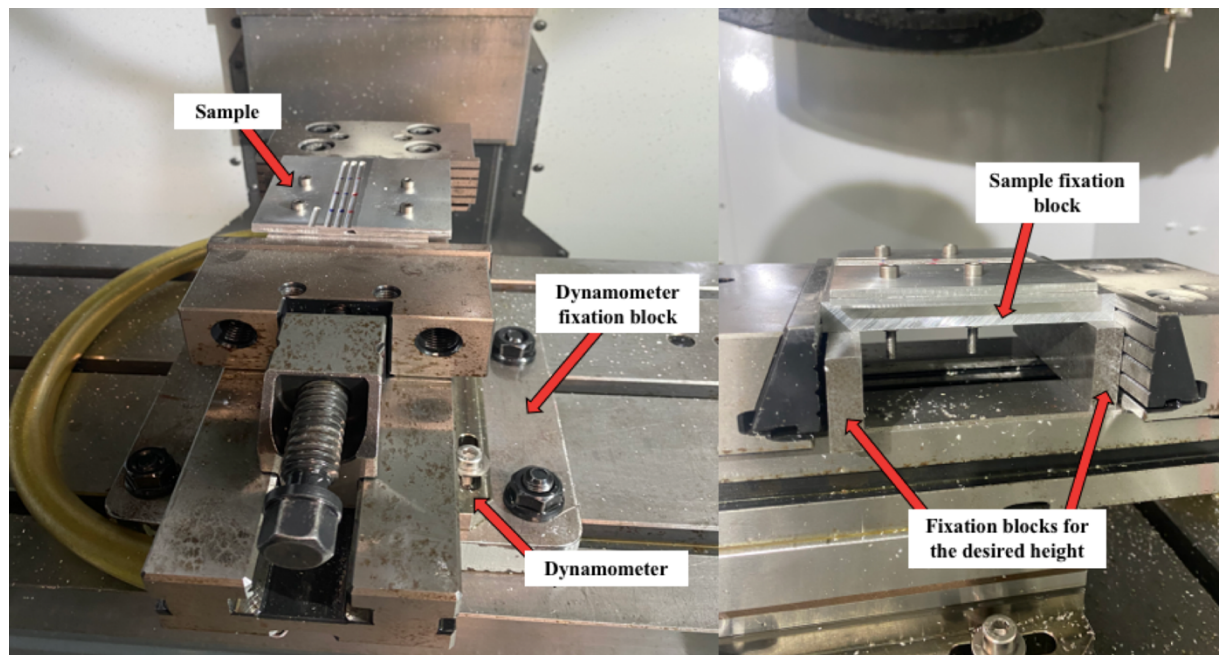


Figure 3.8 – Experimental setup used for the cutting tests.

3.4.5 Cutting forces acquisition

In order to perform the monitoring and data acquisition related to the cutting forces obtained during the milling tests, a Kistler 9257B dynamometer and a Kistler LabAmp Type 5165A charge amplifier with integrated data acquisition were used.

The multicomponent dynamometer, represented in Figure 3.9, allows to measure the three orthogonal components of a force. It consists of four three-component force sensors, which concern the pressure in the z direction and the shear in the x and y direction. According to the load acting on the sensor, the dynamometer produces a proportional charge signal.

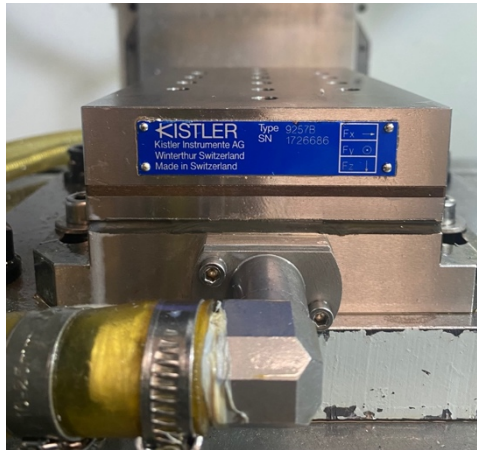


Figure 3.9 - Kistler 9257B multicomponent dynamometer.

The charge signals from the dynamometer are then converted by the charge amplifier, shown in Figure 3.10, into digital values or output voltages, which are also proportional to the forces. The Kistler LabAmp type 5165A also has an integrated data acquisition unit, which is configured and operated in a web-interface and enables the browser-based data download of the measured values. Afterwards, the acquired data was processed in the MatLab software. Figure 3.11 represents the setup used in order to carry out the cutting forces acquisition.



Figure 3.10 - Kistler LabAmp Type 5165A charge amplifier with integrated data acquisition.

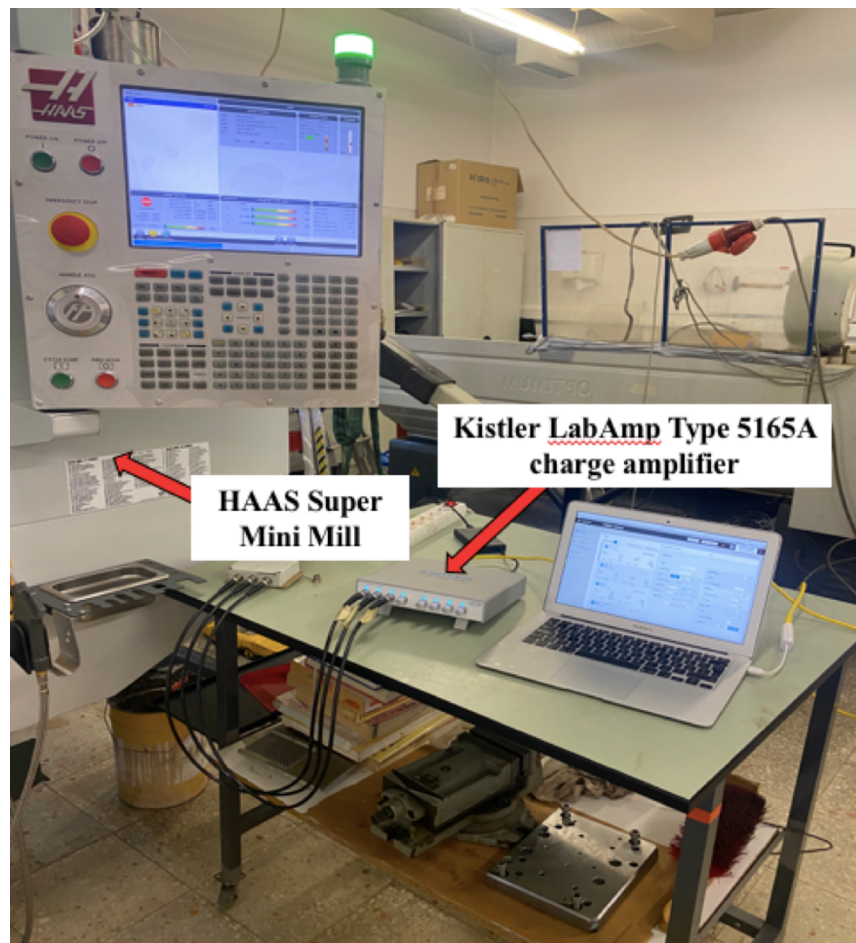


Figure 3.11 - Setup used in order to carry out the cutting forces acquisition.

Before the cutting tests were carried out, simulation tests were performed to check if the multicomponent dynamometer was in good conditions. To verify this, a manual dynamometer was used and three known loads were applied (2 kg, 4 kg and 6 kg) and it was observed if the results in the dynamometer to be used were in agreement. The results obtained were congruent, which shows that the device is reliable.

3.4.6 Tool wear measurements

As can be noticed in the state of the art, another important issue during this type of operations is the wear of the cutting tool. So, in order to analyse the evolution of the tool wear with the variation of the cutting parameters, an image of the cutting edge was acquired at the end of each of the 25 tests. For this purpose, it was used an INSIZE ISM-PM200SB digital measuring microscope, represented in Figure 3.12.

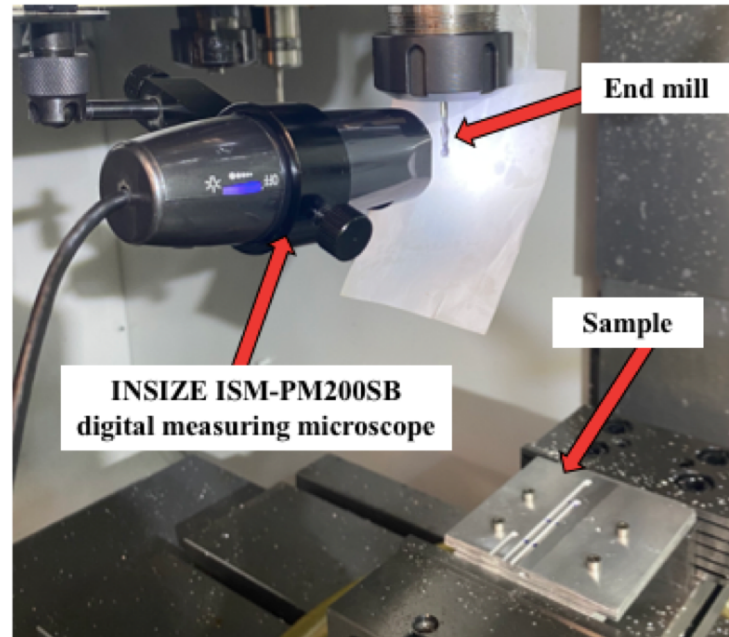


Figure 3.12 - INSIZE ISM-PM200SB digital measuring microscope.

In order to simplify and reduce image acquisition time, a custom-built stand was constructed with steel hardware. This stand was placed inside the CNC and allowed to fix the microscope in a stable way and at the required height and closeness. Therefore, it was possible to obtain images with better quality and more detail. The setup used in all the tests carried out is shown in Figure 3.13.

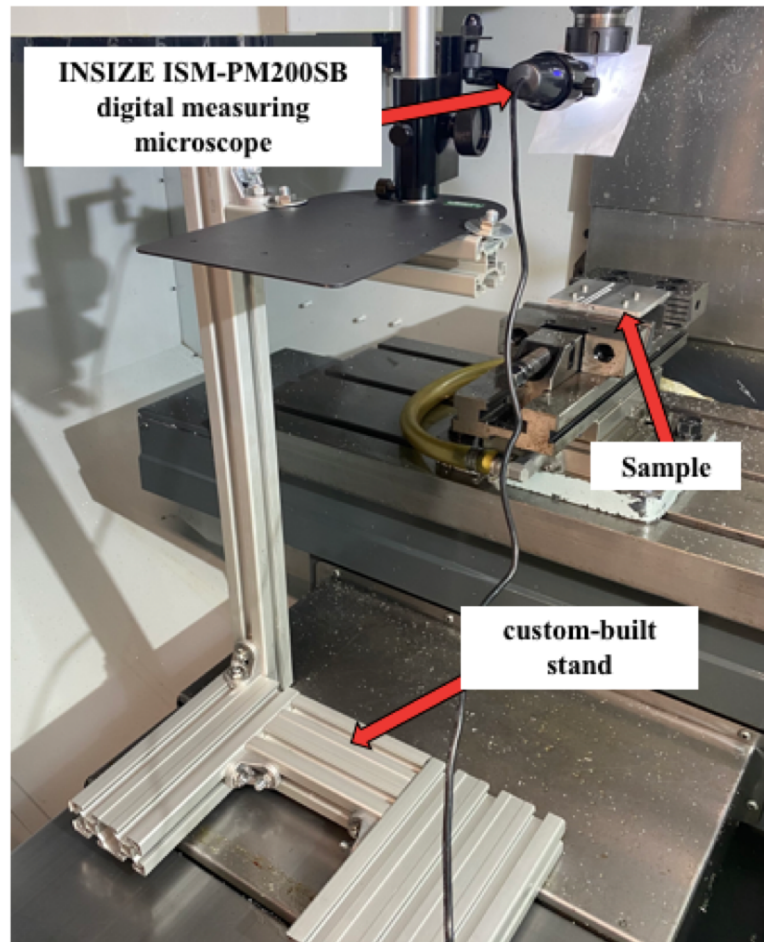


Figure 3.13 – Setup used to acquire the images of the cutting edges.

After acquiring all the necessary images, they were analysed in detail using ImageJ software, as displayed in Figure 3.14, and the tool wear values of each experiment were recorded. It is also important to note that the tool diameter was used as a scale to perform the relevant measurements. Thus, during the acquisition was essential to ensure that the image plane was parallel to the plane containing the tool's cutting edge.

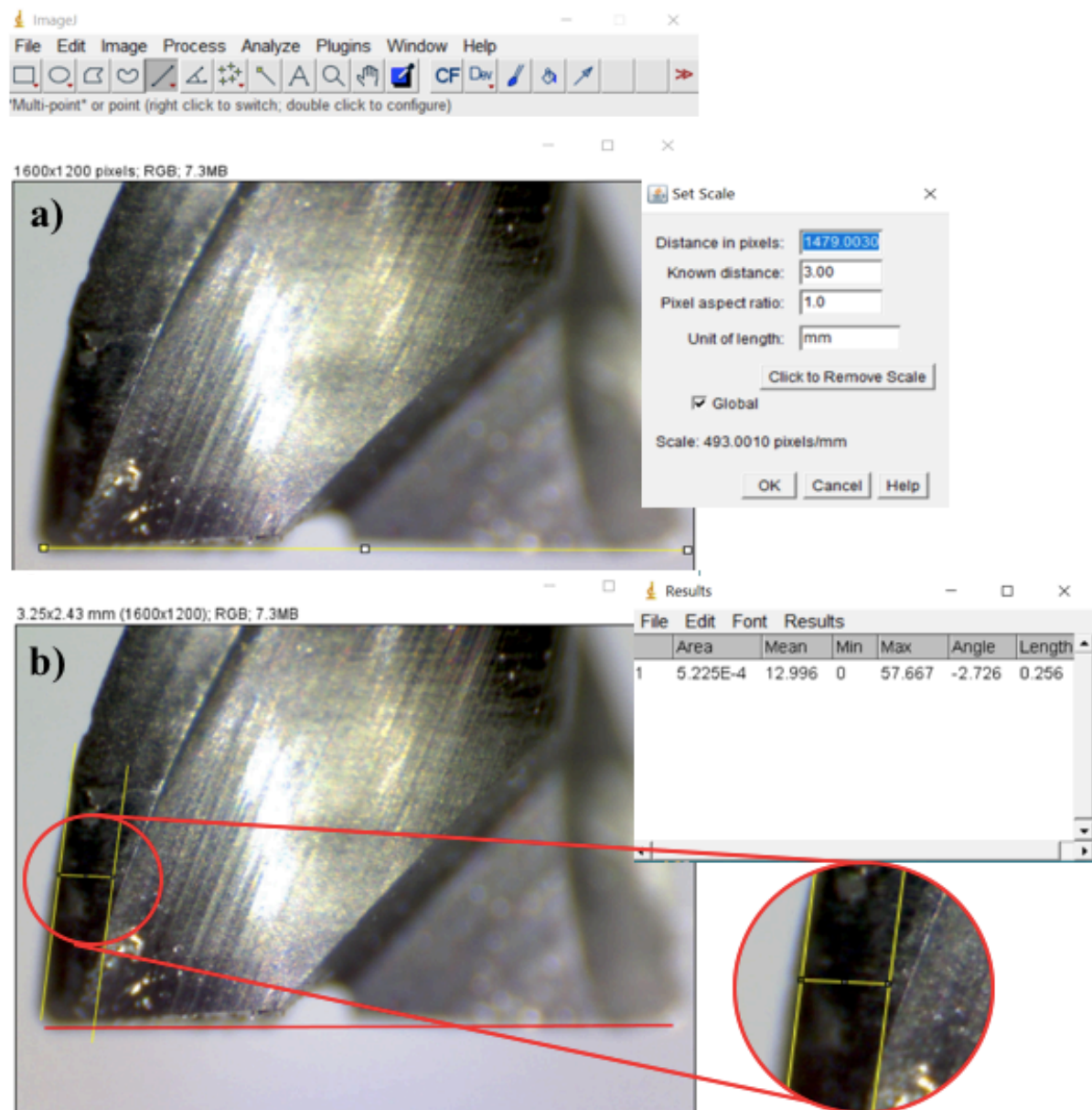


Figure 3.14 – Analysis of the acquired images: a) scale definition and b) flank wear measurement.

3.4.7 Surface roughness measurements

The surface roughness of the samples was measured to evaluate the quality of the milled surface, which also gives an insight into the quality of the milling process. The measurements were performed along the feed direction and by using a Mitutoyo Surftest SJ-210 rugosimeter and the Surftest USB Communication Tool software in the laboratory of the Polytechnic Institute of Setubal. The rugosimeter operation is based on the contact between a probe and the surface to be analysed, in which the movements of the probe are captured by electronic sensors that produce the profile graph. Figure 3.15 shows the setup used to perform the measurements.

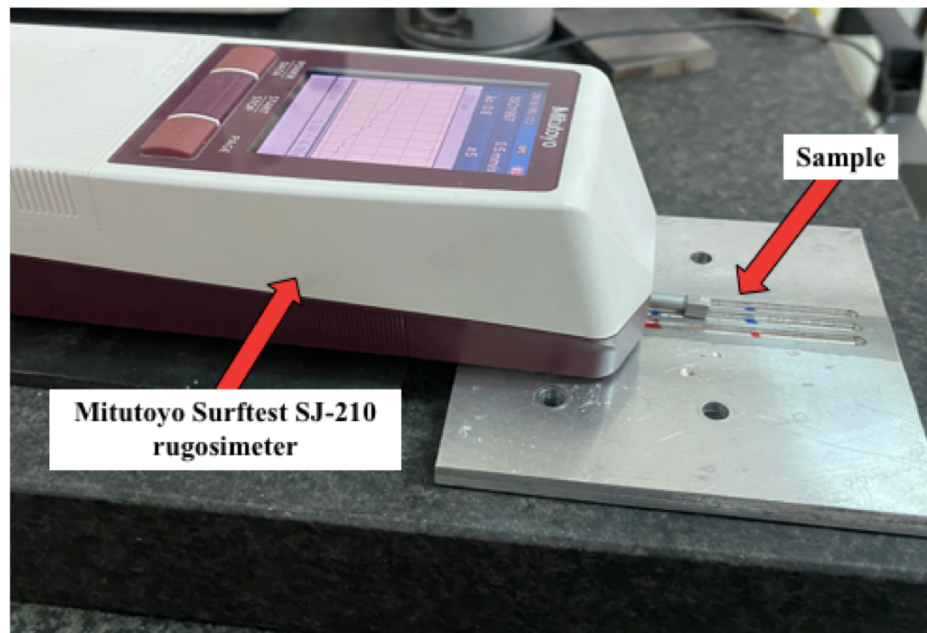


Figure 3.15 – Setup used to perform the surface roughness measurements.

In addition to the profile, illustrated in Figure 3.16, the significant values that were taken from this analysis were the arithmetical mean roughness value (R_a), mean roughness depth (R_z) and the ration R_z/R_a , which provides a perception of the stability of the cutting process.

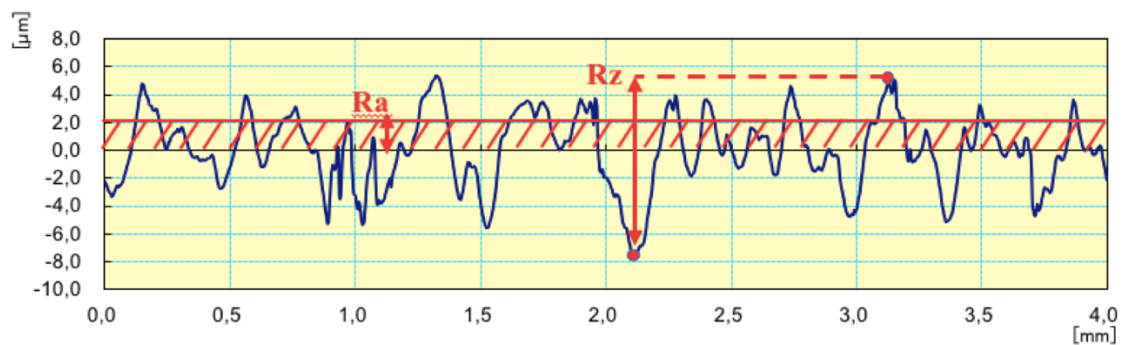


Figure 3.16 – Profile graph of the surface roughness of test 6 and respective representation of R_a and R_z values.

4 RESULTS ANALYSIS

In this stage, an analysis of the achieved results during the machining of these composites was performed. In the first instance, the images obtained in the eddy current tests were studied to better understand the particle distribution of the composites and its influence on the milling process. Additionally, the graphs of the cutting forces were analysed and a microscopic and SEM examination on the tool and material were performed to investigate the tool wear and the material properties. Finally, the surface roughness was also evaluated, which gives us information about the quality of the machined surface.

4.1 Particles' distribution in the composites

As mentioned in the chapter 3.3, the induced current has greater difficulty to circulate in the area containing particles and so this area presents lower impedance. As can be seen in Figure 4.1, the area reinforced with SiC particles is represented as blue and purple. Although the distribution of the particles in the matrix is generally uniform, the zones in purple have a higher concentration of particles, which can complicate the cutting process. More specifically and according to the state of the art, higher particle volume fraction is usually associated with higher cutting forces, more severe tool wear and poorer surface quality. Therefore, the knowledge of the particle distribution is essential and can explain some nonsense results concerning the evolution of these parameters. Additionally, Figure 4.2 represents the profile of the variation of electrical conductivity of the sample represented in Figure 4.1.

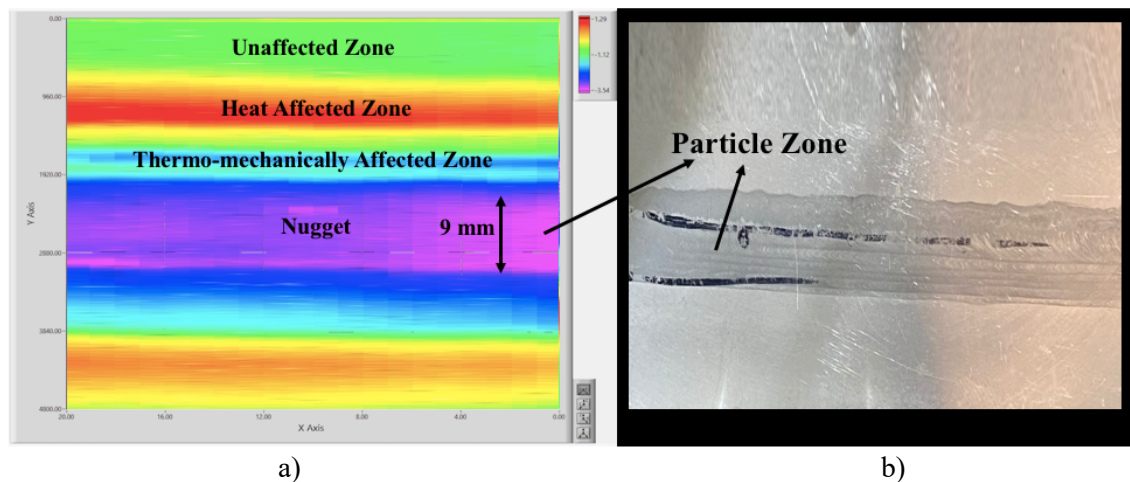


Figure 4.1 – a) Map of the particles' distribution in the sample and b) the respective sample analysed.

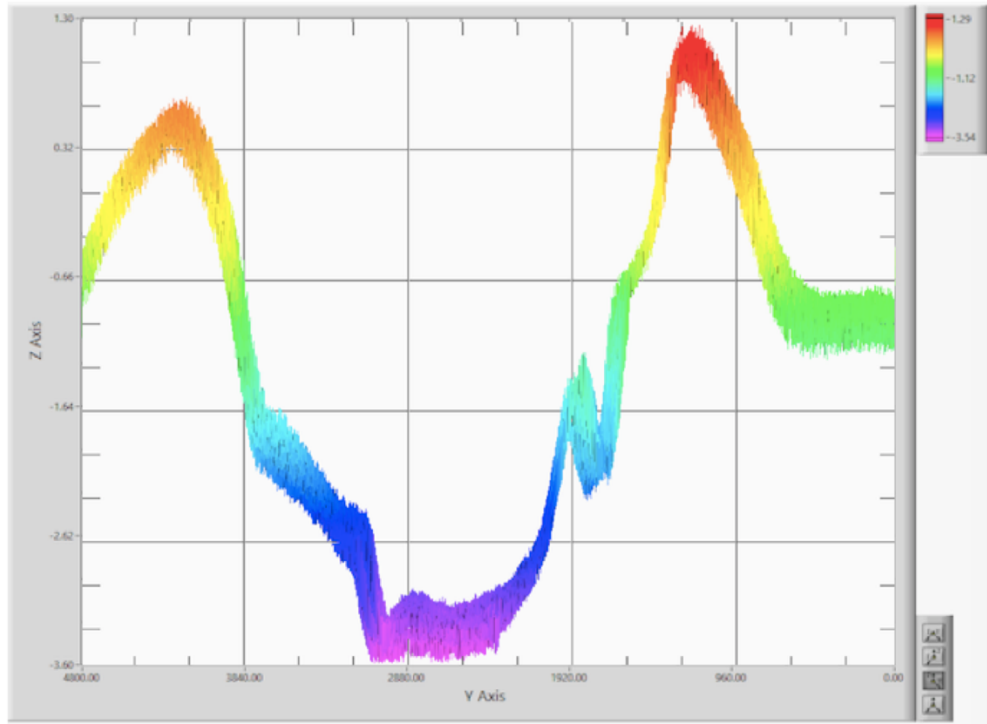


Figure 4.2 - Profile of the variation of electrical conductivity of the sample represented in Figure 4.1.

4.2 Cutting forces

The analysis of the cutting forces was performed using the MatLab software, which provides the graphs of the forces measured by the dynamometer and the respective value of the peak force, which is the most significant point in this analysis. Additionally, a low-pass Butterworth filter was applied to eliminate high frequencies coming from the electrical installation, the machining centre or the dynamometer. The cutting forces in the milling process are exerted in three different planes in order to deform and shear away the material in chip form. The graphs obtained by the program, illustrated in Figure 4.3, allows to study the evolution of the forces in these three planes (x, y and z). However, the relevant force for this analysis is the one registered in the perpendicular direction to the cutting direction, which is the component according to the x direction, F_x . This is due to the fact that the peak of the cutting force in slot milling normally occurs for an immersion angle of 90° .

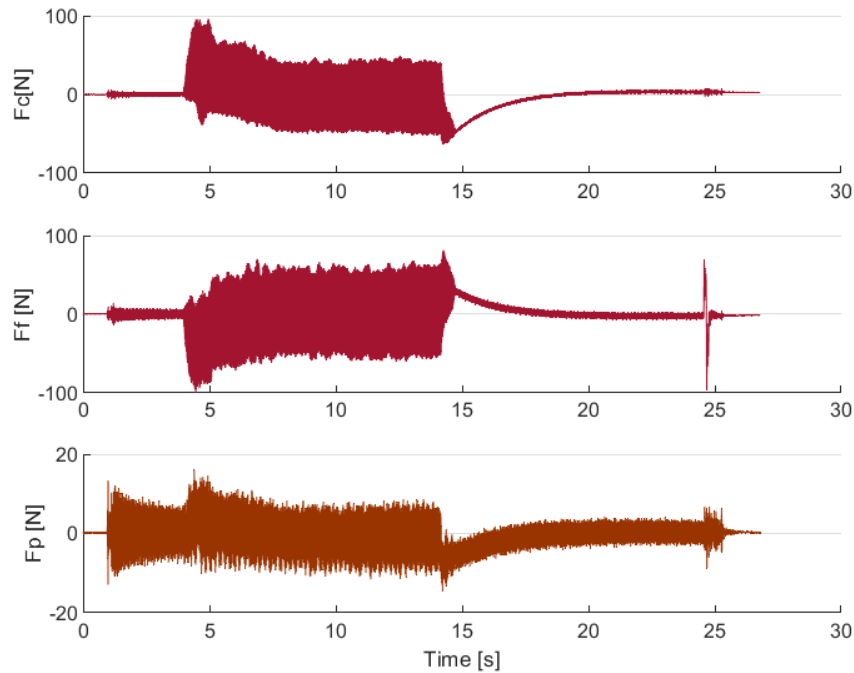


Figure 4.3 – Graphs obtained by the MatLab software in the 3 different planes.

Further on, in order to obtain a more detailed view of the process and the evolution of the forces, another code was executed to visualize a specific time period, as can be seen in Figure 4.4. Through the analysis of the Figure 4.4 it is possible to understand that the loop pattern repeats every other two loops, separated by 360° , which corresponds to a complete rotation of the tool. This happens because the two teeth of the end mill are 180° apart and do not cut simultaneously neither exert the same cutting force. Thus, it is possible to state that one tooth is removing more material than the other. By the observation of the Figure 4.4 and taking into account the reference point marked, it is also possible to establish that Point I represent the point of maximum force when one of the teeth is at the reference point. Afterwards, point II represent the moment when one of the teeth is leaving the workpiece and the other is starting to cut. Point III and IV is, respectively, the point of maximum force but for the other tooth and the moment when one of the teeth is coming out of the workpiece and the other is starting to cut. Additionally, it is also possible to observe the three phases of the milling process. Firstly, when one of the flutes starts cutting, which is followed by a rapid increase in force. Next, the stable phase, where the increase in force is gradual. Finally, when this flute stops cutting, where a sudden decrease in cutting force occurs.

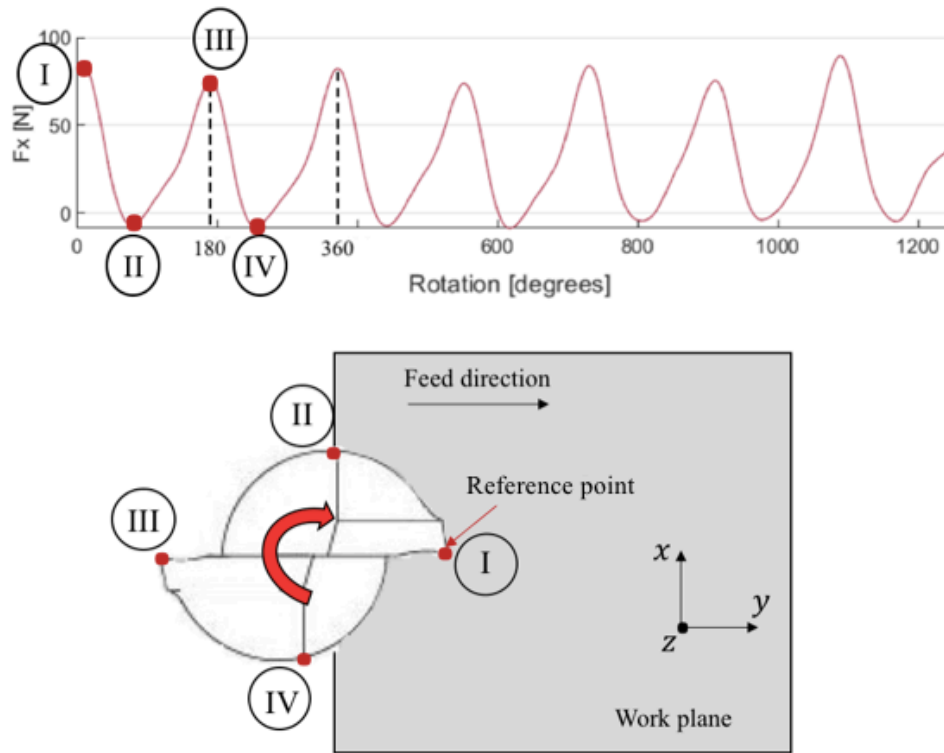


Figure 4.4 – Graph of the cutting force according to the x direction, F_x , as a function of the degree of rotation of the tool.

During the visualization of the graphs of forces, the presence of vibrations was detected, which is a usual problem in the machining of composites and that can also be caused by the poor fixation of the workpiece on the CNC. These vibrations can affect the results obtained in terms of forces, as well as tool wear and surface roughness. Figure 4.5 shows another detailed view of the forces at a certain period, where the presence of vibrations is more evident.

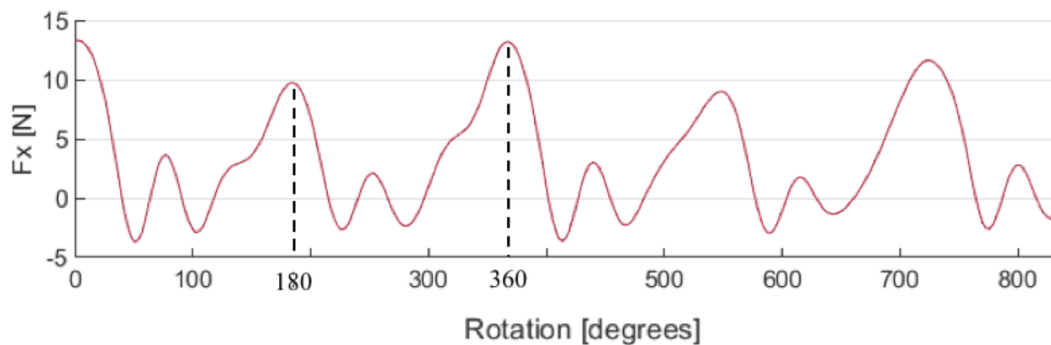


Figure 4.5 -Graph of the cutting force, F_x , where the presence of vibration is more evident.

4.2.1 Cutting parameters

To evaluate the influence of the cutting parameters on the cutting forces, the peak value of the forces obtained in each test was taken into account. As referred in chapter 3.4.3, only the feed and the cutting speed were varied, while the depth of cut was kept constant. Appendix C displays the maximum force obtained for each test and Figures 4.6 and 4.7 present the evolution of the cutting force with the feed and the cutting speed, respectively.

The results obtained regarding the influence of feed are in agreement with the state of the art. This means that the increase in feed contributes to the increase in cutting forces, as is visible in Figure 4.6. The higher friction and shear stress in the cutting zone and the higher resistance of the material against the moving cutting edge are factors that may have contributed to this effect [16,17]

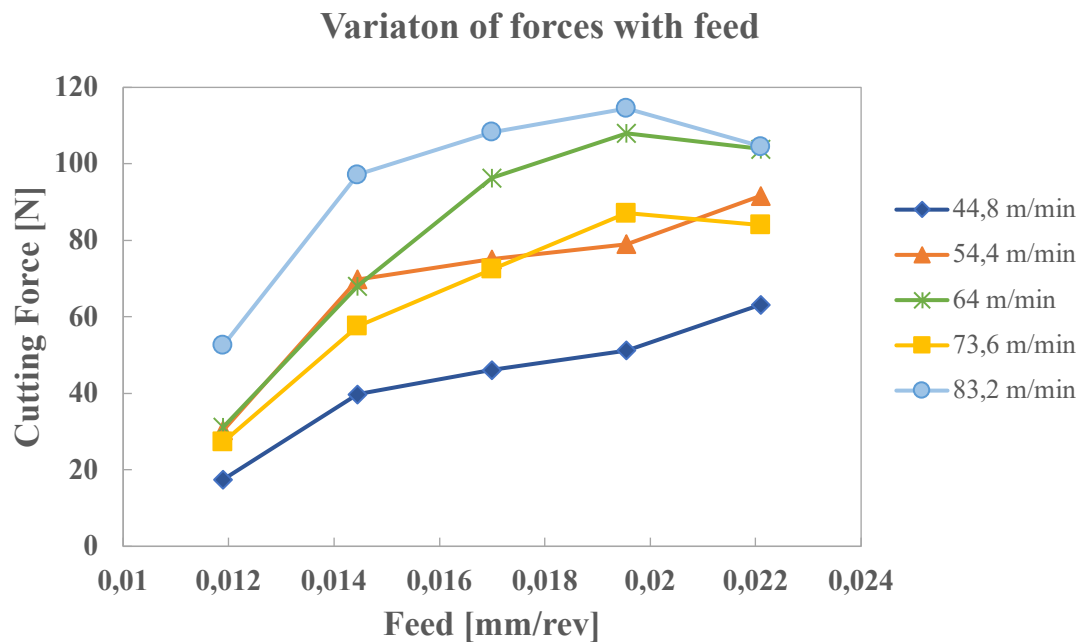


Figure 4.6 -Effect of feed on the cutting forces obtained.

Regarding the cutting speed and according to Figure 4.7, it is possible to state that for low speeds (lower than 64 m/min) the increase of the speed contributes to the increase of the cutting force. This can be explained by the tendency to increase the specific cutting energy at low cutting speeds, which subsequently leads to an increase in cutting force. When increased from 64 m/min to 73.6 m/min, the force value decreased for all feeds maybe because of the thermal softening of the workpiece which decreases the shear stress and resistance of the material against the moving cutting edge [16,17]. Finally, when increased from 73.6 m/min to 83.2 m/min, the force value increased again. However, this increase can be depreciated, since the end mill used for this speed broke after 2 tests and an already used tool

had to be reused to finish the remaining tests for this speed. Thus, the tool wear may have contributed to the need of higher forces to cut the material.

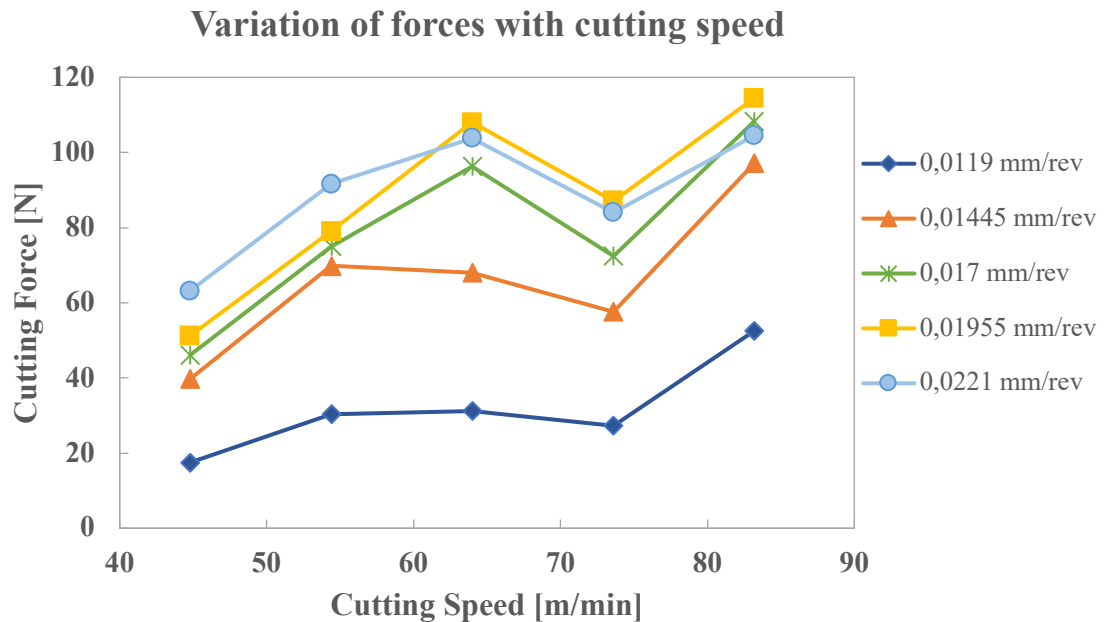


Figure 4.7 – Effect of cutting speed on the cutting forces obtained.

4.3 Tool wear

In order to analyse the results obtained for tool wear and according to the ISO 3685, a maximum value of $VB=0.3$ mm was taken as reference. This means that after this value the end mill should be replaced by a new one. However, as each tool was planned to perform 5 tests to analyse the influence of the cutting parameters, this did not happen. To measure the tool wear, the flank wear was evaluated, and the results are registered in Appendix D. The flank wear evolution for each cutting tool can also be seen in Figure 4.8.

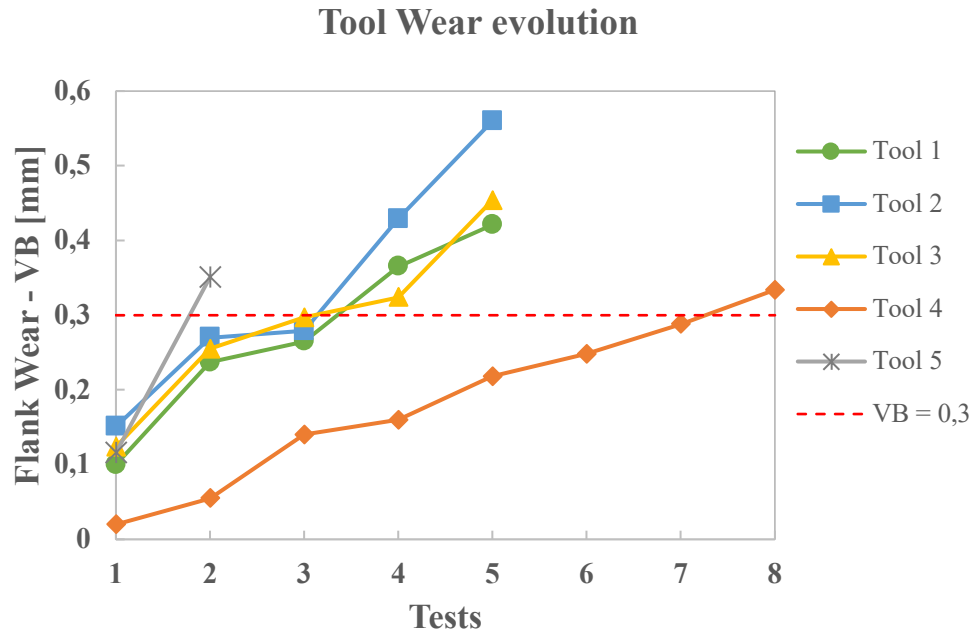


Figure 4.8 – Flank wear evolution of each cutting tool.

Through the observation of both Appendix D and Figure 4.8 it is possible to notice that only the end mill 4 managed to perform the 5 experiments without reaching the maximum value of $VB = 0.3$ mm. All the other tools presented a flank wear higher than that values before concluding the planned tests. Tools 1, 2 and 3 presented values higher than the reference value after 4 tests and the most critical case was the end mill 5 that broke after 2 tests and was replaced by the tool 4. So, it is possible to state that the most adequate cutting speed for machining this type of composites was 73.6 m/min, which is in agreement with the results obtained in [24], where the range of speed values that presented the lowest wear was 60-100 m/min. Regarding the feed, it is perceptible that for speed values of 44.8, 54.4 and 64 m/min, the value of 0.017 mm/rev (recommended value) is the most adequate since it only increased a small amount of flank wear on these tools. On the other hand, for the cutting speed of 73.6 m/min, the feed of 0.01955 mm/rev also provided a suitable result. From an industrial point of view and taking into account that each test corresponds to 20 mm of cutting length, it is possible to conclude that all the tools, except the endmill 4, were not able to achieve more than 60 mm of cutting length without reaching the reference value, which in industrial terms is a quite short distance and makes the process unprofitable.

One of and probably the main reason for the flank wear was the abrasive nature of the reinforcement particles. Abrasive wear is related to the hardness of both particles and cutting edge. Hence, the higher the hardness of the tool, the greater its capacity to resist this type of wear. Additionally, it was also found that the flank face of the cutting tools presented a rounded tip, which was more accentuated at the top.

4.4 Surface roughness

In general and simply by observation, after the cutting tests, the slots made in the samples presented some evident roughness, which is not surprising due to the presence of the abrasive particles. After analysing the results obtained for the surface roughness, it was found that the effect of increasing both feed and cutting speed did not allow consistent conclusions to be drawn, which makes sense as the conditions of each cutting test are not homogeneous. However, it was possible to establish that the most influential parameter for the roughness of the machined surfaces was the volume fraction of the reinforcement particles.

As can be seen from the surface roughness value table and the particles' distribution map, shown in Appendices E and F, respectively, the higher the percentage of particles, the higher the arithmetical mean roughness value (R_a). These results are in accordance with the state of the art and can be explained by the tendency of some particles to be pulled out instead of being cut, originating small gaps on the surface. Thus, the higher the percentage of particles, the higher the number of gaps on the surface [22]. Additionally, as can also be seen in Appendix E, the values of the ratio between the mean roughness depth (R_z) and R_a , are within the expected value for a stable cutting process for aluminium alloys, which is a value around 5. Nevertheless, there are some values of that ratio that slightly diverged from the expected value, as for example the one from cutting test 1. This is due to a larger difference between the values of R_a and R_z , which means that in that cutting length there is an area where there is a particle concentration much higher than the average concentration.

5 CONCLUSIONS AND FUTURE WORK

In this research, milling operations were performed on MMC manufactured via UFSP in order to study the machinability of this type of materials. The composites were produced in a conventional 3-axis milling machine present in the laboratory of Mechanical Processes of NTI and the reinforcement material was SiC particles with a size between 6 and 8 μm . During the machining operations on the CNC equipment the cutting forces and the tool flank wear were measured for all sets of cutting parameters used. Afterwards, using a rugosimeter, the roughness of the machined surfaces was also measured to analyse the quality of the cutting process in each trial.

The selection of the adequate cutting parameters revealed to be very relevant in the obtained cutting forces. Additionally, as expected, tool wear was the most critical parameter and can influence the forces, which makes it a key variable that should be monitored, and the particles' distribution strongly affects the surface roughness

Taken into account the achieved results, some conclusions can be established:

- The presence of vibrations was detected, which is a usual problem in the machining of composites and that can also be caused by the poor fixation of the workpiece on the CNC. These vibrations can affect the cutting forces, tool wear and surface roughness.
- The increase in feed contributes to the increase in cutting forces may be due to the consequent increase of friction and shear stress in the cutting zone and of the resistance of the material against the moving cutting edge.
- At low cutting speeds, higher cutting forces were observed which may be explained by the tendency to increase the specific cutting energy. When increased from 64 m/min to 73.6 m/min, the force value decreased for all feeds maybe because of the thermal softening of the workpiece which decreases the shear stress and resistance of the material against the moving cutting edge [16,17]. Additionally, the unavoidable tool wear can also have a great influence in cutting forces, leading to an increase in the forces for higher values of tool wear.
- Of the 5 tools used, only the end mill 4 realized the five tests planned without exceeding the reference flank wear value, $VB = 0.3 \text{ mm}$. This means that four of the five tools were not able to achieve more than 60 mm of cutting length without reaching the reference value, which in industrial terms is a quite short distance and makes the process unprofitable.
- According to the flank wear values recorded, the cutting parameters that proved to be most suitable for machining these composites are a cutting speed of 73.6 m/min and a feed between 0.017 and 0.01955 mm/rev.
- Abrasive wear may have been the main reason for flank wear due to the abrasive nature of reinforcement particles. The presence of rounded tool tip was also evident and more accentuated at the top.

- The most influential parameter for the roughness of the machined surfaces was the volume fraction of the reinforcement particles and the higher the percentage of particles, the higher the arithmetical mean roughness value (Ra). This is because of the tendency of the particles to be pulled out instead of being cut, which favours the occurrence of small gaps on the machined surface [22].

To understand all the parameters that may influence the machining of MMC and better control aspects like cutting forces, tool wear and surface roughness, further investigations and improvements can be carried out, such as:

- Evaluate cutting forces and roughness of machined surfaces without tool wear having such relevant influence to better understand the evolution of these aspects.
- Evaluate the evolution of tool wear with cutting parameters. For this it would be necessary to use new tools or tools with minimal wear, so that the progressive wear has no influence.
- Analyse the effect of particles dimension on the machinability of MMC.
- Study the influence of the depth of cut in order to obtain the most suitable value for machining these composites.
- Carry out a cost-benefit analysis with diamond tools in terms of machinability to see if it is worthwhile.
- Provide a better way to fix the workpiece to the CNC so as to minimise the vibrations during the milling operation.
- Evaluate the effect of using coolant during the machining of this type of materials.

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APPENDIX A – CUTTING PARAMETERS USED IN THE TESTS

Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]
1	44.8	0.0119	1
2	44.8	0.01445	1
3	44.8	0.017	1
4	44.8	0.01955	1
5	44.8	0.0221	1
6	54.4	0.0119	1
7	54.4	0.01445	1
8	54.4	0.017	1
9	54.4	0.01955	1
10	54.4	0.0221	1
11	64	0.0119	1
12	64	0.01445	1
13	64	0.017	1
14	64	0.01955	1
15	64	0.0221	1
16	73.6	0.0119	1
17	73.6	0.01445	1
18	73.6	0.017	1
19	73.6	0.01955	1
20	73.6	0.0221	1
21	83.2	0.0119	1
22	83.2	0.01445	1
23	83.2	0.017	1
24	83.2	0.01955	1
25	83.2	0.0221	1

APPENDIX B - G-CODE FOR THE SLOT MILLING

M03 S8827.79 // Spindle on clockwise; Defines Spindle speed

G91 // Incremental coordinates

G01 Y45. F195.09 // Linear interpolation; Defines Feed rate

Z20.

G00 Y-45. // Rapid positioning

M05 // Spindle off

APPENDIX C – MAXIMUM CUTTING FORCE MEASUREMENTS

Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]	Maximum Cutting Force (F_x) [N]	Tool	Workpiece
1	44.8	0.0119	1	17.4954	Tool 1	Workpiece 1
2	44.8	0.01445	1	39.7298		
3	44.8	0.017	1	46.0874		
4	44.8	0.01955	1	51.2513		
5	44.8	0.0221	1	63.2096		
6	54.4	0.0119	1	30.3607	Tool 2	Workpiece 1
7	54.4	0.01445	1	69.7848		
8	54.4	0.017	1	75.0449		
9	54.4	0.01955	1	79.0486		
10	54.4	0.0221	1	91.6696		
11	64	0.0119	1	31.1942	Tool 3	Workpiece 2
12	64	0.01445	1	68.0206		
13	64	0.017	1	96.3079		
14	64	0.01955	1	107.9861		
15	64	0.0221	1	103.8504		
16	73.6	0.0119	1	27.2868	Tool 4	Workpiece 3
17	73.6	0.01445	1	57.6092		
18	73.6	0.017	1	72.4944		
19	73.6	0.01955	1	87.1441		
20	73.6	0.0221	1	84.0424		
21	83.2	0.0119	1	52.5436	Tool 5	Workpiece 4
22	83.2	0.01445	1	97.1468		
23	83.2	0.017	1	108.3071	Tool 4	Workpiece 5
24	83.2	0.01955	1	114.4829		
25	83.2	0.0221	1	104.5216		

APPENDIX D – FLANK WEAR MEASUREMENTS

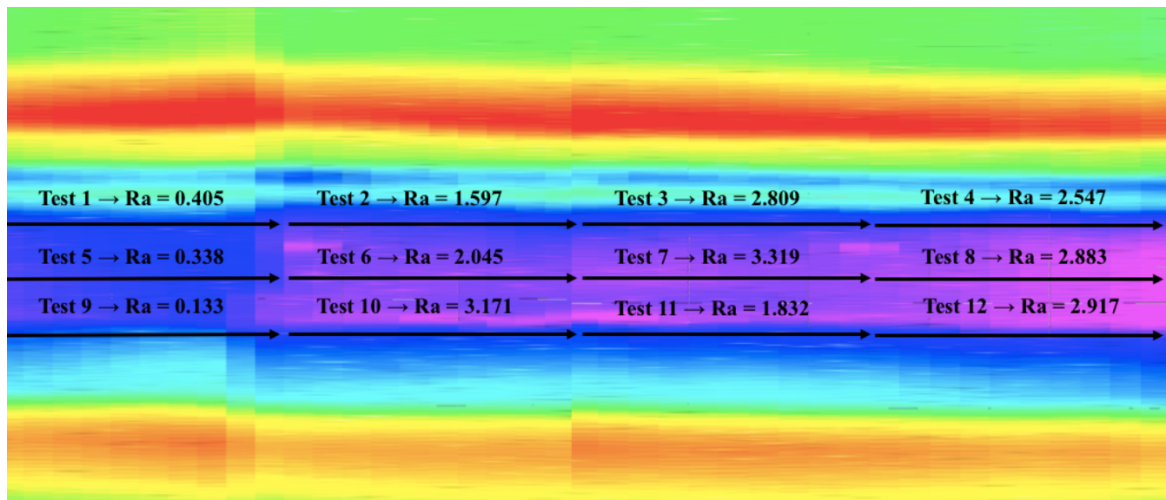
Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]	Flank Wear [mm]	Tool	Workpiece	
1	44.8	0.0119	1	0.1	Tool 1	Workpiece 1	
2	44.8	0.01445	1	0.237			
3	44.8	0.017	1	0.265			
4	44.8	0.01955	1	0.365			
5	44.8	0.0221	1	0.421			
6	54.4	0.0119	1	0.151	Tool 2		Workpiece 1
7	54.4	0.01445	1	0.27			
8	54.4	0.017	1	0.279			
9	54.4	0.01955	1	0.429			
10	54.4	0.0221	1	0.56			
11	64	0.0119	1	0.124	Tool 3	Workpiece 2	
12	64	0.01445	1	0.256			
13	64	0.017	1	0.297			
14	64	0.01955	1	0.324			
15	64	0.0221	1	0.454			
16	73.6	0.0119	1	0.02	Tool 4	Workpiece 3	
17	73.6	0.01445	1	0.055			
18	73.6	0.017	1	0.14			
19	73.6	0.01955	1	0.16			
20	73.6	0.0221	1	0.218			
21	83.2	0.0119	1	0.116	Tool 5	Workpiece 4	
22	83.2	0.01445	1	0.351			
23	83.2	0.017	1	0.248	Tool 4	Workpiece 5	
24	83.2	0.01955	1	0.288			
25	83.2	0.0221	1	0.334			

APPENDIX E – SURFACE ROUGHNESS MEASUREMENTS

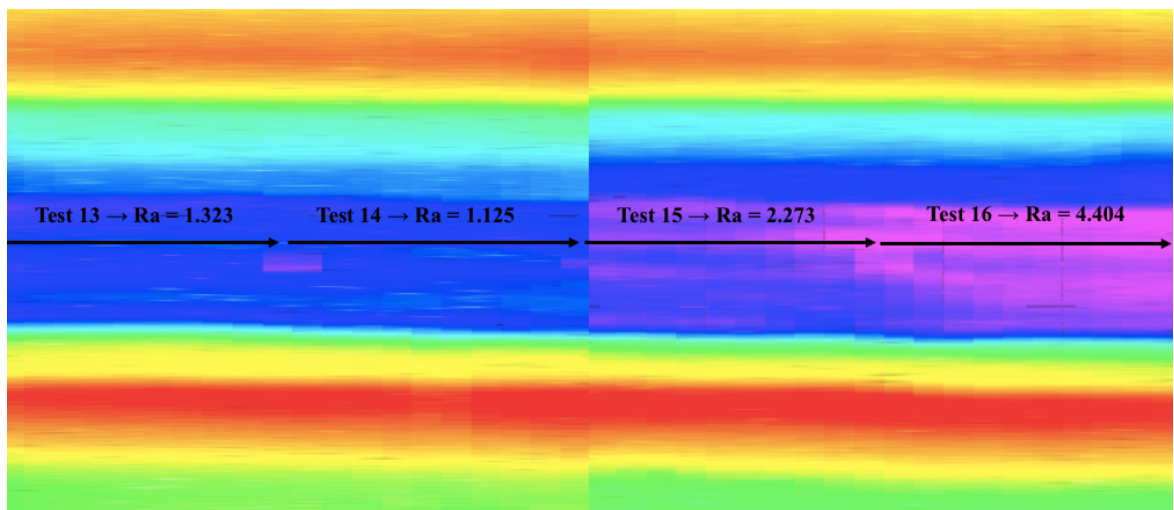
Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]	Ra [μm]	Rz [μm]	Rz / Ra	Tool	Workpiece	
1	44.8	0.0119	1	0.405	3.567	8.807	Tool 1	Workpiece 1	
2	44.8	0.01445	1	1.597	8.338	5.221			
3	44.8	0.017	1	2.809	14.319	5.098			
4	44.8	0.01955	1	2.547	11.72	4.601			
5	44.8	0.0221	1	0.338	2.125	6.287			
6	54.4	0.0119	1	2.045	9.949	4.865	Tool 2		Workpiece 1
7	54.4	0.01445	1	3.319	17.005	5.124			
8	54.4	0.017	1	2.883	15.269	5.296			
9	54.4	0.01955	1	0.133	0.84	6.316			
10	54.4	0.0221	1	3.171	17.606	5.552			
11	64	0.0119	1	1.832	9.694	5.291	Tool 3	Workpiece 2	
12	64	0.01445	1	2.917	15.269	5.234			
13	64	0.017	1	1.323	8.076	6.104			
14	64	0.01955	1	1.125	5.745	5.107			
15	64	0.0221	1	2.273	11.399	5.015			
16	73.6	0.0119	1	4.404	19.984	4.538	Tool 4	Workpiece 3	
17	73.6	0.01445	1	0.586	2.9	4.949			
18	73.6	0.017	1	0.143	0.924	6.462			
19	73.6	0.01955	1	0.303	1.646	5.432			
20	73.6	0.0221	1	1.991	9.438	4.740			
21	83.2	0.0119	1	1.944	10.882	5.598	Tool 5	Workpiece 4	
22	83.2	0.01445	1	1.166	7.331	6.287			
23	83.2	0.017	1	2.199	11.637	5.292	Tool 4	Workpiece 5	
24	83.2	0.01955	1	1.25	6.56	5.248			
25	83.2	0.0221	1	1.415	7.126	5.036			

APPENDIX F - MAP OF PARTICLES' DISTRIBUTION IN THE COMPOSITES WITH THE RESPECTIVE SURFACE ROUGHNESS OF EACH TEST

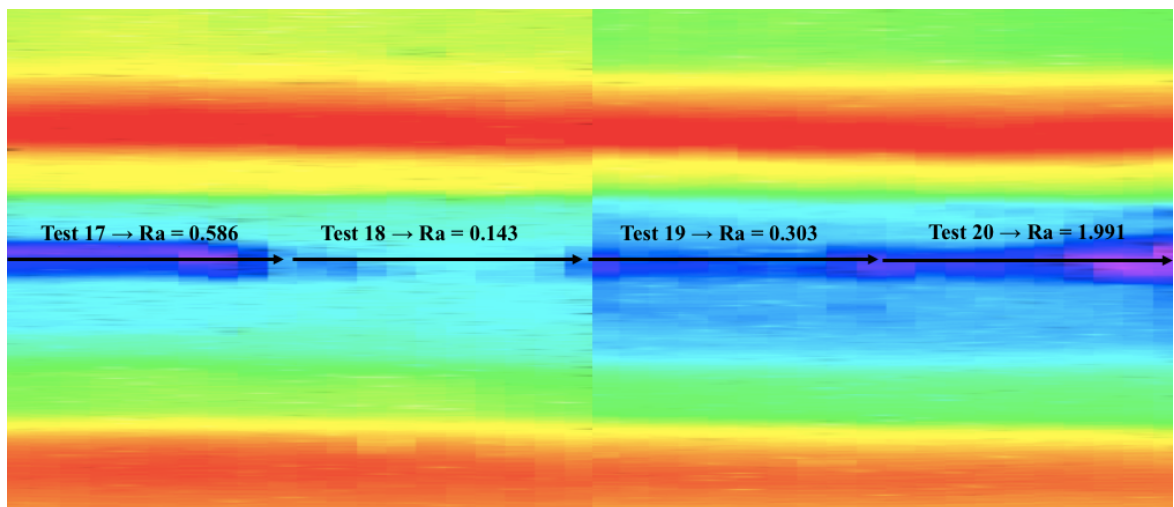
F.1 Workpiece 1



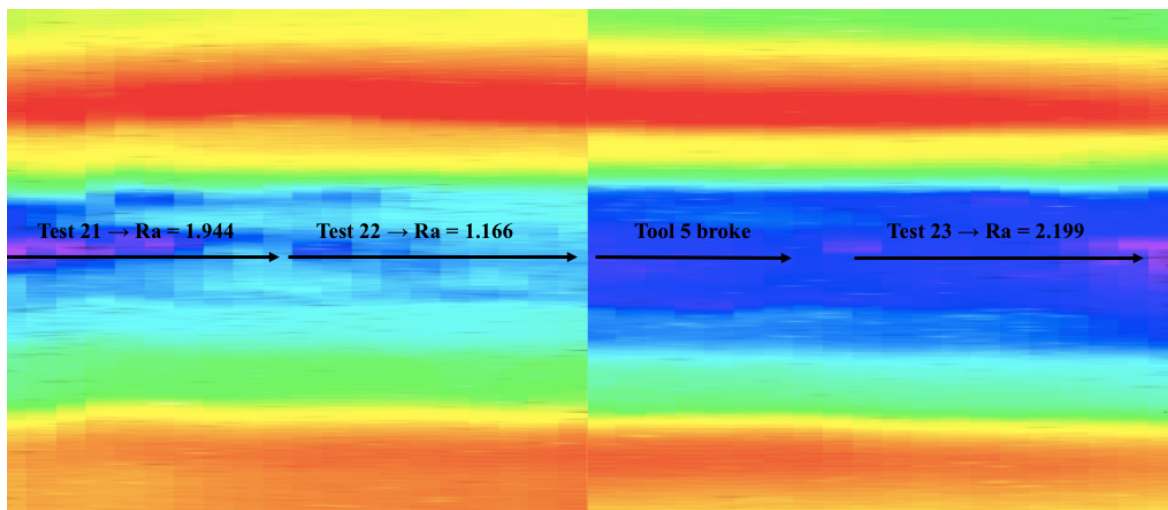
F.2 Workpiece 2



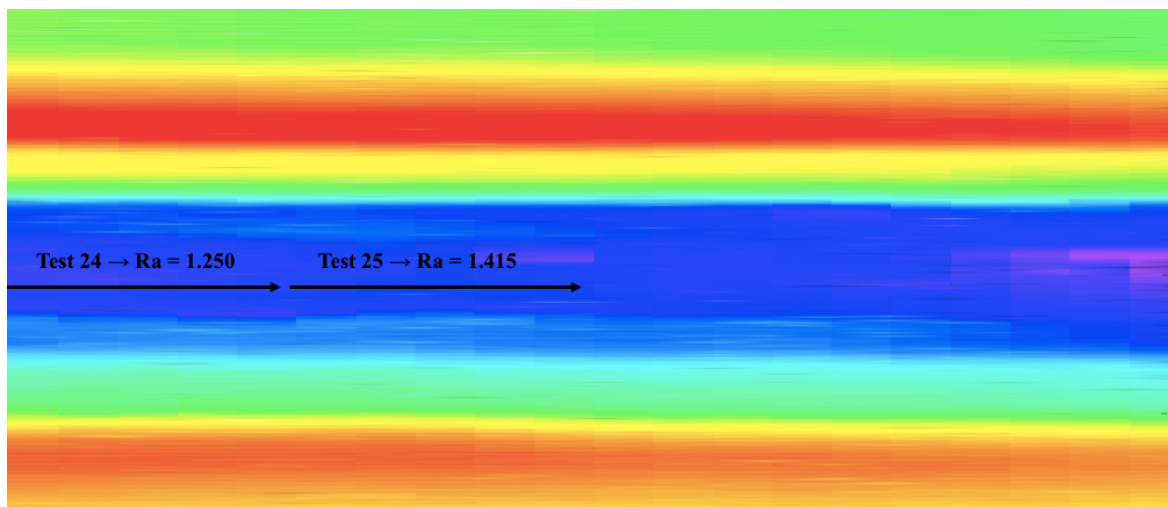
F.3 Workpiece 3



F.4 Workpiece 4



F.5 Workpiece 5





DIOGO MATOS

STUDY OF MACHINABILITY OF METAL MATRIX COMPOSITES PRODUCED BY UPWARD FRICTION STIR PROCESSING