CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

Department of Machining, Process Planning and Metrology

Bachelor Thesis

2019 Mohamad Ghaith Almasri

CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Methods of Use of Engage Movements in Milling

Bachelor Thesis

Study program: Theoretical Fundamentals of Mechanical Engineering

Study branch: Mechanical Engineering

Supervisor: Ing. Jan Tomiček, Ph.D.

Mohamad Ghaith Almasri

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BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Theoretical Fundamentals of Mechanical Engineering**

Branch of study: **No Special Fields od Study**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Methodics of use of engage movements in milling

Bachelor's thesis title in Czech:

Metodika použití najížděcích pohybů při frézování

Guidelines:

The topic is about the possibilities of engage movements in milling programmed by a CAM software. Different methods of ramping, roll-in or particular engagement should be reviewed with evaluation of their efect to resulting surface, vibrations, surface quality and cutting forces with focus to tool life.

Hints to follow:

1) Literary research about engage movements - types, their efect, benefits and negatives of methods will be reviewed
2) CAM software options, cutting direction efect
3) Recommendation for engage movements from different points of view
4) Practical experiment design - forces measurement
5) Evaluation of results and conclusion

Bibliography / sources:

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Date of bachelor's thesis assignment: **02.04.2019** Deadline for bachelor thesis submission: **19.07.2019**

Assignment valid until:

Ing. Jan Tomíček, Ph.D.	Ing. Libor Beránek, Ph.D.	prof. Ing. Michael Valášek, DrSc.
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11/04/2019

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Declaration

I hereby declare that I have completed this thesis having the topic Methods of Use of Engage Movements in Milling independently and I have included a full list of used references.

I do not have a compelling reason against the use of this thesis within the meaning of Section 60 of the Act No 121/2000 Sb., on copyright and rights related to copyright and on amendment to some other acts (The Copyright Act), as amended.

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Foremost, I would like to express my sincere gratitude to my thesis advisor**,** Ing. Jan Tomiček, Ph.D. for the continuous support of my BSc. study and research, for his patience, motivation, enthusiasm, and immense knowledge.

Finally, I would like to thank my family and friends for the unwavering support throughout my life and studies.

Bachelor's Thesis title:

Methods of Use of Engage Movements in Milling

Abstract:

With the constant growth of design methods and their accessibility, there is always a need to enhance the efficiency of manufacturing operations. One of the means to enhance efficiency is by optimizing the cutting forces involved in the machining process. Engage movement methods in milling processes have a significant influence on the output of a milling strategy. The thesis aimed to evaluate which of the engage movement methods in milling strategies are more suitable for selection in order to determine ways through which the operational effectiveness of the engage movement methods can be improved. An experimental approach to examine the effect of these methods on cutting forces was carried out during an end milling of a flat workpiece surface. The methods employed in this study were straight tool entry, horizontal arching, vertical arching, linear ramping, spiral movement, helical interpolation, and straight plunge. The workpiece material was 7075-T6 Aluminum. Siemens NX CAM was used for designing the milled layout and creating the milling strategy for the engage movements. All machining trials were carried out on a vertical 3-axis CNC Machining Center MAS VMC 500 with a controller. Cutting force measurements (Fx, Fy, and Fz) were measured using a Rotating Kistler 4-Component Dynamometer RCD type 9132C. The VHX 6000 Accuracy Optical Microscope with the Keyence Lenses VH-ZST/ RZ x20-200, were used to analyze the tool wear. The employment of engage movement methods had significant effects on the cutting forces, the resultant force in plunge milling was the highest among all tested methods. Linear ramping entry showed dependence on the ramp angle for maintaining a small value of resultant force. The cutting forces in the arcing techniques were smaller than the straight entry cutting forces, even when the same feed and speed were used. Although the dry milling of Aluminum 7075-T6 is not expedient, the minimal cutting forces can be achieved for this material regardless of the cutter-workpiece engagement strategy, using the optimal cutting parameters.

Key words: Engage movements, Milling, Ramping**,** Cutting forces, CNC Machening, Tool wear, Chip Thinning Effect, Arching, Roll-in, Cut entry, Lead-in and Lead-out, Retract, Axial Force, Radial Force

Název bakalářské práce:

Metody Využití Pohybů Při Frézování

Abstrakt:

S neustálým růstem metod navrhování a jejich přístupností je vždy nutné zvýšit efektivitu výrobních operací. Jedním z prostředků pro zvýšení účinnosti je optimalizace řezných sil, které jsou součástí obráběcího procesu. Zapojení pohybových metod do frézovacích procesů má významný vliv na výstup frézovací strategie. Cílem diplomové práce bylo zhodnotit, které z metod pohybu pohybu v frézovacích strategiích jsou vhodnější pro výběr, aby se určily způsoby, jak lze zlepšit provozní efektivitu metod pohybu pohybu. Během čelního frézování rovného povrchu obrobku byl proveden experimentální přístup k posouzení účinku těchto metod na řezné síly. Metody použité v této studii byly přímý vstup nástroje, horizontální oblouk, vertikální oblouk, lineární rampa, spirálový pohyb, spirálová interpolace a přímý pokles. Materiál obrobku byl hliník 7075-T6. Siemens NX CAM byl použit pro návrh frézovaného rozvržení a vytvoření frézovací strategie pro pohyby záběru. Všechny pokusy se prováděly na vertikálním 3osém CNC obráběcím centru MAS VMC 500 s ovladačem. Měření řezné síly (Fx, Fy a Fz) byla měřena za použití rotačního Kistler 4-komponentního dynamometru RCD typu 9132C. K analýze opotřebení nástroje byl použit optický mikroskop VHX 6000 s přesností s Keyence čočkami VH-ZST / RZ x20-200. Využití metod pohybu pohybu mělo významný vliv na řezné síly, výsledná síla při frézování byla nejvyšší ze všech testovaných metod. Lineární vstup do rampy ukázal závislost na úhlu rampy pro udržení malé hodnoty výsledné síly. Řezné síly v technikách oblouku byly menší než přímé vstupní řezné síly, i když byly použity stejné posuvy a rychlost. Ačkoli suché frézování hliníku 7075-T6 není účelné, lze u tohoto materiálu dosáhnout minimálních řezných sil bez ohledu na strategii zapojení řezného nástroje a obrobku s využitím optimálních řezných parametrů.

Klíčová slova: Pohybové pohyby, frézování, rampování, řezné síly, CNC obrábění, opotřebení nástroje, účinek na odštípnutí třísky, klenutí, roll-in, cut cut, lead-in and lead-out, Stahování, Axiální síla, radiální síla

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List of symbols and abbreviations

CAM	Computer Aided Manufacturing
CAD	Computer Aided Manufacturing
CNC	Computer Numerical Control
TDUs	Tool Diameter Units
DC	Cutter Diameter
CFRP	Carbon Fiber Reinforced Plastics-
Ti	Titanium
Al	Aluminum
Si	Silicon
Fe	Iron
Mg	Magnesium
Zn	Zinc
Cr	Chromium
Mn	Manganese
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional

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1 Introduction

1.1 Preamble into Digital Manufacturing Concepts

The manufacturing sector has turned to digital innovation to optimize the manufacturing processes [1]. According to Paritala, Manchikatla & Yarlagadda, The changes in the manufacturing sector that have necessitated digital innovation include market trends that are not only dynamic but also unpredictable, the increasing competitiveness in the sector globally, the increase in the complexity of the products being manufactured, diverse customer requirements, challenges facing the attempts to integrate the processes relating to design, manufacturing, and product support, the reduction of the time required to realize a product, and achieving all this without compromising in the quality of the final product [2]. One of the techniques in digital manufacturing is computer-aided manufacturing. It is a technique that employs computer systems in the planning, management, and the control of the process in a manufacturing facility [3].

1.2 Virtual Manufacturing Concept

As a concept, it allows engineers to define, simulate, and visualize the manufacturing processes through which a product is visualized using simulation-based technologies [42]. The virtual manufacturing process enables the engineers to verify the design of the product from a manufacturability perspective. A cross-functional team of engineers is involved in the realization of a product and the objectives of the manufacturing process such as assembly time, material costs, and the labor costs. The virtual manufacturing process helps this team to determine these elements before the commencement of the manufacturing process to make any changes that might result in an overall reduction in assembly costs [42].

1.3 Virtual Machining Concept

Virtual machining entails the use of computer-aided simulation technology to facilitate the simulation and modeling of the machine tools to be used in the manufacturing process [4].

Virtual machining has a variety of applications in manufacturing. According to Soori, Arezoo & Habibi, it can be used to enhance the accuracy with which the desired part is produced [5]. Soori, Arezoo & Habibi argued that Also, it could be used to identify some of the areas from which errors occur in the manufacturing process [6]. For instance, the thermal distortion of the structures of the machine tool can introduce inaccuracies in the finished part. Errors can also result from a deflection of a tool. Errors can also result from deviations in the geometrical dimensions of a moving axis. The virtual machining process allows engineers to examine the cutting forces that might cause a deflection of the machining tool.

Optimizing the cutting forces helps the engineer ensure the desired surface roughness and the dimensional accuracy of the resultant part [6]. The virtual machining process can also be used to optimize the cost and time aspects of the manufacturing process by identifying the most appropriate order of machining operations [7]. Additionally, the engineers can apply optimization techniques based on the findings of the simulation models in order to enhance the efficiency with which the parts are produced.

1.4 Critical Considerations for Successful Milling

Successful milling is much more than using the milling machines to create the profile of the part of the product desired. Even when the milling processes are programmed using computer-aided manufacturing software, there are various considerations necessary to achieve successful milling. Successful milling, in this case, is defined as realizing the intended part as it was designed and with all the functional and quality attributes. The milling process has offered a feasible alternative for various manufacturing processes, particularly those that require the production of threads, holes, and cavities. The milling process has negated the need for various manufacturing processes such as those involved turning, drilling, and tapping [8]. There are a variety of milling operations that are employed in realizing different parts. Some of them include profile millings, pocketing, shoulder milling, chamfer milling, face milling, fear machining, groove milling, and turn-milling [8]. Some considerations are necessary for achieving successful milling with any of these milling operations.

One of the considerations for successful milling is the milled configuration. This consideration relates to the features of a material or part that will be milled. The machining quality in computer-aided manufacturing is determined by assessing the finished surface [9]. Therefore, it is crucial to set the appropriate machining settings in order to achieve the desired quality of finish. The milled configuration has a significant impact on the determination of the appropriate machining settings. The features that will be milled influence the selection of the machining tool, the cutting forces, and the milling operation to be employed. The milled configuration is also an essential consideration because it affects productivity and the time required to realize a product. According to Sandvik Coromant, the features that will be milled may be located in hard-to-reach areas resulting in more hours for the tooling processes. Depending on the nature of the features to be milled, one might need to reconfigure the milling parameters in order to achieve the desired finish. Also, the milling process might be interrupted periodically to change the machining tools and also have inclusions that all combine to affect the number of parts that can be realized within a specific unit of time [8].

Another consideration for successful milling is the component to be milled. The cutting data that is used in the determination of the machining parameters are influenced by a variety of factors, one of which is the workpiece material. One aspect of the workpiece material that should be considered is its machinability. Machinability describes the ease with which one can mill or machine material to the expected parameters of surface finish using define cutting tools [10]. The machinability of a material is an important consideration because it influences a variety of parameters. For instance, materials that have good machinability will only require a small amount of power compared to materials with bad machinability [10]. Additionally, materials with good machinability have a lesser damaging effect on the cutting tools, can be milled within a shorter time, and are easier to mill to the desired surface finish compared to materials with bad machinability [10].

One has also to consider the machine. This consideration is made with the milling method that one will use in mind. Different axis machines can be used in milling material to realize a product. Some of these machines are suitable for specific milling methods and not for others. For instance, the 3-axis milling machine is the most appropriate when using the slot milling method or the face or shoulder milling method [8]. 4-axis or 5-axis milling machines are the most appropriate when the product to be realized has 3D profiles [8]. The machine is an essential consideration because the selection of the most suitable machine will influence the quality of the outcome significantly.

1.5 Significance of Research in Engage Movement Methods in Milling

Milling is crucial machining process, especially when there is a need to remove material from a workpiece. The engage movements also influence the realization of the desired milled components. Even with the right machines and having considered the other factors discussed above, the use of the wrong engage movements in milling to affect the outcomes significantly. The quality of the milled surface is one of the criteria through which the success of a milling operation is judged. According to Bas, Stoev, and Durakbasa, quality and precision are two critical criteria used in assessing finished products in the machining industry [12]. These criteria include the appearance of the work, the quality of surface finish, work accuracy, and the accuracy of geometrical dimensions. Therefore, research in engage movement methods is vital in order to understand the right tool entry method in order to enhance the quality of the milled surfaces.

The thickness of the chips that are formed during the machining process implies vibrations, tool life, and the quality of the surface finish [14]. Ideally, the start of the chip should be thick and progressively get thinner as the milling process continues. Different engage movement methods produce chips of different thickness. The study on engage movement methods is important for improvements in the chip thinning effect. Enhanced knowledge on how different engage entry methods can enhance the chip thinning effect will proffer benefits such as elongating tool life and improving the quality of surface finish by reducing the vibrations that result from the formation of think chips during the milling process.

This study is also significant because it will explore the various engage movement methods and the effects that they have on tool life, cutting forces, quality of surface finish, and resultant vibrations. This knowledge is vital in optimizing the cutting forces that are needed with every engage movement method to make a cut with the quality of surface finish, vibrations, and tool life into consideration. This knowledge is also significant for optimizing the spindle speed face to face with other milling parameters in order to achieve successful milling. This will help reduce the power consumed in a milling operation, lengthen the life of the tool, and ensure better surface quality.

1.6 Aim of the Thesis

The work described in this thesis aimed to evaluate which of the studied methods in each type of milling strategy is more suitable for selection to achieve a better surface quality and tool life. The study objectives include:

1) To examine the effects of implementing those methods on cutting forces.

2) To investigate the influence of the cutting forces on the resulting surfaces, vibrations, and tool wear.

3) To make recommendations or suggestions to improve the operational effectiveness of the cutter-workpiece engagement methods.

1.7 Organization of the Thesis

The thesis is organized into six distinct sections. The first section is the introduction of the thesis. In this section, I define and discuss the key concepts in this thesis. The discussion also links the concepts to the topic area of the thesis. The introduction section also situates this research by discussing its significance and the rationale for researching the engage movement methods in milling. The introduction section will also highlight the considerations one ought to make during milling operations by discussing their impact on the tool and the finished product. The introduction section will also contain the aim of the thesis.

The next section of the thesis is the literature review. The section will include research and an overview of the different techniques and methods of cutter work-piece engagement in milling, their effects on the resulting surface, cutting forces, vibrations and tool life, and the benefits and negatives of each method.

The next section is a discussion of the CAM software options in Siemens NX, Autodesk PowerMill, and Autodesk Fusion 360 concerning the cutting direction each of these softwares is depicting for the engage movement methods. Some recommendations concerning the effect of these directions will be made.

The next section is the practical experiment measurement section. In this section, the methods of engage movements designed on Siemens NX will be applied and experienced on the chosen material of the workpiece using the chosen material and shape of the cutting tool. With the assistance of the 4D-Component Kistler Dynamometer the cutting forces will be measured.

The results section will provide an overall analysis of the results obtained during the implementation. Based on the calculated and measured values of cutting forces, comparison between theoretical assumptions and the practical results will be discussed.

The final section is the conclusion to the thesis. This section will highlight the contribution and limitation of the research conducted, and the future work that could be carried out based on existing research.

2 Literature Review and Background Research

2.1 Techniques and Methods of Engage Movements in Milling

2.1.1. Ramping: Linear and Circular

Linear ramping refers to two axes ramping approach to material milling where the feed simultaneously in a single radial direction and the axial direction, with an angular path. The feed in the radial direction in this approach to milling occurs in either the X-axis or the Y-axis and never in both directions [15]. The cross-section of the linear ramping method is shown in Figure 1.

Circular ramping, on the other hand, refers to the milling approach where an axial feed is combined simultaneously with a circular feed on both the X and Y axes at a specific pitch [15].

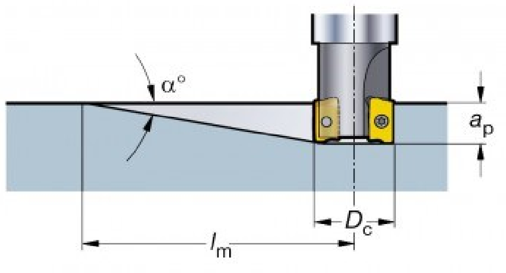
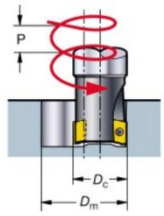


Figure 2:Linear Ramping. Source: (Sandvik Coromant; Ramping: Two Axis Linear and Circular)

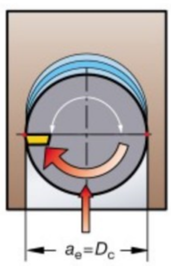


I_m... Lenght of Cut
D_c... Cutter Diameter
a_p... Depth of Cut
D_m... Min. Hole Diameter
P... Pitch
α°... Ramp Angle

Figure 1: Circular Ramping. Source: (Sandvik Coromant; Ramping: Two Axis Linear and Circular)

2.1.1.1 Quality of Resulting Surfaces

The two ramping techniques result in different qualities of finish due to differences in their machining processes. Circular ramping results in a better quality of surface finish compared to linear ramping because the reduction of the radial cut in circular ramping allows for a comparatively smoother finish [15]. Additionally, the pure down-milling operation in circular ramping enables a machinist to achieve a smooth quality of surface finish compared to linear ramping. The large radial force resulting from full slotting (i.e. $a_e = D_c$) in linear ramping results in a surface finish of lower quality compared to circular ramping [15]. Due to the full slotting, additional stress builds up on the tool when applying the linear ramping technique, which generates radial forces and longer chips; therefore, impacting the finished surface [15].

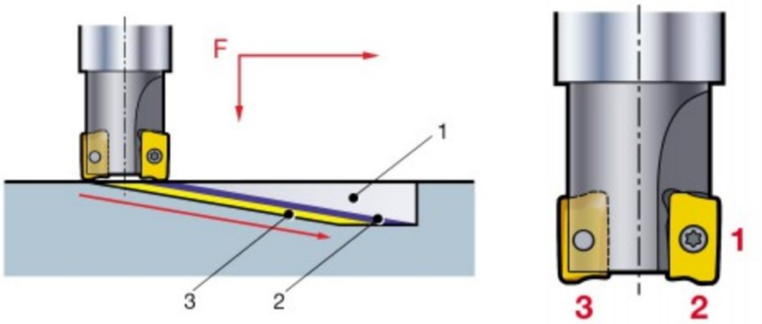


a_e... Radial Depth of Cut
D_C... Cutter Diameter

Figure 3: Full Slotting in Linear Ramping. Source: (Sandvik Coromant; Ramping: Two Axes Linear and Circular)

2.1.1.2 Cutting Forces

The Cutting forces involved in ramping are radial cutting forces and axial cutting forces. These cutting forces result from the three cutting processes involved in the linear ramping technique [15]. The first is the periphery cutting process that occurs on the leading insert of the cutting tool. The cutting forces in this cutting process is the radial cutting forces. The second is the bottom cutting process that occurs on the leading insert [15]. The third cutting process is the bottom cutting process that occurs on the trailing insert of the cutting tool. The cutting force in the last two cutting processes is the axial cutting force [15].



F... Cutting Force.
1... Leading Insert of the cutting Tool
2... Leading Insert of the Cutting Tool
3... Trailing Insert of the Cutting Tool

Figure 4: The Cutting Processes That Occurs in The Linear ramping. Source: (Sandvik Coromant; Ramping: two axis linear and circular).

2.1.1.3 Vibrations

Ramping, mainly circular ramping, provides for a comparatively stable machining process. However, the radial cutting forces might cause vibrations [16]. The vibrations have implications on the quality of the surface finish as well as tool life.

2.1.1.4 Tool Life

The length of the life of a tool is partly influenced by the distribution of the forces to which it is exposed. Of the two ramping techniques, circular ramping offers the best distribution of the cutting forces because, in addition to a reduced radial force, the entire cutting forces are distributed among the three axes. There is a considerable radial engagement when using the linear ramping technique [15]. In addition, the cutting forces are distributed between the two axes. As a result, circular ramping offers a longer tool life compared to linear ramping. Even then, linear ramping results in longer tool life compared to other milling methods where the cutting forces are all channeled through one axis such as plunge milling [15].

2.1.1.5 Advantages and Disadvantages

One of the advantages of ramping comes from the gradual increase in the depth of the machined surface [17]. This has implications on tool life because the increase in the depth of the machined surface prevents breakage of the cutting tools through shock loading. This advantage enhances the tool life. Another advantage of ramping is the production of small chips in comparison to other methods such as plunging [17]. Small Chips have various implications on the machining process. Firstly, small chips can be evacuated with more ease and speed. The implications here is that a machinist using the ramping method can use faster feeds and higher speeds in order to reduce the cycle time. The ramping engage movement is also advantageous because of the extra space that the milling process creates in the tool changer [17]. A disadvantage of the circular ramping method is that it has low productivity when holes of a large diameter are required. Additionally, it is not suitable when large volumes of work are to be done [18].

2.1.2 Helical Interpolation

Helical interpolation is one of the engage movement methods that are used in milling operations. Helical interpolation is one of the most advanced milling techniques that are available for machinists. The total entry technique involves circular movements that coincide in both the X and Y axes [19]. Helical interpolation uses an axial feed that occurs in the Z axis [19].

Helical interpolation is an important technique for certain milling operations. Its versatility in making a hole on a solid component has been proven over time. The technique is also useful when one needs to open up existing holes to a larger diameter or depth. A 3-axis CNC machine is needed when using the helical interpolating method. This is because it allows the programming of the spindle movements on different axes. For instance, the helical interpolating technique is achieved by editing the command for circular interpolation to include a movement in the Z-axis [19].

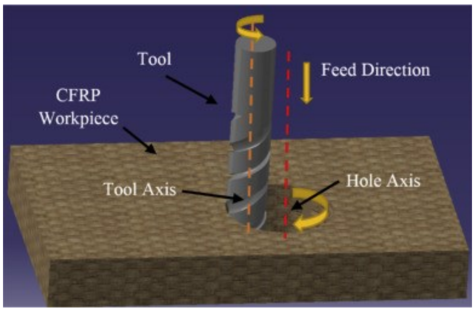


Figure 5: Schematic of Helical Interpolation Engage Entry Movement in Milling. Source: (Amini, Baraheni & Hakimi)

2.1.2.1 Quality of Resulting Surfaces

The quality of the resulting finishes is of concern in milling operations. The analysis of this quality in helical milling is performed based on the micro geometrical deviation, dimensional deviation, and geometrical deviation [16]. Dimensional deviations in the resultant hole when helical interpolation is performed are influenced by the deflection of the cutting tool. The deflection of the cutting tool is influenced by factors such as the cutting forces that are employed, the stiffness of the took, and the orthogonal directions [16]. Previous studies have shown that the dimensional deviation of the holes resulting from helical interpolation varies depending on the type of material. For instance, Pereira et al. found that when working with Carbon Fiber Reinforced Plastics-Ti stacks (CFRP), an increase in the wear of the cutting tools is responsible for variations noted in the diameter of the resultant hole [16]. This wear occurs when one is boring the titanium plate that is at the bottom of the stacks. A variation in the diameter of the resulting hole has also been identified when one is working with laminated materials. According to Pereira et al., the variation occurs because of the difference in the processing characteristics of the different materials that are used in the composite.

According to Wang, Qin, Li & Tan, the joining face in the laminate material and the core material has a significant impact on the nature of the wear of the cutting tool. Additionally, the thickness of the laminated material affects the temperatures to which the cutting end of the milling tool is subjected, resulting in varying degrees of wear [20]. It is these effects that cause the variation in the dimensional quality of the resulting hole. Research has shown that the dimensional quality of the resulting surfaces when using helical interpolation can be improved by using a higher axial feed for every tooth in the cutting tool and combining this effect with higher process forces [21]. Regardless, helical interpolation has been shown to result in an improved dimensional quality when compared to conventional drilling. The use of flood coolant lubrication can help achieve better dimensional quality by reducing the wear of the tool due to high temperatures resulting in a variation in the bore diameter [22], especially when working with aluminum alloys.

The roundness of the resulting hole is another dimension through which the effect of helical interpolation on the resulting surfaces has been analyzed. A study that accessed this effect on A5052 aluminum alloy showed that helical interpolation resulting in a better finish compared to conventional drilling [22]. However, it was noted that lubrication is important in achieving a good quality finish with respect to roundness. The roughness of the resulting hole is also an element of the quality of finish in the resulting surface. Roughness as an element of the surface finish is influenced by the accuracy of the tool, the geometry of the tool, workpiece harness, and the other machining properties. A hard material is likely to result in a high cutting temperature that might result in higher levels of surface roughness unless the cooling lubricant conditions are improved during the milling process [16].

2.1.2.2 Cutting Forces

A machinist needs to understand the cutting forces involved in the machining process as a prerequisite for determining the cutting power. Understanding the cutting forces is also important for modeling the milling process in order to ensure tight tolerances while also reducing the amount of tool wear [16]. The cutting forces of each engage entry method are an important consideration because this attribute is used together with the most appropriate cutting conditions to ensure a high surface quality of the workpiece, a reduction or total elimination of machine tool vibrations, ensuring the stability of the milling process, and enhancing the geometrical accuracy of the resulting holes [16]. The cutting forces involved in the helical interpolation milling technique include the radial cutting force and axial cutting force. The radial cutting force emanates from the cutting edge on the periphery of the cutting tool. The axial cutting force in this technique emanates from the cutting edge at the front of the tool [16].

2.1.2.3 Vibrations

Any vibrations in this milling technique result from the radial deflection that results from the radial cutting forces. According to Pereira et al., radial cutting forces in the helical interpolation technique come from both the cutting edges at the front and the periphery of the cutting tool [16]. The vibrations have the potential to influence the tool life and the quality of the surface finish depending on their magnitude.

2.1.2.4 Tool Life

Cutting tools will inevitably wear continually as it is being used in the milling process. However, specific tool entry methods cause significant wear in the tool too quickly compared to others. According to Iyer, conventional drilling has been shown to result in catastrophic fractures occurring at the cutting edges located in the drill's periphery [23]. Helical milling offers reprieve because the wear of the tool occurs uniformly and progressively. The tool wear is also normally noted in the flank of the tool [23]. Therefore, there is an extended tool life even when the cutting tools are used on hardened D2 tool steel. Helical milling has a much-improved work process compared to conventional drilling; an attribute that has been shown to contribute to its extended tool life.

2.1.2.5 Advantages and Disadvantages

One advantage of helical interpolation is that it prevents the breakout of the work material. In conventional drilling, the hole exit is characterized by excessive thrust forces [23]. These thrust forces are responsible for the fractures on the cutting tool depending on the hardness of the work material. The helical interpolation technique is advantageous because it has a helical trajectory that removes the material at the hole's center by cutting it instead of extruding it as is the case in conventional drilling. The result is lower thrust forces that prevent the breakout of the work material towards its exit [23].

Helical interpolation, as an engage entry method, offers a machinist an opportunity to widen the diameter of a hole and with high surface quality and precision without necessarily using the different tool [24]. Conventional drilling requires the use of a multiplicity of tools, often with a poor surface finish. One then requires a host of other tools after widening the tool in order to achieve the desired quality of finish. Helical interpolation is advantageous in that it only requires the use of two tools at most. A machinist would require an endmill in order to create a profile of the hole before switching to a smaller feed that will allow the widening of the hole to the desired diameter, tolerance, and surface quality [24].

Helical interpolation is also advantageous because it allows for better chip removal and low cutting temperatures. The endmill that is used in this milling technique occupies a small portion of the bore. This attribute negates the need for extracting the endmill to remove the chips. A machinist can introduce a coolant into the bore in order to remove the chips and decrease the temperature [24]. Another merit of this technique is that it allows one to model the wear of the cutting tool using mathematical calculations. The outputs can then be used to modify the trajectory of the tool to extend their life [24]. One disadvantage of the helical interpolation is that it is not as productive when the depth of the hole to be realized is big [18]. Helical interpolation is also limited to low volumes of work [18].

2.1.3Straight Plunge

Plunge milling is rough machining process where the end of the tool is used in the removal of materials rather than the tool's periphery. As shown in Figure 6, the plunge milling operation sinks holes into the component being drilled in an axial direction [25].

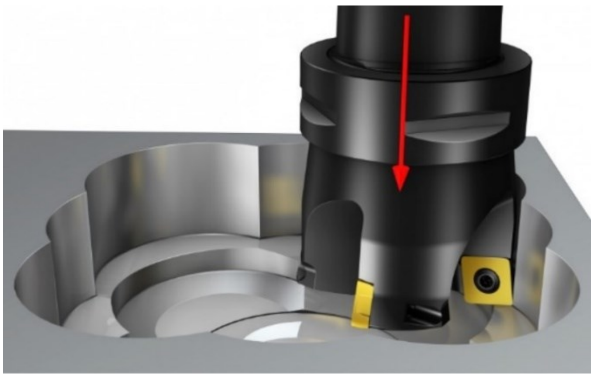


Figure 6: Plunge Milling Operation. Source: (Sandvik Coromant - Plunge Milling)

2.1.3.1 Quality of Resulting Surface

The roughness of the resulting surface is an important element of its quality. As a rough machining process, it is expected that the surface quality of the material milled using the plunge technique may not be as smooth as surfaces milled using other techniques. According to Danis, Wojtowicz, Monies, Lamesle & Lagarrigue, there is an element of roughness in surfaces milled using the plunge milling technique. The roughness emanates from the take up of materials as the cutter rises against the material that has already been machined [26]. Danis et al., found that the roughness of the resulting surfaces increased as the feed rates increased. The feed rate can be optimized to achieve a smoother surface. Based on the finding by Danis et al., there is a feed rate below which the resulting surfaces are without any vibrations of visible pull-outs and past which the resulting surfaces exhibit the effect of the end mill pulling out the materials and the vibrations of the cutting tool [26]. Plunge milling may not result in the deformation of the grain structure on the finished surface when the cutting edges used are sharp, and the rake face is polished. According to Danis et al., this is because of the milling process under these conditions does not result in a significant increase in temperature. In addition, the use of this method does not alter the hardness values of the material being milled [26].

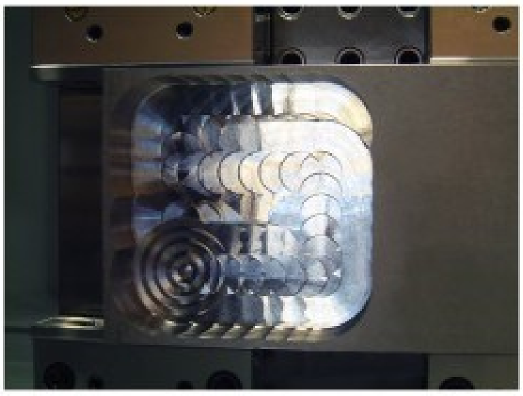


Figure 7: Resulting Surface After Using Plunge Milling for Milling this Slot. Source: (Sandvik Coromant - Plunge Milling)

2.1.3.2 Cutting Forces

The cutting forces in plunge milling include the axial cutting force and the tangential cutting force. According to Danis, Monies, Lagarrigue & Wojtowicz, the radial forces in plunge milling are reduced significantly in comparison with the traditional milling techniques. It is this reduction in the radial cutting forces that give this technique its characteristic cutting stability. The axial cutting force during a plunge milling operation describes the force that ensures sustained contact between the cutting tool and the material being milled. The axial force acts perpendicularly to the surface being milled [31]. The tangential force, on the other hand, describes the force that offers resistance to the rotation movement of the work. The tangential force during plunge milling is low when the cutting tool is rotating at low revolutions. However, the tangential cutting force increases significantly when the cutting tool is operating at high speeds [31].

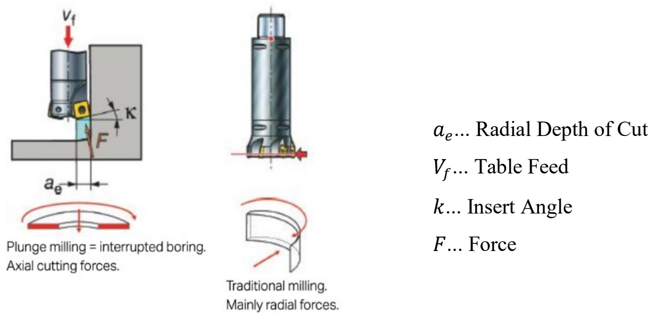


Figure 8: Cutting Forces in Plunge Milling. Source: (Sandvik Coromant - Plunge Milling)

2.1.3.3 Vibrations

The negligible radial cutting force in plunge milling offers cutting stability as one of the advantages. However, the influence of the tangential cutting force cannot be underestimated, given that it resists the rotational movement of the work [31]. At low cutting speeds, the tangential force is not significant enough to cause vibrations. Tangential cutting forces increase significantly as the milling operation gets deeper. As the cutting tool removes material from deeper in the material, the increase in the tangential cutting forces has been shown to result in chatter and vibrations. The chatter and vibrations have a negative effect on the surface quality of the finished work [31].

2.1.3.4 Tool Life

Plunge milling results in lesser tool damage compared to alternative roughing milling techniques that have the same rate of material removal. The reduced damage on the cutting tools results from the fact that the several overlapping passes that characterize the tool path of the plunge milling process on the Z-axis create a stable cutting process. Additionally, the plunge milling process, with proper management of the feed rate and cutting speeds, has a lower likelihood of vibrations and chatter that are likely to damage the cutting tools. The plunge milling process eliminates the side pressures that come from the X-axis and Y-axis. The concentration of all the cutting forces on the plane's Z-axis reduces the peripheral damage of the cutting tool, even when making deep bores [32]. All these factors work in concert to ensure a long tool life. An example offered by 3D Systems reported that Norfolk Specialties, a company that uses plunge milling had used a new Computer-Aided Manufacturing feature to program its plunge milling process and, in the process, reduced the time taken to machine a component in half and extended the tool life four times over [32]. In addition to a 50% reduction in the machining time, Ouverson Engineering and Machine also reported an 88% extension in tool life when using plunge milling [32].

2.1.3.5 Advantages and Disadvantages

One of the advantages of the plunge milling operation is that the removal of materials is done using the axial direction rather than the radial direction [25]. The axial direction is one where the cutting force is applied parallel to the shaft of the component to be milled. In comparison, the cutting force in the radial direction is applied at a 90-degree angle to the shaft of the component to be milled. The direction on which the cutting forces are applied is significant in the milling process. The spindle of the milling machine is more stable when the cutting forces are applied in the axial direction compared to the radial direction [27]. According to Li, Liu, Ming, Wang & Dong, the axial ratio to the tangential feed per tooth of the milling machine significantly affects the stability of the spindle [11]. The spin speed of the spindle also has an influence of its stability in either direction [28]. Considering these factors, the axial direction offers the best milling conditions for the stability of the spindle of the cutting machine. The structural rigidity of the milling machine's spindle is highest in the axial direction [29], hence the advantageous nature of the plunge milling method.

Another advantage of plunge milling is that it offers an alternative milling process when it is not possible to mill the component from its side as a result of the distorting effect of the resultant vibration. Vibrations in the component being drilled can be the result of a variety of factors. For instance, vibrations can occur when one is working with materials that have low machinability. The machining of titanium alloys can be a challenging experience during the milling process. According to Cedergren, Frangoudis, Archenti, Pederson & Sjoberg, the machining process of the alloys results in shear- localized chips [30]. The shear-localized chips cause the cutting forces to varying cyclically. It is the cyclic variation that produces the vibration that makes the machining process difficult. The problematic cyclic variations can be reduced by lowering the speed at which the material is machined. The same effect can also be achieved by lowering the feed rates so that instead of the shear-localized chips, continuous chips, which do not cause the cutting forces to vary cyclically, are formed [30]. This approach is not appropriate in a manufacturing perspective because it results in an increase in the time in which a product is realized and also reduces the sustainability of the machining process.

According to Antonialli, Diniz & Pedriva, Titanium alloys have characteristically low Young modulus [33]. As a result, the alloys tend to show more elastic behavior during the machining process compared to other alloys with a high Young modulus. Additionally, the thickness of the chip varies significantly during the material's elastic behavior. Titanium alloys are also characterized by low heat conductivity. The impact of this attribute is that the machining process results in serrated chips. The serrated chips cause the cutting forces to varying significantly [33]. The cutting temperature and the resultant vibrations make for challenging machining of titanium alloys [34]. This advantage makes plunge drilling a versatile milling operation. Plunge milling can also be used when the cutting tool has an overhang that is bigger than (4 x D_C) when working on semi-finishing corners when the component to be milled cannot be fastened in a stable manner [25].

Plunge drilling is also advantageous because it offers alternative methods of milling a component when the machine in use has a limited amount of torque. Working with milling machines that have a low torque even at high revolutions can be problematic. Plunge milling offers reprieve according to Sandvik Coromant – Groove or Slot Milling [35].

A demerit of plunge milling is that the rate of material removal is low. Despite the fact that the milling method exploits the strongest axis of a machine, the fact that it removes material at a low rate makes it unpopular among many machinists [36]. This is in the context of new milling machines that while providing a high tool, also have a comparatively impressive axial tool pressure. Plunge milling is disadvantageous in that the tools that are at the disposal of the machinist are greatly reduced with this milling method according to Sandvik Coromant – Groove or Slot Milling [35]. Additionally, the productivity of the method is low even when the conditions under which the milling operation is performed are optimal according to Sandvik Coromant – Groove or Slot Milling [35].

2.1.4Arcing (Horizontal and Vertical)

Arching tool engagement techniques are another alternative to conventional milling. These techniques involve the rotation of the cutter on a specific pivot point as it enters the workpiece [14]. The entry of the tool into the workpiece is gradual until the machinist achieves the desired nominal width. An arching entry strategy is utilized with the intention of ensuring that as the tool exits the cut, the thickness of the resulting chip is as small as it can be. The cross-section of the arching entry techniques is shown in Figure 9 and Figure 10.

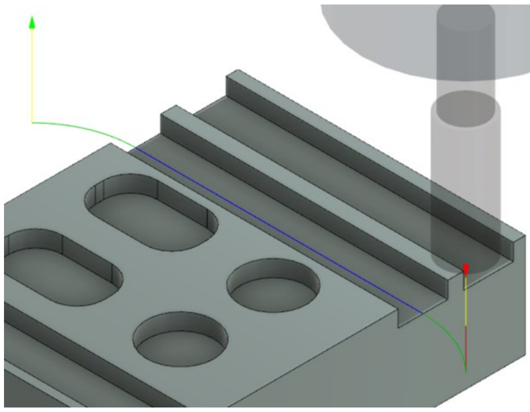


Figure 10: Horizontal Arching (Roll-in).

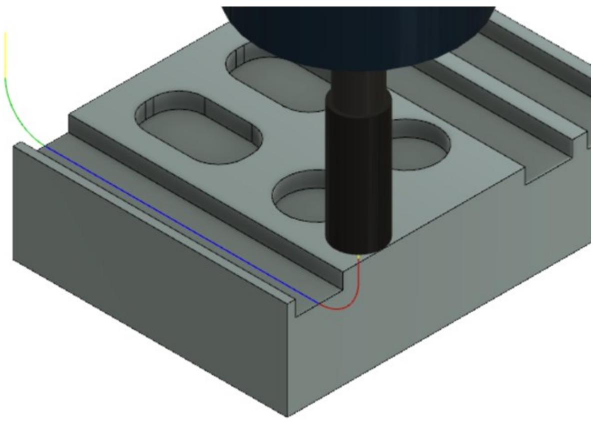


Figure 9: Vertical Arching Entry Method

2.1.4.1 Quality of Resulting Surface

The smooth entry of the cutting tool in an arching technique ensures an improved surface finish compared to surfaces that result from the straight entry of the cutting tool. The quality of the surface finish is also enhanced by the fact that this milling strategy also entails exiting out of the cut in an arc motion, thereby reducing the likelihood of the damage of the cut surface by the tool or the exiting chips [37].

2.1.4.2 Cutting Forces

The cutting forces involved in the roll in technique were also modeled by Perez et al. in their study. The resultant graphical representation is shown in Figure 11.

The two cutting forces were determined in the X-axis and were parallel to the direction of the feed. A small arc of engagement characterizes the first zone of the milling process. This occurs until a full engagement of the cutting tool with the work surface is achieved. The cutting forces in this zone are characteristically small. As the arc of engagement increases in the second zone, the cutting forces increase in tandem despite the transient nature of the entry of the tool into the material. The cutting force profile levels off in the third zone after the rolling of the cutting tool into the desired pivot point [14].

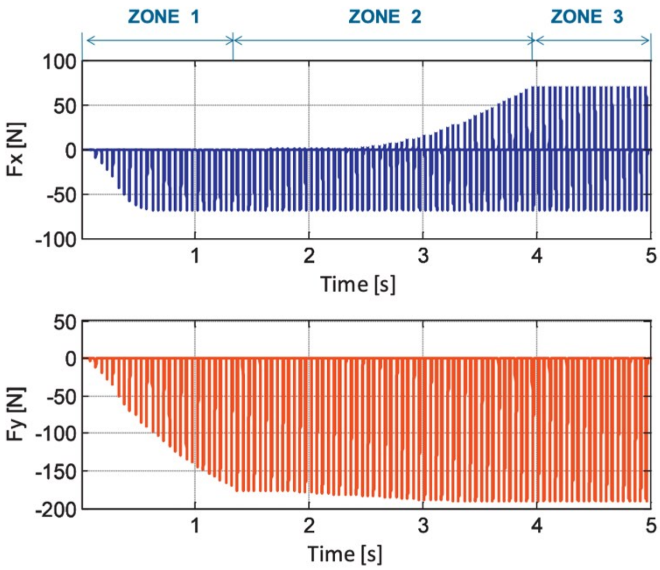


Figure 11: Cutting Forces F_x and F_y for Workpiece Entry Rolling into the Cut

$(D = 8\ [mm]; N_z = 2;\ \lambda_s = 30°; f_z = 0{,}08\ [mm];\ a_e = 4\ [mm])$

Source: (Perez et al. 576)

2.1.4.3 Vibrations

One of the causes of vibrations during the machining process is the size of the resultant chips. Milling processes that result in thick chip thickness often experience significant vibrations. The amount of vibration in any machining process is a significant consideration because it affects, among others, the life of the cutting tool and the quality of the resulting finish [14].The modeling of the cutting forces for the roll-in entry strategy by Perez et al. helped determine the thickness of the resulting chips as a way of studying a variety of other parameters, including the vibrations resulting from a machining process using the roll-in entry method. The researchers found that the roll-in technique creates thin chips. The exit of these chips from the bore area does not create vibrations [14].

2.1.4.4 Tool Life

The most significant damage to the cutting tool occurs during the entry of the tool into the work surface. This is especially the case when a machinist uses a high feed rate before the full engagement of the cutter into the work surface [37, 38]. The roll-in entry technique extends the tool life of the cutter because rather than entering the work surface in a straight line, the entry is smooth and in an arc motion [37, 38]. The lower temperatures that the cutting tool in the roll-in milling technique experiences also enhances the tool life by reducing the resultant wear and tear on the tool. The low temperatures result from the use of a small engagement arc in the roll-in technique [14]. The roll-in technique also results in a thin chip when compared to other methods of entry, such as the straight entry method. As a result of the think chip thickness, the pressure on which the tool is exposed is considerably smaller compared to the straight entry method. The result of these factors is an enhanced tool life [14].

2.1.4.5 Advantages and Disadvantages

The arching technique has several advantages that machinists can exploit. One of the advantages is the reduction in the tool wear that results from the head-on collision when the tool engages with the work material in a straight toolpath. Long tool life is beneficial for machinists from a cost-effectiveness perspective**.** The reduction in the vibration on the machines due to the thin chip thickness upon exits contributes to a quality surface finish. This means that this method can be used for milling of precision parts where the quality of the finish is of paramount importance. A demerit of the roll-in technique according to [14], is that the roll in technique is not the most appropriate when working with soft materials because as the number of entries tends towards one thousand, there is a noticeable negative difference in the wear of the cutting edge.

2.1.5Straight Tool Entry

As the name suggests, the straight tool entry method is one where the cutting edge engages with the workpiece at 90° angle regardless of whether it is face milling or peripheral milling. The schematic of the entry method is shown in Figure 12.

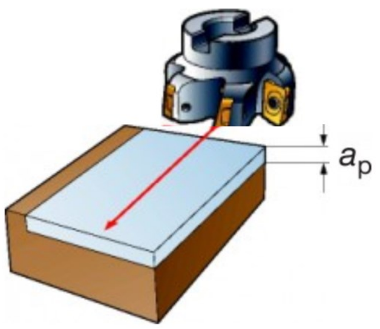


Figure 12: Straight Tool Entry . Source: Sandvik Coromant (Face Milling)

2.1.5.1 Quality of Resulting Surfaces

The Vibration that characterize the entry method have an impact in the quality of the surface finish. This thick chip thickness results in surface finish of lesser quality compared to the other methods such as the arching technique where the cutter exits the workpiece with a smaller chip thickness [14].

2.1.5.2 Cutting Forces

The cutting forces associated with this entry method are the F_x and F_y cutting forces. These forces act on the two axes and are experienced by the tool immediately as it engages with workpiece. The two forces as modelled by Perez e al., are shown in Figure 13 [14].

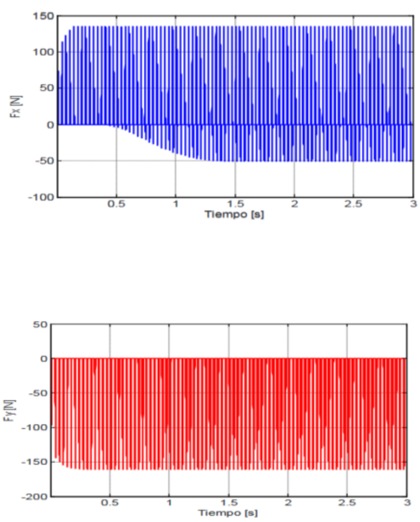


Figure 13: Cutting Forces in Straight Tool Entry Method Source: (Perez et al. 579).

2.1.5.3 Vibrations

This tool entry method is prone to vibrations because as the cutter exits the milled area, the thickness of the chip is thicker than the instant the tool engaged with the cut. In result, this creates thick chip on entry and thicker chip on exit [14]. Smashing the cutter with full immersion into the cut also a factor in producing vibrations.

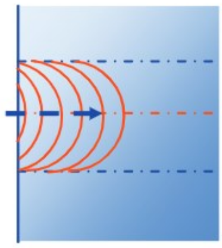


Figure 14: Straight Tool Entry. Source: (Perez et al. 574)

2.1.5.4 Tool Life

The straight tool entry method places the tool under immense pressure immediately as it engages with the workpiece [14]. The pressure significantly wears to the cutting edge, an outcome that reduces the tool life. When working with the straight entry method, it is advisable to reduce the feed rate of the milling operation by half until the cutting tool is fully engaged into the workpiece. The cutting flute of the straight tool entry is also characterized by high temperatures because of the arc of engage is longer compared to other methods such as the horizontal arching method [14]. The high temperatures also affect tool life negatively. Figure 14 demonstrate the orientation of the feed rate; longer tool life with higher cutting speed and feed rate. Greater depth of cut [14].

2.1.5.5 Advantages and Disadvantages

One disadvantage of the straight tool entry method is that it results in significant tool wear [14]. According to Perez et al. [14], the cutting tool is exposed to high pressures; immediately, it engages with the work surface. These high-pressure result in significant wear of the cutting tool, a factor that shortens its tool life. Another disadvantage of the straight entry method is the vibrations that result from the tendency of the method to create chips with a more thickness compared to other strategy techniques such as the roll in [14]. Vibrations are a significant consideration in milling processes because they affect the quality of finish in the resultant surface.

2.1.6Spiral Milling Movement

The spiraling milling movement.

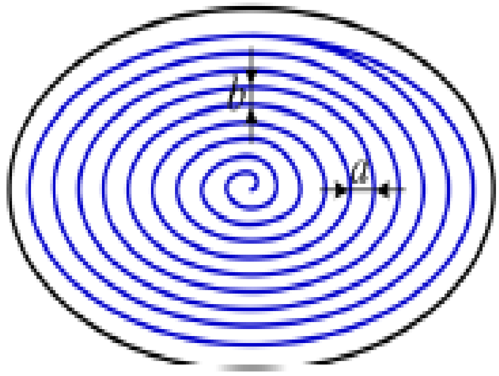


Figure 15: Pocket machining toolpath for the spiral milling movement. Source: (Huang, Lynn and Kurfess 1).

2.1.6.1 Quality of Resulting Surface

One of the important aspects of surface finish of the milled surface with the spiral milling movement is the dimensional accuracy. One of the advantages of using this approach over others for pocket milling is the resultant finish does not have sharp corners [47]. Additionally, the spiral milling movement does not create self-intersections [47]. These attributes of the tool engagement method contribute to a high-quality surface finish particularly from a dimensional accuracy and smoothness perspective. The spiral tool path used with the spiral milling movement also contributes to a high quality of surface finish because it does not have retraction and is characterized by a smooth finish [48]. The spiral tool path has also been implicated in low quality of surface finish because of the high cutting forces involved in tool entry method. According to Shajari, Sadeghi and Hassanpour, the tool-chip contact area with this method results in a surface finish of poor texture, especially when the milling surfaces have low curvature convex [59].

2.1.6.2 Cutting Forces

Axial and radial cutting forces are involved in the spiral milling movement. The axial cutting forces result from the bottom cutting process resulting from the leading insert of the cutting tool and the bottom cutting process resulting from the trailing insert of the cutting tool. The radial cutting force emanates from the cutting processes occurring on the leading insert of the tool as well as the periphery of the cutting tool.

2.1.6.3 Vibrations

The radial cutting force is significantly reduced in the spiral milling movement. As a result, the vibrations that come with this cutting force are reduced [16].

2.1.6.4 Tool Life

Despite its high machining efficiency, the rate of tool wear with the spiral milling movement is low [47].

2.1.6.5 Advantages and Disadvantages

One advantage of the spiral milling movement is that it eliminates sharp corners from the milled surface [47]. This is an advantage especially when the desired shape of the milled surface requires smooth dimensions. Another advantage of the spiral milling movement is that it eliminates self-intersections [47]. Self-intersections might occur in a milling process where the cutting edge takes several passes on the milled surface. Self-intersections have a significant impact on the quality and aesthetics of the surface finish. The fact that this tool movement method eliminates them is advantageous for machinists. One disadvantage of the spiral milling movement is that the processes that are required to remove the self-intersections are laborious and require the machinist to invest a lot of time [48]. Another disadvantage is that one needs to use complex algorithms to remove the invalid loops [48].

3 CAM Software Options – Cutting Direction Effects

Three different CAM softwares were chosen to design the studied engage movement methods, Siemens NX, Autodesk Fusion 360, and Autodesk PowerMill. Each one of these CAM softwares has a different mechanism in approaching the cut entry techniques. This section will review the options given in the mentioned softwares. Additionally, some recommendations and suggestions concerning their suitability of use will be made.

3.1 Autodesk PowerMill:

PowerMill is an Autodesk CAM software; it supports 3- and 5-axis subtractive machining. Seeking optimum machining operation requires additional modification options; the software has various selections to obtain the optimum tool path for a designed layout, and it also gives a broad span of options when choosing the suitable engage movement of the tool path [64].

3.1.1. Leads-in and Leads-out

- **Surface Normal Arc:**
  This option enters a tangential arc movement at the beginning and the tip of each cutting path. This arc rests in the plane determined by the toolpath's tangent direction and the surface normal [39].

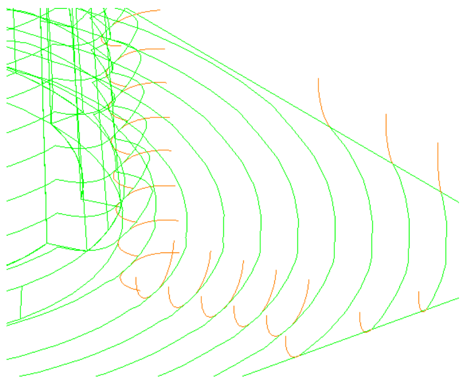


Figure 16: Surface Normal Arc in PowerMill. Source: Autodesk Knowledge; PowerMill

The Surface Normal Arc choice allows a process of automatically collecting the orientation that is suited for each section by using the surface normal at that point. The direction of the Surface Normal Arc differs with the steepness of the surface. On depthless regions, it approximates to a vertical arc, but on steep areas, it approximates to a horizontal arc.

To define the form of the Surface Normal Arc movement; distance, angle, and the radius fields must be appropriately chosen.

There is a critical condition for using this option; the toolpath requires having contact normals selected [39].

- **Vertical Arc:**
  This option enters a tangential arc movement at the beginning and the tip of each cutting path. This arc rests in a plane including the tangent direction and the tool axis (Figure 16).

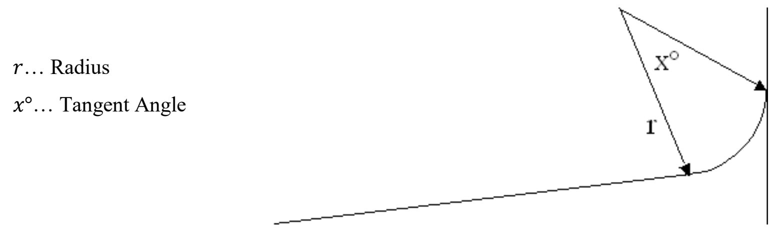


Figure 17: Vertical Arc Scheme. Source: Autodesk Knowledge; PowerMill

The radius and angle domains manage the tangential arc generated.

Important Note: Horizontal arc leads can be joined to open as well as closed sections. Horizontal arc leads do not rest in a horizontal plane when the tangent direction is not itself flat [39].

- **Horizontal Arc:**

  This option enters a tangential arc movement at the beginning and the tip of each cutting path. This arc rests in the plane including the tool axis and the tangent direction, twisted by 90° about the tangent direction.

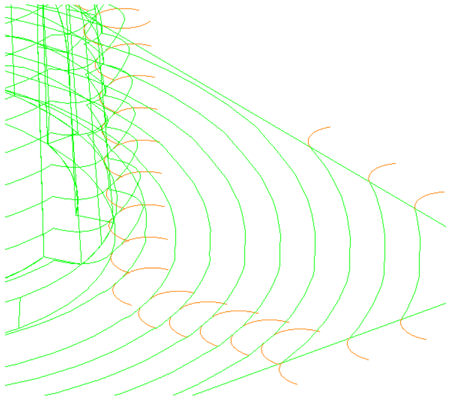


Figure 18: Horizontal Arc in PowerMill. Source: Autodesk Knowledge; PowerMill

Like the Vertical Arc, the radius and angle domains manage the tangential arc generated (Figure 17).

- **Extended Move:**

This option enters a straight tangential movement at the beginning and the tip of each cutting path.

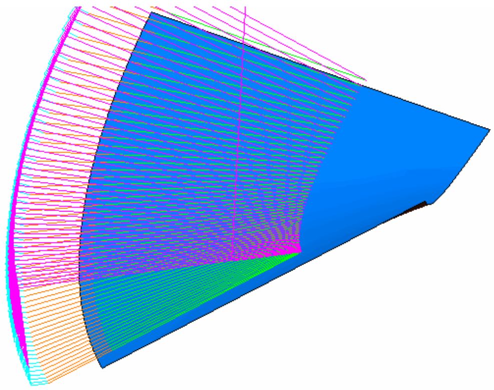


Figure 19: Extended Move in PowerMill. Source: Autodesk Knowledge; PowerMill

The distance domain limits the length of the Extended Move [39].

- **Boxed:**

This option enters a horizontal movement at the beginning and the tip of each cutting path.

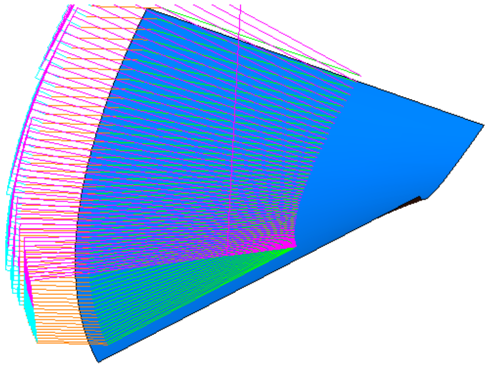


Figure 20: Boxed Option in PowerMill. Source: Autodesk Knowledge; PowerMill

Like the Extended Move, the distance domain defines the length of the Boxed Move [39].

- **Straight:**

This option enters a straight movement the beginning and the tip of each cutting move. The direction of the move is defined by the angle.

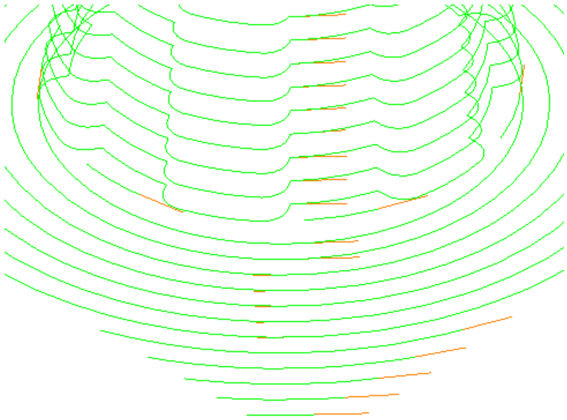


Figure 21: Straight Entry in PowerMill. Source: Autodesk Knowledge; PowerMill

The distance and angle ranges specify the form of the Straight Moves [39].

- **Pocket center:**

This option generates a tangential lead movement, in the case of a Lead In, begins at the middle of the pocket (a Lead Out ends at the middle). The middle is the middle of the box that encloses the closed section. This option is helpful when profiling pocket features which have been pre-drilled at the middle, although it can be used with any closed section. This option is unavailable for lead extensions [39].

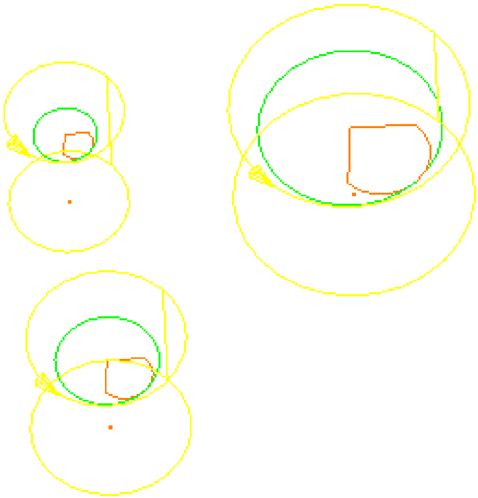


Figure 22:Pocket Center Movement in PowerMill. Source: Autodesk Knowledge; PowerMill

3.1.2. Ramp:

This option ramps the tool into the figure at a chosen angle. This ramp allows to use a non-plunging tool, but this is dependent on the tool and the material. Selecting this option enables the Ramp options button [39].

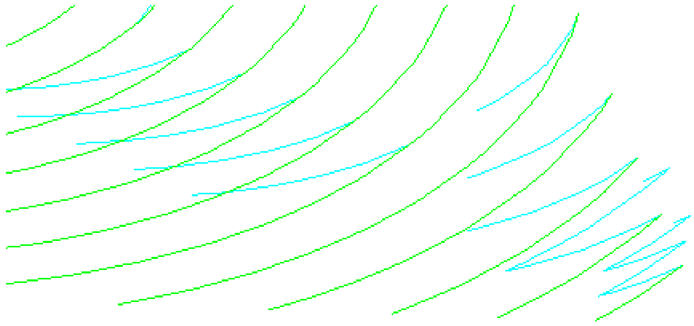


Figure 23: Ramp in PowerMill. Source: Autodesk Knowledge; PowerMill

The Ramp options' selections allow the user to designate how the tool ramps into the workpiece.

There are a variety of Ramp Option dialogs:

- **Follow**:

This option chooses how to guide the direction of the ramp.

- **Toolpath**:

In this option, the ramp movement trails the profile of the toolpath.

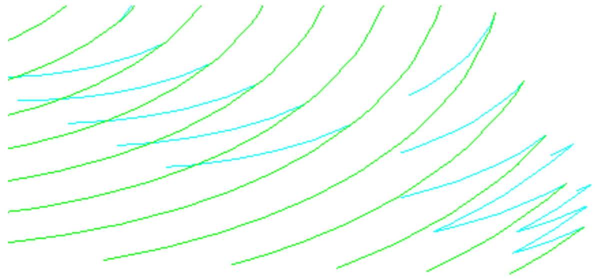


Figure 24: Trailing the Toolpath Using Ramp Movement in PowerMill. Source: Autodesk Knowledge; PowerMill

- **Line**:

The ramp movements are normal to the cutting direction at that point. If the demanded line cannot be implemented into the area, then the default toolpath option is done automatically.

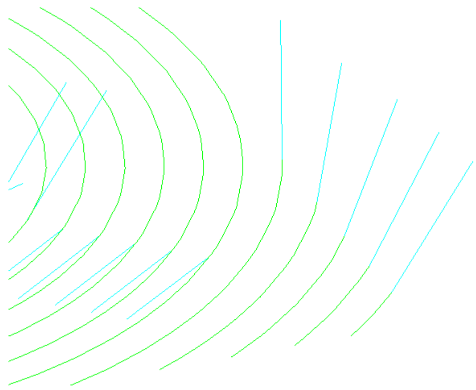


Figure 25: Line Option in Ramp Choices in PowerMill. Source: Autodesk Knowledge; PowerMill

- **Circle**:

By selecting this option, the ramp movements are circular. If the wanted circle cannot be adjusted into the area, then the Line method is set automatically.

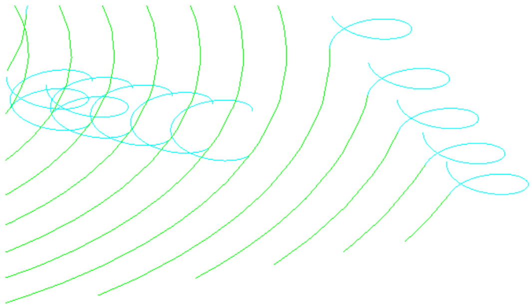


Figure 26: Circle Method in Ramp Options in PowerMill. Source: Autodesk Knowledge; PowerMill

3.1.2.1. Ramping Options:

- **Max Zig Angle:**

Enable the user to determine the angle of descent formed as the tool ramps into the workpiece.

- **Closed Segments Only:**

When chosen, the ramp movements are entered only into closed toolpath sections.

- **Circle Diameter (TDU):**

Allows entering the diameter of the circle using tool diameter units (TDUs).

Important Note: Tool Diameter Units is the distance corresponding to the tool diameter. So, a 10 mm tool and a TDU of 2, gives an actual value of 20 mm [39].

- **Ramp Height:**

This option is calculated relative to the tool axis. For 3-axis machining, the tool axis is the Z-axis. For multi-axis machining, the tool axis is designated on the Tool Axis dialog [39].

- **Height:**

This option allows the user to enter the height of the origin of the ramp above the option chosen in the Type box [39].

- **Finite Ramp Length:**

When selected, it is recommended to enter a maximum ramp length. When deselected, the tool ramps down in a single pass.

Important Note: Usually, the Ramp Length should be higher than the tool diameter to enable swarf to clear from underneath the tool [39].

- **Length:**

This length determines the number of zig and zag moves required in the ramp. This value is expressed in Tool Diameter Units [39].

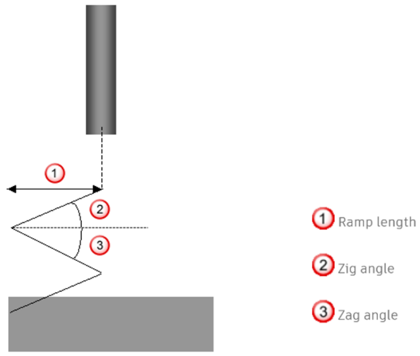


Figure 27: Ramp Technique domains in PowerMill. Source: Autodesk Knowledge; PowerMill

3.2 Autodesk Fusion 360:

Fusion 360 incorporates extensive CAM software tools. The combination of CAM into this high-level CAD program efficiently enhances the overall effectiveness.

This software reaches the entire procedure of planning, testing, and executing a 3D design. It has reliable parametric tools and analytic mesh tools that are well-suited to most difficulties in industrial design [64].

The software generates a suitable method of toolpath strategy for the machined layout. The choices of leads-in and leads out in Fusion 360 are more generalized in terms of choices than in another CAM softwares:

3.2.1. Leads and Transitions:

- **Lead-in Entry:**

This option inserts a lead-in movement [54].

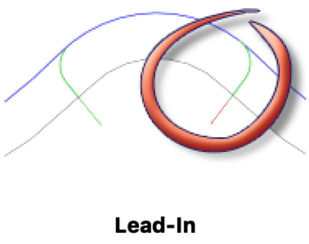


Figure 28: Lead-in in Fusion 360. Source: Autodesk Knowledge; Fusion 360

- **Horizontal Lead-In Radius:**

This option specifies the radius for horizontal lead-in moves. By adjusting the radius of the horizontal lead-in (source), the software inserts a tangential arc movement at the beginning of each cutting path. This arc rests in the plane, including the tool axis. The tangent direction twisted by 90° about the tangential direction similar to the technique adopted in different softwares.

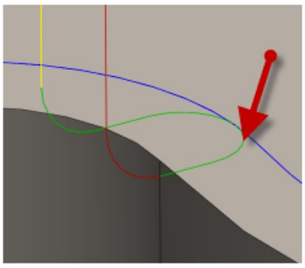


Figure 29: Horizontal Lead-in Radius. Source: Autodesk Knowledge; Fusion 360

- **Lead-in Sweep Angle:**

This option determines the sweep of the lead-in arc [54].

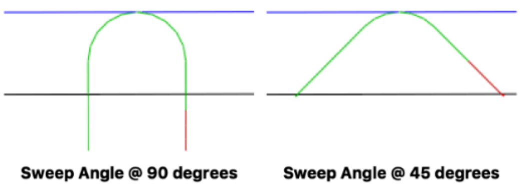


Figure 30: Sweep Angle Fusion360. Source: Autodesk Knowledge; Fusion360

- **Linear Lead-in Distance**

This option defines the length of the linear lead-in move for which to activate radius compensation in the controller [54].

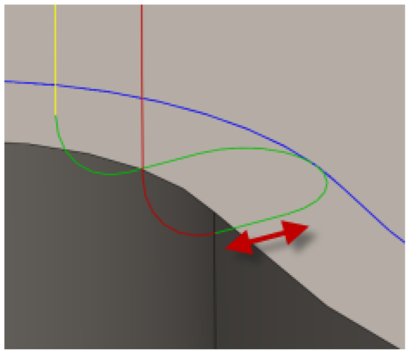


Figure 31: Linear Lead-in Length. Source: Autodesk Knowledge; Fusion 360

- **Perpendicular:**

This option substitutes extensions of lead-in/lead-out arcs with a movement perpendicular to the arc [54].

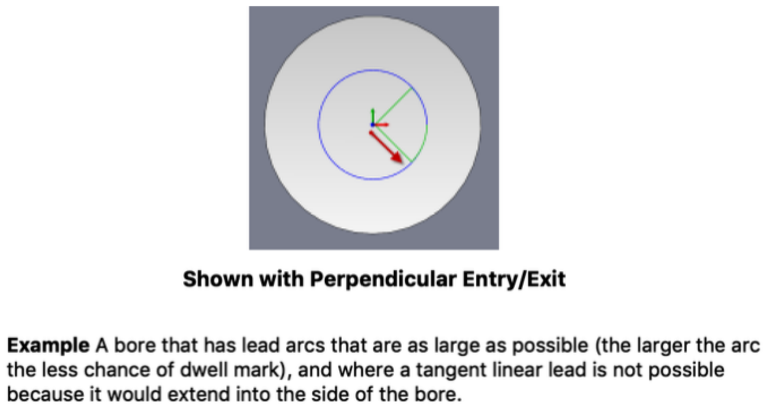


Figure 32: Perpendicular Entry/Exit. Source: Autodesk Knowledge; Fusion 360

- **Vertical Lead-in Radius:**

This option designates the radius of the vertical arc smoothing the entry move as it goes from the entry move to the toolpath itself [54].

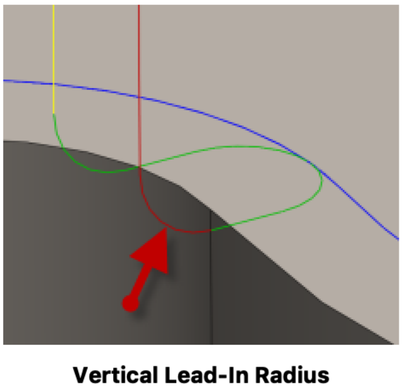


Figure 33: Source: Autodesk Knowledge; Fusion 360

- **Lead-out (Exit):**

This option allows to produce a lead-out [54].

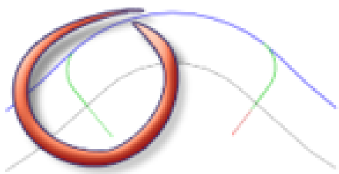


Figure 34: Lead-out. Source: Autodesk Knowledge; Fusion 360

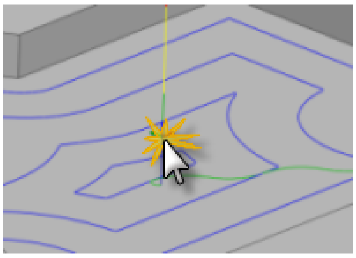
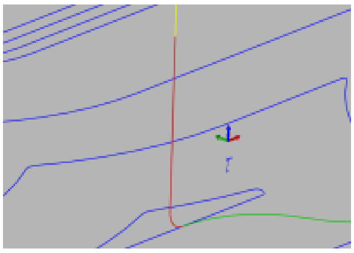
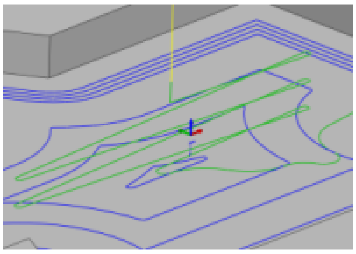
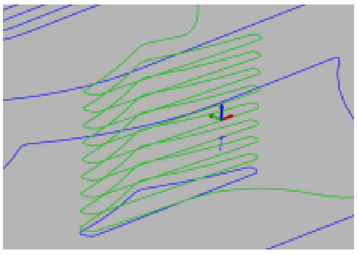
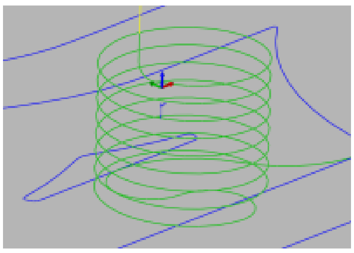
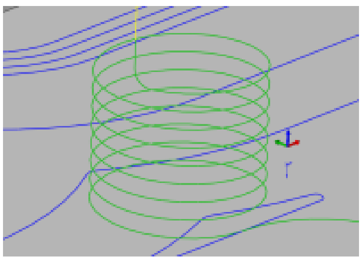
- **Same as Lead-in:**

This option allows the lead-out values to be identical to the lead-in values [54].

3.2.2. Ramping:

This option defines how the cutter travels down for each depth cut [54].

Table 1: Ramping Types in Fusion360 Source: Autodesk Knowledge; Fusion 360

Type	Movement on Shape	Notes
Predrill		For using this option, predrill locations must be specified [54].
Plunge		
Zig-Zag		There are smooth transitions on the Zig-Zag ramp type [54].
Profile		
Smooth Profile		
Helix		

3.2.2.1. Ramping Options:

- **Ramping Angle (deg)**

This option regulates the angle of the helix that leads into the hole or pocket [54].

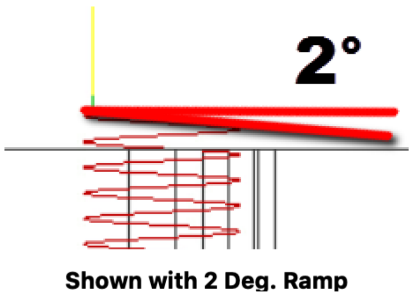


Figure 35: Ramp Angle Control. Source: Autodesk Knowledge; Fusion360

- **Maximum Ramp Stepdown:**

This option defines the maximum stepdown per evolution on the ramping profile. This parameter enables the tool load to be constrained when doing full-width cuts during ramping [54].

- **Ramp Clearance Height**

This option is to specify the clearance above the top height, where the helix ramp will start [54].

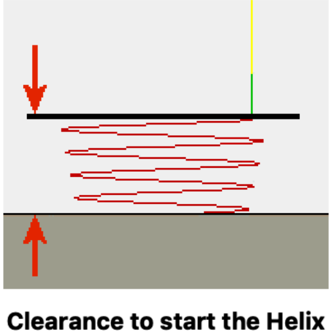


Figure 36: Ramp Clearance (Helical) in Fusion 360. Source: Autodesk Knowledge; Fusion360

- **Ramp Radial Clearance**

This option defines the minimum distance to the contour for the lead-in helix [54].

- **Helical Ramp Diameter**

This option to determine the maximum diameter to use for a helical entry into the cavity.

An optimal value originates the tool to overlap it is center, while still generating the maximum helical bore for the entry into the cavity. The goal is for proper chip evacuation. If the value is more significant than the diameter of the tool, it can leave a boss standing in the center of the helix.

The system will determine the best location for the entry helix unless an entry position is selected. (Entry positions are shown below). The complete area will always be cleared, regardless of the diameter. Note: The area width should tool diameter + ramp diameter + stock, or the helical entry will fail [54].

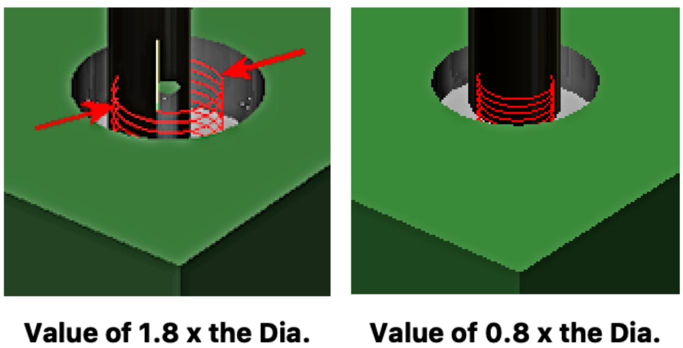


Figure 37: Helical Ramp Diameter in Fusion360. Source: Autodesk Knowledge; Fusion360

- **Minimum Ramp Diameter**

This option determines the minimum helix ramp diameter that is acceptable.

This value should always be smaller than the helix ramp diameter, so the system can calculate a range that fits the available pocket or channel. Smaller diameters can reduce the chip evacuation, create jerking machine motion and can cause tool breakage [54].

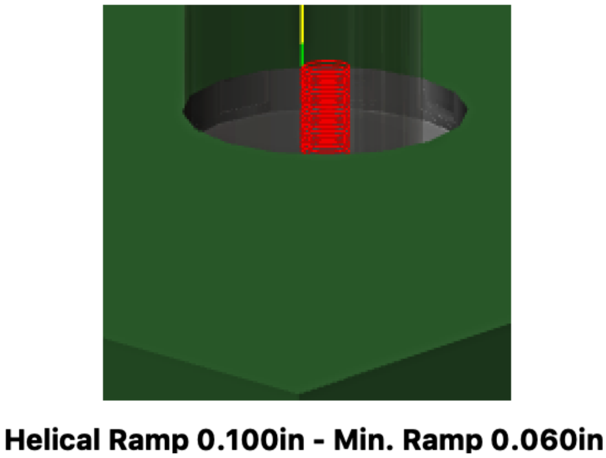


Figure 38: Helical Ramp Diameter in Fusion360. Source: Autodesk Knowledge; Fusion 360

3.3 Siemens NX

Siemens NX CAM can be employed to set up and manage a complete manufacturing series of milling and turning machines. Siemens NX CAM’s universal access to machining and manufacturing includes the possibility to simulate the physical setup of the process virtually. This feature enables the user to identify physical struggles like machine limits or collisions with fixtures and other parts. The analytical tools can also assist the user to learn to what degree the tool paths are accurate to the original layout and explore ranges that are either under-machined or over-machined [64].

3.3.1. Open Area:

- **Linear, Linear Relative to Cut**

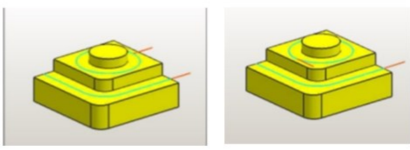
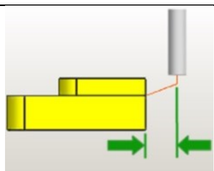
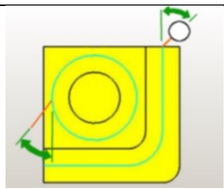
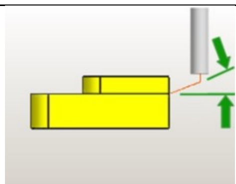
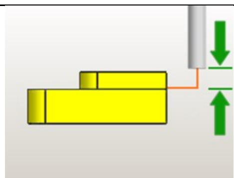
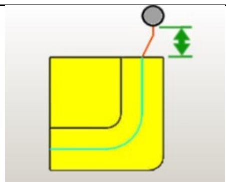


Figure 39: (a) Linear, and (b) Linear Relative to Cut

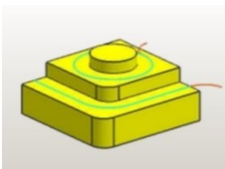
The tool engages with the cut in a straight line perpendicular to the tool axis. On the other hand, the option linear relative to cut, the tool engages in the cut with a line tangent to the toolpath generated.

In the linear and linear relative to cut options, there are some selections that would help adjusting the engage strategy chosen to fit the specifications of the machined feature:

Table 2: Linear and Linear Relative to cut options

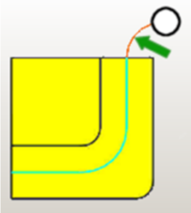
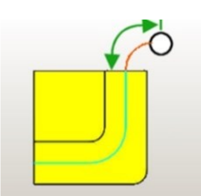
Option	Shape	Description
Length		This option limits the range of the linear line distance to the engage point.
Swing Angle		This option determines the angle of the linear line that the tool follows to enter the cut relative to the chosen path.
Ramp Angle		This option inserts the value of the ramp angle if chosen to approach the cut with a linear ramp entry.
Height		This option determines the distance length of the vertical line.
Minimum Clearance		This selection adjusts the distance specified for the tool to take from the workpiece.

- **Arc**

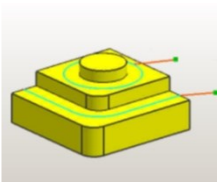


The tool engages in the cut with an arc either horizontally or vertically. Using this option requires more specifications to be determined:

Table 3: Arc Options

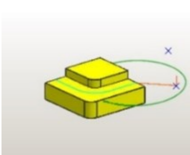
Option	Shape	Description
Radius		This option allows the determination of the radius of the arc generated.
Arc Angle		This option controls the value of the arc's angle.

- **Point**



This option allows the user to specify a point from which a linear line is generated for entering the cut. The most important option for this method:

Table 4: Point Options

Option	Shape
Effective Distance	

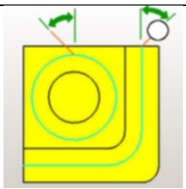
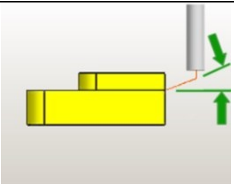
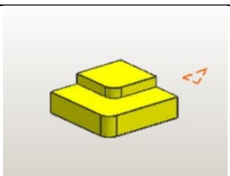
- **Linear-Along Vector**

This method uses a vector direction as an orientation for the linear movement generated.

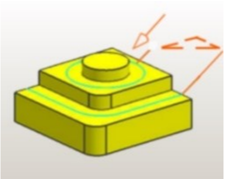
- **Angle-Angle Plane**

This method is generated by two angles. Specifying a plane is crucial for using this method:

Table 5: Angle-Angle Plane Options

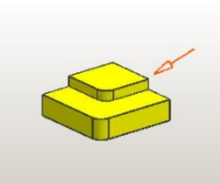
Option	Shape
Swing Angle	
Ramp Angle	
Specify Plane	

- **Vector Plane**



This method approaches the cut from the vector specified on the chosen plane.

3.3.2. Closed Area:



- **Helical, Ramp on Shape**

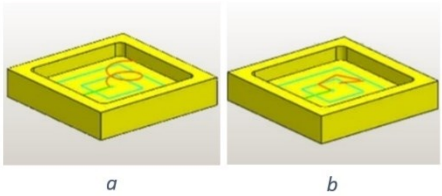
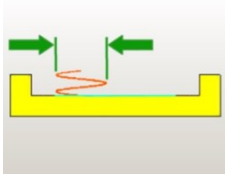
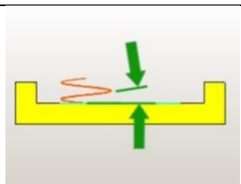
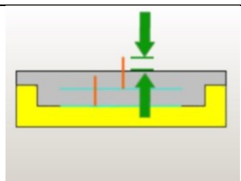
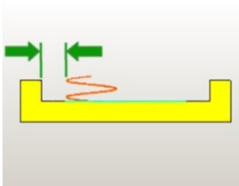
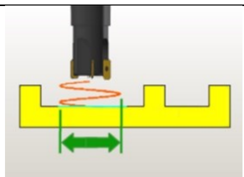


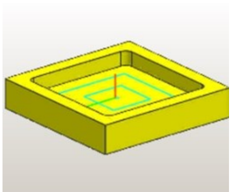
Figure 40: (a) Helical, and (b) Ramp on Shape

The tool engages in the cut with a ramping movement either linearly or helically. The options below specify the ramp form generated:

Table 6: Helical, Ramp on Shape options.

Option	Shape	Description
Diameter		This option specifies the diameter of the helical ramp.
Ramp Angle		This option specifies the Helical or Ramp on Shape ramp angle.
Height		This option determines the height of the ramp from the milled shape.
Minimum Clearacne		This option specifies the distance between the ramp movement and the wall of the cavity milled.
Minimum Ramp Length		This option sets the allowed value of the ramp length based on the cutting tool diameter.

- **Plunge**



In this method the tool enters the cut perpendicular to the surface cavity. The point where the plunge enters can be specified.

3.4 Recommendations for CAM Software:

Choosing the preferable direction for entering the cut is a crucial matter that requires some hints in order to avoid large cutting forces, thick chips, vibrations, and poor surface quality.

Vertical line lead-in perpendicular to the milled surface is always set during default tool path strategies for pocket, slots, and hole milling operations in CAM.

There are two main recommendations to follow when the tool path chosen generates a vertical line entry:

- The first is adjusting the lead-in option to a horizontal arc entry instead of a vertical line-entry; this improves the output of the cutting process. Arching entries are always more favorable than linear entries because they enhance the thinning chip effect [27].
- As for the second, choosing a liner ramp with a small ramp angle instead of the vertical line entry would reduce the impacts of the axial cutting forces [15].

4 Practical Experiment Design – Cutting Forces Measurement

The aim of the experimental work is to investigate the effect of cutter engage movement methods and cutting parameters on cutting forces when end milling of a flat workpiece surface.

4.1 Experimental Work

Different possible methods for tool engage movements can be used. The engage movement methods employed in this study were straight tool entry, horizontal arching, vertical arching, linear ramping, helical interpolation, straight plunge, and spiral movement. It should be noted that in all the techniques mentioned climb milling are performed. Figures below illustrate schematically the work-piece design and the 3d-tool engagement entry path of the strategies tested.

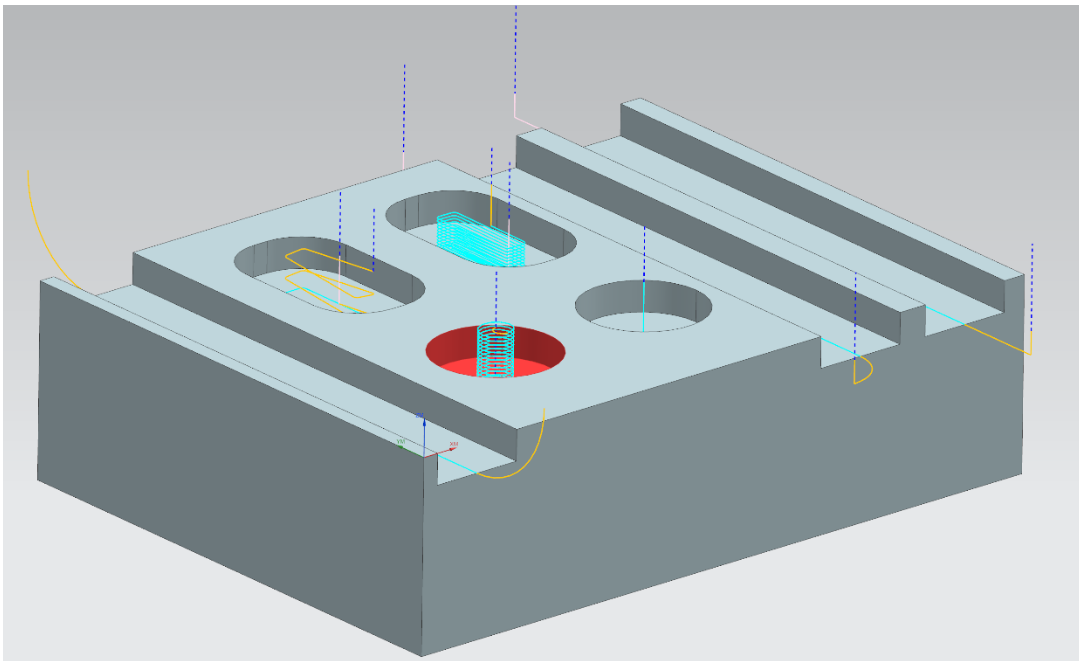


Figure 41: Work-piece deign and the Engage Movement Methods Tested in Siemens NX

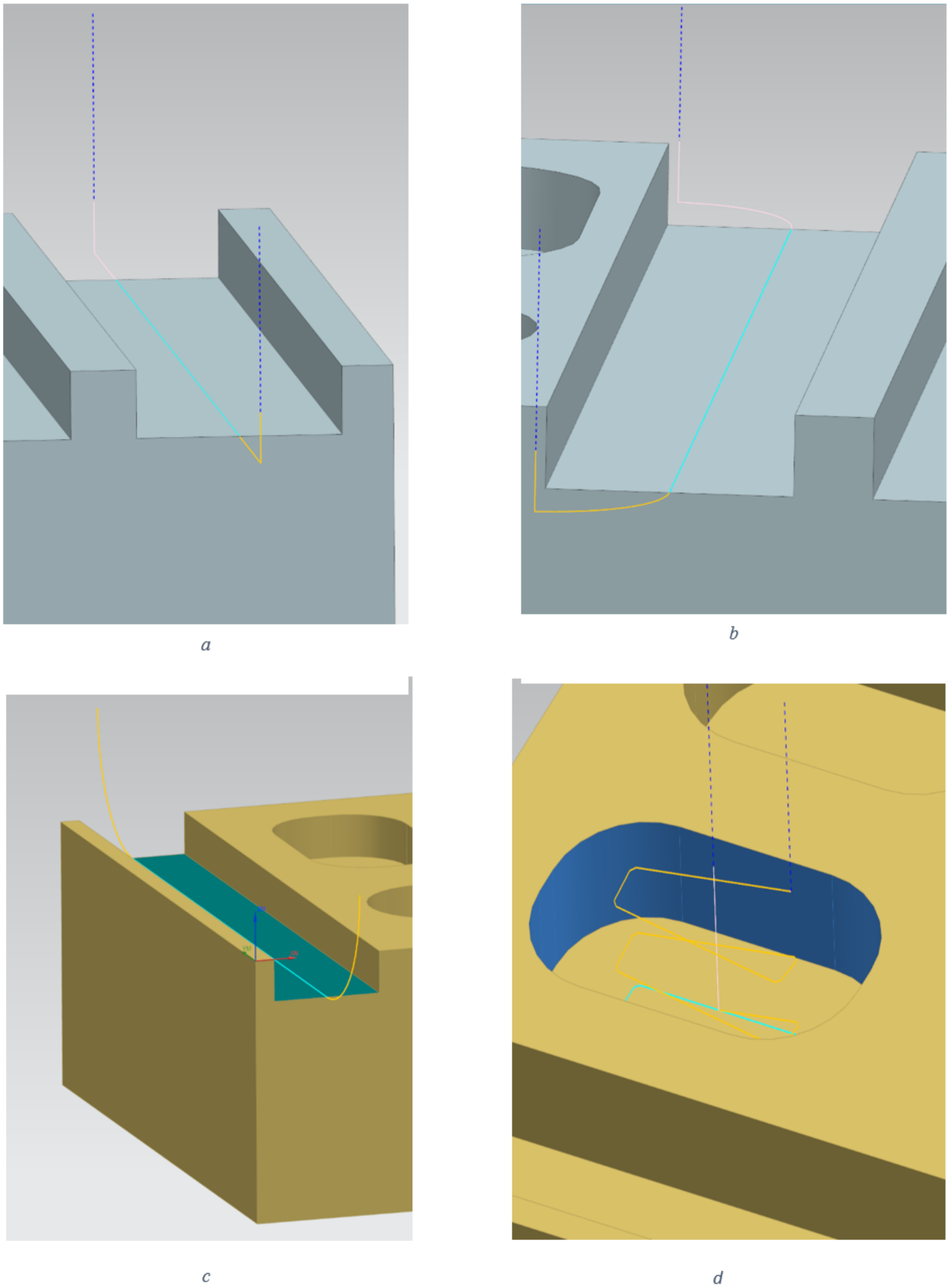


Figure 42: Methods in Siemens NX where: (a) Straight Tool Entry, (b) Horizontal Arching, (c) Vertical Arching, and (d) Linear Ramping.

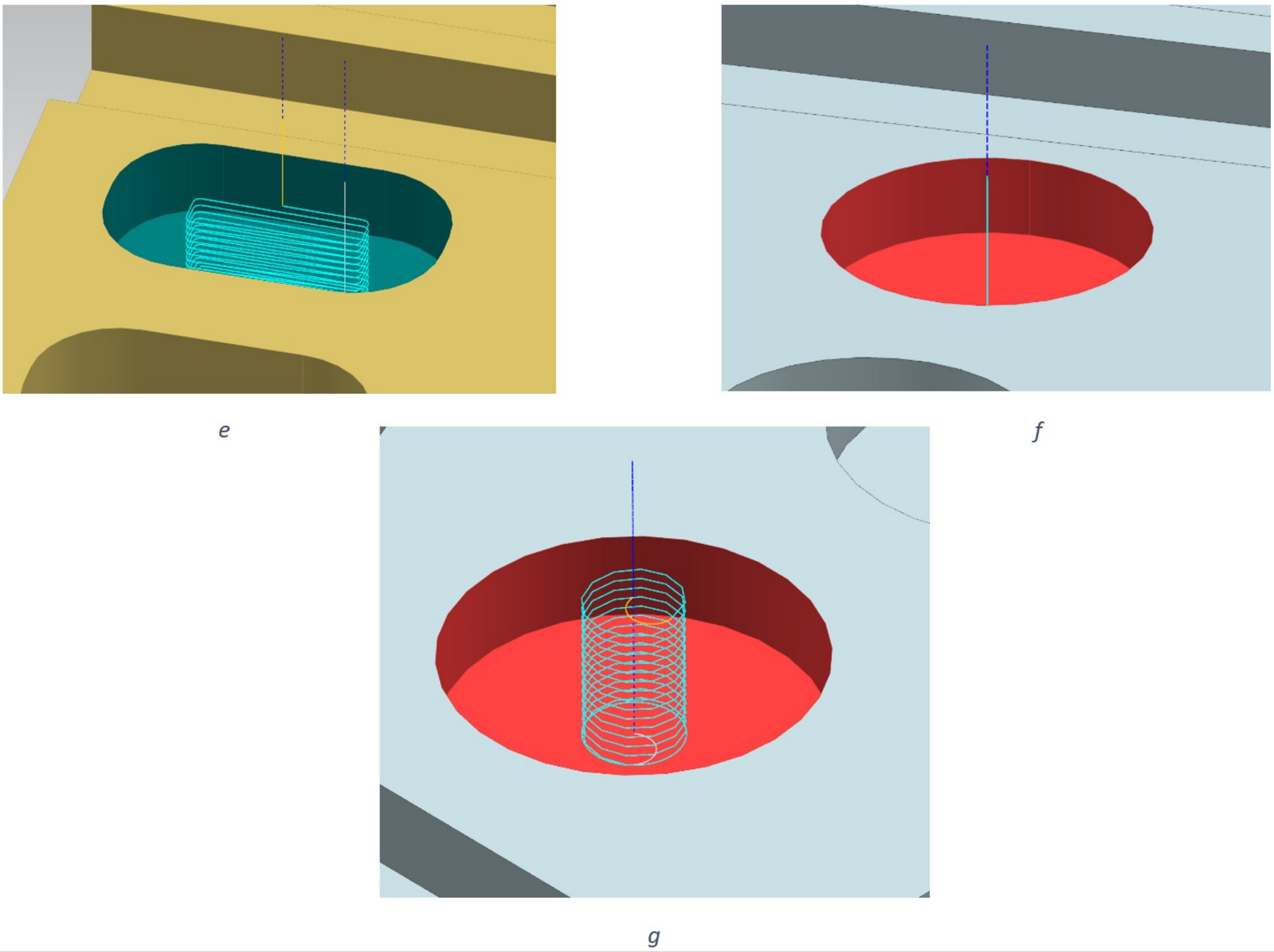


Figure 43: Methods in Siemens NX where: (e) Spiral , (f) Straight Plunge, and (g) Helical Interpolation

4.1.1 Workpiece Material and Cutting Tool

The workpiece material was 7075-T6 Aluminum, which is used in various applications such as aircraft wing spar and ground support equipment [40]. Also, in gears and shafts, fuse parts, meter shafts and gears, aerospace and defense applications; bike frames, all-terrain vehicle (ATV) sprockets. Its nominal composition is 87.1 - 91.4% Al, 0.18 - 0.28% Cr, Max 0.5% Fe, 2.1 - 2.9% Mg, Max 0.3% Mn, Max 0.4% Si, Max 0.2% Ti, 5.1 - 6.1% Zn, Max 0.05% other each, Max 0.15% other total (all weighs percent). Table 7 shows the mechanical properties of this material. The workpiece is machined into rectangular block with dimensions of $91\ mm\ \times 69.5\ mm\ \times 25\ mm$ (see Figure 44).

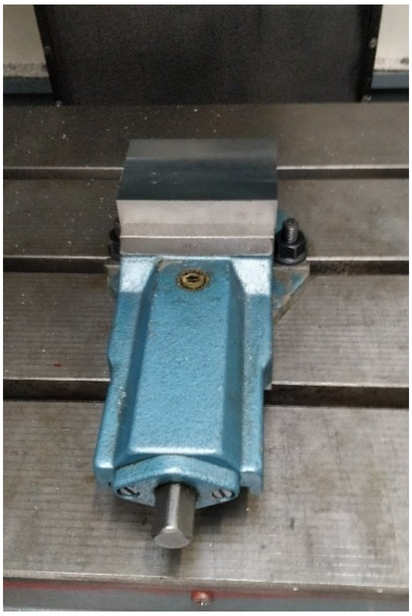


Figure 44: Workpiece Specimen's geometry and dimensions

Table 7: Mechanical Properties of 7075-T6 Aluminum Alloy

Property	**7075-T6**
Density	2.81 [g/cc]
Tensile Strength	572 [Mpa]
Yield Strength	503 [Mpa]
Modulus of Elasticity	7.71 [GPa]
Coefficient of Thermal Expansion @ 20 - 100°C Temperature	23.4 [µm/m-°C]
Thermal conductivity	0.960 J/g-°C

To avoid the transient state, the comparison between the strategies took place with a restrictive domain of a flat surface. Otherwise, the result of performance characteristics will be changed when using different domains of workpiece surface curvature.

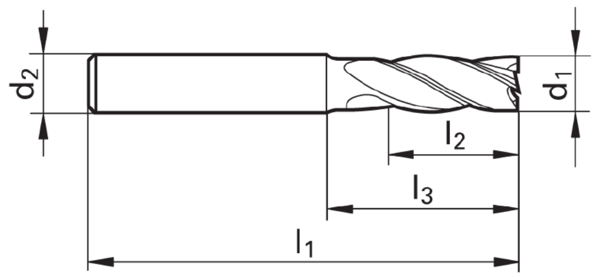
The cutting tool selected is 4 flutes inserted coated carbide end mill with 12 [mm] diameter made by Guhring. Table 8, Table 9, and Figure 45 show the geometrical and mechanical properties of the cutting tool.

Table 8: Mechanical Properties of the Cutting Tool

EDP #	9033660120000
Series	3366
Order Code	12.000
Coating	FIREX
Coolant	With
Cutting Direction	Right Hand
Cutting Edge	High Performance
	Mild & Free-Cutting Steels
Helix Angle	40/42
Material	Carbide
Shank	Weldon Flat
Type	Mild & Free-Cutting Steels
Tolerance	h10

Figure 45: 12 [mm] Carbide End Mill Solid Carbide FIREX

Table 9: Geometrical Specifications of the Cutting Tool



		Dia	Shank dia	OAL	LOC	Reach	Corner	Corner		
EDP #	Order Code	d1	d2	l1	l2	l3	Radius	Chamfer	Flutes	Shank Type
		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		
9033660120000	12.0000	12.0000	12.0000	83.0000	26.0000	36.0000		0.2000	4	Weldon flat

4.1.2 Experimental Equipment and Procedure

All machining trials are carried out on a vertical 3-axis CNC Machining Center MAS VMC 500 with a controller (Figure 25). This has a maximum spindle speed of 6000 [rpm], and a maximum power 3.7 [KW]. In the experiment, no use of any coolant or removing chips by air pressure was employed.

Figure 46: Milling Machine Used in the Measurement

4.1.3 Cutting Forces Measurement

Cutting force measurements ($F_x, F_y, and\ F_z$) are made using a Rotating Kistler 4-Component Dynamometer RCD type 9132C. The dynamometer consists of a four-component sensor fitted under high preload between a baseplate and top plate. The four components are measured practically without displacement. It must be considered that combined and eccentric loads may reduce the measuring ranges. The sensor is mounted ground-insulated. Therefore, ground loop problems are largely eliminated. For each component a 2-range miniature charge amplifier is integrated in the dynamometer. The output voltages of the charge amplifiers are digitized and transmitted by telemetry to the stator. The remote-controlled range switching, and an optionally switchable zoom channel allow to use the measuring ranges in an optimal manner. The voltage is supplied per induction. A zero-point identification (Type 5221B2) is used which allows to correlate the force signals with the tool edge. The dynamometer is preferably delivered with integrated spindle adapter (according to option). For mounting the cutting tools, tool adapter Type 9163 is used (Appendix 1). The whole system was checked and calibrated prior to use. The cutting force data is downloaded and information on cutting force signatures is stored onto a PC and after processing of the cutting force, data analysis is performed using DynoWare Software.

Figure 48: Rotating 4-Component Dynamometer RCD type 9132C. Source: Kistler

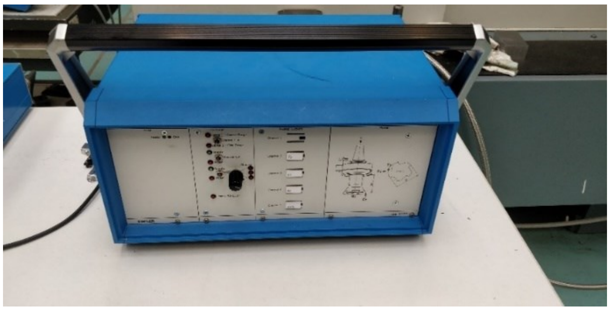


Figure 47: Stator and Multichannel Signal Conditioner

4.1.4 Tool Wear Analysis

The VHX 6000 Accuracy Optical Microscope and the Keyence VH-ZST/ RZ x20-x200, x200-x2000 Lenses were used to analyze the cutting tool, tool wear and the build-up edge effect (Figure 49). This system enables a variety of analyses, and interface can be used effectively.

Figure 49: Optical Microscope

4.2 Experimental Conditions

The machining conditions are determined by taking the cutter and the workpiece material into consideration. Four factors are determined as controllable cutting parameters, including cutting velocity (v_c), feed rate (v_f), feed per tooth (f_z), and spindle speed (n). These parameters are the same for all the strategies tested, as shown in Table 4. For the 2d cutting movements, full immersion (Straight, Horizontal Arching, Vertical Arching), the amount of the axial depth of cut (a_p) is set for 4 [mm], the radial depth of cut (a_e) is set for 12 [mm], and these two parameters are fixed throughout all tests. On the other hand, the axial depth of cut a_p and radial depth of cut (a_e) for the other strategies examined are different and they vary from one strategy to another, as shown in Table 4. The specific cutting force per unit area of the cut $\boldsymbol{K_C}$ is obtained from Equation (1), it is the multiple of the tensile strength of a workpiece metal $\boldsymbol{R_m}$ with the constant $\boldsymbol{C_k}$. The constant $\boldsymbol{C_k}$ is affected by changes in nominal chip thickness or feed, cutting speed, tool rake…, etc. The constant $\boldsymbol{C_k}$ ranges for milling operation from 4 to 10. Since 4 is for roughing operations and 10 is for finishing operations, $\boldsymbol{C_k = 6}$ is more likely to suit the operations applied in these measurements:

$$\boldsymbol{K_C = C_k \,.\, R_m} \quad \textbf{(1)}$$

Table 10: Machining Parameters

Milling Operations	**2D-Cutting Movement**			**Pocket Milling**		**Hole Milling**	
Engage Movement Methods	**Straight Tool Entry**	**Horizontal Arching**	**Vertical Arching**	**Linear Ramping**	**Spiral Movement**	**Straight Plunge**	**Helical Interpolation**
$\boldsymbol{D_C\ [mm]}$	12	12	12	12	12	12	12
$\boldsymbol{v_c\ [mm/min]}$	230	229	229	229	229	229	229
$\boldsymbol{v_f\ [mm/min]}$	1854	1846	1846	1846	1846	1846	1846
$\boldsymbol{f_z\ [mm]}$	0.076	0.076	0.076	0.076	0.076	0.076	0.076
$\boldsymbol{n\ [rpm]}$	6101	6074	6074	6074	6074	6074	6074
$\boldsymbol{a_p\ [mm]}$	4	4	4	6	0.4	2	1.2
$\boldsymbol{a_e\ [mm]}$	12	12	12	10	9	12	8
$\boldsymbol{K_C\ [MPa]}$	The Chosen Specific Cutting Force for Al 7075-T6 is 3432 [MPa]						

It should be noted, that CAM Software allows management of various modes of tool engage movement paths leaning on the geometry of the surface to be machined. Different engage strategies can be used for the same shape. Nevertheless, the choice of a specific strategy remains an expert field. Thus, the cutter workpiece engage movement used in this study are simulated on CAM software (Siemens NX) before machining process.

It must be pointed out that in this study the feed was overridden by 50% form the stated value in Table 10; => $\boldsymbol{v_f} = \mathbf{923}\ [\boldsymbol{mm/min}]$

Figure 50: Experimental Stand Arrangement

5 Results and Discussion

The components of the cutting force $F_x, F_y, and\ F_z$, were measured using the dynamometer, following the directions of the dynamometer reference system (Figure 51). The component F_z is vertically oriented over the surface of the machined workpiece.

The component F_x is aligned with line of action of the feed rate movement and the F_y component is perpendicular to the tool's axis. The cutting forces were measured with corresponding feed per tooth and cutting speeds which are specified before in Table 10.

Two measurements were performed to determine the cutting forces for the engage movement methods. Within each measurement, a file with the machining data and results of the force components was acquired using the dynamometer signals. By processing the acquired data files on DynoWare program, a diagram exhibiting the behavior of the three force components $F_x, F_y, and\ F_z$ in time is obtained for each measurement, Figure 52, 53.

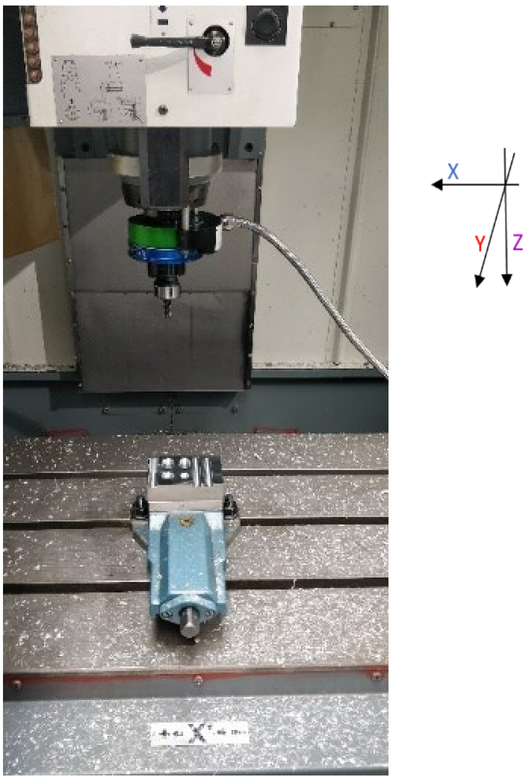


Figure 51: Machining Area

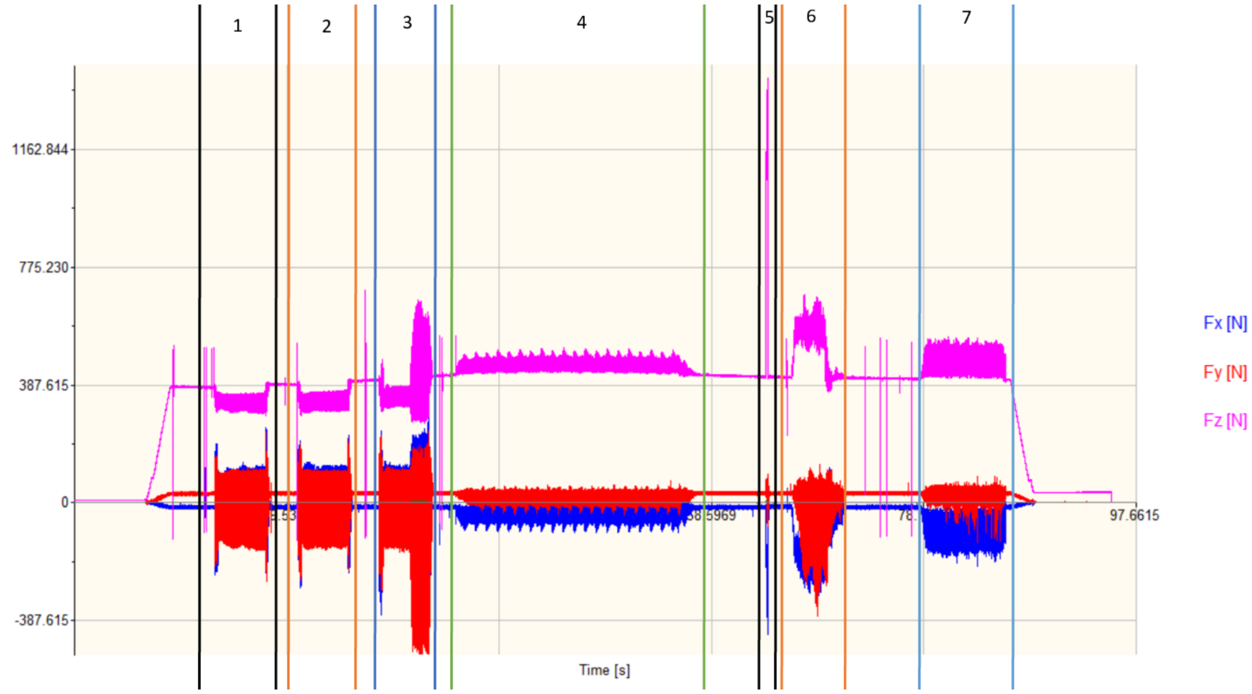


Figure 52: Experiment No.1

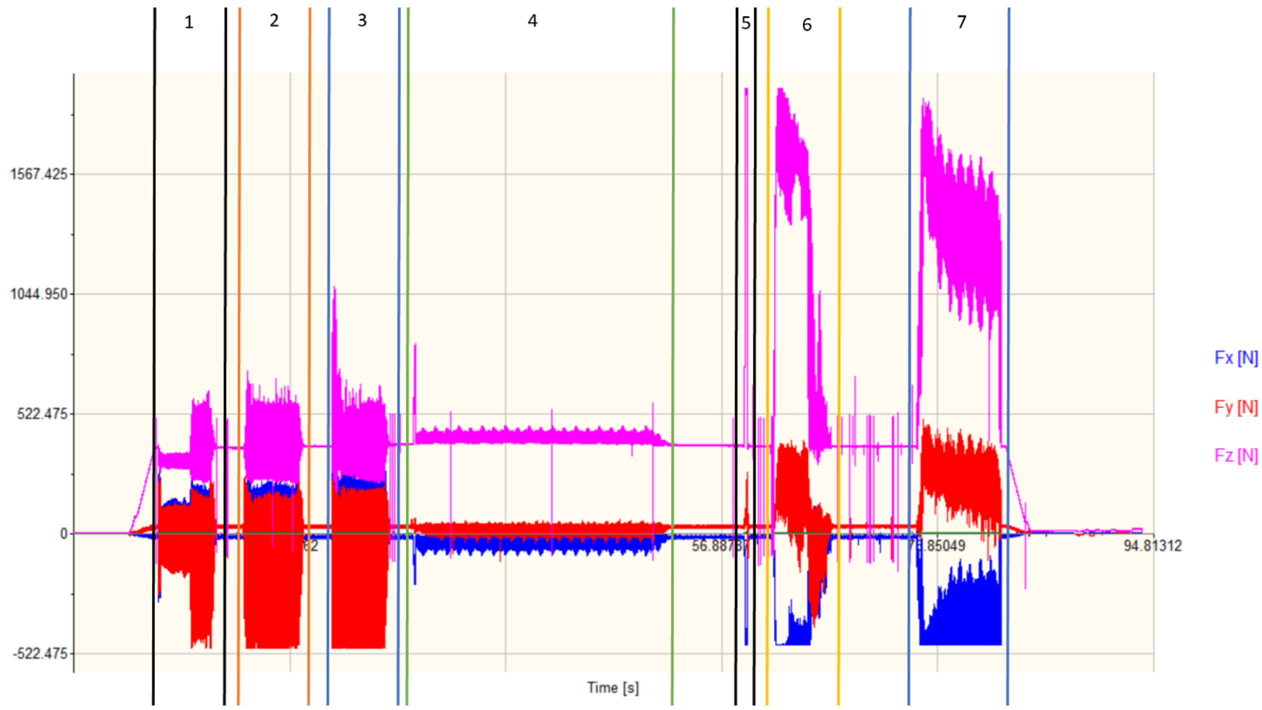


Figure 53: Experiment No.2

The table below states the method of engage movement used in each interval marked in Figures 52, 53:

Table 11: The Methods Used in each Interval in the Figures above

Interval	No.1	No.2	No.3	No.4	No.5	No.6	No.7
Experiment No.1	**Straight Tool Entry**	**Horizontal Arching**	**Vertical Arching**	**Spiral Movement**	**Plunge Milling**	**Linear Ramping**	**Helical Interpolation**
Experiment No.2	**Straight Tool Entry**	**Horizontal Arching**	**Vertical Arching**	**Spiral Movement**	**Plunge Milling**	**Linear Ramping**	**Helical Interpolation**

The numerical values of each force component of the cutter-workpiece engagement region may be determined for each moment or interval of the measurement using options from the DynoWare program toolbar.

Notable results picked from the experimental determinations are recorded. The values of the measured forces are determined directly by the cutting depth $\boldsymbol{a_e}$ and $\boldsymbol{a_p}$, by the feed per tooth $\boldsymbol{f_z}$, and the cutting speed $\boldsymbol{v_C}$.

The workpiece milling was done, with one end mill having diameters $\boldsymbol{D_C} = \mathbf{12}\ [\boldsymbol{mm}]$, and number of teeth $\boldsymbol{Z_C} = \mathbf{4}$. The different used engagement methods are imposing many effects on cutting forces and vibrations. All components of the cutting force present similar variation when the cutter is fully immersed in the cut, and the cutting conditions are similar. This is happening in the first three regions shown in Figures 52, 53 in both measurements. The cutting forces remain similar during the pass, the resultant force during the pass cut, and in the engagement regions is obtained through Equation (2). For measuring the force component on the Z-axis, the reference axis of the force was measured using mean tool in DynoWare program. This reference axis is measured to specify the zero-level of the F_z force component.

5.1 2D Cutting Movement

For region No.1, No.2, and No.3 in both measurements, 2D cutting movements were applied. From the DynoWare program, the time taken for each of these entry methods to reach the full immersion into the cut was determined using the cursor tool function in the DynoWare program (Table 12). The distribution of the force components was determined using the mean tool function in DynoWare program. At last, the resultant cutting force (as F_{total}) is obtained as determined in Eq.2 for each strategy:

$$\boldsymbol{F_{total}} = \sqrt{\boldsymbol{F_x^2 + F_y^2 + F_z^2}} \quad \textbf{(2)}$$

Table 12: Significant Results from the Experimental Determinations for 2D Cutting Movements

2D Cutting Movements		F_x [N]	F_y [N]	F_z-reference (Zero-Level)	F_z [N]	F_{total} [N]	Duration of Engagement Entry (Time) [s]		F_{total} [N]
Engagement Region of Straight Tool Entry	Exp No.1	-17.55	-11.76	380.1	-34.7	40.625	0.2936	**Full Immersion Region**	50.631
	Exp No.2	-15.66	-8.1	375.1	-44.9	48.237	0.3070		75.905
Engagement Region of Horizontal Arching	Exp No.1	-13.36	-1.171	380.1	-22.9	26.538	0.4736		46.589
	Exp No.2	-39.6	-104.4	375.1	17	112.945	0.5676		157.835
Engagement Region of Vertical Arching	Exp No.1	-23.63	-11.81	380.1	-4.6	26.814	0.4276		57.2148
	Exp No.2	-76.03	-145.8	375.1	118.2	202.508	0.4952		151.398

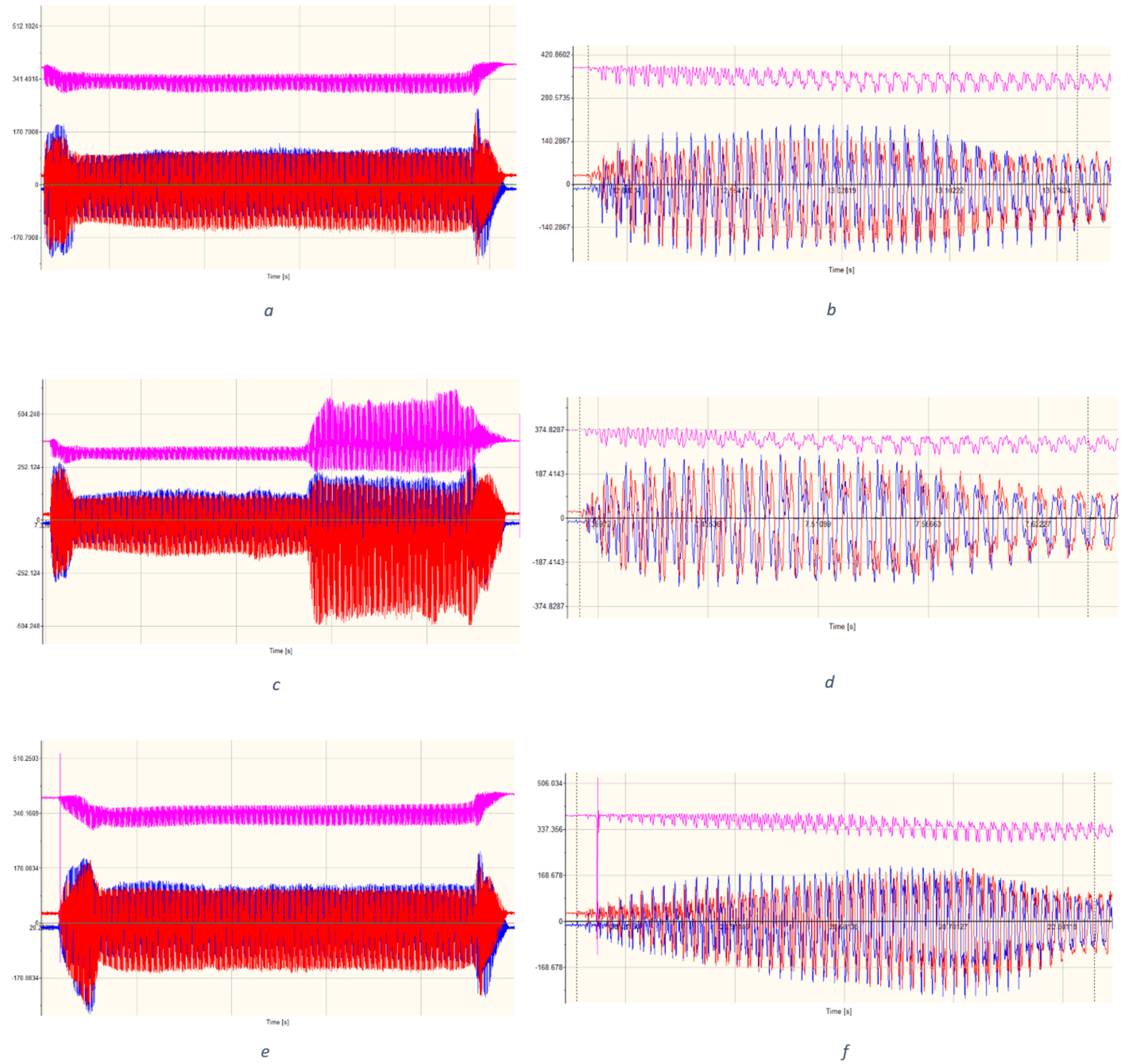
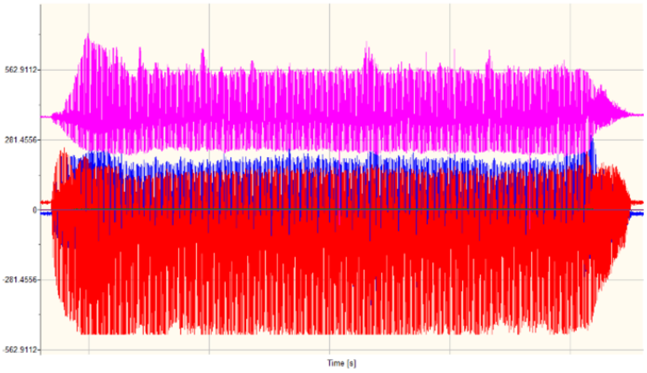
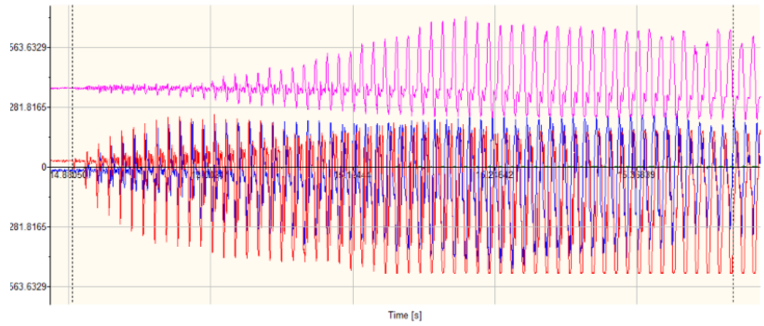


Figure 54: 2D Cutting Movements in Exp No. 1 & 2. (a) Straight Tool Entry Region in Exp.1, (b) Engagement Region of Straight Tool Entry in Exp.1, (c) Straight Tool Entry Region in Exp.2, (d) Engagement Region of Straight Tool Entry in Exp.2, (e) Horizontal Arching Region in Experiment No.1, and (f) Engagement Region of Horizontal Arching in Exp. 1





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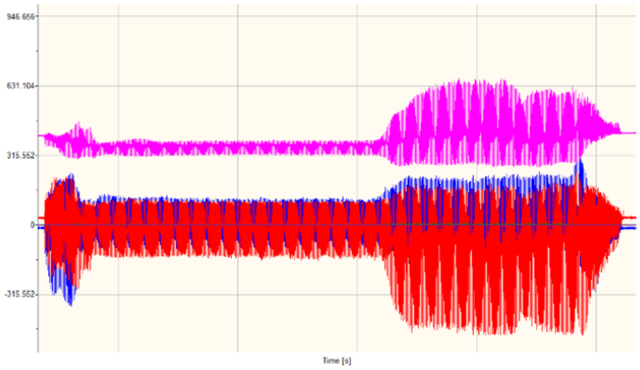

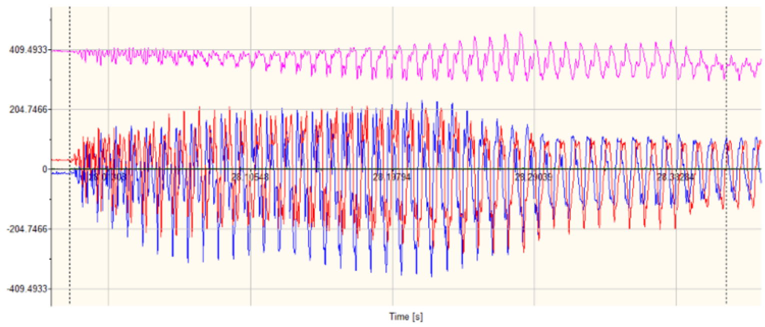

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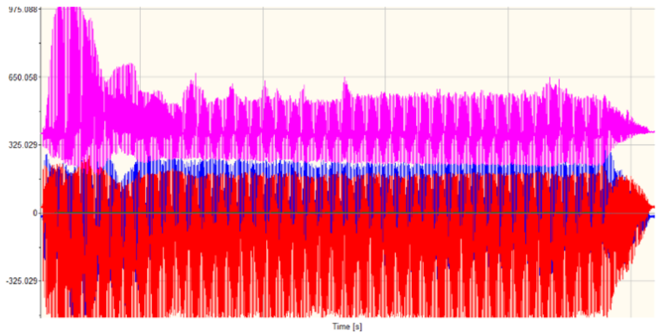

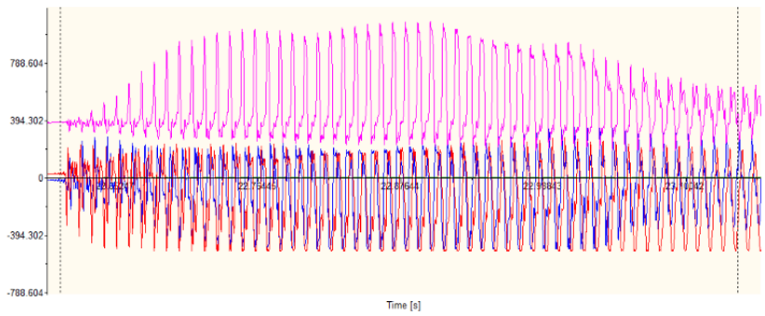

l

m

Figure 55: 2D Cutting Movements in Exp No. 1 & 2. (g) Horizontal Arching Region in Exp.2, (h) Engagement Region of Horizontal Arching Region in Exp.2, (i) Vertical Arching Region in Exp.1, (k) Engagement Region of Vertical Arching Region in Exp.1, (l) Vertical Arching Region in Exp.2, (m) Engagement Region of Vertical Arching Region in Exp.2.

From the figures obtained and the calculations made, the straight tool entry showed similar results to what the theory predicted. As the cutting edge engaged in the cut, a sudden distortion in the forces parallel to the feed rate direction F_x, F_y occurred. The cutting force was mostly acting on the axes of F_x, F_y force components [14], as shown in Figures (54; a,b,c,d) . In Theory, when applying the straight tool entry or the horizontal arching technique, forces acting on the z-axis shouldn't appear or could be neglected due to their small influence on the cut. However, in both experiments, the variation in the force component of the z-axis (F_z) is due to the thermal distortion that was adhering the material of the workpiece on the cutting tool (Figure 56) causing higher forces acting on the vertical z-axis. (Figures 54;55; a to h).

Figure 56: Workpiece Material Clung on the Cutting Tool due to Heat Accumulated on the Cutting Edge.

As the tool was exiting the cut in all the 2d cutting movement techniques, an immediate change of behavior occurred on both horizontal force components F_x, F_y (Figures 54;55). It might be due to many reasons, but the most important one to mention is the smashes of the cutter flutes as the effective cutting diameter was exiting the cut causing a thick chip in entry and thicker as the cutter flute retreat.

After the cutting tool was fully immersed into the cut, the forces showed linear behavior along the time axis in all 2d cutting movements. Figure (55; i) shows a case where a change of this linear behavior occurred, the forces showed sudden change in their distribution due to the vibrations that occurred. One of the reasons to this vibration, a fault that was made in calibrating the z-axis before the measurement in Experiment No.1. The impact of this fault in calibration on the emerging vibrations is the largest in the cut where the vertical arching entry method was used (Figure 55; i), and the results of these vibrations can be seen clearly on the left machined slot in Figure 57.

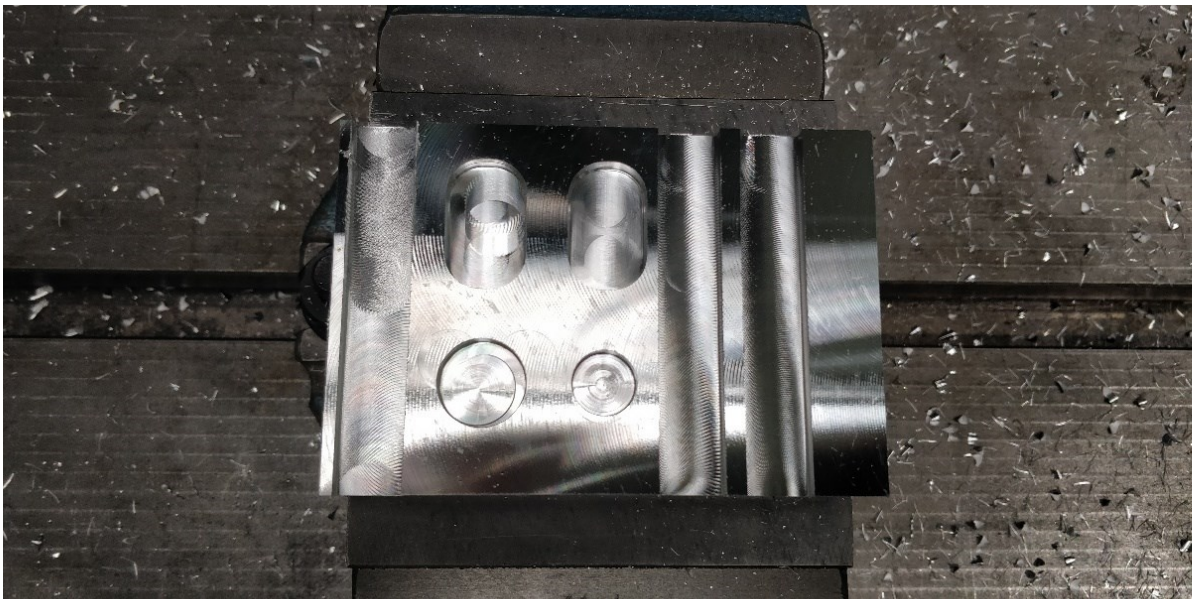

Figure 57: Resulting Surface in Experiment No.1

As the cutting tool started engaging in the cut when applying both of the vertical and horizontal arching techniques, the components of the forces on the horizontal F_x, F_y started increasing progressively until the full immersion in the cut was achieved (Figures 54;55; f, k), as it was anticipated from the theory prediction [14]. However, in the vertical arching technique, the cutting force acting on the z-axis is higher and more involved in the cut than in the straight tool entry and the horizontal arching (Figures 55; i to m). This force behavior in the z-axis may result in faster tool wear and larger vibrations than in the horizontal arching method.

In Experiment No.2, after calibrating correctly the z-axis, the vibrations appeared again and more powerful than the first time. This time, the cutting edge started to wear off due to the heat accumulated on its edge, and due to the high thermal conductivity of the machined material of the workpiece (Figures 54;55 c,g,l). The build-up edge effect started while the tool was milling the first slot using the straight tool entry method (Figure 54; c).

Figure 59: Build-up Edge Effect

The built-up edge impacted the forces behavior during the cut, therefore, the forces exhibited more vibrations through all the cut engagement strategies used in Experiment No.2. Also, the machined surface quality was extremely influenced, as shown in Figure 60. The build-up edge accumulated material in the direction of the feed rate F_x, and the cutting tool movement axis F_y (Figure 58).

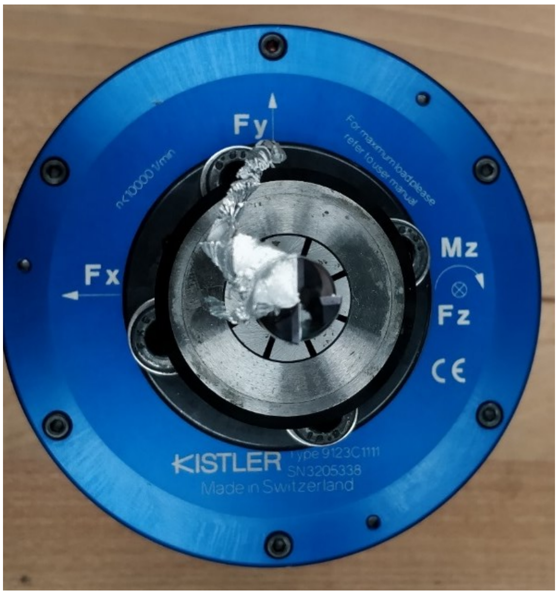

Figure 58: Build-up Edge Directions

Figure 60: Resulting Surface in Experiment No.2

The cuts for all the tested methods in both measurements were made without using any coolant to cool off the cutting edge and prevent any tool wear. Because of this thermal distortion, the material was clinging on the tool, which resulted in different behavior from the anticipated theoretical behavior of the force component acting on the z-axis (F_z).

Because of the difference in feed rate and cutting speed between the 2D cutting movements, the duration of engagement was the fastest for the straight tool entry. After comparing the results of the total force between the 2d cutting movement methods from Table 12, the straight tool entry method showed higher cutting force compared to the arching techniques.

Due to the build-up edge effect that happened in the second experiment, the forces showed very high values compared to experiment No.1. The results calculated in Table 12 for both experiments, showed larger values of forces in the vertical arching technique than the horizontal arching approach.

It should be pointed out, the theory suggested that in using the arching techniques the feed rate must be slowly increased as the tool is merging into the cut [14]. In both measurements, the feed rate kept the same. Therefore, applying the method of increasing the feed rate gradually as the tool is engaging in the cut is essential to achieve better resulting forces when using the arching methods.

5.2 Pocket Milling

For region No.4, and region No.6; pocket milling operations were applied. The methods used in entering the cuts are linear ramping and spiral movement. In linear ramping, the tool approached the cut with a ramp angle of 5° on both horizontal axes (x, y) resulting in a significant stepdown engagement. On the other hand, the spiral movement entered the cut with a vertical line and engaged in the cut with 0.4 [mm] stepdown. The cutting forces emerged from these methods are measured using the mean tool function from the DynoWare program, then the resultant force calculated using Equation 2. The Duration taken to engage in the cut using these entry methods are measured using the cursor tool function in DynoWare program. All measured and calculated values related to the pocket milling operations are presented in Table 13 below.

Table 13: Significant Results from the Experimental Determinations for Pocket Milling

Pocket Milling		F_x [N]	F_y [N]	F_z-reference (Zero-Level)	F_z [N]	F_{total} [N]	Duration of Engagement Entry (Time) [s]		F_{total} [N]
Engagement Region of Linear Ramping	Exp No.1	-119.8	26.79	420	78	145.443	0.4508	**Full Cut Region**	238.565
	Exp No.2	-378	145	389.3	990.7	1070.231	0.4712		859.581
Engagement Region of Spiral Milling	Exp No.1	-29.64	30.75	420	34.6	54.966	0.077		53.785
	Exp No.2	-137.5	35.30	389.3	250	287.493	0.1388		50.271

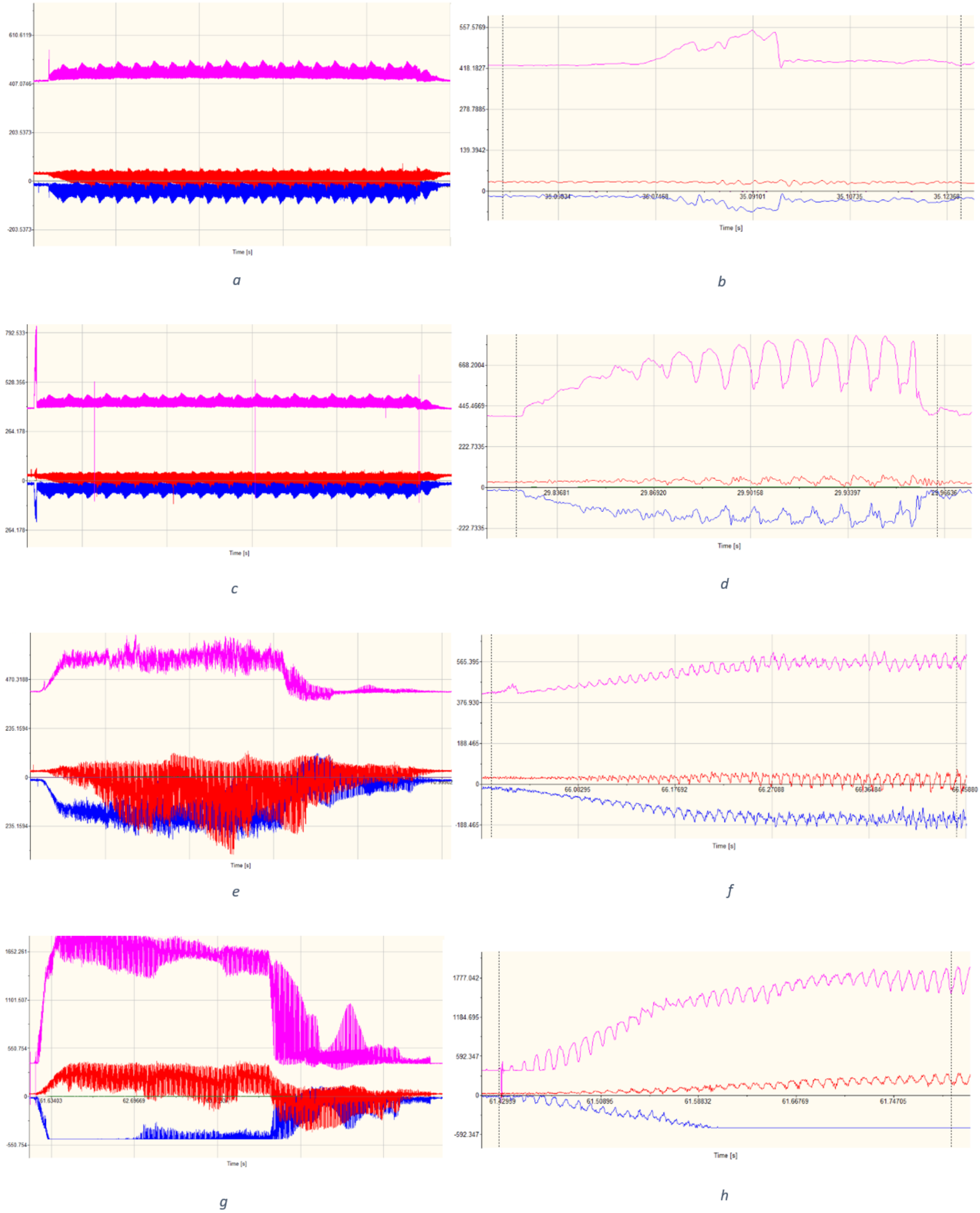

Figure 61: Pocket Milling (a) Spiral Milling Region in Exp.1, (b) Engagement Region of Spiral Milling in Exp.1, (c) Spiral Milling Region in Exp.2, (d) Engagement Region of Spiral Milling in Exp.2, (e) Linear Ramping Region in Exp.1, (f) Engagement Region of Linear Ramping in Exp.1, (g) Linear Ramping Region in Exp.2, and (h) Engagement Region of Linear Ramping in Exp.2

In the spiral milling method, the forces exhibited uniform distribution throughout the cutting region, because of the uniform pattern the cutting tool made in the cutting path. The forces in the y-axis and the x-axis are mainly influenced as the cutting tool moved in the radial direction. As the cutting tool moved in the vertical direction, the force component of the z-axis increased rapidly. The behavior demonstrated in Figures 61; a to d, showed the prediction offered in theory.

Due to the vertical entry in spiral milling, the force in the z-axis showed a sudden increase as the cutting tool merged into the cut, as shown in Figures 61; a, c .

The cutting tool in spiral milling method engaged into the cut with a small ramp angle and stepover, this resulted in a small variation of forces compared with the forces resulted from the larger ramp angle taken in the linear ramping method. Besides, the time taken to engage in the cut was faster with the small ramp angle when compared with the larger ramp angle in the linear ramping technique (Table 13).

The values of the resultant forces of the spiral milling in the engagement region and the full cut region in both experiments are smaller than the values of the resultant forces of the linear ramping method. These results mainly influenced by the ramp angle value taken for the stepdown movement (Table 13).

The resultant force of the engagement region for the spiral milling method in experiment No.2 is larger than the resultant force of the engagement region in experiment No.1. These large changes in resultant forces occurred because of the vibration that happened due to the build-up edge effect in experiment No.2.

In the linear ramping entry method (Figures 61; f, h), the force component in the z-axis increased progressively as the leading flute of the cutting tool started with the bottom cutting process (Figures 61; f, h). As the tool started engaging when the periphery cutting process started, the force component acting on the y-axis increased steadily in stages. Moreover, the force component acting on the x-axis showed a steady decrease as the trailing flute of the cutting tool engaged in the cut. These behaviors are compatible with the behaviors predicted in the theory [15].

Comparing the two methods, the spiral milling characterizes better forces properties than the linear ramping method when the cutting tool is fully immersed in the cut. It illustrated more uniform forces distribution than the linear ramping technique. However, when comparing the two methods in terms of engagement, the spiral milling exhibited very sudden changes in the vertical force component F_z, and in the radial force component F_x, while the linear ramping depicted steadily increase in the vertical and radial force components (F_x, F_z). These behaviors have a crucial influence on the tool life, vibrations, and the resulting surfaces.

As seen in Figures 61; c, d, g, h, the build-up edge effect in experiment No.2 and the vibrations resulted from it, increased the forces drastically in the engagement region for the linear ramping method. In result, the surface quality was immensely impacted (Figure 60).

5.3 Hole Milling

In region No.5 and region No.7; straight plunge milling method and helical interpolation method were applied. Significant results rising from the use of these methods are discussed. The cutting forces emerged from these methods are measured using the mean tool function from the DynoWare program, then the resultant force calculated using Equation 2. The Duration taken to engage in the cut using these entry methods are measured using the cursor tool function in DynoWare program. All measured and calculated values related to the hole milling operations are presented in Table 14 below.

Table 14: Significant Results from the Experimental Determinations for Hole Making

Hole Milling		F_x [N]	F_y [N]	F_z-reference (Zero-Level)	F_z [N]	F_{total} [N]	Duration of Engagement Entry (Time) [s]		F_{total} [N]
Engagement Region of Straight Plunge	Exp No.1	-134.3	58.23	407.7	468.6	490.931	0.0462	**Full Cut Region**	747.552
	Exp No.2	-317.7	72.14	383	990	1042.227	0.102		1383.263
Engagement Region of Helical Interpolation	Exp No.1	-54.31	25.7	407.7	447.4	451.416	0.4104		120.421
	Exp No.2	-302	142.8	383	706	781.045	0.594		1120.512

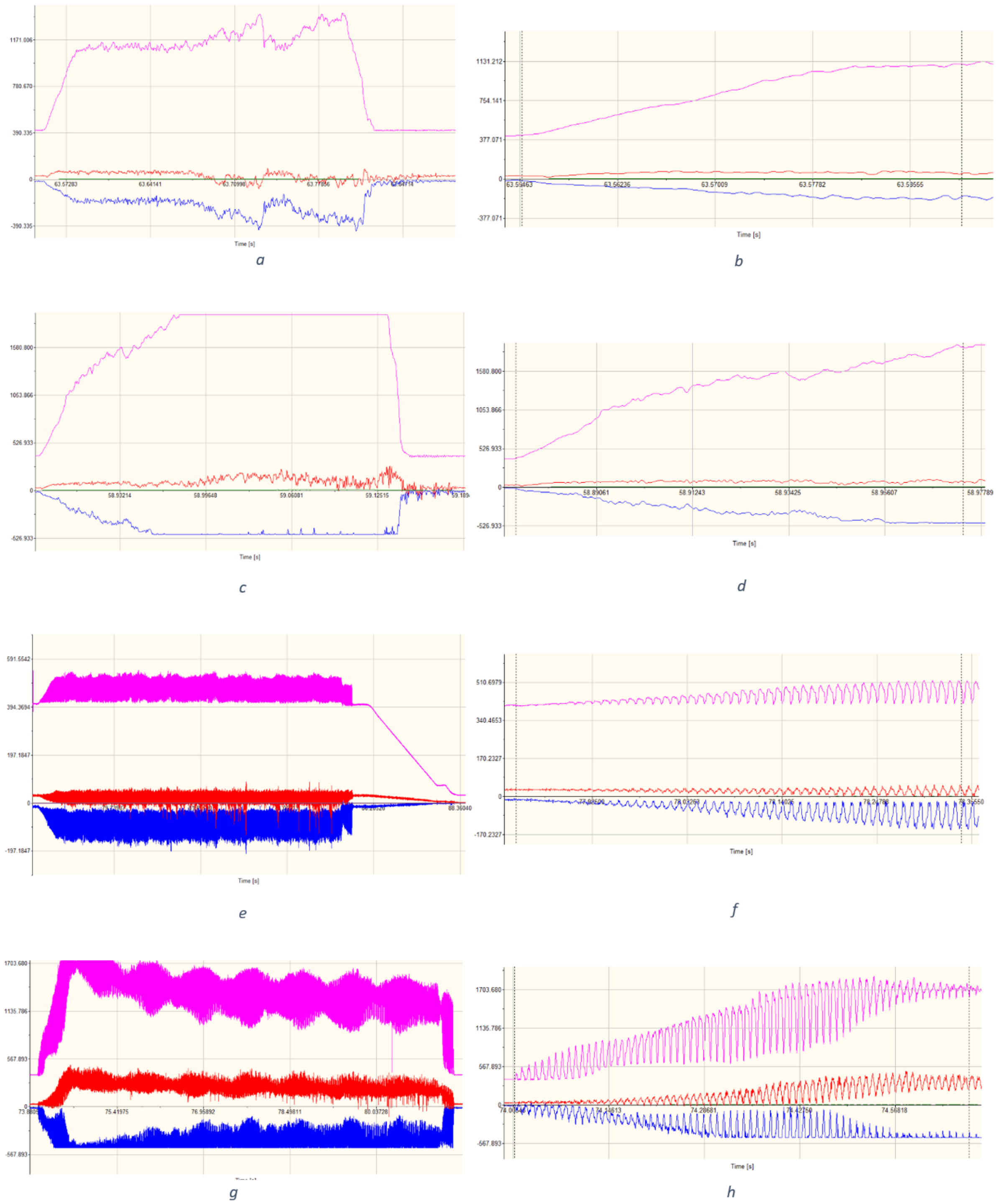

Figure 62: Hole Milling (a) Plunge Milling Region in Exp.1, (b) Engagement Region of Plunge Milling in Exp.1, (c) Plunge Milling Region in Exp.2, (d) Engagement Region of Plunge Milling in Exp.2, (e) Helical Interpolation Region in Exp.1, (f) Engagement Region of Helical Interpolation in in Exp.1, (g) Helical Interpolation Region in Exp.2, and (h) Engagement Region of Helical Interpolation in in Exp.2

In the straight plunge method, the acting forces are the radial force F_x and the axial force F_z. As the cutting tool engaged in the cut, the axial forces increased suddenly as the cutter was pushing vertically against the surface, where in contrast, the radial force showed immense reduction due to the vertical path the cutter was taking through the cut. On the other hand, the tangential force component F_y showed low values compared to the other two force components. The spindle speed was fixed throughout the whole milling operation of the tested workpiece. In terms of plunge milling, the spindle speed should be kept low to ensure low tangential forces [31]. Figures 62; b, d, showed the behavior of the theory assumptions. Since the milled hole wasn't deep, the force acting on the y-axis remained low, therefore, reducing the amount of the resulted vibrations.

The time measurement for the plunge engagement showed the efficiency of using this method compared to the helical interpolation method. However, the vertical engagement in milling holes showed huge change in the distribution of forces, which impacted the tool wear and the surface quality, as shown in Figures 59, 60. In both experiments, the resultant force of the plunge milling in the engagement region and in the full cut region are larger than the resultant forces of the helical interpolation. In Experiment No.2, the resulted vibrations from the cutting tool build-up edge impacted dramatically the forces behavior in the plunge milling method, causing very large forces distribution in the engagement region as well as the full cut region. (Figures 62; c, d)

In the helical interpolation, the forces increased in stages as the radial and the axial forces engaged in the cut. The tangential force component was relatively low as the tool was immersing in the cut. The forces disturbution of this method along the time axis showed almost uniform behavior, some variation in this uniform behavior was due the vibration from the tool wear (Figures 62; g, h). In general, the method showed similar performance to what the theory predicted in the behavior of the radial forces and the vertical force. The duration of engagement was relativly larger compared to the plunge milling technique. The steady increase in the acting forces would prevent any large vibrations and tool wear. Therefore, the helical milling approach is preferable in hole milling operation of large holes. The resultant forces in both regions for the two measurements made were smaller than the forces in the plunge milling technique.

It must be indicated that when helical interpolation was applied, chips evacuated from the cut easier than in plunge milling, because of in both experiments no use of any cutting fluid and compressed air took place, which are techniques implemented in plunge milling for better chip evacuation.

In experiment No.2, when plunge milling excuted, the resulted build-up edge from the prior milled cuts impacted the forces hugely (Figure 62; d). The consequence of this entry on the tool and the build-up edge appeared clearly when the tool was examined under the microscope. The measured length of the distorted geometry matched the depth of the milled hole (Figure 63). The distorted geometry affected badly one of the cutting tool flutes leaving a strange behavior on the radial and the axial forces (F_x, F_y), as shown in Figure 62; c.

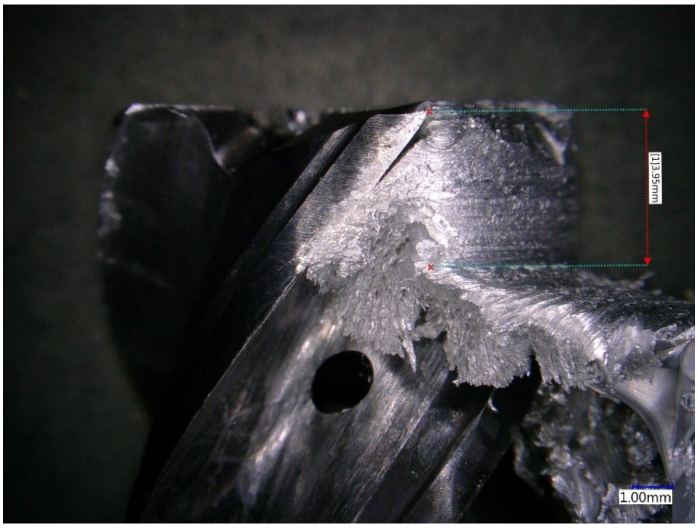

Figure 63:The length of the Distorted Geometry on the Build-up Edge.

6 Conclusion

Different methods of cutter-workpiece engage movements in milling programmed by CAM software for various milling operations were evaluated in the literary review, in addition to their effects on the cutting forces, vibrations, resulting surfaces, and tool wear. For pocket milling, the cut entries chosen were particularly, linear ramping and spiral milling. As for 2D cutting movements entry strategies, straight tool entry and arching methods were investigated. While for hole milling techniques, straight plunge entry and helical interpolation (circular ramping) were reviewed.

In the discussion of the CAM software options, the approaches to the cutter-workpiece engagement were presented in Siemens NX, Autodesk Fusion 360, and Autodesk PowerMill. As the information offered in the literature review, some recommendations were made to apply in the CAM software when mainly designing the entry type for the pocket milling operations and hole milling operations. The arc approach to the cut is always favored more than the straight vertical entry when a tool path strategy is designed for milling a hole. As for the pocket milling operations, the linear ramp entry path with a small ramp angle is preferred more than the straight vertical entry path when followed with a ramp or spiral tool path.

As the data displayed in the investigation made in the experimental work, the employment of different cutter-workpiece engage movement method when dry end milling of a flat surface of Aluminum 7075-T6 has significant effects on the cutting forces, resulting surfaces, tool life, and vibrations.

The resultant cutting force of the engagement region in the 2d cutting movement entry methods was the highest when the straight tool entry was applied in experiment No.1, regardless of the cutting conditions, and the vertical arching entry exhibited the highest value of resultant force when it was applied in experiment No.2. The cutting tool build-up edge effect had a significant rule in these results in experiment No.2. As a result, poor surface quality is obtained. Overall, dry milling of Aluminum 7075-T6 is not advisable at all, plus, using the arching techniques requires more control of the feed rate upon engaging in the cut. In terms of time, the arching methods required more time to immerse in the cut fully.

As for the pocket milling operations, the resultant cutting force was the highest when the linear ramping was implemented. Despite the vertical straight entry that was adopted in the spiral method, the large value selection of the ramp angle showed more influence on the behavior of the forces, and the resulting surface.

In the hole milling strategies, the plunge milling showed the highest value of the resultant cutting force. However, the duration to mill the hole using the straight plunge technique was faster.

Underdetermined operating conditions, the minimal cutting forces can be achieved, regardless of the cutter-workpiece engagement strategy, using the optimal cutting parameters would influence the results significantly, or by using proper coolant method to cool off the heat generated and to evacuate the chips properly when high speeds and feeds are applied.

Future work concerns more in-depth analysis and evaluation of particular cut entry mechanisms, specifically, the vertical arching technique in the 2d cutting movements, where the study can examine various cutting conditions to utilize the use of this method under optimal cutting parameters.

Works Cited

1. Marinov, Val & Seetharamu, Sreenath. Virtual machining operation: A concept and an example. *Proceedings of SPIE - The International Society for Optical Engineering*. Nov. 2004. Web. 1 Jul. DOI: 10.1117/12.571333
2. Paritala, Phani, Manchikatla, Shalini & Yarlagadda, Prasad. Digital Manufacturing-Applications Past, Current, and Future Trends. *Procedia Engineering,* 174(2017): 982-991.
3. Mourtzis Dimitris, Makris Sotris, Chryssolouris, George. Computer-Aided Manufacturing. In: Chatti S., Laperrière L., Reinhart G., Tolio T. (eds) *CIRP Encyclopedia of Production Engineering*. Springer, Berlin, Heidelberg. 2018.
4. Soori, Mohsen; Arezoo, Behrooz; Habibi, Mohsen. Dimensional and geometrical errors of three-axis CNC milling machines in a virtual machining system. *Computer-Aided Design*, 45.11(2013): 1306–1313.
5. Soori, Mohsenm Arezoo, Behrooz & Habibi, Mohsen. Virtual machining considering dimensional, geometrical and tool deflection errors in three-axis CNC milling machines. *Journal of Manufacturing Systems*, 33.4 (2014): 498–507.
6. Soori, Mohsen, Arezoo, Behrooz & Habibi, Mohsen. Tool Deflection Error of Three-Axis Computer Numerical Control Milling Machines, Monitoring and Minimizing by a Virtual Machining System. *Journal of Manufacturing Science and Engineering*. 138.8 (2016): 081005.
7. Denkena, Berend, Bob, Volker, Nespor, Dennis & Rust, Felix. Simulation and evaluation of different process strategies in a 5-axis re-contouring process. *Procedia CIRP*, 35(2015): 31-37.
8. Sandvik Coromant. *What is successful milling?* Web. 1 Jul. 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/Pages/default.aspx
9. Sutar, Pooja & Gujar, Anantkumar. Study the effect of machining parameters on surface roughness in CNC Milling of AISI 316L. *International Journal of Engineering Research and Technology*, 10(2017): 801-804.
10. Li, Zhongqun & Liu, Qiang. Surface topography and roughness in hole-making by helical milling. *The International Journal of Advanced Manufacturing Technology*, 66(9-12), 1415-1425.
11. Li, Zhongqun, Liu, Qiang, Ming, Xingzu, Wang, Xin & Dong, Yafeng. Cutting force prediction and analytical solution of regenerative chatter stability for helical milling operation. *International Journal of Advanced Manufacturing Technology*. 73(2014): 433-442.

12. Bas, Gokcen, Stoev, Lachezar & Durakbasa, Numan. Assessment of the Production Quality in Machining by Integrating a System of High Precision Measurement. *Procedia Engineering*, 100(2015): 1616-1624.
13. Basil, Ahmed. A Study of the Effect of (Cutting Speed, Feed Rate and depth of cut) on Surface Roughness in the Milling Machining. *Engineering and Technology Journal*, 33.8(2015): 1785-1797.
14. Perez, H., Diez, E., Perez, J. & Vizan, A. (2013). Analysis of machining strategies for peripheral milling. *Procedia Engineering*, 63, 573-581.
15. Sandvik Coromant. (n.d.). *Ramping: two axis linear and circular.* [Online]. Available at:<https://www.sandvik.coromant.com/en-gb/knowledge/milling/milling-holes-cavities-pockets/pages/ramping.aspx> [Accessed July 11, 2019].
16. Pereira, Robson. Brandao, Lincoln, Paulo de Paiva, Anderson, Ferreira, Joao & Davim, Paulo. A review of helical milling process. *International Journal of Machine Tools & Manufacture*, 120(2017): 27-48.
17. Harvey Tool Company, LLC. (2017). *Ramping to success.* [PDF]. Available at :< http://www.harveytool.com/secure/Content/Documents/Tech_RampingToSuccess.pdf> [Accessed July 11, 2019].
18. Tegelman, Matt. A More Productive Alternative to Helical Interpolation for High Volume Holemaking. 6 May. 2016. Web. 7 Jul. 2019. http://www.fabricatingandmetalworking.com/2016/05/productive-alternative-helical-interpolation-high-volume-holemaking/
19. Hendeley, Nate. *Making holes with helical interpolation.* Canadian Metal working. 10 Dec. 2018. Web 7 Jul. 2019. https://www.canadianmetalworking.com/article/cuttingtools/making-holes-with-helical-interpolation
20. Wang, Haiyan, Qin, Xuda, Li, Hao & Tan, Yanqing. A comparative study on helical milling of CFRP/Ti stacks and its individual layers. *The International Journal of Advanced Manufacturing Technology,* 86.5-8(2016): 1973-1983.
21. Denkena, B., Boehnke, D. & Dege, J.H. Helical milling of CFRP–titanium layer Compounds. *CIRP Journal of Manufacturing Science and Technology*, 1(2008): 64–69.
22. Sasahara, Hiroyuki, Kawasaki, Makoto & Tsutsumi, Masaomi. Helical Feed Milling with MQL for Boring of Aluminum Alloy. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, 2.6(2008): 1030-1040.
23. Iyer, Ravishankar. *Helical milling: An enabling technology for machining holes in fully hardened AISI D2 Tool steel.* Feb. 2006. Web. 7 Jul. 2019. https://macsphere.mcmaster.ca/bitstream/11375/7732/1/fulltext.pdf

24. Wayken. *How to Make the Right Metal Machining Strategies?* 10 Aug. 2018. Web. 7 Jul. 2019. https://www.waykenrm.com/metal-machining-strategies.html
25. Sandvik Coromant. *Plunge milling.* Web 5 Jul. 2019. https://www.sandvik.coromant.com/en-us/knowledge/milling/milling-holes-cavities-pockets/pages/plunge-milling.aspx
26. Danis, I., Wojtowicz, N., Monies, F., Lamesle, P. & Lagarrigue, P. Cutting Conditions and Surface Integrity During Dry Plunge-milling of a Wrought Magnesium Alloy. *Procedia Engineering*, 63(2013): 36-44.
27. Sandvik Coromant. *Face milling.* Web. 12 Jul, 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/pages/face-milling.aspx
28. Seguy, Sébastien, Insperger, Tamás Arnaud, Lionel, Dessein, Gilles & Peigné, Grégoire On the stability of high-speed milling with spindle speed variation. *International Journal of Advanced Manufacturing Technology*, 48.9-12 (2010): 883-895.
29. Ko, Jeong & Altintas, Yusuf. Time domain model of plunge milling operation. *International Journal of Machine Tools & Manufacture*, 47(2007): 1351-1361.
30. Cedergren, Stefan, Frangoudis, Constantinos, Archenti, Andreas, Pederson, Robert & Sjoberg, Goran. Influence of work material microstructure on vibrations when machining cast Ti-6Al-4V. *International Journal of Advanced Manufacturing Technology*, 84.9-12(2016): 2277-2291.
31. Fairuz, Dimin Mohd, et al. "[PDF] Investigation of Tangential Force, Horsepower and Material Removal Rate Associating HAAS CNC Milling, Al6061-T6511 Work Material & TiAlN Coated End Mill Tool - Semantic Scholar." [PDF] Investigation of Tangential Force, Horsepower and Material Removal Rate Associating HAAS CNC Milling, Al6061-T6511 Work Material & TiAlN Coated End Mill Tool - Semantic Scholar, 1 Jan. 1970,
32. "Plunge Roughing: Overcoming Programming Challenges." 3D Systems, www.3dsystems.com/customer-stories/plunge-roughing-overcoming-programming-challenges.
33. Antonialli, Armando, Diniz, Anselmo & Pedriva, Robson. Vibration analysis of cutting force in titanium alloy milling. *International Journal of Machine Tools and Manufacture,* 50.1(2010): 65-74.
34. Wang, Zhigang, Nakashima, Shogo & Larson, Mark. Energy Efficient Machining of Titanium Alloys by Controlling Cutting Temperature and Vibration. *Procedia CIRP*, 17(2014): 423-528.
35. Sandvik Coromant. *Groove or slot milling.* Web 5 Jul. 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/pages/groove-or-slot-milling.aspx
36. Hendley, Nate. *Is plunge milling still viable?* 4 Oct. 2016. Web 5 Jul. 2019. https://www.canadianmetalworking.com/article/cuttingtools/is-plunge-milling-still-viable

37. Warfield, Bob. *Climb Milling versus Conventional Milling [Sneaky CNC Tricks]*. Web. 12 Jul, 2019. https://www.cnccookbook.com/climb-milling-versus-conventional-milling/
38. Warfield, Bob. (2018). *Milling Finish: Complete Guide [Feeds Speeds Master Class Lesson 7]*. [Online]. Available at :< https://www.cnccookbook.com/milling-finish-complete-guide-feeds-speeds-master-class-lesson-7/> [Accessed July 11, 2019].
39. "*Types of Lead in and Lead out Moves (PartMaker, Advanced Surface Manufacturing).*" Autodesk Support & Learning, knowledge.autodesk.com/search-result/caas/CloudHelp/cloudhelp/2018/ENU/PMAKER-ReferenceHelp/files/GUID-305BD083-2EDB-499A-9B61-7A341925AB82-htm.html.
40. Ding, Ye, Zhu, LiMin & Ding, Han. On a novel approach to planning cylindrical cutter location for flank milling of ruled surfaces. *International Journal of Production Research,* 47.12(2009): 3289-3305.
41. Amini, Saeid, Baraheni, Mohammad & Hakimi, Emad. Enhancing dimensional accuracy and surface integrity by helical milling of carbon fiber reinforced polymers. *International Journal of Lightweight Materials and Manufacture*, https://doi.org/10.1016/j.ijlmm.2019.03.001
42. Chang, Kuang-Hua. Introduction to e-Design. In *Design theory and methods using CAD/CAE*. Amsterdam. Elsevier Inc. 2014, pp.1-37.
43. Dabhi, B. & Parmar, K. A Review Paper On Latest Trend On Face Milling Tool. *International Journal of Advance Engineering and Research Development*, 2.1(2015): 59-61.
44. Direct Industry. *Shell-End Milling Cutter / Insert / Roughing / Face.* Web. 12 Jul, 2019. `http://www.directindustry.com/prod/sandvik-coromant/product-14460-1447013.html
45. Ferrell, Evan. *Analysis Of Tool Wear And Tool Life Of Cutting Tool Inserts Using Statistical Process Control Charts: A Case Study.* 28 Apr. 2017. Web. 12 Jul,2019. https://scholarworks.moreheadstate.edu/cgi/viewcontent.cgi?article=1097&context=msu_theses_dissertations
46. Harvey Tool Company, LLC. Conventional Milling vs. Climb Milling. 2017. Web. 12 Jul, 2019. http://www.harveytool.com/secure/Content/Documents/Tech_ConventionalMillingVsClimbMilling.pdf
47. Huang, Nuodi, Lynn, Roby and Kurfess, Thomas. Aggressive Spiral Toolpaths for Pocket Machining Based on Medial Axis Transformation. *Journal of Manufacturing Science and Engineering*, 139(2017), 1-8.
48. Zhou, Bo, Zhao, Jibin, Li, Lun and Xia, Renbo. A smooth double spiral tool path generation and linking method for high-speed machining of multiply-connected pockets. *Precision Engineering*, 46(2016): 48-64.

49. Indiamart. *Cylindrical Cutter.* Web. 12 Jul, 2019. https://www.indiamart.com/proddetail/cylindrical-cutter-11702513112.html
50. Korkut, I &Donertas, M.A. The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool chip contact length during face milling. *Materials and Design*, 28(2007): 308-312.
51. Lawal, S.A., Ahmed, A.M., Lawal, S.S. & Ugheoke, B.I. Effect of HSS and Tungsten Carbide Tools on Surface Roughness of Aluminium Alloy during Turning Operation. *American Journal of Mechanical Engineering*, 4.2(2016): 60-64.
52. Moltrecht, K H. *Machine Shop Practice.* New York, N.Y: Industrial Press, 1981. Print.
53. Oliaei, S. & Karpat, Y. Experimental Investigations on Micro Milling of Stavax Stainless Steel. *Procedia CIRP,* 14(2014): 377-382.
54. "2D Adaptive Clearing." Autodesk Support & Learning, knowledge.autodesk.com/support/hsm/learnexplore/caas/CloudHelp/cloudhelp/2019/ENU/Inventor-HSM/files/GUID-74087F36-6388-4BF4-8840-B666C38E6811-htm.html.
55. Olofson, C. T., Gurklis, J. A., & Boulger, F. W. Machining and Grinding of Ultrahigh-Strength Steels and Stainless Steel Alloys. *Machining and Grinding of Ultrahigh-Strength Steels and Stainless Steel Alloys*. NASA SP-5084. 1968.
56. Praneeth, Jammula & Naveen, Narraa. Machining of Aluminum alloys: a review. *International Journal of Research in Applied Science & engineering Technology*, 5.10(2017): 1333-1338.
57. Sandvik Coromant. *Milling holes and cavities/pockets.* Web. 12 Jul, 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/milling-holes-cavities-pockets/pages/default.aspx
58. Sandvik Coromant. *Shoulder milling.* Web. 12 Jul, 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/pages/shoulder-milling.aspx
59. Sandvik Coromant. *What is profile milling?* Web. 12 Jul, 2019. https://www.sandvik.coromant.com/en-gb/knowledge/milling/pages/profile-milling.aspx
60. Shajari, Shaghayegh, Sadeghi, Mohammad and Hassanpour, Hamed. The Influence of Tool Path Strategies on Cutting Force and Surface Texture during Ball End Milling of Low Curvature Convex Surfaces. *The Scientific World Journal*, 2014. http://dx.doi.org/10.1155/2014/374526
61. Smithy. *Face Milling.* Web. 12 Jul, 2019. https://smithy.com/machining-handbook/chapter-4/page/49
62. Thamizhmanii, S. & Hasan, S. Machinability of Hard Martensitic Stainless Steel and Hard Alloy Steel by CBN and PCBN Tools by Turning Process. *Proceedings of the World Congress on Engineering WCE 2011, July 6 - 8, 2011, London, U.K*, 1(2011): Virasak, LamNgeun. *Manufacturing processes 4-5.* Open Oregon. 2017.

63. Ye, Dong-Hee, Koo, Joonyoung, Park, Young-Koon & Kim, Jeong-Suk. Analysis on the Effects of Tool Rake Angle and Helix Angle of a Flat End-mill in the Milling of Ti- alloy. *Journal of the Korean Society of Manufacturing Technology Engineers,* 24(2015): 508-513. 10.7735/ksmte.2015.24.5.508.
64. “12 Best CAM Software Tools for SolidWorks, AutoCAD & Co.” All3DP, 14 June 2019, all3dp.com/1/best-cam-software-solidworks-autocad/#use.

List of Appendices

Appendix 1: Kistler Dynamometer Datasheet

Force – FMR

KISTLER
measure. analyze. innovate.

Rotating 4-Component Dynamometer RCD

for Cutting Force Measurement up to 10 000 1/min

Type 9123C..., 5221B1, 5223B...

Rotating 4-component dynamometer for measuring of cutting forces and torques on the rotating tool spindle. Transmission of measured data by telemetry hence without wear.

- Cutting force measurement on the rotating edge
- 4-component force/moment measurement
- Data transmission by telemetry
- Internal coolant supply
- Conforming to CE

Description

The dynamometer consists of a four component sensor fitted under high preload between a baseplate and top plate.
The four components are measured practically without displacement.
It must be taken into account that combined and eccentric loads may reduce the measuring ranges.
The sensor is mounted ground-insulated. Therefore ground loop problems are largely eliminated.
The dynamometer is rustproof and protected against penetration of splashwater and cooling agents.
For each component a 2-range miniature charge amplifier is integrated in the dynamometer. The output voltages of the charge amplifiers are digitized and transmitted by telemetry to the stator. The remote controlled range switching and an optionally switchable zoom channel allow to use the measuring ranges in an optimal manner.
The voltage is supplied per induction.
A zero point identification (Type 5221B2) is available as an option which allows to correlate the force signals with the tool edge.
The dynamometer is preferably delivered with integrated spindle adapter (according to option). For mounting the cutting tools, tool adapter Type 9163 is available.

Applications

Investigations of wear and cutting processes near the tool edge during milling and drilling. The acting force vector on one-edged tools can directly be measured. This dynamometer is especially suitable for high speed fine machining.

Technical Data

Dynamometer Type 9123C...

Speed		1/min	max. 10 000
Range 1 FSO	F_x, F_y	kN	–5 ... 5 **
			–3 ... 3 ***
	F_z	kN	–20 ... 20
	M_z	Nm	–200 ... 200
Range 2 FSO (switchable)	F_x, F_y	N	–500 ... 500
	F_z	kN	–2 ... 2
	M_z	Nm	–20 ... 20
Overload range 1		%	20
Threshold	F_x, F_y	N	<1
	F_z	N	<4
	M_z	Nm	<0,04
Sensitivity (Range 1)	F_x, F_y	mV/N	≈2
	F_z	mV/N	≈0,5
	M_z	mV/Nm	≈50
Linearity		%FSO	≤±1
Hysteresis		%FSO	≤1
Crosstalk	$F_x \leftrightarrow F_y$	%	≤±2
	$F_z \rightarrow F_{x,y}$	%	≤±3
	$F_{x,y} \rightarrow F_z$	%	≤±3
	$M_z \rightarrow F_z$	1 N/Ncm	≤±0,01
Natural frequency Type 9123Cxx11 measured without telemetry	f_n	kHz	≈2,0

000-121e-01.04 (DB06.9123Cm)

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Operating temperature range		°C	0 … 60
Coolant pressure		bar	≤70
Degree of protection			IP67
Weight Type 9123C1111		kg	≈3

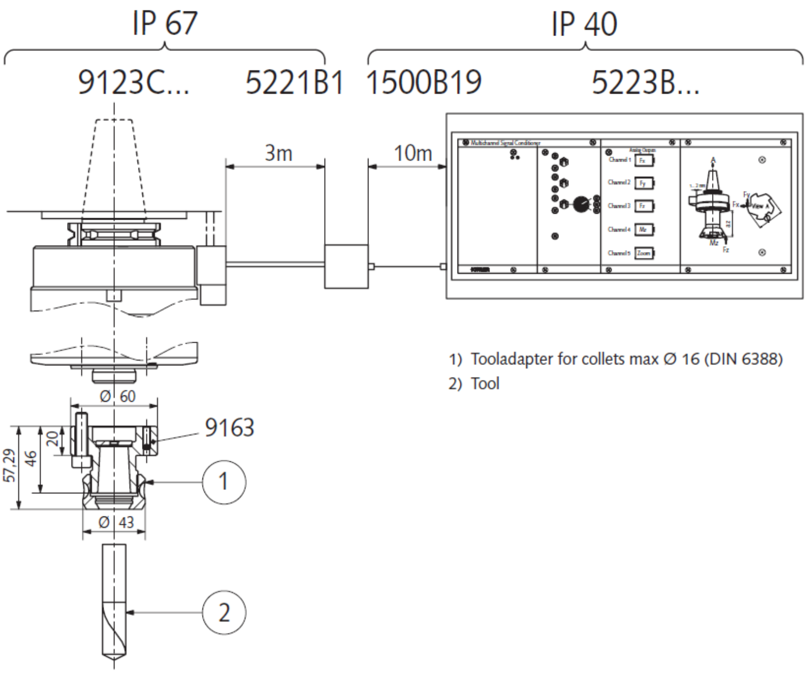
** Force application point on the top plate area
*** Force application point 100 mm above top plate area

Stator and Multichannel Signal Conditioner
Type 5221B1 and Type 5223B…

Ratio range 1 / range 2			10
Number of channels			5
Number of ranges per channel			2
Cut-off frequency per channel	f_{cutoff}	kHz	1,0
Sampling rate per channel		kHz	7,8
Resolution/tolerance		bit/%	12/±0,025
Signal output (FSO)		V	±10
Output connector (analog signal)			5 x BNC neg. 15 pin D-Sub

Operating temperature range	°C	0 … 60
Power supply	V/AC	230/115
(switchable)	%	+15/–22
	Hz	48 … 62
Power consumption	VA	≈30
Dimensions		
(DIN 41494, part 5)		
Width	TE	63
Height of instrument	HE	4
Height of plug-in	HE	3
With case	mm	340x187x280
Weight Type 5223B…	kg	8
Interface		RS-232C
for remote control		
Zero point identification		
(only Type 5223B2)		
Signal output	V	+5
Output connector		BNC neg.

Zoom (window amplifier):
The zoom decouples the output signal of an optional channel and amplifies the signal by a factor 10.



1) Tooladapter for collets max Ø 16 (DIN 6388)
2) Tool

Fig. 1: Rotating cutting force measuring system

000-121e-01.04 (DB06.9123Cm)

KISTLER
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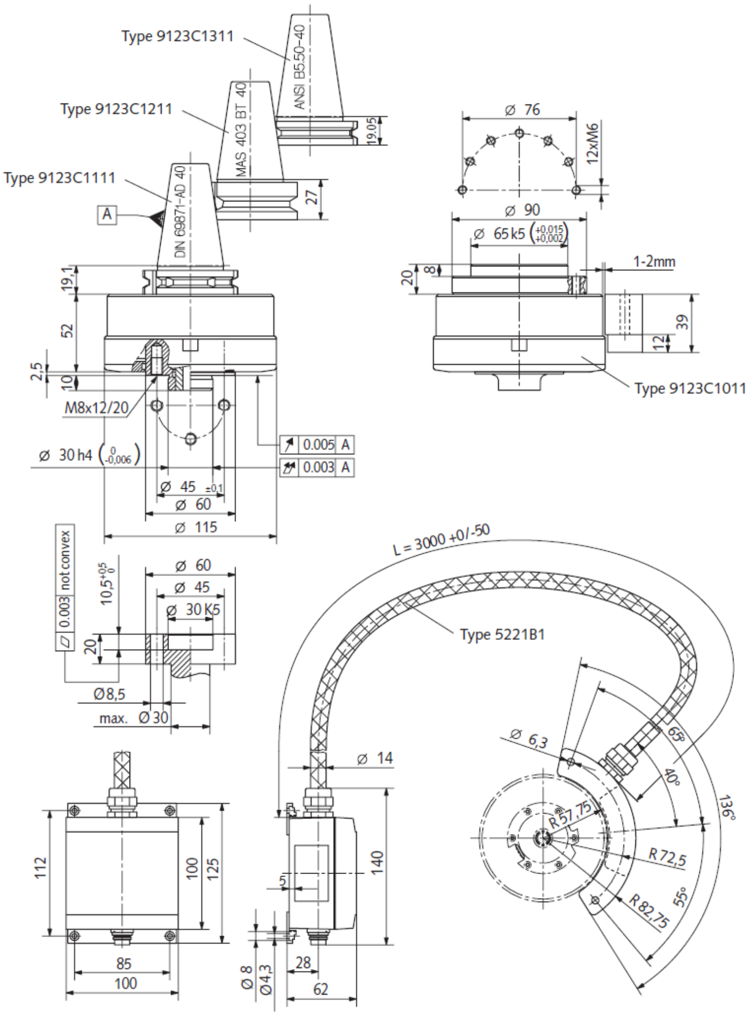


Fig. 2: Dimensions Dynamometer Type 9123C…

Optional Accessories	Type
• Stator	5221B1
• Connecting cable	1500B19
• Multichannel signal conditioner	5223B1
• Multichannel signal conditioner with zero point identification	5223B2
• Tool holder (without collets)	9163

Ordering Key

9123C □□11

Spindle adapter*	
without spindle adapter	10
DIN 69871-AD 40	11
MAS 403 BT 40	12
ANSI B5,50 - 40	13

* other spindle adapters on request

000-121e-01.04 (DB06.9123Cm)

Appendix 2: Cutting Tool Datasheet

GUHRING

Use this number when searching for this item:

9033660120000

12 MM CARBIDE END MILL Solid Carbide FIREX

>> Item Info

EDP #	9033660120000
Series	3366
Order Code	12.000
Coating	FIREX
Coolant	With
Cutting Direction	Right Hand
Cutting Edge	High Performance
	Mild & Free-Cutting Steels
Helix Angle	40/42
Material	Carbide
Shank	Weldon Flat
Type	Mild & Free-Cutting Steels
Tolerance	h10

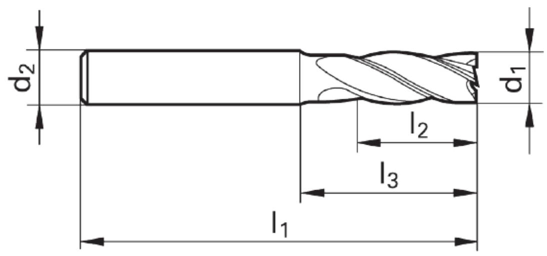
>> Features

- with internal coolant supply
- neck clearance
- centre cutting

>> Suggested Materials

- Aluminum
- Alloyed Steels
- Free Cutting Steels
- Tool Steels
- Stainless Steels
- Ti and Ti-alloys
- Cast Iron
- Brass
- Bronze
- Copper
- Magnesium
- Special Alloys
- Hardened Steels

>> Technical Specs



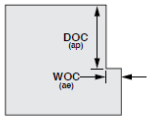
		Dia	Shank dia	OAL	LOC	Reach	Corner	Corner		
EDP #	Order Code	d1	d2	l1	l2	l3	Radius	Chamfer	Flutes	Shank Type
		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		
9033660120000	12.0000	12.0000	12.0000	83.0000	26.0000	36.0000		0.2000	4	Weldon flat

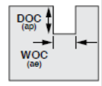
WARNING:
This product contains Cobalt, a chemical known to the State of California to cause cancer. For more information go to www.P65Warnings.ca.gov

*** **DISCLAIMER:** Data on this PDF is subject to change at any time without notice.

FEEDS & SPEEDS FOR RF100 U, F, VA, A, SF, Ti, H, RF 50

INCH





$$RPM = \frac{SFM}{d_1} \times 3.82$$

IPM = No. of teeth x IPT x RPM

For finishing use WOC (ae) .01 up to .1xd, use SFM from .25xd column, do not increase IPT from table values

Material	Hard-ness	TYPE	Surface feet per minute - SFM: High Speed Milling, DOC 2xd, WOC .05xd	High Speed Milling, DOC 2xd, WOC .1xd	High Speed Milling, DOC 2xd, WOC .25xd	Rough, DOC 1xd, WOC .4 to .9xd	Slot, DOC 1xd, WOC 1xd	Feed Rate Inch per Tooth - IPT, d1 End Mill Diameter: 1/8 (3.17mm)	1/4 (6.35mm)	5/16 (7.94mm)	3/8 (9.52mm)	1/2 (12.70mm)	5/8 (15.87mm)	3/4 (19.05mm)	1 (25.40mm)
			2.5	2.3	1.5	1	1	← Multiply IPT x this factor based on WOC							
Structural + free-cutting steels, unalloyed heat-treatable + case hardened steels A283, 1151, 1215, L10, 10Lxx, 11Lxx, 12Lxx, 41Lxx, 51Lxx, 86Lxx, 86Lxx, 10xx	up to 28 HRc	F VA SF	1200	1100	900	650	575	.0007	.0013	.0016	.0023	.0030	.0040	.0045	.0060
Free-cutting steels, unalloyed case hardened steels, nitriding steels 1151, 1215, L10, 10Lxx, 11Lxx, 12Lxx, 41Lxx, 51Lxx, 86Lxx, 86Lxx, 10xx, 11xx	28 to 38 HRc	U F SF	1100	1000	850	650	525	.0006	.0012	.0015	.0021	.0028	.0035	.0041	.0056
Alloyed heat-treatable, tool and high speed steels 13xx, 2340, 31xx, 32xx, 33xx, 34xx, 40xx, 41xx, 43xx, 4640, 50xx, 51xx, 61xx, 71xx, 86xx, 87xx, 92xx, 98xx, 98xx, Ax, Ox, Dx, Hxx, Lx, Wx, Mx, Tx	28 to 44 HRc	U U SF	900	800	680	650	425	.0006	.0011	.0014	.0019	.0025	.0031	.0038	.0052
Hardened Steels Carbon and Alloy Steels, Tool & Die Steels	Up to 54 HRc	U SF H	480	460	360	250	225	.0005	.0009	.0011	.0015	.0020	.0023	.0030	.0040
	54 to 60 HRc		250					Finishing only WOC less than .1xd: .0003	.0006	.0008	.0010	.0013	.0016	.0019	.0028
Stainless steel 303, 410, 420F, 430, 430F, 416	Up to 28 HRc	VA VA SF	840	760	450	450	400	.0006	.0011	.0014	.0019	.0025	.0031	.0038	.0052
Stainless steel 304, 304L, 420, 17-4PH, 17-7PH, 15-5PH, 13-8PH	up tp 28 HRc	VA VA SF	525	475	330	330	250	.0005	.0010	.0013	.0017	.0023	.0027	.0034	.0044
Stainless steel 310, 316, 316B, 316L, 317, Duplex	over 28 HRc	VA/F VA/F SF	420	380	260	260	200	.0005	.0009	.0011	.0015	.0020	.0023	.0030	.0040
Titanium Alloys 6Al-4V, 5Al-2.5 Sn, 6Al-2Sn-4Zr-6Mo, 3Al-8V-6Cr4Mo-4Zr, 10V-2Fe-3Al, 13V-11Cr-3Al	up to 42 HRc	Ti/F VA SF	420	380	260	260	200	.0003	.0007	.0009	.0012	.0016	.0020	.0023	.0032
High-Temperature Alloys Inconel, Nimonic, Monel, Hastelloy, Waspalloy, A286, Rene 41, Udimet, Stellite	up to 42 HRc	Ti/U VA SF	210	190	130	130	100	.0004	.0006	.0008	.0009	.0013	.0016	.0019	.0024
Cast iron, grey cast iron, spheroidal graphite and malleable cast iron 0.6010 EN-GL100 (GG10), 0.6020 EN-GJL-200 (GG20), 0.7050 EN-GJS-500-7 (GGG50), 0.8535 EN-GJMW-350-4 (GTW35)	up to 240 HB 30	F U SF	1100	1000	850	620	525	.0007	.0014	.0017	.0024	.0033	.0039	.0049	.0064
Cast iron, grey cast iron, spheroidal graphite and malleable cast iron 0.6025 EN-GL250 (GG25), 0.6035 EN-GJL-350 (GG35), 0.7070 EN-GJS-700-2 (GGG70), 0.8170 EN-GJMB-700-2 (GTS70)	over 240 HB 30	U VA SF	950	860	720	550	450	.0006	.0013	.0016	.0021	.0028	.0035	.0041	.0056
Aluminum, Al-wrought alloys, Al-alloys 2024, 6061, 7075, 1050, 6351, 5005, 2017, 7075	up to 3% Si	A	3400	3090	2600	1950	1625	.0008	.0016	.0020	.0030	.0040	.0051	.0060	.0080
Aluminium-cast alloys 3.2131 G-AlSi5Cu1, 3.2153 G-AlSi7Cu3, 3.2573 G-AlSi9, 3.2581 G-AlSi12, 3.2583 G-AlSi12Cu, - G-AlSi12CuNiMg	over 3% Si	A	1575	1425	1200	1000	750	.0007	.0014	.0017	.0023	.0030	.0039	.0045	.0060
Magnesium-alloys MgMn2, G-MgAl8Zn1, G-MgAl6Zn3	–	A F SF	1210	1100	920	725	575	.0006	.0013	.0016	.0021	.0028	.0035	.0041	.0056
Non-ferrous metals (copper, short- or long-chipping brass or bronze)	up to 28 HRc	A F SF	1680	1520	1280	975	800	.0007	.0014	.0017	.0023	.0030	.0039	.0045	.0060