MODELING AND OPTIMIZATION OF MICRO SCALE POCKET MILLING OPERATIONS

A THESIS
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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

by
Bengisu Sert
May, 2014

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Asst. Prof. Yiğit Karpat (Advisor)

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Prof. Selim Aktürk

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Asst. Prof. İlker Temizer

Approved for the Graduate School of Engineering and Science

Prof. Levent Onural

Director of the Graduate School of Engineering and Science

ABSTRACT

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Bengisu Sert
M.S. in Industrial Engineering
Supervisor: Asst. Prof. Yiğit Karpat
May, 2014

Manufacturing of micro scale parts and components made from materials having complex three dimensional surfaces are used in today's high value added products. These components are commonly used in biomedical and consumer electronics industries and for such applications, fabrication of micro parts at a low cost without sacrificing quality is a challenge. Micro mechanical milling is a viable technique which can be used to produce micro parts, however the existing knowledge base on micro milling is limited compared to macro scale machining operations.

The subject of this thesis is micro scale pocket milling operations used in micro mold making which are used in micro plastic injection in mass production polymer micro parts. Modeling of pocket milling while machining of basic pocket shapes are considered first. The developed milling model is then extended to more complex mold shapes. Minimum total production time is used as the objective to solve single pass, multi pass, and multi tool problems. Case studies are presented for each problem type considering the practical issues in micro milling. A software has been developed to

optimize machining parameters and it is shown that the developed pocket milling optimization model can successfully be used in process planning studies.

Keywords: Micro milling, tool path generation, sharp corner milling, pocket milling, optimization

ÖZET

MİKRO ÖLÇEKLİ CEP FREZELEME İŞLEMLERİNİN MODELLENMESİ VE ENİYİLEMESİ

Bengisu Sert
Endüstri Mühendisliği, Yüksek Lisans
Tez Yöneticisi: Yrd. Doç. Dr. Yiğit Karpat
Mayıs, 2014

Bugünün yüksek katma değerli ürünlerinde, karmaşık üç boyutlu yüzeylere sahip malzemelerden yapılmış olan mikro ölçekli parça ve komponentler kullanılmaktadır. Bu komponentler genellikle biyomedikal ve elektronik sektörlerinde kullanılmaktadır ve bu mikro parçaları kaliteden ödün vermeden düşük maliyetle üretmek çözülmesi gereken bir sorundur. Mikro mekanik frezeleme, mikro parçalar üretmek için kullanılabilecek uygun bir tekniktir, ancak mikro frezeleme hakkındaki mevcut bilgi veri tabanı makro ölçekli işleme operasyonlarına kıyasla daha sınırlıdır.

Bu tezin konusu mikro ölçekte kalıp yapımında kullanılan mikro ölçekli cep frezeleme işlemleri üzerinedir. Bu kalıplar mikro plastik enjeksiyon yönteminde ve mikro parçaların seri üretiminde kullanılmaktadır. Cep frezeleme işlemleri ilk olarak temel cep şekilleri ele alınarak modellenmiştir. Geliştirilen frezeleme işlem modeli daha sonra daha karmaşık kalıp şekilleri için genişletilmiştir. Minimum toplam üretim zamanı modellerde tekli geçiş, çoklu geçiş ve çoklu takım sorunlarını çözmek için amaç olarak kullanılmıştır. Vaka çalışmaları, herbir problem tipi için mikro frezeleme yönetimleri göz önünde bulundurarak sunulmuştur. İşleme parametrelerini eniyilemek için bir yazılım geliştirilmiştir. Geliştirilmiş olan cep frezeleme eniyileme modellerinin süreç planlamalarında başarılı olarak kullanılabileceği gösterilmiştir.

Anahtar Sözcükler: Mikro frezeleme, cep frezeleme, takım yol oluşumu, keskin köşe frezeleme, eniyileme

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Chapter 1

Introduction

The aim of manufacturing is to convert raw materials into finished products. During this process, some essential activities which need to be satisfied in order to fulfill the demands of the customers are listed by Kalpakjian and Schmid [1] as:

1. meet the design requirements, product specifications and standards,
2. manufacture the products economically and environmentally friendly,
3. satisfy the quality,
4. have flexible production methods to catch the changing market demands,
5. develop continuously the materials, production methods and computer integrations on both technological and managerial activities,
6. work for continuous improvement of products,
7. achieve high level of productivity

While manufacturers try to fulfill the demands of the customers, increasing demand due to rapid growth of the human population (Figure 1.1) resulted in reduction of the natural resources. It is shown that if the consumption rate remains the same, the oil is going to run out in 40 years, natural gases in 60 years and the coal in 185 years (Figure 1.2) [2].

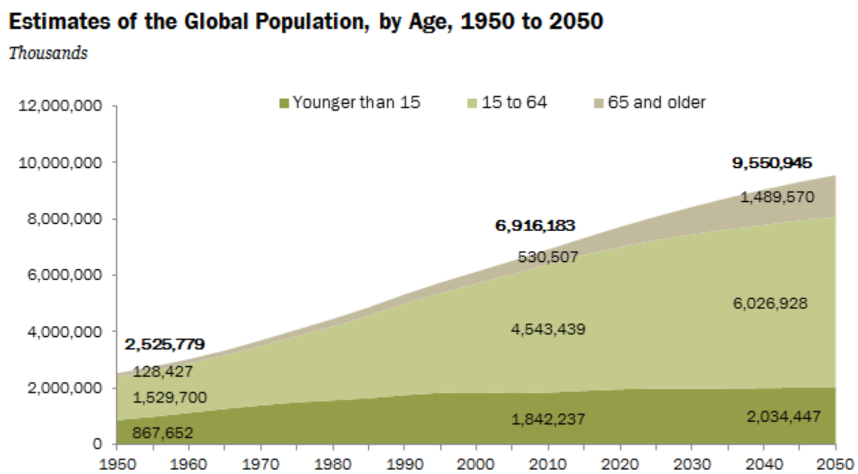


Figure 1.1 World population estimates [3, 4]

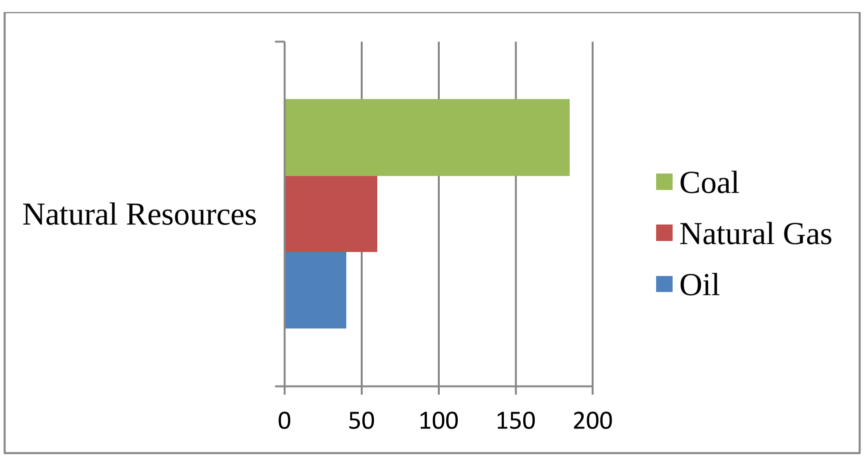


Figure 1.2 Run out of times of the important natural resources [2]

Excessive use of the resources by the people also triggers the global warming. Figure 1.3 shows the global average temperature increase through years. Thus, it is challenge for manufacturers to find ways to produce their products environmentally friendly, economically, and quickly while satisfying customer requirements.

Figure 1.3 Global temperature changes (1861-1996) [2]

Based on above considerations, sustainability of manufacturing activities has become an important subject. The aim of sustainable manufacturing is to create the products both economically and by minimizing the negative environmental impacts [4, 5]. Among manufacturing processes, machining constitutes a large percentage. Therefore, machining industry as a whole has to find ways to improve the machining process from both economical and environmental points of view [6].

Manufacturing processes can be classified as casting, forming, machining, joining, finishing, and nanofabrication [1]. Machining constitutes a significant portion of the general manufacturing activities and affects the costs of the products. Thus, it is important to find proper machining parameters to maximize productivity and minimize cost. In practice, machining process parameter selection is based on the experimentation which is costly and time consuming. In order to select the operational parameters properly, some analytical or computational models need to be developed to simulate the complex systems [7, 8].

1.1 Motivation

In manufacturing industry, there is an increasing demand for micro parts. These parts have micro scale dimensions with complicated features and strict tolerances. Hence, micro machining has become important for the manufacturing sector in general. For instance, the electronics industries aim to add more features to their products, the medical industry is interested in devices which relieve pain, less chance to get infection and having faster healing time [9]. Aerospace industry is interested in micro sensors, flow-control systems [10]. By using micro machines and the tools, many complex products can be produced. However, the production environment for micro machining must satisfy certain conditions. Some major factors that may affect the features of the products can be summarized as temperature changes and ground vibrations. Since the size of the products is so small and due to tight dimensional and form tolerances, with the small changes on the variables and the environmental factors, all the outputs of the products are affected significantly. In macro scale manufacturing, the impacts of those factors are less when compared with the micro scale manufacturing. Thus, in micro machining, it is extremely important to consider the details with emphasis on manufacturing the products precisely. Robert Aronson claims "the old manufacturing rules don't apply in the micro world" [11]. Physics of the process at micro scale need to be understood to extend the limited process knowledge. It is important to develop reliable process models. Some of the other challenging parts of manufacturing the micro scale parts can be summarized as standardization, validation, part handling, inspection, and processes [11].

The goal of this thesis is to develop model-based strategies for the micro scale machining operations. The micro milling operation is taken into consideration. One use of the micro milling processes is to create molds for the micro polymer products. The designs of the molds may have complicated shapes depending on the finish product geometries. Thus, in order to create basis and knowledge for machining complicated shapes of basic pocket shapes are examined in this study.

Milling operations can be divided to two as roughing and finishing. The aim of the roughing processes is to remove large amount of material as rapidly as possible. After the roughing operation, the products' shape is close to its finished form. Finishing is used to improve surface quality and it is used to achieve the tolerances and final dimensions which have high importance for the molds. In this thesis, process optimization for the roughing operations of the micro scale pocket milling is considered. The aim is to minimize the total production time of the micro molds by using micro scale milling operations so that the manufacturers can earn from the time and their resources. Furthermore, the aim may also be to find machining conditions to machine the whole pocket with one tool when there is a single tool diameter to be used. The mathematical model and the tool path generation strategies for different shapes of the pockets for single and multi tool cases of single and multi pass problems are defined. Without using complicated and expensive programs to simulate the micro milling processes, the strategies to machine the pockets are defined and the objective functions are presented to find the optimal cutting speeds for different shapes. Furthermore, a software module is developed to solve the mathematical models proposed for multi tool machining of equilateral triangular pockets. Furthermore, as a complex machining example, the micro needle production is also taken into consideration and the aim is to minimize the total production time.

1.2 Organization of the Thesis

The organization of the thesis is expressed as:

In Chapter 2, the general information about the micro milling is expressed. The machines, tools, and products of the micro milling are defined. The benefits and the difficulties while machining the products are discussed.

In Chapter 3, the mathematical models of the milling operations for the circular, square, rectangle and triangle pockets are presented. For the four shapes, the differences occur on calculating the tool path length and the machining strategies. The objective is to minimize the total production time of a pocket and machine the whole pocket with one tool without having to change the cutting tool during process.

In Chapter 4, firstly, multi-tool single pass problem of the equilateral triangle is defined. In micro molding processes and micro machining, sharp corners of the pockets can be required. As a focus, it is assumed that the corners of the equilateral triangle are sharp so the corner machining strategies are defined in detail. The objective is to define the tool path creation strategy when multiple tools are used and the objective of the problem is to minimize the total production time. The mathematical model is defined for each tool used to machine the product. This chapter also focuses on the multiple-tool multiple-pass problems. Thus, the strategy to find the best combinations to produce the equilateral pocket with sharp corners is defined. The software module is used to find the optimal cutting speed for multiple-tool and multiple-pass case. After the run of the module, the results for different combinations of the tools can be seen and the best number of pass for each combination can be found.

In chapter 5, an example for the complex shape of pockets is examined which is micro needle production which has 2.5D island inside the pockets. Firstly, the mathematical model of micro scale milling operations for the micro needle is presented. The aim is to create the tool path for roughing operations of micro needle and obtain the minimum total production time which is an objective function of the problem.

In chapter 6, the thesis is summarized and the possible future works are outlined.

Chapter 2

Micro-Scale Milling Operations

Micro scale production is a growing industry which requires substantial changes in the manufacturers' understanding of machining. Some products obtained as a result of micro manufacturing are shown in Figure 2.1.

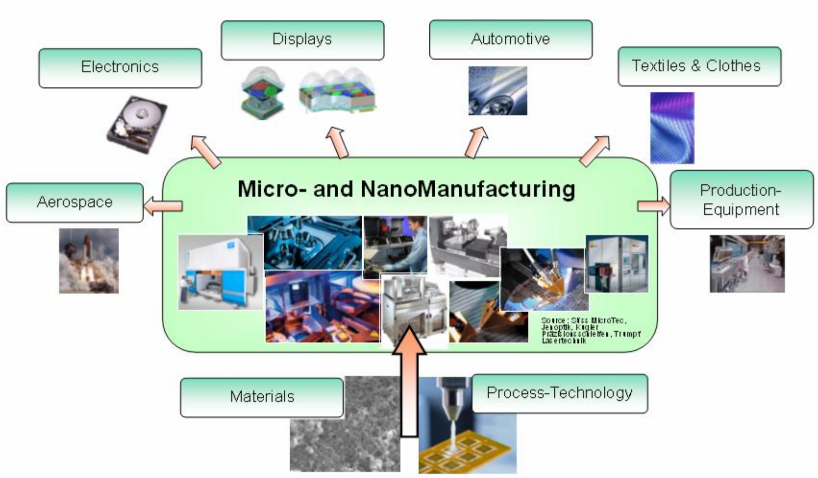


Figure 2.1 Sectors where Micro and Nano Manufacturing products can exist [9]

For instance, the micro molding is the technology to obtain tiny or microscopic parts for micro devices having complex shapes and tight tolerances. The challenges that are faced to produce these parts can be summarized as creating 3D shapes, selecting and developing processes that satisfy the functional and the economical demands [12]. In 2005, a study by Micro Manufacturing by the World Technology Evaluation Center Inc. in association with NIST (National Institute of Standards and Technology), NSF (National Science Foundation), DOE (Department of Energy Office of Science), and the Naval Research Academy described the value of the micro manufacturing to US with these terms [13]:

- It gives the opportunity to make use of nano world technologies and fill the gap between nano and the macro world.
- It changes our thinking style by considering how, when, where the products are manufactured.
- It redistributes the capability from hands of few to many.
- It improves the competitiveness by reducing capital investments, space and energy cost and increasing portability and the productivity.

The fundamental physics at the micro scale is not known well when it is compared with the macro scale. Thus, there is a need to develop reliable and scalable models to understand the principles of the micro production. There are studies about the micro scale models but more studies are needed to improve the software modules, material specifications, and simulation modules of the micro production [13]. Different types of micro scale machining processes can be used in the manufacturing processes. One of them is the mechanical micro machining process. Unlike lithography or etching methods, it is possible to create 3D surfaces by using a wide range of materials. While creating the micro scale molds, these properties of the mechanical micro machining have high importance. Some of the examples of the micro scale milling machines can be seen in Figure 2.2.

Figure 2.2 (a) DT-110 [14] (b) W-408MT [14] (c) Hyper2j [14] (d) Kugler [14] (e) Kern [14] (f) Mori Seiki [14]

Some of the examples of the micro scale products created through micro molding are shown in Figure 2.3.

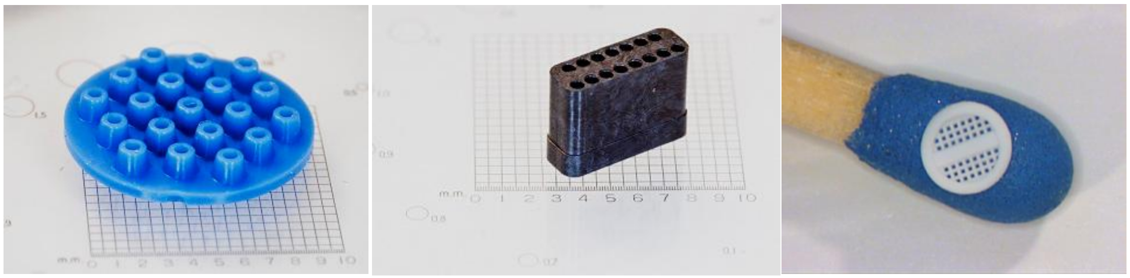


Figure 2.3 Examples of micro products [15,16]

Basic milling processes are shown in Figure 2.4(a, b, c). The picture 2.4d represents the ball end milling cutter and the picture 2.4e shows five axis milling process. In Figure 2.5, a micro end mill with two teeth is shown.

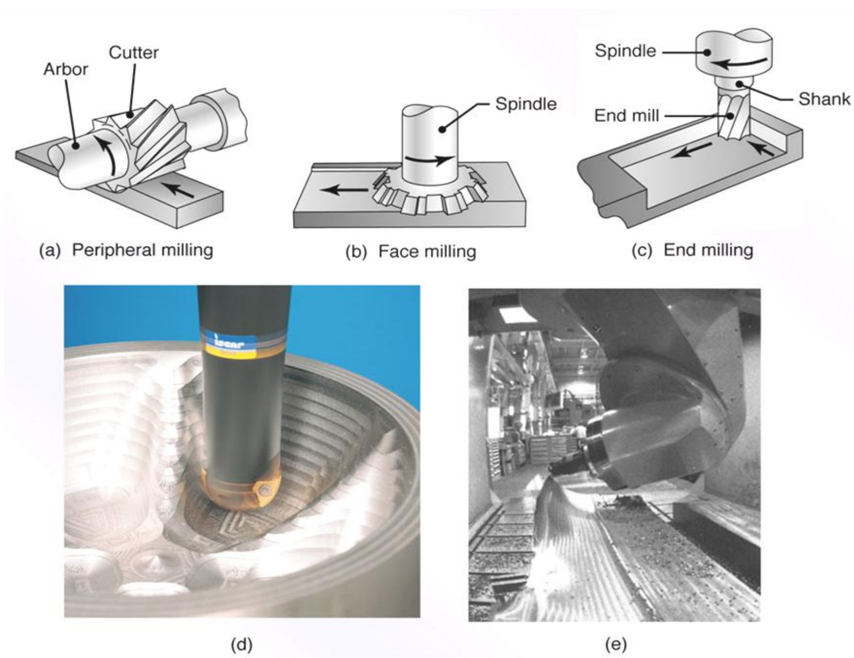


Figure 2.4 The basic types of cutting tools [7]

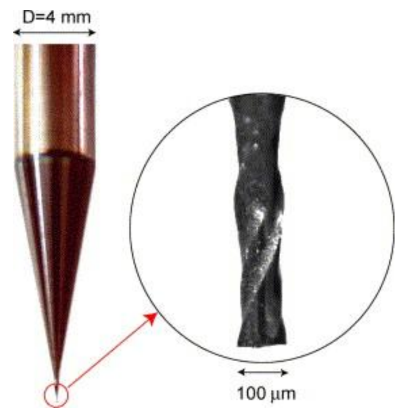


Figure 2.5 Micro end mill with two teeth [17]

A milling cutter may rotate clockwise or counter clockwise, which has a high importance while machining the products. In conventional milling (up milling), the tool rotates counter clockwise where the maximum cutting chip thickness is faced at the end of the cut and it pushes the workpiece upwards. In climb milling (down milling), the tool rotates clockwise where the maximum chip thickness is faced at the start of the cut. The advantage of it is that the cutting force holds the workpiece on its place (Figure 2.6). The representation of chip forming of down and up milling can also be seen in Figure 2.7 where D represents the tool diameter and B is for the immersion amount to the material.

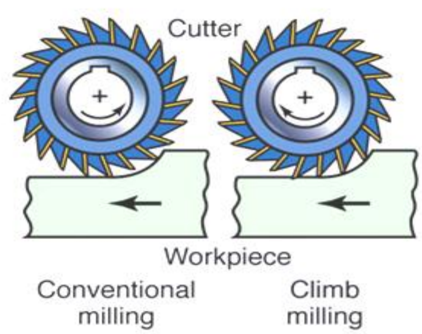


Figure 2.6 Milling Cutting strategies [1]

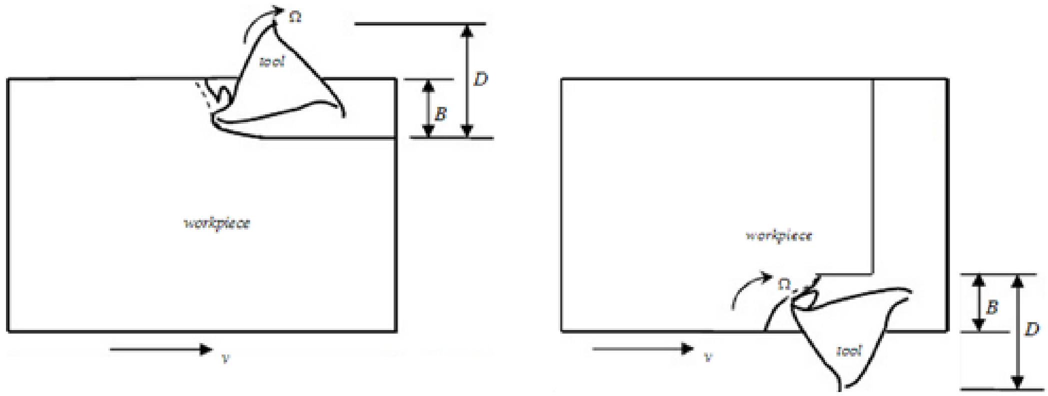


Figure 2.7 Up and down milling representation [18]

The immersion amount depends on the cutting positions of the tools. Radial immersion ratio can be found by B/D (Figure 2.8). The first picture represents an example of the 100% immersion and the second picture is for 50% immersion.

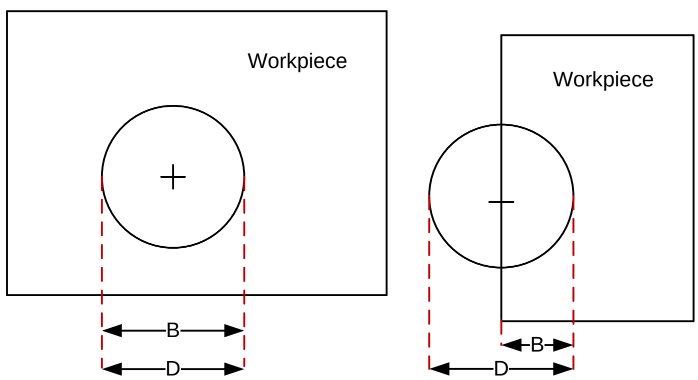


Figure 2.8 Different immersion amounts representation

By using these specified machines and the tools, the materials of the workpiece are removed. The machining area is defined by the designer of the product. The area that will be machined defined with the borders is called "pocket" as shown in Figure 2.9.

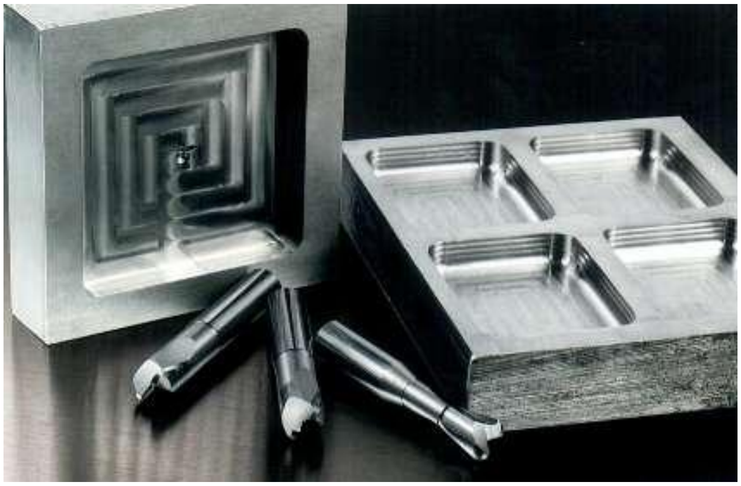


Figure 2.9 An Example of the pocket [19]

There are dependent and the independent variables in the milling processes. The independent variables can be summarized as:

- Tool material and coating
- Tool geometry
- Workpiece material
- Cutting speed, feed, depth of cut

The cutting speed is the surface speed at the diameter and the feed is the representation of the movement of the tool in relation to the workpiece which is dependent on the feed per tooth. Feed per tooth is the movement distance the tool travels per tooth [20]. The dependent variables are that are influenced from the changes of the independent variables can be summarized as [21]:

- Type of chip produced
- Force and energy dissipated during cutting

- Temperature rise in tool, workpiece and chip
- Tool wear and failure
- Surface finish

One important subject when machining the workpiece is the tool life. It is a measurement that shows how much time the tool can cut the material satisfactorily. It is represented with symbol T. Because of changes on the geometry of the tool such as the nose wear, plastic deformation of the tool tip or the breakages of the tool affect the surface quality and the performance of the machines. Some of the examples that affect the tool life can be summarized as: cutting speed, feed, depth of cut, tool material and cutting fluid. F. W. Taylor proposed a basic tool life equation by making some empirical studies about the tools, which can be seen in the Equation 2.1 and he realized that increase in the cutting speed decreases the tool life and causes the delays on the production because of the tool replacements or reconditioning the tool [21]. On the equation, V, T, n, C represent cutting speed, tool life, constant and the empirical constant, respectively.

$$V.T^n = C \tag{2.1}$$

Taylor was the first who showed the dependence of the economic performance of machining on the performances of the technologies. It was realized that there is a need to select optimal cutting conditions in process planning [21]. Taylor tool life equation is extended so that it can be used for more complex and specific types of the cutting tools. Figure 2.10 expresses the summary of the extended Taylor tool life equations. In these equations, T represents the tool life, K, K_1, K_2, K_3, 1/n's and m's are the empirical constants defining the impact of the cutting tool and the workpiece material combinations on the tool life. The other variables' definitions can be summarized as: V is the cutting speed, f is the feed, a_p is the depth of cut, D is the drill diameter for the drilling equation and cutter diameter for other equations, f_z is the feed per tooth, a_a is the axial depth of cut, a_r is radial depth of cut, z is number of teeth, δ is helix angle of the teeth. It can be understood from the extended Taylor tool life equations that increase of V, f, a_p, a_r, a_a and z decreases the tool life; however, increasing D and helix angle increases the tool life.

Turning	$T = \frac{K}{V^{1/n} f^{1/n1} {a_p}^{1/n2}}$
Drilling	$T = \frac{K_1 D^m}{V^{1/n} f^{1/n1}}$
Peripheral and End-Milling	$T = \frac{K_2 D^m \delta^{1/n3}}{V^{1/n} {f_z}^{1/n1} {a_a}^{1/n3} z^{1/n4}}$
Face Milling	$T = \frac{K_3 D^m}{V^{1/n} {f_z}^{1/n1} {a_a}^{1/n3} z^{1/n4}}$

Figure 2.10 Extended Taylor tool life equations [21, 1]

For the end milling operation, there are some constraints of the empirical constants which are $\frac{1}{n} > 1, \frac{1}{n_1} > \frac{1}{n_3} > \frac{1}{n_2} > \frac{1}{n_4} > 0, 0 < n_4 < 1, m > 0, \frac{1}{n} > \frac{1}{n_1} > 0$ [21]. Taylor tool life and the extended Taylor tool life models give information about how much time the tool can be used without disrupting the machined surface. There are some other subjects that are studied in the literature to learn more about the milling operations. These are summarized in section 2.1.

2.1 Literature Review on Micro Milling Operation Problems

For the future development of the technologies, the miniaturization of the machine components ought to be perceived. The benefits of the miniature components are having smaller footprints, lower power consumption, and high heat transfer. Thus, in order to create these components, micro scale fabrication methods become highly important. The translation of the knowledge for the macro scale machining to the micro scale machining is required. Only scaling down to the micro level cannot be efficient since the micro scale machining have different limitations and challenges. There are several critical issues when shifting from macro scale to the micro scale machining. One of them is that the performance of the end mills is influenced by small vibrations and the excessive forces which affect the tool life and the tolerances of the finish product. Another challenge is the tool-workpiece interactions. The micro scale cutting may not form the chips because of having small depth of cut which causes the elastic deformation of the surfaces that causes the cutting instability. Furthermore, due to small sizes it can be difficult to handle manually and measure them which makes the testing environment difficult. [17]

Micro end milling is the most important micro scale machining process that is widely used in the manufacturing industry. The reason is that it has the capability to create different geometric shapes with good accuracy and surface finish. In the study of Periyanan et al., it is focused on the material removal rates (MRR) of the micro milling processes. MRR is the volume that is machined per unit time and the MRR indicates the processing time, production rate, and the cost. Thus, their aim is to maximize the MRR by considering the spindle speed, feed rate, and the depth of the cut as the cutting parameters. With the study, it is realized that the Taguchi method, a statistical method to improve quality of the products and reduce the variations in the processes, is suitable for this problem and optimal combination for higher MRR is satisfied with medium cutting speed, high feed rate and high depth of cut for the analyzed 3 different parameter levels [22]. The disadvantages of the Taguchi method is that without statistical knowledge, it may not be easy to apply his techniques to real life problems. Furthermore, the use of signal-to-noise ratios to identify the nearly best factor levels to minimize quality losses may not be efficient and most of the discussions about the Taguchi method point that it poses some computational problems [23]. Schmitz et al. explain in their papers that people spend most of their times to predict the outcomes of the experiments before making the experiments. In today's competitive global market, it is highly important to create the first part correctly with the accurate dimensions. Thus, the activities of the manufacturing processes have to be modeled properly. Furthermore, there is a need to identify the appropriate inputs of the model, and understanding the relations between the inputs and the outputs has occurred [24]. Another focused subject in milling processes is the energy consumption while machining the products. Diaz et al.'s study focuses on the energy consumption of the 3-axis milling machine tool during processes. The goal is to assess the accuracy of machine tool energy model to estimate the energy consumption while manufacturing the part with varied material removal rates. It is realized with the experiments that there is an inverse relation between electrical energy consumption while machining the material and MRR [25]. Diaz et al.'s study is analyzing the impact of the process parameter selection on the energy consumption per part manufactured. As a process, the end milling is taken into consideration. The power demand of the machine tool can be divided into two:

- The constant power demand such as computer, fans, and lightening (independent on process parameters)
- The variable power demand (dependent on process parameter selections)

These two power demand effects are studied and the impacts of the feed rate on them can be seen in Figure 2.11 [26]. When the feed rate increases, the processing time is decreasing and it decreases the constant power demand per unit of product; however, when the feed rate increases, the machine demands more power and it causes the increase of the energy consumption per unit of product [26].

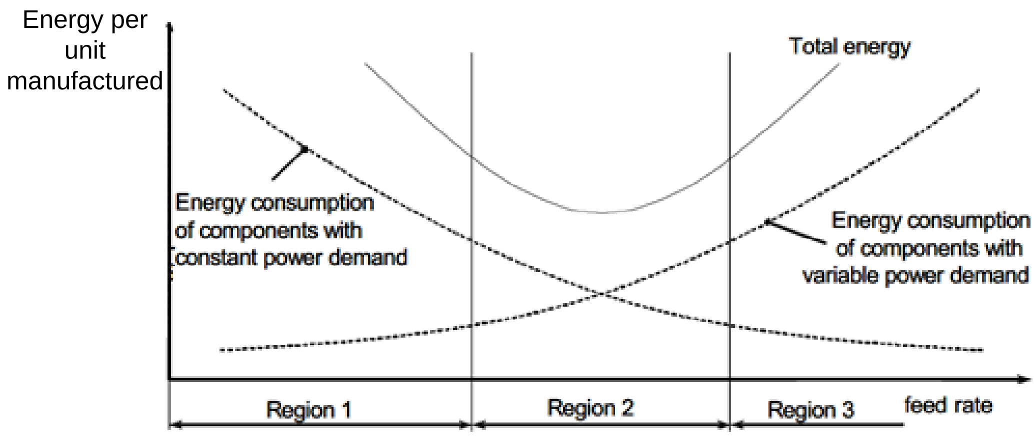


Figure 2.11 Effects of feed rate on energy per unit manufactured [26]

Another study done by Diaz et al. is the impact of feed rate when the feed per tooth is constant. The obtained plot and the parameters used on the experiments can be seen in Figure 2.12. It shows that the energy consumption by the tool per unit product decreases when the feed rate increases. However, the tool wear increases significantly [26].

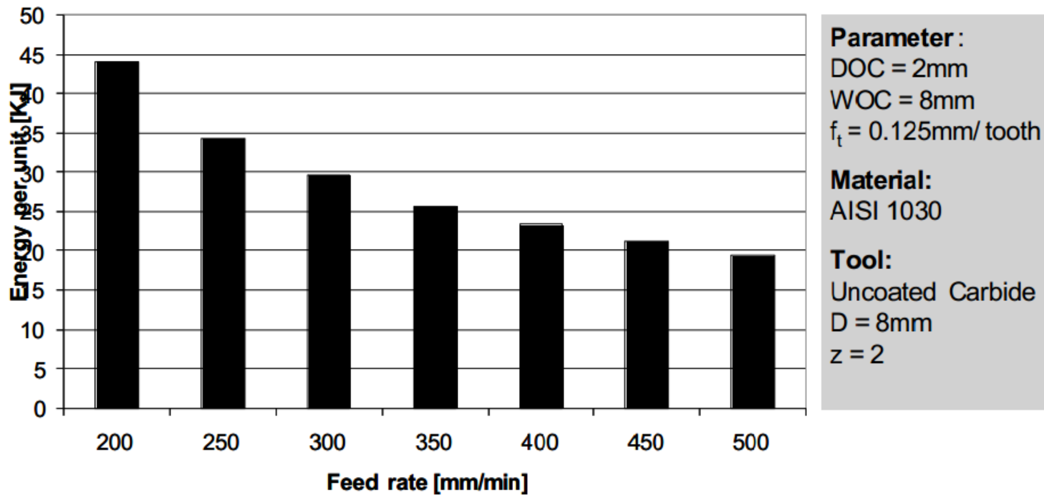


Figure 2.12 Energy per unit manufactured product versus feed rate [26]

Before modeling the pocket machining, the appropriate strategies that can be used to machine the pockets should be defined, which is the other research subject on the literature. While machining the pockets, different tool paths can be created. These path generation strategies affect the total production time and the quality of the surfaces. In the literature, different strategies of pocketing are critiqued and examined to understand the outcomes of these strategies. Some of the examples of the strategies can be seen in Figure 2.13.

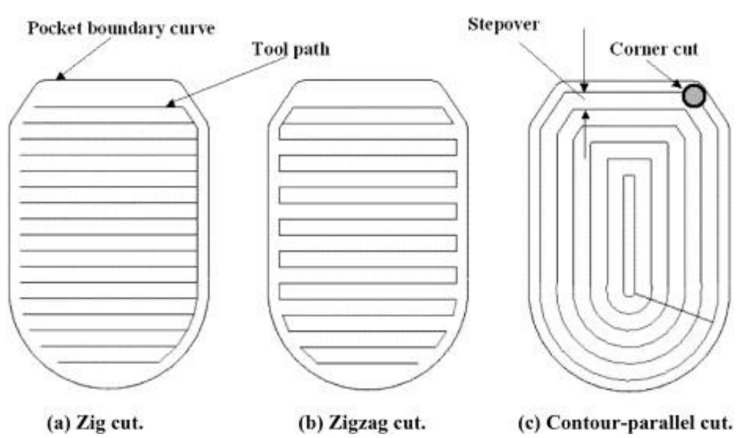


Figure 2.13 Commonly used tool path generation strategies [27]

Choy and Chan discuss different tool path generation strategies. One example is zig path, which is unidirectional. The disadvantage of this method is nonproductive time when going back to the starting position after each cutting path end. The other method is zigzag path. The disadvantage of this method is that the tool changes from up cut to down cut leading to the short life time of the tool and the machine chatter. The last one is the counter-parallel path. The advantage of this method is that most of the time the tool has a contact with the material which decreases the idle time for lifting, positioning and plunging the tool to the material. Furthermore, the cutting strategy is same for all the time, it is either up cut or the down cut method and it is especially preferred for the large scale of material removals [27]. Rad and Bidhendi present that machining parameters have a significant role when performing machining operations; thus, the optimal or the best parameters are the focus of the studies. They explain that with the optimal or the best solutions, the machining efficiencies can be increased [28]. Monreal and Rodriguez study the influence of the tool path length on the cycle time of high speed milling and expressed that the tool path strategy has the significant effect on the cycle time of the production. The aim of their study is to give a methodology to guess cycle time for the zigzag milling processes [29]. Mativenga and Rajemi focus on the minimum energy footprint while calculating the optimum cutting parameters. Most of the studies focus on the cost of the machining; however, with the nowadays demand, the energy expenses become an important issue. Thus, they found that the optimal tool life for the objective minimum energy footprint can be used to constrain the variables and choose the optimal conditions of the machining, this objective can be used to reduce the cost and energy consumption [30].

While creating the mathematical model, after choosing the appropriate tool path generation strategies of the pockets, it is important to define the parameters and the operations of the problem correctly. On the other hand, the aim of the models should be defined in detail and the constraints of the models ought to be discussed carefully so as to create the desired model and obtain the outputs correctly. In the paper of Rad and Bidhendi, the authors focused on the single tool and the multi tool milling operations. It is defined that optimal machining parameters are the concerns of many manufacturing industries. CNC machines can decrease the lead times considerably, but machining times of the CNC machines are the same with the conventional machining if the machining parameters are selected from the booklets and the database of the machines. CNC machines have high capital and machining costs; thus, in order to have the advantages when compared with the conventional machines, it is necessary to find the optimal or the best values of the parameters. The paper focuses on three objectives individually, minimum production cost, minimum production time and maximum profit rate for single tool and the multi tool operations. Depth of cut, feed rate and the cutting speed are considered as a parameter of the model. Depth of the cut is determined before the start of the production by considering the work piece geometry. Thus, the aim is to find the appropriate cutting speed and feed rate combination. The limitations of the problems are maximum power of the machine, surface requirements, and maximum cutting force. The model becomes nonconvex, nonlinear, multi variable and multi constraint model. Thus, as a strategy, the feasible directions are used because of having quickest responses when compared with the other strategies. Starting with the feasible solution and the iterations are done and one attempts to improve the objective function [28]. In the study of Hbaieb et al., the rectangle pocket is taken into consideration. The spiral movement from outside to inside and the roughing process are considered. The methodology to calculate the total time of production is created. Since the radial depth of cut varies during the machining procedure, the roughing time is considered as the ratio of the pocket volume by removed material rate [31].

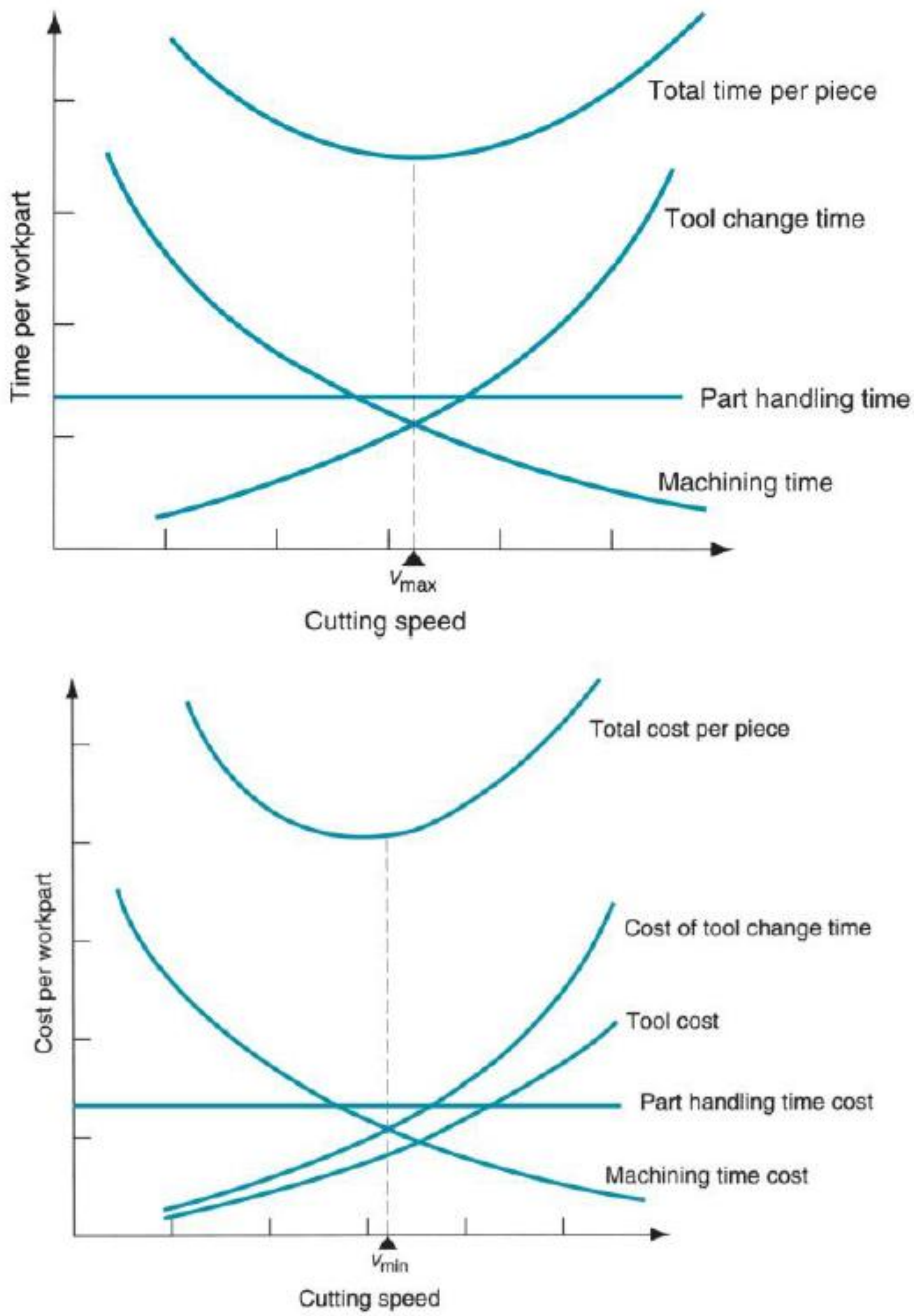


Figure 2.14 Time and cost to produce workpiece [32]

In Groover's book, the changes of the time with respect to the cutting speed are studied (Figure 2.14). The handling time is considered as a constant. It is said that when the tool cuts the material fast, then the machining time decreases which influences the machining time cost but increases the tool cost because of using more tools to machine the same workpiece. The tool change time rises since the need to change the tool increases and it also increases the tool change time cost [32].

In some of the studies in the literature, the zigzag path generation is preferred as a strategy but as Choy and Chan explain in their paper that the counter-parallel tool path generation strategy has more advantages when compared with the other techniques [27]. Thus, in this thesis, the counter-parallel tool path generation is preferred.

There are different objectives that are used in the literature depending on the expectations from the models. Some of the papers focus on the energy consumption of the machines while machining the pockets, others concentrate on MRR, cost of total production and the total production time. The difference of this thesis from the other studies is that the objective function of the problem is minimizing the total production time and if there is one tool diameter size, it is tried to machine the whole pocket with one tool without changing it. Furthermore, when there is more than one variable such as cutting speed and feed per tooth, then the mathematical model becomes nonconvex and with using the heuristic methods the best solution can be found. Thus, in our study, only the cutting speed is taken as a variable and the optimal values of the mathematical models are found. The mathematical models are written based on the proposed tool path length calculation strategies. With the written software module, the optimal cutting speed which minimizes the total production time can be found for single and multi tool cases of single and multi pass problems. In this study, the physical constraints of the micro milling operations are not considered in order to understand the structure of the problems and our aim in this study is to create a basis for more complicated applications of the micro milling. In the literature, there is less information of the micro scale pocket milling operations and the applicability of the given strategies on the papers are also criticized to find better solutions. Thus, our aim is to give an approach to solve the single and multi tool cases for single and multi pass problems.

Chapter 3

Modeling Micro-Scale Milling Operations for Circular, Square, Rectangle and Triangle Pockets

The aim of this chapter is to propose a mathematical model which minimizes the total production time of a given pocket shape and the aim is to machine a whole pocket by using one tool, if possible. In order to calculate the machining time, the tool path generation strategies for the different pockets are defined and by creating the tool path and calculating the tool path lengths, the micro-milling operation models are presented for different shapes of the pockets. The basic shapes of the pockets are taken into consideration in order to obtain detailed information about the tool path generation strategies which will provide a basis for the complicated shapes of pockets. The main objective of the models is to minimize the total production time of the pocket by using single tool. In this chapter, first the mathematical model is given. Then, for the different shapes of pockets the tool path creation strategy is defined and the tool path calculation model is formulated.

3.1 Mathematical Model

The notation of the parameters, their units and their illustrations that are used in the models are as follow:

$D: diameter\ of\ the\ tool\ (mm)$

$D_c: diameter\ of\ the\ circular\ pocket\ (mm)$

$w_s: edge\ length\ of\ the\ square\ pocket\ (mm)$

$w: edge\ length\ of\ the\ equilateral\ triangle\ pocket\ (mm)$

$a: short\ edge\ of\ the\ rectangle\ pocket\ (mm)$

$b: long\ edge\ of\ the\ rectangle\ pocket\ (mm)$

$p: length\ of\ the\ cutter\ (mm)$

$z: number\ of\ the\ tool\ teeth$

$N: spindle\ speed\ (rpm)$

$v: feed\ rate\ (mm/min)$

$V: surface\ speed\ (m/min)$

$V_u: upper\ limit\ of\ the\ surface\ speed\ (m/min)$

$V_l: lower\ limit\ of\ the\ surface\ speed\ (m/min)$

f: $feed\ per\ tooth\ (mm/tooth)$

f_u: $upper\ limit\ of\ the\ feed\ per\ tooth\ (mm/tooth)$

f_l: $lower\ limit\ of\ the\ feed\ per\ tooth\ (mm/tooth)$

d: $total\ axial\ depth\ of\ cut\ (mm)$

a_p: $axial\ depth\ of\ cut\ (mm)$

a_e: $radial\ depth\ of\ cut\ (mm)$

δ: $immersion\ ratio\ \left(\frac{d}{a_e}\right)$

T: $tool\ life\ (min)$

T_m: $actual\ machining\ time\ to\ produce\ one\ pocket\ (min)$

T_{total}: $total\ production\ time\ of\ a\ pocket\ (min)$

T_r: $tool\ replacement\ time\ (min)$

T_h: $material\ handling\ time\ (min)$

n_p: $number\ of\ parts\ produced\ by\ one\ tool\ (min)$

T_a: $idle\ time\ (mm)$

L_{total}: $total\ tool\ path\ length\ of\ one\ pocket\ (mm)$

n: $number\ of\ tours$

n_{mp}: $number\ of\ passes$

In Figure 3.1, the axial depth of cut, radial depth of cut and the length of the cutter are illustrated.

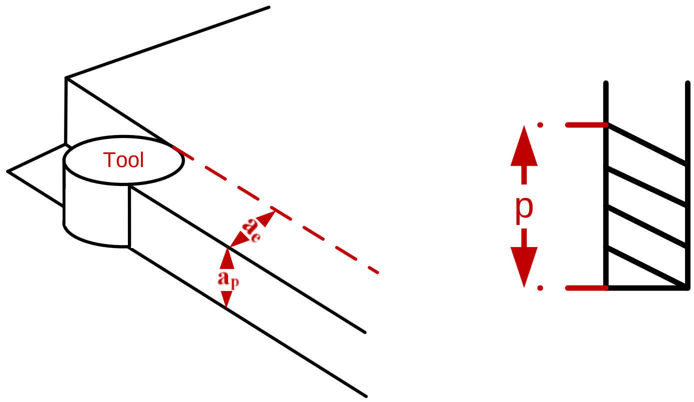


Figure 3.1 Representation of the axial depth of cut and representation of the length of the cutting edge of the tool

3.1.1 Milling Process Problems

There can be different objectives such as minimizing cost, minimizing cutting force, maximizing the profit and maximizing the surface quality. In this study, minimization of production time is considered where cutting speed is used as a variable. In micro milling, since tools are small, the aim is to be able to machine the whole pocket only with one tool. Thus, after finding the optimal cutting speed, whether the whole pocket can be machined with one tool or not must be examined. The flow chart to solve such problems can be seen in Figure 3.2 where T is the tool life, T_m is the actual machining time and T_{tot} is the total production time. The mathematical model is solved and the optimal cutting speed is found. Then, the actual machining time and the tool life are calculated. If the tool life is larger than the actual machining time, then it can be said that the whole pocket can be machined with one tool and the calculated cutting speed is optimal for the problem. Otherwise, a new constraint being the tool life larger than or equal to the actual machining time is added and the mathematical model is solved again. The resulting cutting speed is the best solution for the problem in hand and the total production time can be calculated by using the calculated cutting speed.

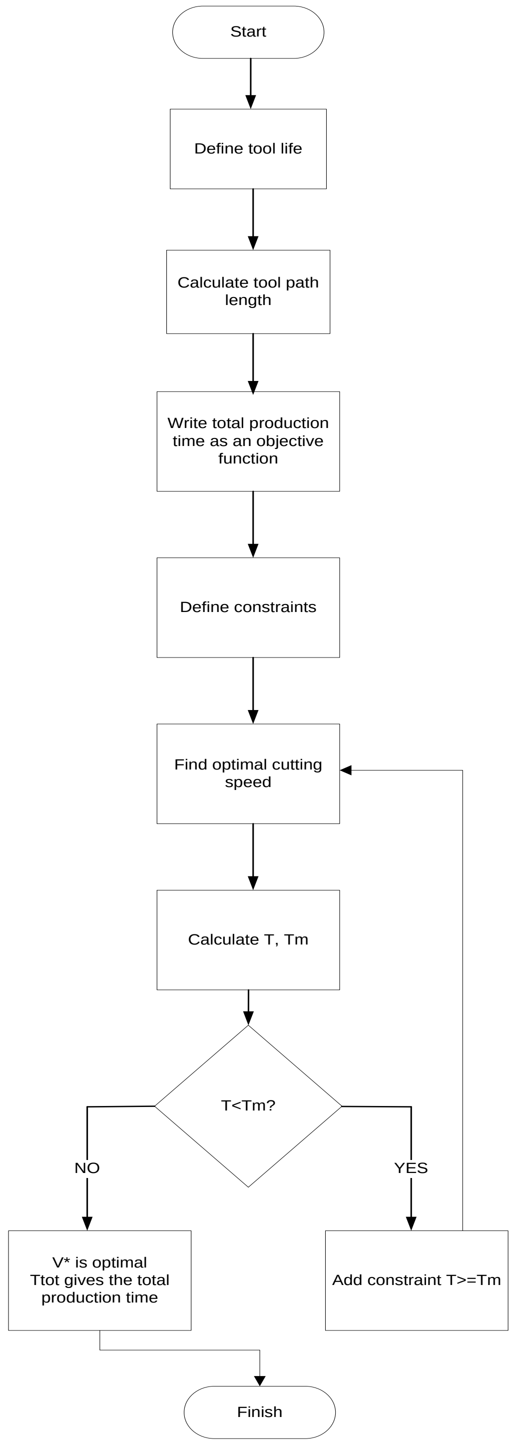


Figure 3.2 Flow chart of single tool problems

The total production time is the summation of the actual machining time, material handling time, idle time and the tool replacement time when producing one pocket. The actual machining time (T_m) to produce a pocket is calculated as the total tool movements when machining the workpiece material, which can be formulized as the tool path length (L_{total}) divided to the feed rate (v) which can be seen in Equation (3.1).

$$\boldsymbol{T_m} = \frac{L_{total}}{v} \tag{3.1}$$

In order to write the feed rate with respect to cutting speed, Equations (3.2) and (3.3) can be used. We are assuming that these equations are valid for the micro scale milling operations; since, in the literature, there is not study that shows the relations of the cutting speed with other parameters properly.

$$\boldsymbol{N} = \frac{1000V}{\pi D} \tag{3.2}$$

$$\boldsymbol{v} = fNz \tag{3.3}$$

Thus, total machining time is rewritten in Equation (3.4).

$$\boldsymbol{T_m} = \frac{L_{total}}{v} = \frac{L_{total}}{fNz} = \frac{L_{total}\pi D}{f(1000)Vz} \tag{3.4}$$

In this section, it is assumed that we have only one tool diameter with constant number of teeth. Thus, all the area of the pocket will be machined with one tool with specified diameter. Only rough milling processes are considered. The tool is assumed to plunge into the work piece material to create the first tour. The spiral movement of the tool from inside to outside is preferred as a strategy. The movement of the tool is assumed to start from pocket center point which is taken as a reference point.

When the tool gets worn or broken, they need to be changed. The available time to use one tool with the given machining parameters can be basically found by using Taylor tool life equation. The tool ought to be changed when it completes its tool life, the tool is replaced with the new tool with the same diameter size; hence the time to change the tool is thought as a constant represented as T_r. In order to find the tool replacement time for one pocket, the tool replacement time is divided into the number of pockets created by one tool (n_p) which can be expressed by tool life divided into the actual machining time of one pocket. Hence, the total time to produce one pocket (T_{total}) is the summation of total machining time and the tool replacement time per pocket which can be seen in Equation (3.5). In Equation (3.6), n_p is replaced with T/T_m and in Equation (3.7), the information at the Equation (3.4) is used and the total production time is rewritten.

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r}{n_p} \tag{3.5}$$

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r}{T/T_m} \tag{3.6}$$

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r.\frac{L_{total}\pi D}{fVz}}{T} \tag{3.7}$$

For producing one pocket, the handling time of the material (T_h) can be considered as a constant value. Then, the total production time can be expressed as (Equation (3.8)):

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r}{n_p} + T_h = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r.\frac{L_{total}\pi D}{f(1000)Vz}}{T} + T_h \tag{3.8}$$

During the optimization, the material handling time can be ignored since it has a constant value.

When cutting speed is the only decision variable and there are no constraints on the problem, the optimal cutting speed can be found by taking the derivative of total production time with respect to the cutting speed (V). Since, according to Weierstrass Theorem, if function f:[a,b]→R on the closed interval is continuous, then the problem f(x)→min a≤x≤b has a point of global minimum. Let x' be the local minimum of the function f. The Fermat theorem implies that f '(x)=0 gives the stationary point. Thus, the found point from the Fermat theorem is the global minimum point. Furthermore, as a corollary, if f:R→R is continuous and coercive meaning that $\lim_{|x|\to\infty} f(x) = +\infty$ for the minimization problem, then the problem f(x)→min, x is an element of R has a point of global minimum.

Let assume that the tool life is equivalent to the Taylor tool life equation with known empirical constants C, n and 0<n<1, C>0. The aim is to understand the impact of the tool life on the optimal cutting speed. Then, the tool life and the total production time can be written as in Equation (3.9) and the simplified version can be seen in Equation (3.10).

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r L_{total}\pi D V^{1/n}}{C^{1/n} f(1000)Vz} + T_h \quad (3.9)$$

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r L_{total}\pi D V^{(\frac{1-n}{n})}}{C^{1/n} f(1000)z} + T_h \quad (3.10)$$

It is known that cutting speed cannot be less than or equal to zero. Furthermore, the objective function is coercive, continuous and differentiable; thus, we can choose sufficiently large M satisfying M>0 and define the closed interval of [1/M, M]. The objective function is continuous on the given closed interval; thus, the found point from the Fermat theorem gives the global minimum point. In Equation (3.11), the first derivative of the objective function is taken and equated to zero.

$$\frac{\boldsymbol{dT_{total}}}{\boldsymbol{dV}} = -\frac{L_{total}\pi D}{f(1000)V^2 z} + \frac{(1-n)}{n} . \frac{T_r L_{total}\pi D V^{\left(\frac{1-2n}{n}\right)}}{C^{1/n}(1000)fz} = 0 \tag{3.11}$$

Hence, the optimal cutting speed can be found as in Equation (3.12).

$$\boldsymbol{V}^* = \left(\frac{nC^{\frac{1}{n}}}{(1-n)T_r}\right)^n \tag{3.12}$$

From Equation 3.12, it can be understood that the optimal cutting speed depends on the empirical constants of the tool life and the tool replacement time. It is realized that when the tool replacement time decreases the optimal cutting speed can be increased.

In milling, tool life equation can be extended to include other process variables as shown in Equation 3.13. C is the empirical constant and α, β, γ, ε are the constants related to axial and radial immersion and feed. The limitations of the constants are that C>0 and α>1, β>0, γ>0 and ε>0.

$$\boldsymbol{T} = \frac{C}{V^{\alpha}(1000.f)^{\beta}(1000.a_p)^{\gamma}(100.a_e/D)^{\varepsilon}} \tag{3.13}$$

The total production time can be written as (3.14) and when the tool life equation is plugged in, the equation can be seen in (3.15).

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{fVz} + \frac{T_r L_{total}\pi D}{TfVz} + T_h \tag{3.14}$$

$$\boldsymbol{T_{total}} = \frac{L_{total}\pi D}{fVz} + \frac{T_r L_{total}\pi D V^{\alpha}(1000.f)^{\beta}(1000.a_p)^{\gamma}(100.a_e/D)^{\varepsilon}}{CfVz} + T_h \tag{3.15}$$

Because of the total production time function is coercive and continuous on [1/M,M] when M is the sufficiently large number which is greater than zero, the optimal cutting speed can be found when the derivative of the total production time is taken which can be seen in Equation (3.16). The optimal cutting speed can be found by using the Equation (3.17).

$$\frac{\boldsymbol{dT_{total}}}{\boldsymbol{dV}} = -\frac{L_{total}\pi D}{fV^2 z} + (\alpha - 1)\frac{T_r L_{total}\pi D V^{\alpha-2}(1000.f)^{\beta}(1000.a_p)^{\gamma}(100.a_e/D)^{\varepsilon}}{Cfz} = 0 \tag{3.16}$$

$$\boldsymbol{V}^{*} = \left(\frac{C}{(\alpha-1)T_r(1000.f)^{\beta}(1000.a_p)^{\gamma}(100.a_e/D)^{\varepsilon}}\right)^{1/\alpha} \tag{3.17}$$

Again, the optimal cutting speed depends on the tool change time, feed per tooth, axial and radial depth of cut but it does not depend on the total tool path length. However, the tool path length affects the total production time and at the same time the cost of the production and the total tool path length is influenced from the preferred strategy to machine the whole pocket depending on the limitations of the machines, the features of the tools and the workpiece. In the following section, the strategies to calculate the total tool path length are described and the mathematical model for the single tool and the single pass problem is defined.

3.1.2 Single-Tool Single-Pass Problem: Derivation of Objective Function, Constraints and Limitations

The aim of the single tool single pass problem is to minimize the total production time of the pocket by using single tool diameter size and cutting the total depth of cut in one pass. Thus, the total time to produce one pocket can be calculated as the summation of the actual machining time of one pocket, the tool replacement time per a pocket and the tool handling time which was defined in Equation (3.8).

The tool life equation given in (3.18) represents the influence of milling parameters on tool life. These parameters of the Taylor tool life are found by the experiments; which is valid for one of the applications of the milling operation. However, for different cases of it, the tool life parameters ought to be calculated.

$$\boldsymbol{T} = \frac{1.0146.10^{5}}{V^{1.3417}(f.1000)^{0.4653}(a_p.1000)^{0.1491}(100.a_e/D)^{0.7017}} \qquad (3.18)$$

The objective function can be rewritten by using the given equation of the tool life equation which can be written as follow (Equation (3.19)):

$$\boldsymbol{T_{tot}} = \frac{L_{total}\pi D}{f(1000)Vz} + \frac{T_r V^{1.3417}(f/1000)^{0.4653}(a_{p/1000})^{0.1491}(100.a_e/D)^{0.7017}}{1.0146.10^5} . \frac{L_{total}\pi D}{f(1000)Vz} \tag{3.19}$$

The limitations and the constraints of the problem are summarized in Equations (3.20), (3.21), (2.32). The first inequality (3.20) represents that the axial depth of cut should be less than or equal to the length of the cutter. The second (3.14) and the third inequalities (3.15) are to represent the limitations of the machine.

$$a_p \leq p \tag{3.20}$$

$$V_l \leq V \leq V_u \tag{3.21}$$

$$f_l \leq f \leq f_u \tag{3.22}$$

3.1.3 Single-Tool Multi-Pass Problem: Derivation of Objective Function, Limitations and Constraints

There can be some cases where the tool cannot finish machining the pocket with one pass since the depth of the pocket is larger than the maximum allowable depth of cut of the tool. Therefore, in order to satisfy the total depth of cut, the tool machines the pocket with more than one pass. In the first pass, the tool creates the pocket's shape with axial depth of cut less than the total axial depth of cut. This process is repeated until reaching the total axial depth of cut. It is assumed that the axial depth of cut of each pass is the same and the number of passes (n_{mp}) is integer. Assumptions of the single-tool single-pass problem are also valid in this problem. With these assumptions, the number of the passes can be written as in Equation (3.23):

$$\boldsymbol{n_{mp}} = d/a_p \tag{3.23}$$

n_{mp}, d, a_p represent the total number of the passes, total axial depth of cut of the pocket and the axial depth of cut of the pass respectively.

Single-tool single-pass problem formulation is modified by considering the details of the multi-pass problem. The total production time for the single-tool multi-pass problem is modified from the Equation (3.19). Thus, it is the summation of the actual machining time, tool replacement time, material handling time and the tool idle time when moving to the center of the pocket after finishing the pass. In Equation (3.25), Equation (3.24) is rewritten by using the Equality (3.4).

$$\boldsymbol{T_{tot}} = T_m . n_{mp} + \frac{T_r T_m}{T} . n_{mp} + T_h + T_a \tag{3.24}$$

$$\boldsymbol{T_{tot}} = \frac{L_{total} \pi D}{f 1000 Vz} . n_{mp} + \frac{T_r}{T} . \frac{L_{total} \pi D}{f 1000 Vz} . n_{mp} + T_h + T_a \tag{3.25}$$

The addition to the single tool single pass problem is that the tool moves to the center of the pocket after finishing to machine the pass which equals to the T_a. It is assumed that at the last pass, the tool does not move on the center of the pocket. Furthermore, T_m represents the actual machining time of the one pass; thus, it is multiplied with the number of the passes.

An additional constraint and limitation of the problem can be seen in (3.26).

$$n_{mp} \text{ is an integer number} \tag{3.26}$$

In order to calculate the total production time, it is necessary to calculate the total tool path length of the pockets. For each pocket type, the strategies to machine the pockets are defined in detail and the total tool path length will be calculated.

3.1.4 Tool Path Length Calculation for Circular Pockets

The circular pockets can have different radius values, by changing the radius of the pocket, the size of the circular pocket gets smaller or larger. Thus, the model depends on the radius value of the circle. The word "tour" represents that the tool goes outward and moves with the same shape of the pockets until it creates the actual pocket. Thus, the first tour of the model starts from the center of the circle. The tool moves Dδ amount outward and creates a circle which is shown on the Figure 3.3. The tool path length of the first tour equals to $D\delta + 2\pi D\delta$ where the tool first goes outward Dδ amount and then creates a circle with the radius of Dδ.

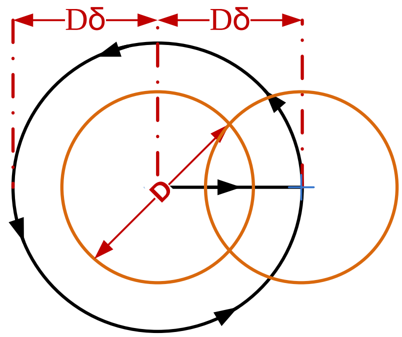


Figure 3.3 Representation of the first tour of the circular pocket

The second tour is also created by going outward by an amount Dδ and then creating the circle. Thus, the path of the second tour can be seen in Figure 3.4. The tool path length of the second tour becomes $D\delta + 2\pi(2D\delta)$. Hence, the covered area is $\pi\left(2D\delta + \frac{D}{2}\right)^2$.

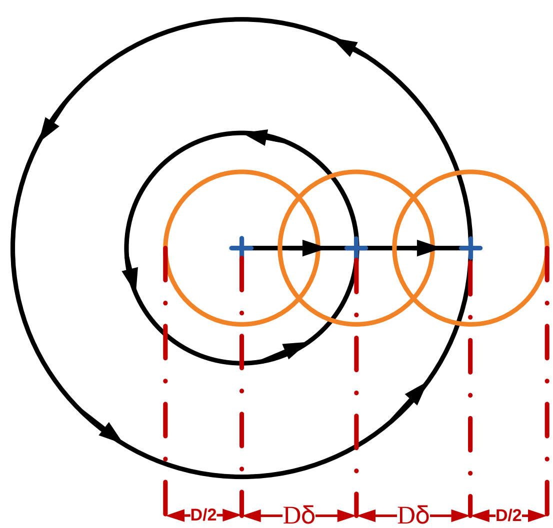


Figure 3.4 Representation of the second tour of the circular pocket

Until creating the required circular pocket diameter, the tool continues to create tours. If the last tour cannot be created with the immersion ratio δ, the last tour is created with less than the immersion ratio δ. The number of necessary tours of the circular pocket can be written as in Equation (3.27). In each tour, the tool moves Dδ amount and the total length to be moved outward is $\left(\frac{D_c}{2} - \frac{D}{2}\right)$.

$$\boldsymbol{n} = \left(\frac{D_c}{2} - \frac{D}{2}\right) . \frac{1}{D\delta} \tag{3.27}$$

Hence, the generalized form of the tool path length can be written as in Equation (3.28).

$$\boldsymbol{L_{total}} = \lfloor n \rfloor D\delta + \sum_{i=1}^{\lfloor n \rfloor} 2.\pi(iD\delta) + (n - \lfloor n \rfloor)D\delta + \pi(D_c - D)(\lceil n \rceil - \lfloor n \rfloor) \tag{3.28}$$

In each tour, the tool moves Dδ amount outward from the center of the circle. $\lfloor nD\delta \rfloor$ shows the total outward move length of the tool. The circular movements of the tool can be calculated as $\sum_{i=1}^{\lfloor n \rfloor} 2.\pi(iD\delta)$. n can be the decimal number, then the tour number $(\lfloor n \rfloor + 1)$ will be created with less than δ immersion ratio which can be calculated as $\pi(D_c - D)$+$(n - \lfloor n \rfloor)D\delta$. The term $(n - \lfloor n \rfloor)D\delta$ shows the last tours' outward move amount. The specific limitation of the circular pocket is that it is assumed that the first tour can be created; thus, the additional inequality that will be added to the model is shown in (3.29).

$$2D\delta + D \leq D_c \tag{3.29}$$

For the multiple pass of circular pocket operations, the total idle time spent to move to the center of the can be expressed as in Equations (3.30) and (3.31).

$$\boldsymbol{T_a} = (n_{mp} - 1)\left(\frac{D_c}{2} - \frac{D}{2}\right)\frac{1}{v} \tag{3.30}$$

$$\boldsymbol{T_a} = (n_{mp} - 1)\left(\frac{D_c}{2} - \frac{D}{2}\right)\frac{\pi D}{f1000Vz} \tag{3.31}$$

The tool moves $\left(\frac{D_c}{2} - \frac{D}{2}\right)$ amount to come to the center of the pocket. The tool does not move to the center after machining the last pass; thus, the total moves to the center equals to $(n_{mp} - 1)$.

3.1.5 Tool Path Length Calculation for Square Pockets

The property of the square pocket is that all the edges are the same and the total axial depth of the pocket is fixed at all the bottom surface.

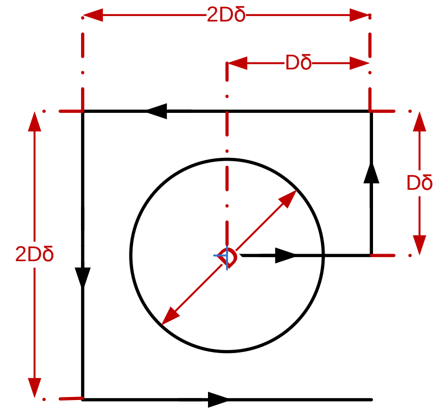


Figure 3.5 Representation of the first tour of the square pocket

First of all, the tool starts to machine from the center of the square pocket and it goes outward from the center of the pocket and the tool creates a square with the edge length $2D\delta$ (Figure 3.5); thus, the tool path length for the first tour equals to $8D\delta$. The created pocket area is $(D + 2D\delta)^2$, because in each edge the half of the diameter will go outside of the tool path. The second tour of the tool can be shown in Figure 3.6. The second tour tool path length is $(16D\delta)$. The area of the pocket becomes $(4D\delta + D)^2$.

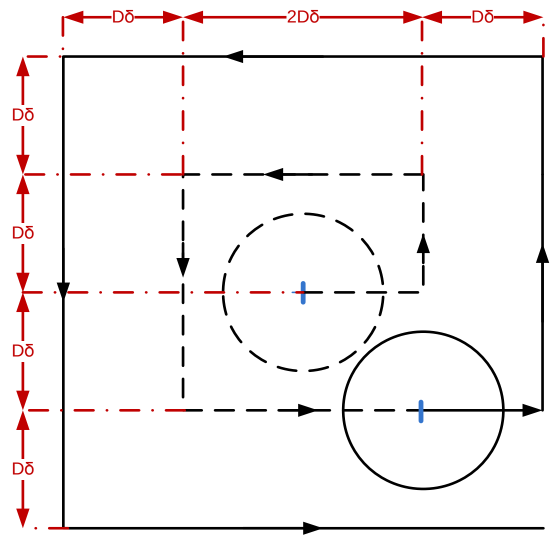


Figure 3.6 Representation of the second tour of the square pocket

Thus, when the tool path length calculation is generalized, the total path length and the number of tours can be written as in Equation (3.32) and Equation (3.33). In equation (3.33), $(w_s - D)$ represents the total outward movement length of the tool center and the total number of passes can be calculated as the total length of the outward moves $(w_s - D)$ divided into the outward movements of the tool in each pass which equals to $2D\delta$. The number of passes can take decimal values, then it is rounded down which shows how many tours can be created with the immersion ratio δ. If there is a decimal part, $(\lceil n \rceil - \lfloor n \rfloor)$ part becomes one, otherwise it equals to zero and the tool path length of the last tour when it is decimal number equals to $4(w_s - D)$. In the first tour, the tool center moves $2D\delta$ in each edge. In the second tour, at one edge the tool moves $4D\delta$ and in the third tour, the movement at one edge increases into $6D\delta$ and it maintains to increases with $(2)D\delta$ at each tour, i represents the tool number, it changes from 1 to $\lfloor n \rfloor$. Thus, the total tool path length can be calculated as in the Equation (3.32).

$$\boldsymbol{L_{total}} = \sum_{i=1}^{\lfloor n \rfloor} 4(2i)D\delta + (\lceil n \rceil - \lfloor n \rfloor)4.(w_s - D) \tag{3.32}$$

$$\boldsymbol{n} = (w_s - D).\frac{1}{2D\delta} \tag{3.33}$$

The specific limitation of the square pocket is that as an assumption the first tour can be created. Hence, the additional inequality to model is given in (3.34).

$$2D\delta + D \leq w_s \tag{3.34}$$

For the multiple pass, the total idle time to move to the center of the square can be expressed as in Equation (3.35). The moves of the tool from the corner of the square to the center of the square pocket can be calculated as $\left(\frac{w_s\sqrt{2}}{2}\right) - \left(\frac{D}{2}\right)\sqrt{2}$.

$$\boldsymbol{T_a} = \left[\left(\frac{w_s\sqrt{2}}{2}\right) - \left(\frac{D}{2}\right)\sqrt{2}\right]\left(n_{mp} - 1\right).\frac{\pi D}{f1000Vz} \tag{3.35}$$

The tool movement for each pass is $\left(\frac{w_s\sqrt{2}}{2}\right) - \left(\frac{D}{2}\right)\sqrt{2}$ amount. The term $\left(\frac{w_s\sqrt{2}}{2}\right)$ equals to the half length of the diagonal and $\left(\frac{D}{2}\right)\sqrt{2}$ is the diagonal distance of the tool center from the corner of the pocket. At last pass, the tool does not move to the center of the pocket which is presented with $\left(n_{mp} - 1\right)$ and it is multiplied with the total tool path length at each pass and divided into feed rate which gives the total time idle time when moving to the center of the pocket.

3.1.6 Tool Path Length Calculation for Rectangle Pockets

While machining the rectangle pocket, the tool moves outward diagonally and creates a rectangle pocket. The representation of the rectangle pocket can be seen in Figure 3.7. The tool starts to machine the pocket from the center of the pocket and moves Dδ amount outward in each tour. The total diagonal moves of the tool center equals to $\sqrt{(a^2+b^2)} - D.\sec\theta$. Thus, the number of tours can be calculated as shown in the Equation (3.36).

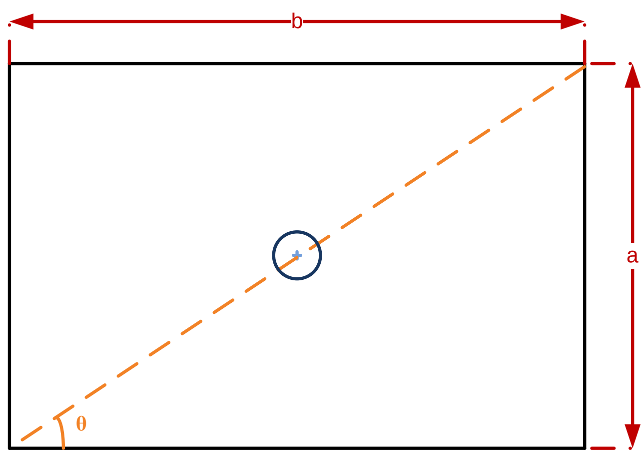


Figure 3.7 Representation of the rectangle pocket

$$\boldsymbol{n} = \frac{\left(\sqrt{(a^2+b^2)} - D.\sec\theta\right)}{2D\delta} \tag{3.36}$$

The first tour of the tool can be seen in Figure 3.8. The tool path length of the first tour is $4D\delta(\sin\theta + \cos\theta) + D\delta$.

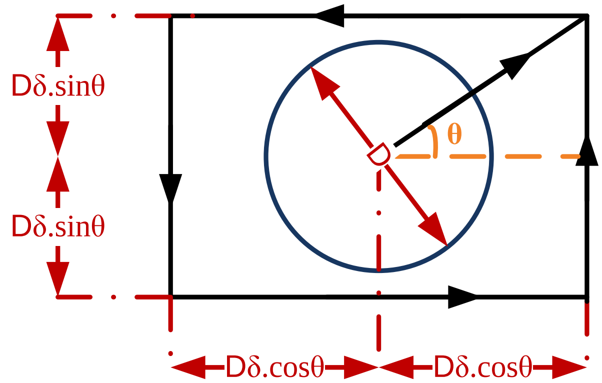


Figure 3.8 Representation of the first tour of the rectangle pocket

In the second tour, the tool goes outward Dδ amount and creates the rectangle which is represented in Figure 3.9. The tool path length of second tour is $8D\delta(\sin\theta + \cos\theta) + D\delta$.

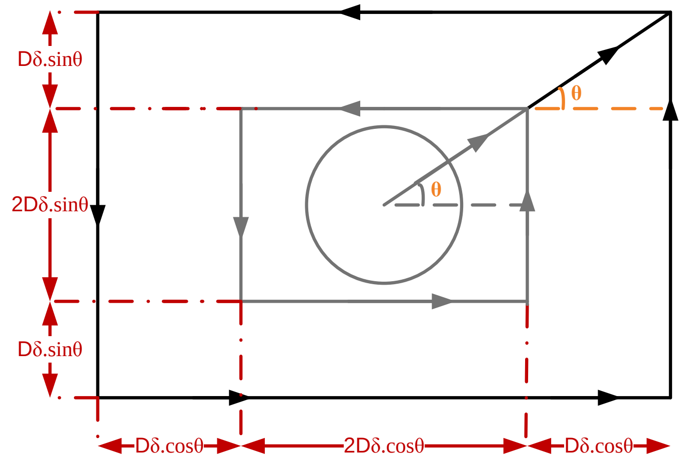


Figure 3.9 Representation of the second tour of the rectangle pocket

Thus, the generalized form of the total tool path length can be written as shown in Equation (3.37). If the number of tour takes decimal values, the last the tour is not machined with the immersion ratio δ. The last tour's tool path length when the number of tour is decimal can be calculated as $(n - \lfloor n \rfloor)D\delta + 2(a - D) + 2(b - D)$. The part $(n - \lfloor n \rfloor)D\delta$ is the outward movement length of the tool and $2(a - D) + 2(b - D)$ represents the rectangle movement of the tool.

$$\boldsymbol{L_{total}} = \lfloor n \rfloor D\delta + \sum_{i=1}^{\lfloor n \rfloor} 4iD\delta(\sin\theta + \cos\theta) + (\lceil n \rceil - \lfloor n \rfloor)((n - \lfloor n \rfloor)D\delta + 2(a - D) + 2(b - D)) \quad (3.37)$$

The specific constraints and the limitations of the rectangle pocket are summarized in (3.38) and (3.39). The two inequalities are added so that the assumption of machining the first tour can be satisfied.

$$2D\delta \sin\theta + D \leq a \tag{3.38}$$

$$2D\delta\ cos\,\theta + D \leq b \tag{3.39}$$

For the multiple pass problem, the total moves to the center of the rectangle is $\sqrt{\left(\frac{a}{2}-\frac{D}{2}\right)^2+\left(\frac{b}{2}-\frac{D}{2}\right)^2}$ amount so that the idle time to move to the center of the rectangle can be seen in Equation (3.40). As an assumption, the tool does not move to the center of the pocket when the last tour is finished.

$$\boldsymbol{T_a} = \left[\sqrt{\left(\frac{a}{2}-\frac{D}{2}\right)^2+\left(\frac{b}{2}-\frac{D}{2}\right)^2}\right]\left(n_{mp}-1\right).\frac{\pi D}{f1000Vz} \tag{3.40}$$

3.1.7 Tool Path Length Calculation for Equilateral Triangle Pockets

As an assumption, the corner radius of the pocket equals to the radius of the tool. Therefore, all the area of the pocket can be machined with only one tool diameter size. It is assumed that the tool starts from the center of the gravity point of the triangle and it goes outward with the given immersion amount. The tool radius is less or equal to one third of the height of the pocket. The pocket will be created with circular corners which can be seen in Figure 3.10.

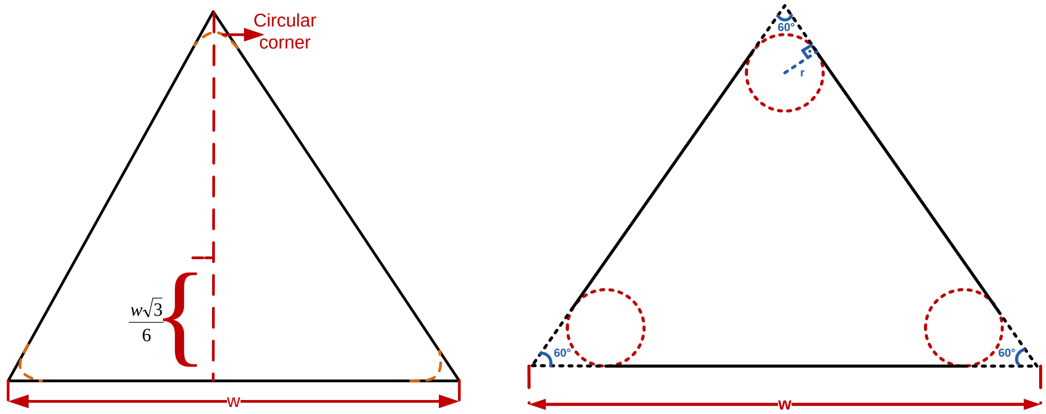


Figure 3.10 Representation of the equilateral triangle pocket with circular corners

In order to create the first tour, the tool starts from the center point of the triangular pocket which is shown on the Figure 3.11 as a point A and goes upward to the point B and then it creates the triangle. Therefore, the first tour's path length is $D\delta + 6D\delta\sqrt{3}/2$. The first tour's height is considered as low as possible in order to minimize the part that is not machined. The second tour will start from the point B and it goes upward about $2D\delta$. Then, the larger triangle path is created with the edge length $3\sqrt{3}D\delta$ (Figure 3.12). Thus, the tool path length of the second tour is $2D\delta + \frac{6D\delta 3\sqrt{3}}{2}$.

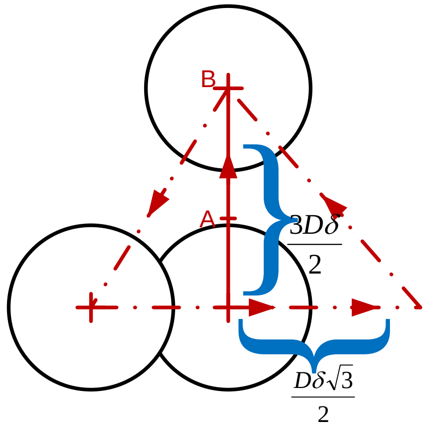


Figure 3.11 First tour of the tool for the triangular pocket

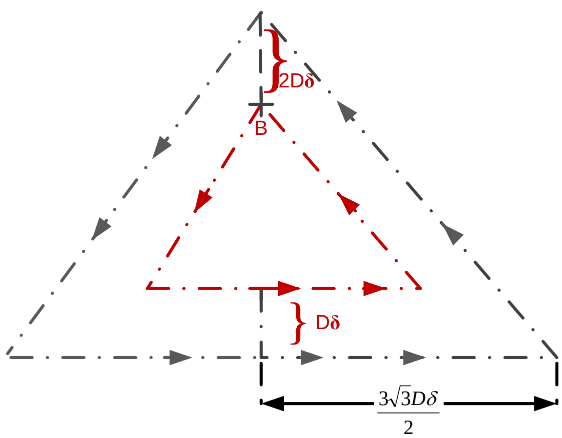


Figure 3.12 Second tour of the tool for the triangular pocket

Until creating the triangle pocket with the edge length w, the tool creates the tours by going outward. The number of tours (n) after creating the triangular path with the edge length $D\delta\sqrt{3}$ (identified as first tour) can be calculated as shown in Equation (3.41). The tool moves $\left(\frac{w\sqrt{3}}{6} - \frac{D}{2} - \frac{D\delta}{2}\right)$ amount from the reference point of the triangle. $\left(\frac{w\sqrt{3}}{6}\right)$ is the one third of the height. The first tour and the half size of the tool because of taking the tool center as a reference point are extracted from the height in order to find the number of tours.

$$\boldsymbol{n} = \left(\frac{w\sqrt{3}}{6} - \frac{D}{2} - \frac{D\delta}{2}\right) . \frac{1}{D\delta} \tag{3.41}$$

The number of the tours of the pocket can be a decimal number; thus, the last tour is created with less than given radial immersion ratio (δ). Hence, the generalized form of the tool path length of the triangle with the edge length w can be written as Equation (3.42). $D\delta + 3D\delta\sqrt{3}$ represents the tool path length of the first tour. Then, the number of passes are calculated and the length that the tool goes outward equals to $\lfloor n \rfloor 2D\delta$. If n is the decimal number, the last tour tour's tool path length can be calculated as $2D\delta(n - \lfloor n \rfloor) + 3\left(w - D\sqrt{3}\right)(\lceil n \rceil - \lfloor n \rfloor)$.

$$\boldsymbol{L_{total}} = D\delta + 3D\delta\sqrt{3} + \lfloor n \rfloor 2D\delta + \sum_{i=1}^{\lfloor n \rfloor}(2i + 1)3\sqrt{3}D\delta + 2D\delta(n - \lfloor n \rfloor) + 3\left(w - D\sqrt{3}\right)(\lceil n \rceil - \lfloor n \rfloor) \tag{3.42}$$

The specific limitation of the problem is expressed in inequality (3.43). The inequality is for the assumption of creating the first tour tool path length.

$$\frac{3D\delta}{2} + \frac{3D}{2} \leq \frac{w\sqrt{3}}{2} \tag{3.43}$$

There are cases that the tool cannot cut the material in one pass. Some of the reasons can be the limit of the torque and force limit of the tool, tool geometry. Therefore, in order to satisfy the given depth of cut of the pocket, there ought to be multiple passes. When moving to the other pass, the tool moves to the center of the pocket which can be calculated as in Equation (3.44). It is assumed that the tool does not move to the center of the triangle after machining the last past.

$$\boldsymbol{T_a} = \left[\frac{w\sqrt{3}}{3} - D\right](n-1).\frac{1}{v} \tag{3.44}$$

In the following section, the total machining time estimation algorithm of the single tool single pass problem is compared with the commercial Cimatron software in order to validate the analytical tool path calculation model.

3.1.8 Comparison of Analytical Model Outputs with the Cimatron Software

The Cimatron program is similar to the CAM programs which helps to create tool paths and calculate total machining time when the parameters are given by the user. However, how the Cimatron program creates the tool paths is not known since the algorithm and the equations that used in the program are not accessible.

To compare the Cimatron software calculations and the proposed total machining time algorithm, the edge length of the equilateral triangle is taken as 23 mm, diameter of the tool is considered as 3 mm. The spindle speed, cutting speed, feed rate, axial depth of the cut and the immersion ratio are taken as a parameter. The results of the Cimatron and the written software algorithm are compared. The input parameters and the results can be seen in Table 1. A total of 40 experiment runs were made.

Table 1. Experiment results

Experiment number	D (mm)	N (rpm)	V (m/min)	v (mm/min)	ap (mm)	δ	Cimatron (sec.)	Model (sec)	Difference (%)
1	3	6,366	60	150	3	0.5	56	54	4
2	3	6,897	65	100	3	0.5	84	80	4
3	3	7,427	70	120	3	0.5	70	67	4
4	3	5,305	50	110	3	0.5	77	73	5
5	3	5,623	53	140	3	0.5	60	57	4
6	3	5,835	55	200	3	0.5	42	40	4
7	3	7,639	72	130	3	0.5	65	62	5
8	3	6,684	63	115	3	0.5	73	70	4
9	3	8,488	80	124	3	0.5	68	65	5
10	3	4,244	40	127	3	0.5	66	63	4
11	3	4,774	45	150	3	0.5	56	54	4
12	3	5,517	52	160	3	0.5	53	50	5
13	3	6,685	63	122	3	0.5	69	66	5
14	3	5,836	55	140	3	0.5	60	57	4
15	3	6,366	60	160	3	0.5	53	50	5
16	3	4,775	45	111	3	0.5	76	72	5
17	3	5,517	52	145	3	0.5	58	55	5
18	3	5,836	55	140	3	0.5	60	57	4
19	3	6,154	58	120	3	0.5	70	67	4
20	3	6,366	60	110	3	0.5	77	73	5
21	3	6,366	60	130	3	0.5	65	62	5
22	3	5,836	55	100	3	0.5	84	80	4
23	3	5,305	50	100	3	0.5	84	80	4
24	3	5,623	53	142	3	0.5	59	57	4
25	3	6,578	62	155	3	0.5	54	52	4
26	3	5,305	50	140	3	0.7	51	46	10
27	3	5,623	53	135	3	0.3	85	79	7
28	3	7,639	72	157	3	0.75	54	42	22
29	3	6,685	63	165	3	0.3	70	65	7
30	3	6,048	57	143	3	0.8	55	48	13
31	3	5,093	48	130	3	0.3	88	82	6
32	3	5,411	51	111	3	0.2	137	142	4
33	3	6,366	60	146	3	0.4	65	67	3
34	3	6,048	57	150	3	0.2	102	105	3
35	3	4,669	44	163	3	0.8	48	42	13
36	3	3,501	33	122	3	0.7	59	53	11
37	3	4,244	40	120	3	0.2	127	131	3
38	3	6,366	60	105	3	0.4	90	93	4
39	3	5,305	50	130	3	0.3	88	82	6
40	3	7,003	66	140	3	0.7	51	46	10
							Average % difference		**6**

In Cimatron program, the spindle speed and the feed value are taken as an input and the actual machining time is calculated. The data obtained with the experiments (Table 1) are shown on Figure 3.13.

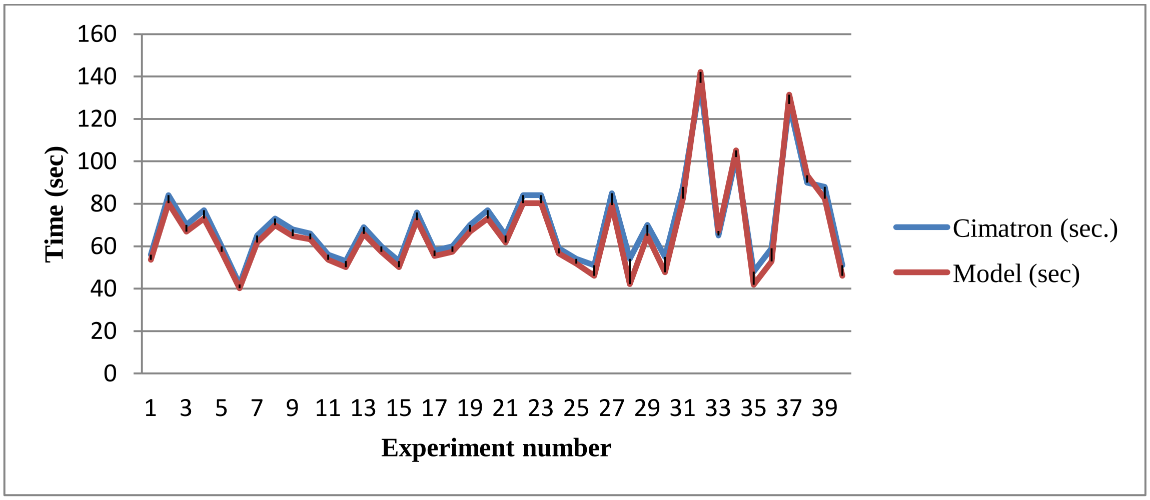


Figure 3.13 Comparing Cimatron results and the developed algorithm

It can be said that the written algorithm to find the total machining time is similar to the program Cimatron. The reasons of differences might be because of the differences on the generation of first tour between Cimatron software and our algorithm. When the immersion ratio becomes 0.7 or more, the tool creates tours with different shape which is like a star as shown in Figure 3.14 and Figure 3.15, which was not considered in our study. However, the difference is about 10%, which is assumed to be acceptable. For the immersion ratio of 0.5, the created tool path is similar to our propose strategy which can be seen in Figure 3.16, the similar path is created for the immersion ratio 0.6. Thus, the model to find the production time of the triangle pocket is cost effective when compared with the cost of the software Cimatron and efficient to be used.

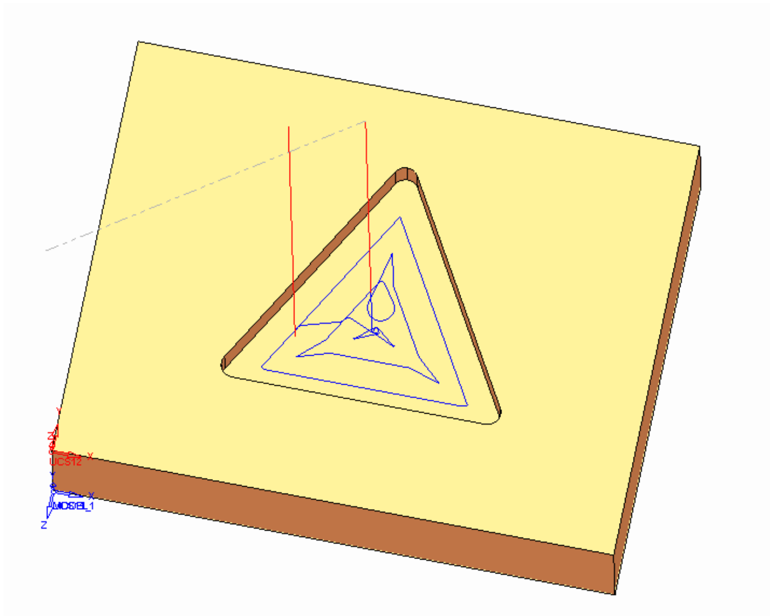


Figure 3.14 Tool path of the experiment number 28 having the immersion ratio 0.75

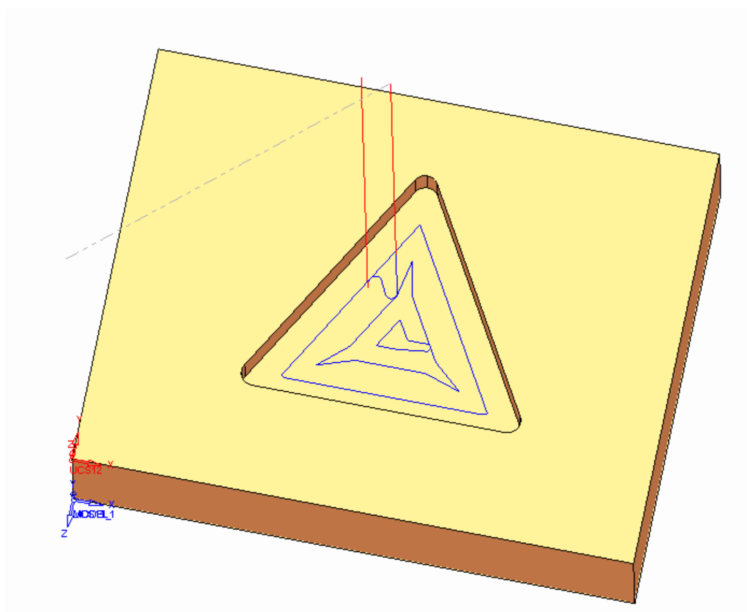


Figure 3.15 Experiment number 30 having the immersion ratio 0.8

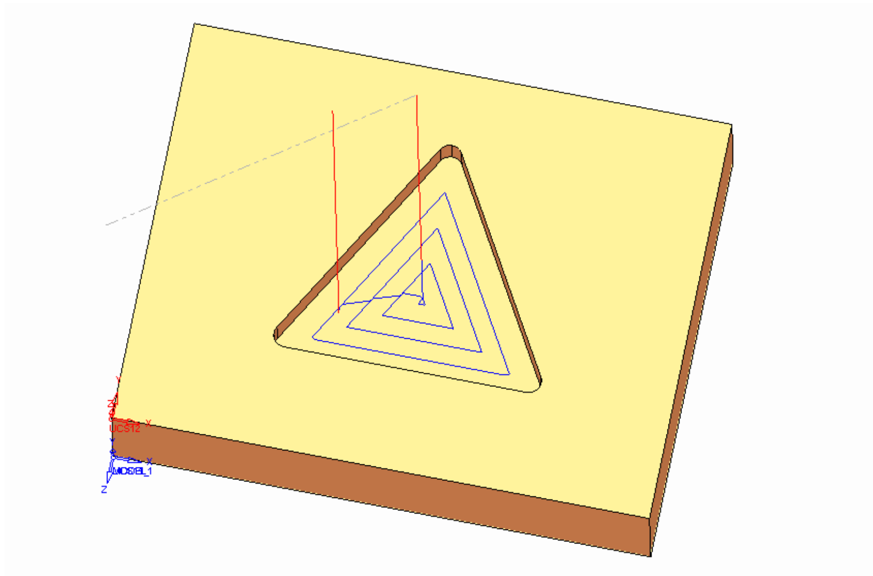


Figure 3.16 Experiment number 1's tool path having immersion ratio 0.5

3.2 Single-Tool Single-Pass Problem for the Combination of Different Shapes of Pockets

As an example study, the pocket shape given in Figure 3.17 is studied. At the given shape, there are 1 square and 2 circular pockets. It is assumed that only one tool with the diameter 1 mm is used. The immersion ratio is taken as 0.7. As an assumption, the tool machines one of the basic pocket and then moves to the other shape rapidly to machine the new shape. As a strategy, first the square pocket is machined. Then, one of the circular pocket is machined and finally the tool machines the other circular pocket. The input parameters of the problem and their values are summarized on the Table 2.

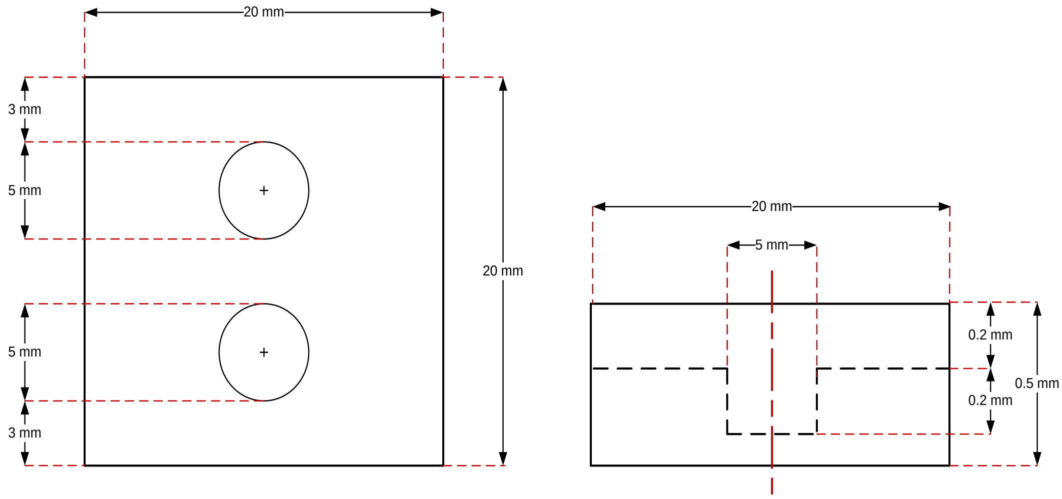


Figure 3.17 Example of combinations of shapes pocket top view and front view

Table 2. Parameter values for production of combination of different shape of pockets

Parameters	Value	Unit
z	2	
D	1	mm
sigma	0.7	
f	0.0175	mm/tooth
Tr	5	min
ap	0.2	mm
ae	0.5	mm
w_s	20	mm
V	20-200	m/min

The objective function of the mathematical model is the minimization of the total production time. For each pocket shape, the total production time can be calculated as given in the Equation (3.45).

$$\mathbf{T_{tot}} = \frac{\mathrm{L_{total}}\pi \mathrm{D}}{\mathrm{f(1000)Vz}} + \frac{\mathrm{T_r V^{1.3417}(f.1000)^{0.4653}(a_p.1000)^{0.1491}(100.a_e/D)^{0.7017}}}{1.0146.10^5} . \frac{\mathrm{L_{total}}\pi \mathrm{D}}{\mathrm{f(1000)Vz}} \qquad (3.45)$$

First, the square pocket is machined, it is checked whether the first tour can be created (Equation (3.34)). The number of tours of the square pocket calculated as **13.57** as shown in (3.46).

$$\mathbf{n} = \left(\frac{\mathrm{w_s}}{2} - \frac{\mathrm{D}}{2}\right) . \frac{1}{\mathrm{D}\delta} = \left(10 - \frac{1}{2}\right) . \frac{1}{0.7} = 13.57 \qquad (3.46)$$

Thus, total tool path length for the square pocket becomes **585.6 mm**. The cutting speed constraint of the problem is $20 \leq \mathrm{V} \leq 200$. The form of the tool life equation is same as the tool life used in milling process problem calculation; thus, the optimal cutting speed can be calculated as **80.57 m/min**. The total production time of the square pocket becomes **2.56 min.** The other shape contained in the pocket is the circular pocket. It is checked that the parameters satisfy the inequality (3.29). The number of tours can be calculated as in Equation (3.47). Thus, the total tool path length for one circle can be calculated as **27.76 mm**.

$$\boldsymbol{n} = \left(\frac{D_c}{2} - \frac{D}{2}\right) . \frac{1}{D\delta} = \frac{\left(\frac{5}{2} - \frac{1}{2}\right)}{0.7} = \mathbf{2.857} \qquad (3.47)$$

Thus, the optimal solution of the cutting speed is same as the optimal value of the square pocket which is **80.57 m/min**. The reason of being equal is that the optimal cutting speed does not depend on the tool path length. The total production time for one circular pocket is **0.12 min.** The total production time for the given combined shape of the pocket becomes **2.8 min**.

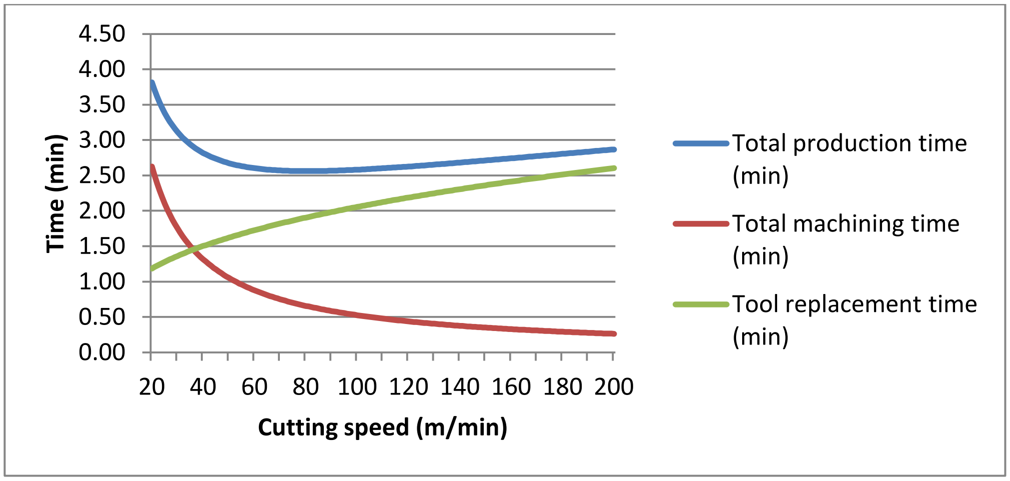


Figure 3.18 Impact of changes of cutting speed on the production time of square pocket

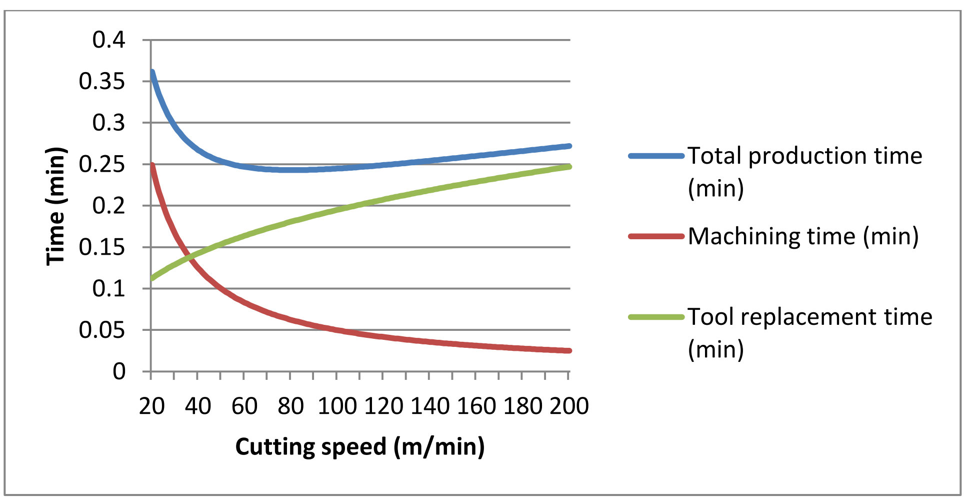


Figure 3.19 Impact of changes of cutting speed on the production time of square pocket

Total machining time is plotted against cutting speed in Figures 3.18 and 3.19. It can be understood that the machining time decreases when the cutting speed increases; however, the time spent on tool replacement increases. The reason is that the pocket can be machined faster when the cutting speed increases; but, it causes to the decrease of the tool life. As a result, it is needed to change the tools more. In Appendix 1 and 2, the data of the table can be seen. The optimal cutting speed is **80.57 m/min** as calculated above.

In addition to the objective function of minimizing the total production time of the whole pocket, we also think to machine the one pocket by only one tool without changing the tool meaning that the tool life ought to be larger or equals to the total machining time of one pocket. When we look at the example problem, the tool life can be calculated as in Equation (3.48).

$$\boldsymbol{T} = \frac{1.0146.10^{5}}{(80.57^{1.3417})((0.0175).1000)^{0.4653}((0.2).1000)^{0.1491}(70)^{0.7017}} = \mathbf{1.71}\ \boldsymbol{min} \qquad (3.48)$$

It is assumed that the whole pocket is machined with the same cutting speed. Thus, from the Table 4, 5, 6 and Appendix 1, 2 and 3, it can be realized that the whole pocket can be machined with one tool without changing it, since the actual machining time of the square pocket is **0.65 min** and the actual machining time of two circles is **0.06 min**. The summation 0.71 min is less than 1.71 min. Thus, the optimal solution can be used to machine the whole pocket with one tool.

3.3 Summary of Findings

In this chapter, first of all the mathematical models to minimize the total production time are represented. It is realized that the objective function is convex; thus the optimal solutions can be found by using Weierstrass and Fermat theorems for the single tool problems. It is found that for the single tool single pass problem, the optimal cutting speed does not depend on the tool path length; however, it is depended on empirical constants, tool replacement time, feed per tooth, axial and radial immersion ratios when the extended Taylor tool life equation is used. The total production time is represented as the summation of the actual machining time, material handling time, idle time and the tool replacement time. In order to find the machining time, first the tool path length is calculated; thus, the strategy to calculate the tool path length is represented in detail. As a strategy of the tool movement, the counter parallel tool path generation is used because of the benefits defined by Choy and Chan. [27]

As a study, actual machining time calculation is compared with the program Cimatron and realized that the average differences for the given experiments are about 6%. However, when the immersion ratio is higher than 0.7, the Cimatron does not use the same algorithm that we prefer to apply which increases the differences between two models; which does not give the reliable solutions to compare for the higher immersion ratios. Furthermore, it is realized that there is a reverse relation between actual machining time and the tool replacement time. When the cutting speed is increased, the tool replacement time increases since the tool gets worn faster. The mathematical models for all basic shapes of pockets are defined. Because the tool path length calculations are depended to the shapes of the pockets, for each shape of the pockets the tool path calculation models are defined and the mathematical models are identified for single tool single pass and the single tool multi pass cases.

Chapter 4

Micro-Scale Milling Operations of Multi Tool Optimization Problems for Equilateral Triangle Pockets Having Sharp Corners

The equilateral triangular pockets can have different edge lengths, corner radius and depth of cuts. In order to satisfy the given parameters of these inputs, there can be different strategies to produce the pockets. If we use the tool with large radius, then there cannot be sharp corners; however, we can machine larger areas in a shorter time. For the thick depth of cut, we can produce it with low cutting speed and the larger volume can be machined without doing more passes. However, there is a tradeoff between these alternatives. Therefore, our aim in this chapter is to develop the models that will minimize the total production time for the multiple tool cases. While minimizing the model, the cutting speed (V) is thought as a decision variable.

This chapter presents the procedure that is followed to find the optimal value of the cutting speed which minimizes the total production time for each tool diameter. Furthermore, it focuses on the decision processes of choosing the right combinations of the tools which has the less production time when compared with the other combinations.

First of all, the studies on the literature are discussed, then the tool path generation strategies with the multi tool single pass and multi pass problems are examined. The mathematical models of the problem are described. Finally, the decision analysis algorithm to choose appropriate tool combinations and best solutions is described in detail and the module to solve the problem is presented.

4.1 Literature Review

Kyoung, Cho and Jun explain that the important factors for the optimal process plan of the pockets are the tool size selections, width of cut at each pass, and finally the machining time. [33] It is emphasized that the most important factor is the tool diameter selection, since the other factors are dependent to it. Thus, the paper focuses on the method to select optimal tool combinations for the pocket machining. The branch and bound technique and breadth-first search technique are used (Figure 4.1). The largest and the smallest tool that can be used to machine the pocket are defined. Then, the optimal tool combination is tried to be found. All the combinations of the tools are created and it starts to search from the case of using one tool which equals to T1 since minimum sized tool should be in the optimal combination. T1 is thought in the optimal tool set, then the case of having two tools are calculated. If the calculated time is larger than T1's time, the nodes are pruned. In other case, the calculated minimum value is thought in the optimal tool set. It is maintained until there is no node to be pruned. As a strategy, the tool paths are created by spiral outward cutting. Then, the total machining time is calculated. Thus, the optimal combinations of the tools are found [33].

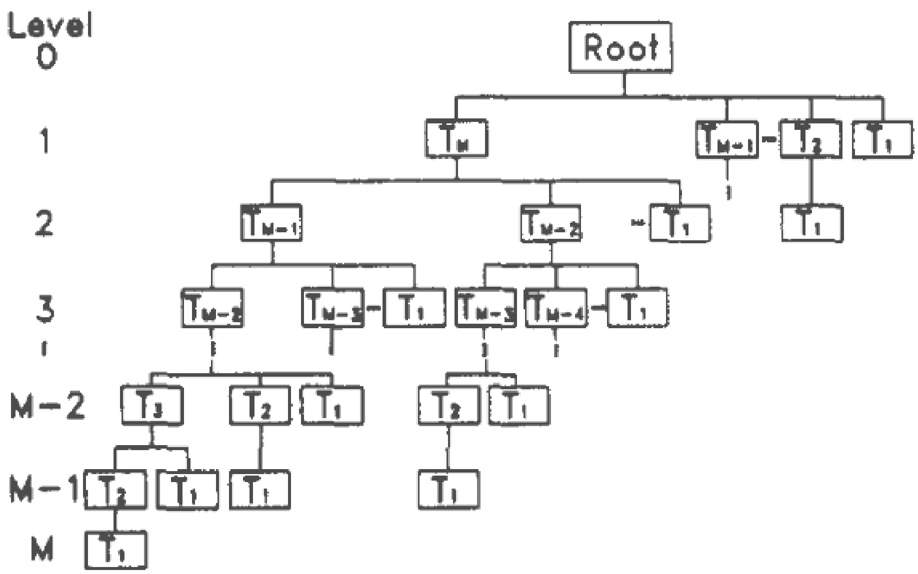


Figure 4.1 Tool combination tree [33]

Bouaziz and Zghal explain that the machining time is affected significantly from the number and the diameters of the tools. Thus, the paper of Bouaziz and Zghal focuses on the algorithm to find the optimal set of tools for the given shape of the pocket. Main focus is on the 3D pockets. It is anchored in the calculation of the tool trajectory for different machining steps. There are two essential steps which are finding the optimal diameter of the tools for pocket machining and determining the optimal tool for pockets under roughing operation. First of all, the trajectory of the roughing operation is found, then the corners are machined and found the trajectories of the corners. For all available tools, the total time is calculated. The tools with having less machining time are chosen for corner and roughing operation. The model helps to find the most appropriate tool sets. [34]

Choy and Chan explain that in milling, when machining the corners, the resistance increases considerably which can cause the tool breakage or shorter tool life. When the corners are machined, it is preferred to make multiple passes by creating loops. By the corner looping tool path generation, the cutter contact length can be controlled by changing the number of loops. Thus, the cutting resistance can be changed. In the article of Chan and Choy, the procedure to create tool paths for the different shapes of the corners are explained [27].

When machining the corners, different strategies can be used. One of the example can be seen in Figure 4.2.

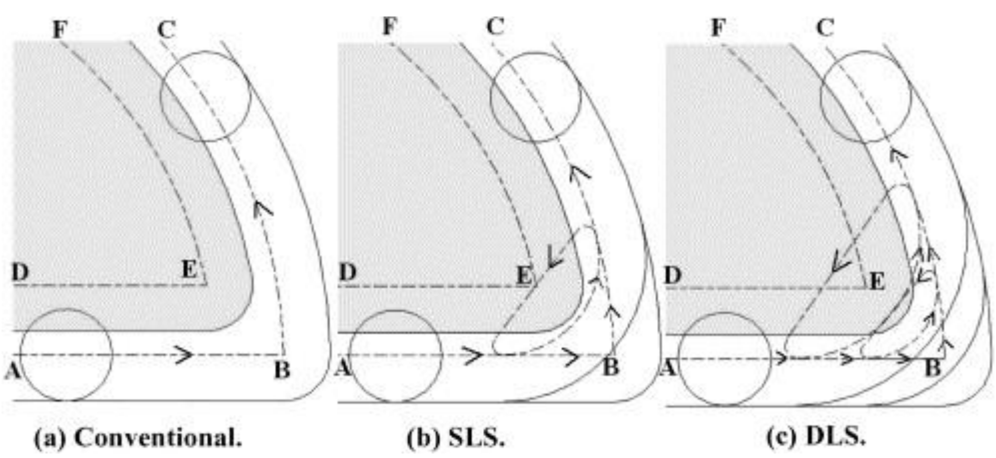


Figure 4.2 Corner machining strategy [27]

The corner cutting strategies defined by the authors Choy and Chan are Conventional, Single Loop Strategy (SLS) and Double Loop Strategy (DLS). These strategies are examined by the experiments and it is found that SLS and DLS strategies reduce the cutting force significantly. However, these methods are increasing the tool path. It is emphasized that the increment of the tool path length can be compensated by decrement of the cutting force, slot milling situation is avoided. Furthermore, the stable state of the machine can be achieved. [27]

The problems defined by Veeramani and Gau stem from the CAD/CAM system's inability of choosing multiple tool sizes to produce a 2.5D pockets. The problem is restricted to the prismatic pockets with round corners. The tools are used from the descending order. The counter parallel machining strategy is preferred. The smallest cutting tool size is thought as a corner diameter of the pocket. Thus, in the paper of Veeramani and Gau, two phase methodology is described. In the first phase, the material volume that is removed by a specific cutting tool size, the volume of the material remained to be machined and the cutter paths for all cutting tools are calculated. Then, in the second phase, the DP (Dynamic Programming) algorithm is applied to select the cutting tool sizes based on the processing time. Each cutting tool is considered as a "state" and workpiece configuration results from the use of tool show a "stage". It is tried to find the route from stage 0 to N. Stage 0 is the initial stage and it shows the unmachined raw material. Stage 1 represents using largest tool and stage N shows using the smallest tool. In Equations (4.1), (4.2), (4.3), (4.4) and (4.5), the model is presented. Pj(i,j) represents the total processing time including tool j with the previous tool i. TPT(i,j) shows the total processing time for tool j for the area left from tool i. T(i,j) is the tool change time from i to j. When (TPT) is zero, then T(i,j) is zero since j is not feasible tool. With the experiments, it is realized that the multiple tool selection saves significant time. [35]

$$Objective\ function = P_N^*(N) \tag{4.1}$$

$$P_j(i,j) = TPT(i,j) + T(i,j) + P_i^*(i), 0 \leq i \leq j-1, 1 \leq j \leq N \tag{4.2}$$

$$T(i,j) = 0\ if\ TPT(i,j) = 0 \tag{4.3}$$

$$P_i^*(i) = \min\{P_i(k,i) |\ \mathrm{TPT(k,i)} > 0\}, 0 \leq k \leq i-1, 1 \leq i \leq N \tag{4.4}$$

$$P_0^*(k) = 0, TPT(0,k) = 0, 1 \leq k \leq N \tag{4.5}$$

Another paper written by Veeramani and Gau is developing a procedure to select optimal set of cutting tools for the stair case milling strategy of the triangular pocket with the round corners. The aim is to minimize the machining time. Thus, first of all, the analytical model of the machining time by using a specific tool is determined. Then, the DP algorithm is applied to find the best set of the cutting tools from the set of the available tools. [36]

Soepardi, Chaeron, Aini focus on the optimization of the pocket machining operations. The inner and the corner portion processes of the pocket machining are identified separately. The zig-zag machining strategy is used. The largest tool is used to remove the bulk material parts of the pockets. Then, for the rest of the area located on the corners are machined with the smaller tool diameters. The aim is to make the tool path length shorter and minimize the machining time. [37]

Cakir and Gurarda discuss the procedure to minimize the production cost by changing the machining conditions. First, the best values for the each pass are found by using the circular direction search method. For each tool and each pass, the optimal values of cutting conditions are looked for. In the developed model, the user can define the inputs which are workpiece specifications, cutting tool and machine tool specifications, various costs and time values. Furthermore, the effects of the constraints are examined graphically. As an assumption, the tool change time for the worn tool is ignored [38].

Another study from Veeramani and Gau focus on the development of an analytical model of the tool path length for a pocket. The 2.5D equilateral triangle with round corners is used. The model is to develop tool path lengths for the 2.5D equilateral triangle. The machining strategy is divided into two as inner portion stage and the corner portion stage. In inner portion stage, the tool moves staircase from the base to the top. After machining inner part, there can remain some parts on the corners that are not machined. Then, the smaller tool is chosen and the corners are machined. If there is again the part to be machined, then the smaller tool is chosen and the corner is machined. This process is maintained until there is not a part that is not machined [39].

Jung identifies the feature based cost estimation system for the parts. The reason of focusing on this topic is that it gives valuable information to its designers. The cost estimation is based on the machining activities which are proportional to the time, operation and nonoperational time. Operation time consists of rough cutting operation and the finishing operations, which are calculated by considering MRR. The nonoperational time are mathematically defined by using the past experiments [40].

Hinduja et al. focus on the determination of the optimal cutter diameter for the 2.5D pockets. In the study, the radial immersion ratio is not considered as constant. Optimal cutter diameter is chosen for different immersion ratios through the cutter path. It examines the trade of between large tool with shorter tool path and the small tool with the longer tool path but suitable variations [41].

In our study, the counter parallel tool path generation strategy is preferred. In the literature, there are different objective functions depending on the expectations of the authors. Some of the examples are minimizing total production time, minimizing the energy consumption, minimizing the tool path length, maximizing the material removal rate. In our study, the total production time is considered as an objective function. For each tool, the tool path lengths are expressed in detail which helps to visualize the production of the pocket and make the calculations easier. Furthermore, the best combinations of the tools are tried to be found. There are some studies to find the best combinations. Some of them prefer to use DP algorithm or branch and bound technique. In our study, for each combination of the tool, the total production time is calculated for different tool passes. The reason is that it gives an opportunity to see all the alternatives and their differences, which can be helpful when the cost effectiveness is considered and sometimes the proposed alternative may not be applicable. It also helps to see the whole picture and choose one of the alternatives regarding the applicability. Furthermore, in order to calculate the total production time of the combinations, the software module is presented, which helps to calculate all the alternatives and choose the best solution.

4.2 Mathematical Model

There are some assumptions of the problem. Spiral movement from inside to outside is assumed. Furthermore, the tool with two teeth is preferred and only the roughing process is considered in these models. One of the examples of the spiral movement of the tool can be seen in Figure 4.3. Furthermore, the corner diameter of the pocket equals to the smallest tool diameter.

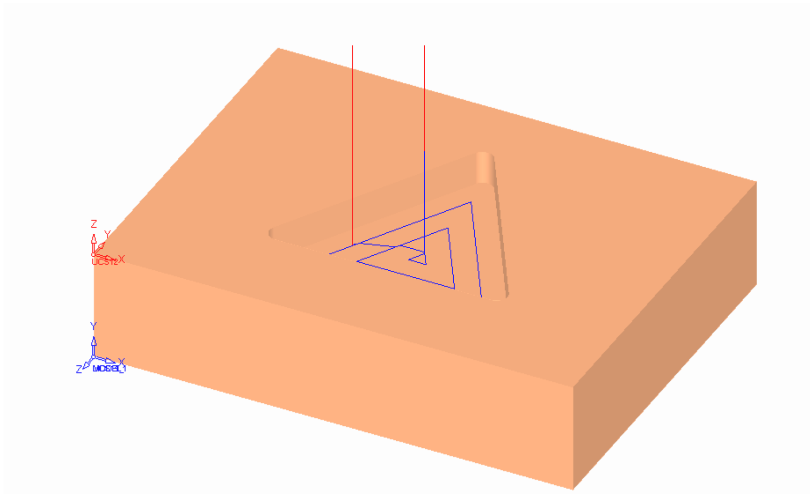


Figure 4.3 Example of the tool paths of the equilateral triangle

The additional notations and the changes to the expressions given on the Chapter 3 with their units and their illustrations can be listed as:

D: $diameter\ of\ tool\ with\ largest\ radius\ (mm)$

D_i: $diameter\ of\ tool\ i\ with\ property\ D_1 > D_2 > D_3 \ldots and\ i = 1,2 \ldots,$

p: $cutter\ length\ of\ the\ tool\ with\ diameter\ D\ (mm)$

p_i: $cutter\ length\ of\ the\ tool\ with\ diameter\ D_i\ (mm)$

4.2.1 Multi Tool Single Pass Problem

It is assumed that there are multiple tools available for the job and tools machine the pocket until they cannot machine anymore due to geometrical conditions. Thus, the tools are going to be used from the largest one to the smallest one. The reason is that with the largest tool, we can machine larger areas and the machining time can be less. Furthermore, if we prefer to use the tool with the smaller size first, then we do not need to use the larger tools anymore to machine the pocket. The reason is that there is no area that the larger tool can reach after machining with smaller tool.

First of all, it is assumed that we have 2 different tool diameter sizes, then the decision tree can be expressed as in Figure 4.4. Thus, we calculate the total production time with one tool and two tools cases, where case with less time to produce a pocket will be selected. In Figure 4.4, T_1 and T_2 represent the total production time to machine a pocket.

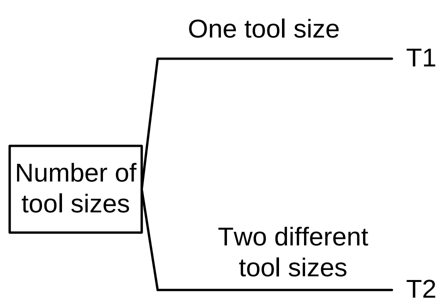


Figure 4.4 Decision tree for having 2 tools case

If we have 3 tools with diameters D1> D2> D3, then the decision tree can be expressed as in Figure 4.5. There are 4 different combinations of these three tools. We can prefer to use three of them, D_1 and D_3, D_2 and D_3 or only D_3. Thus, by comparing total production times, the combination with the minimum time production can be selected. The similar decision trees can be created for higher number of tools.

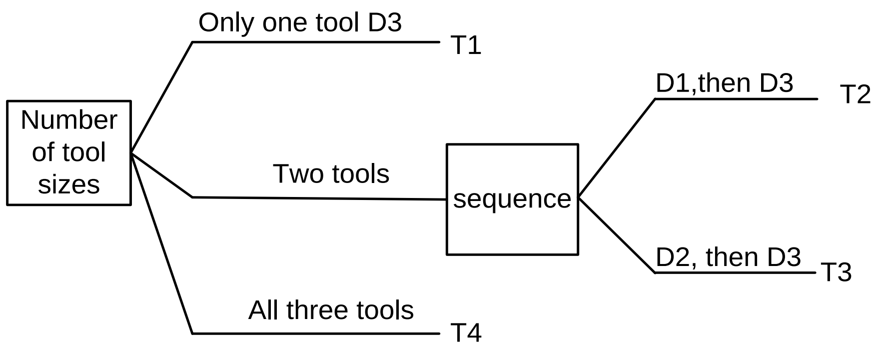


Figure 4.5 Decision tree for having 3 tools case

First of all, before generalizing the problem for the multiple tools, it is assumed that we have 3 tools with diameters D> D_2> D_3. Thus, the corner diameter is equal to D_3. After understanding the properties of the problem, the model is going to be generalized.

4.2.1.1 Starting pocketing with the largest tool diameter D

The center of gravity of the triangle with an edge length *w* is thought as a starting point, and it creates a small triangle. Then, it goes outward, creates another triangle which is larger than the previous one. This algorithm maintains to create triangles until the tool does not move further. The example of it can be seen below on Figure 4.6. It can be seen in the example that the tool's diameter is larger than the corner diameter and to remove unmachined area of the pocket, the smaller tool diameter ought to be used.

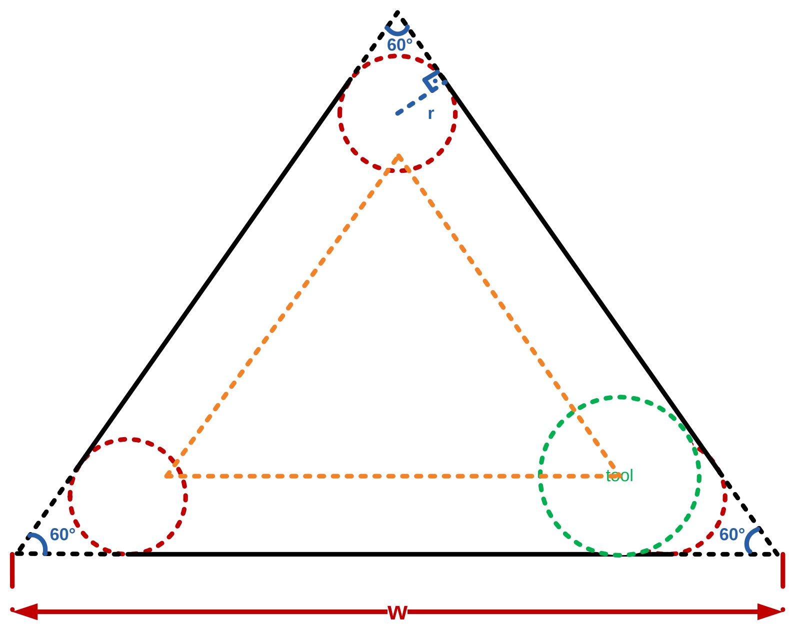


Figure 4.6 Machining with big tool

In Figure 4.7, the first tour of the pocket is represented. The tool starts from point A, goes upward Dδ amount and creates the triangle path with the edge length $D\delta\sqrt{3}$ and at the end, it comes to the point B. The immersion ratio is ignored for the first tour. The reason of preferring the height equals to 3Dδ/2 is that when the immersion ratio equals to 1, then it is the largest height that the tool can machine the pocket without having unmachined area inside the first tour's tool path. Hence, its path length for the first tour equals to $D\delta + \frac{6D\delta\sqrt{3}}{2}$. As an assumption, the first tour can be created with the diameter D.

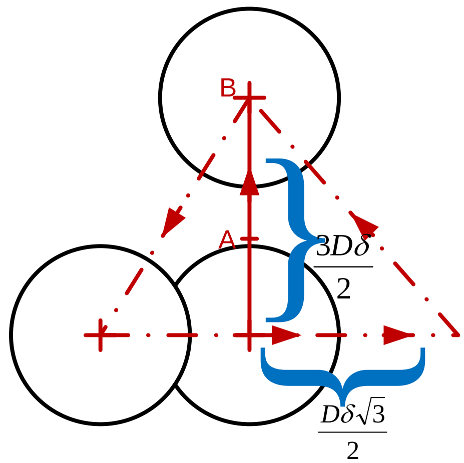


Figure 4.7 First tour of the tool for equilateral triangle pocket

After creating the first tour, the tool moves from the point B upward 2Dδ amount. The tool path length for the second tour is shown in Figure 4.8. Hence, the tool path length equals to $2D\delta + 6\left(\frac{3\sqrt{3}D\delta}{2}\right)$. If the third tour exists, the tool path length of the third tour is $2D\delta + 6\left(\frac{5\sqrt{3}D\delta}{2}\right)$.

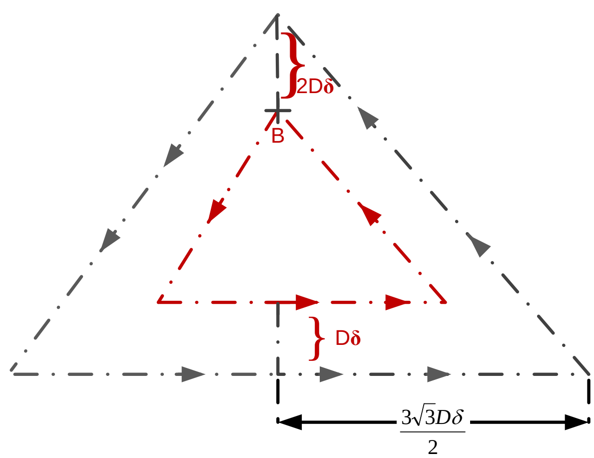


Figure 4.8 Second tour of the tool for equilateral triangle pocket

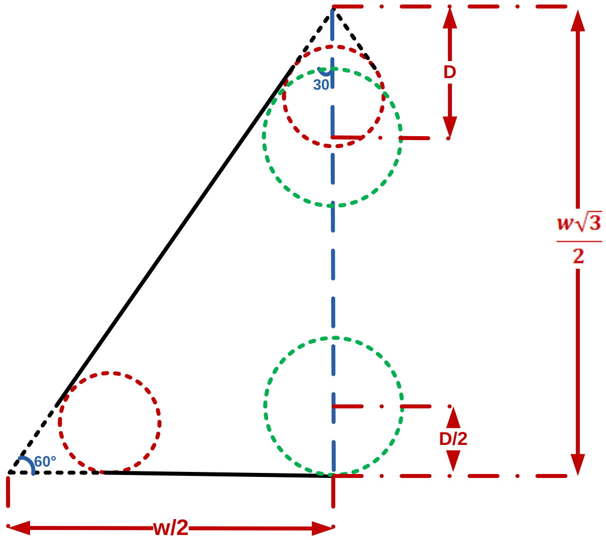


Figure 4.9 Last tour of the largest tool for equilateral triangle pocket

In order to find the number of tours to machine the triangle, the Equation (4.6) can be used. $\frac{w\sqrt{3}}{2}$ shows the height of the triangle, D/2 and D are the distance of the tool center from the edge and the corner of the pocket, $\frac{3}{2}$Dδ is the first tour's height and in each tour the height of the triangle increases 3Dδ amount (Figure 4.9). As an assumption, the number of tours is calculated after creating the first tour. Hence, the simplified version of the number of tours can be seen in Equation (4.7).

$$\frac{w\sqrt{3}}{2} = \frac{D}{2} + D + 3D\delta(\mathrm{n}) + \frac{3}{2}\mathrm{D}\delta \qquad (4.6)$$

$$\boldsymbol{n} = \frac{w\sqrt{3}}{6D\delta} - \frac{1}{2\delta} - \frac{1}{2} \qquad (4.7)$$

Thus, the generalized tool path length for the largest tool can be written as in Equation (4.8). The term $\left(D\delta + 3\sqrt{3}\mathrm{D}\delta\right)$ represents the tool path length of the first tour. The term $\lfloor n \rfloor 2\mathrm{D}\delta$ equals to the total outward movements of the tool, n is rounded downward since it can be a decimal number. If n is the decimal number, the last tour cannot be machined with the immersion ratio δ. The summation part of the equation represents the total tool path lengths of the created triangles. $(\mathrm{n} - \lfloor n \rfloor)2\mathrm{D}\delta + (\lceil \mathrm{n} \rceil - \lfloor n \rfloor)3(\mathrm{w} - \mathrm{D}\sqrt{3})$ part takes value larger than zero when n is the decimal number. Thus, it represents the upward movement and the created triangle tool path's edge length.

$$\boldsymbol{L_{total}} = D\delta + 3\sqrt{3}\mathrm{D}\delta + \lfloor n \rfloor 2\mathrm{D}\delta + \sum_{\mathrm{i}=1}^{\lfloor n \rfloor}(2\mathrm{i}+1)\,\mathrm{D}\delta 3\sqrt{3} + (\mathrm{n} - \lfloor n \rfloor)2\mathrm{D}\delta + (\lceil \mathrm{n} \rceil - \lfloor n \rfloor)3(\mathrm{w} - \mathrm{D}\sqrt{3}) \tag{4.8}$$

4.2.1.2 Continue Pocketing with Second Largest Diameter D_2

After machining with the tool D, there are parts that are not machined with the tool D. These parts appear at the corners of the pockets. Thus, the relations of the tools D_2 and D are examined in order to create a strategy to machine these parts of the pocket. There are cases that affect the strategies. The first case is that the tool with diameter D_2 can intersect at least one point with the tool D at the corner of the pocket (Figure 4.10).

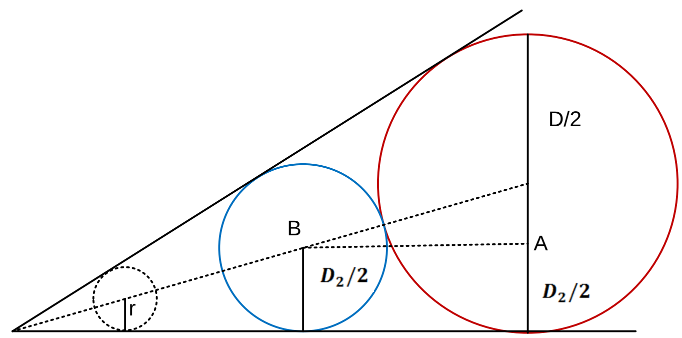


Figure 4.10 Case 1- Tool D_2 can intersect at one point with the Tool D

In order to intersect the tools with diameters D_2 and D, they ought to satisfy the Equation (4.9). It means that the tool with diameter D is less than or equals to $3D_2$ and as known D is larger than D_2. In this case, the un-machined area can be machined with one tour.

$$D = D_2 + \frac{D_2}{2} + \frac{D}{2} \tag{4.9}$$

The tool with diameter D_2 starts from point A and then moves to the point B. After this movement, the similar path is made for the other edge of the corner by starting from point B (Figure 4.10). For each corner, same path is created. Thus, the tool path length for the tool with diameter D_2 can be expressed as in Equation (4.10).

$$\mathbf{L_{D2total}} = 3.2\left(\frac{D\sqrt{3}}{2} - \frac{D_2\sqrt{3}}{2}\right) \tag{4.10}$$

The immersion ratio when the two tools intersect can be thought as 0.5 since at the start of machining the immersion ratio is zero and on the corner of the pocket it becomes 1. Hence, the increase of the immersion ratio can be considered as linear in order to make the calculations easier. When the two tools intersect in two points and the tool D_2's center is outside the tool D's area (Figure 4.11), x value equals to D/2- D_2 since the hypotenuse of the triangle ABC can be written as Equation (4.11). Hence, the case when the x value is larger than zero is considered and in this case, D should be larger than $2D_2$. The largest distance when machining the corner can be calculated as $(x + D_2/2)$ which equals to $(D/2 - D_2/2)$. When the two tools intersect in two point and the tool D_2's center is inside the tool D's area (Figure 4.12), x value equals to D/2- D_2 since the hypotenuse of the triangle ABC can be written as Equation (4.12) and it is known that x is larger than zero. Thus, the largest distance when machining the corner can be calculated as (x) which equals to $(D/2 - D_2/2)$. Hence, it can be summarized that when the two tools intersect in one point then the immersion ratio is considered as 0.5, otherwise the immersion ratio equals to $x/2D_2$ since as an assumption the linear increase of the immersion ratio is considered and the maximum and the minimum immersion ratios are calculated. The minimum immersion ratio is equivalent to zero and maximum immersion ratio is $(D/2 - D_2/2)/D_2$; thus, the average immersion ratio equals to $(D/2 - D_2/2)/2D_2$.

$$\boldsymbol{D} = D_2 + x + D/2 \tag{4.11}$$

$$\boldsymbol{D} = D_2 + \frac{D_2}{2} + \left(\frac{D}{2} - (D_2 - x)\right) \tag{4.12}$$

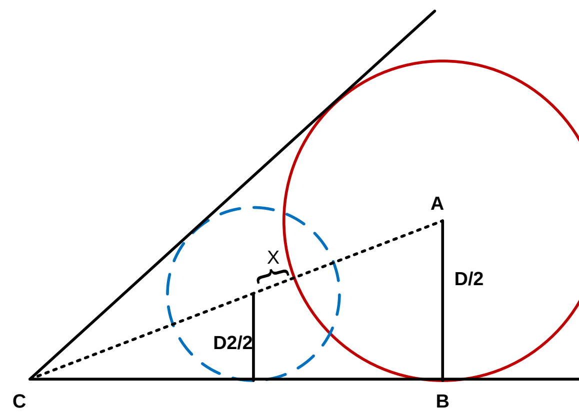


Figure 4.11 When two tools intersect in two points and tool D_2's center is outside the tool D's area

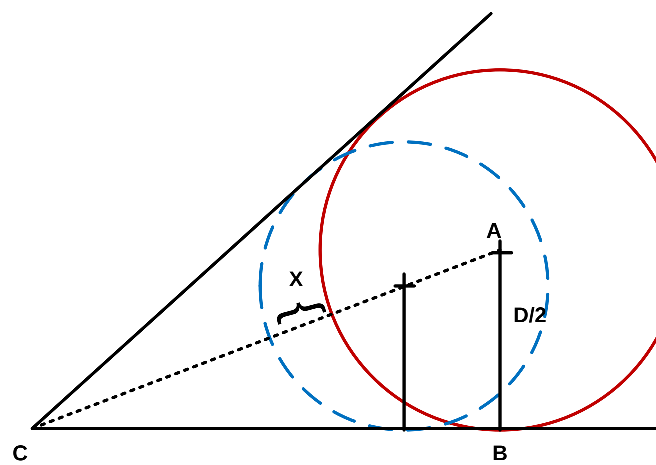


Figure 4.12 When two tools intersect in two points and tool D_2's center is inside the tool D's area

When tools D and D_2 are at the corner of the pocket, they may not intersect to each other (Figure 4.13). Thus, the tool with diameter D_2 can either create a triangle on the corner of the pocket or make a same move in Figure 4.10. There is a relation in order to understand which case is going to be used. In Figure 4.14, the tools D and D_2 do not intersect to each other; however, when taking the parallel lines to the edges, it can be realized that the tool D_2 can machine the bulk material on the corner with the same move that is previously defined in Equation (4.10). The tool moves from point A to B and then makes the same movement on the other edge of the pocket (Figure 4.10). This movement is done for other corners too. The relation of the diameters of the tools are given in Equation (4.13), which explains that |OA| length is equivalent to the half of the diameter D and at the same time it equals to $2\left(\frac{D}{2} - D_2\right)$. Thus, if the tool diameter D_2 is between 3D and 4D, then the Equation (4.10) can be used. The immersion ratio of this case can be considered as 1 since the tool has to move with 100% immersion in some period of the path and it affects highly the performance of the tool when compared with the other immersion ratios.

$$2\left(\frac{D}{2}\right) - 4\left(\frac{D_2}{2}\right) = \frac{D}{2} \tag{4.13}$$

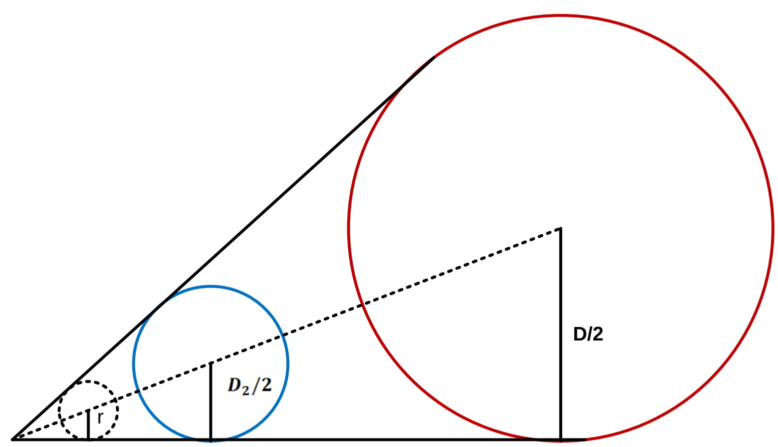


Figure 4.13 Case 2 Tool D2 cannot intersect at one point with the Tool D

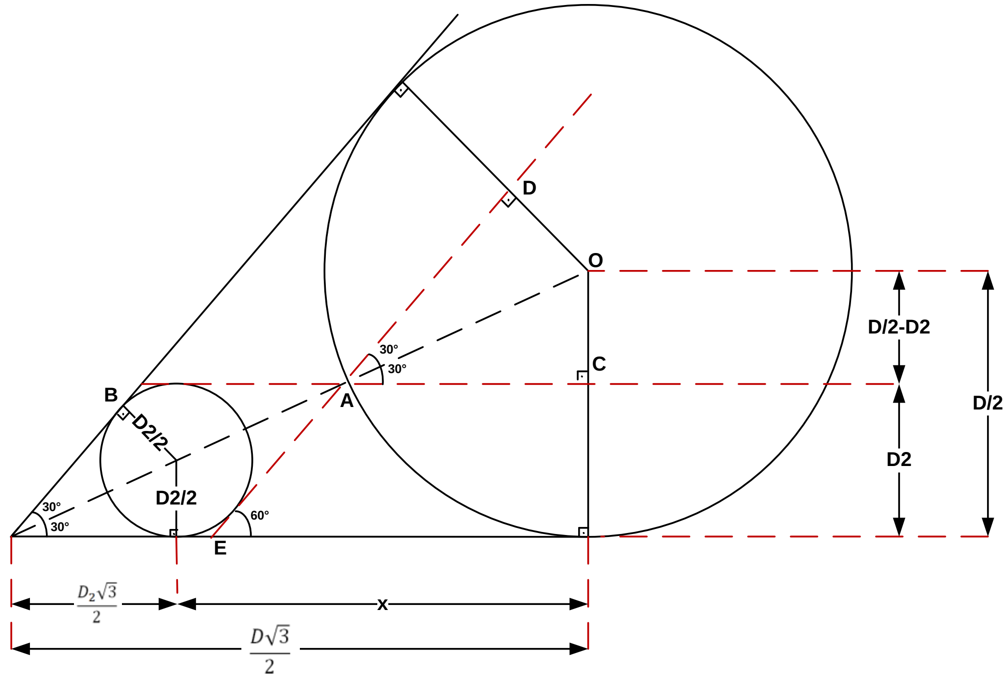


Figure 4.14 The case when D_2 machines the bulk material in one tour

If the tool diameter D is larger than $4D_2$, another case of machining ought to be considered. The other case of machining the corner is that the tool does not machine the material in one tour. Thus, the triangle tool path is created on the corner which is defined in Figure 4.15. The last tour of the tool is going to be ABC triangle. It is realized that the first tour of the tool (Figure 4.16) with the height $\frac{3D_2\delta}{2}$ can fit into the ABC triangle since the height of the triangle ABC is $\frac{\left(\frac{D}{2}-\frac{D_2}{2}\right)3}{2}$. When the immersion ratio equals to 1, then it can be said that $\frac{\left(\frac{D}{2}-\frac{D_2}{2}\right)3}{2}$ is larger or equivalent to $3\,\frac{D_2}{2}$ since it is known that diameter D is larger than $4D_2$.

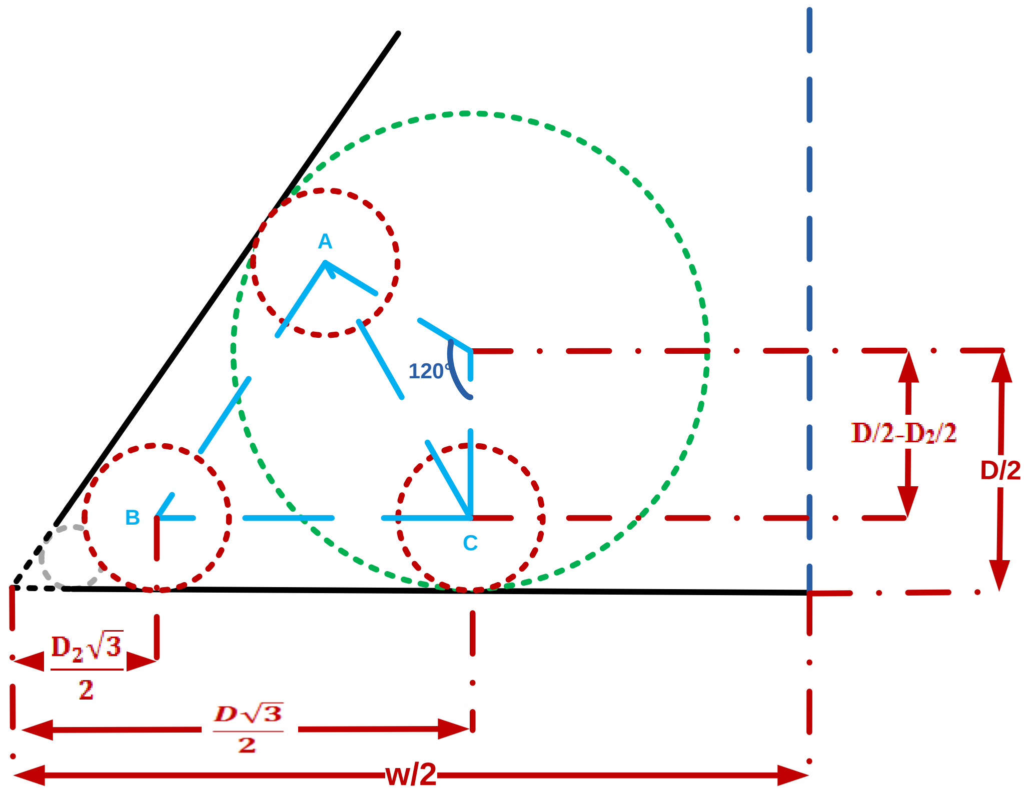


Figure 4.15 Last tour of the tool D_2 at Case2

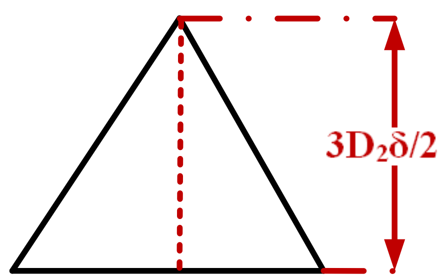


Figure 4.16 First tour of the tool D_2 inside the ABC triangle

If the first tour can be created inside the ABC triangle, then on the corner, we create a triangle. First tour will be with the edge length $\sqrt{3}D_2\delta$. The height of the triangle ABC is $\left(\frac{D}{2}-\frac{D_2}{2}\right).\frac{3}{2}$. The number of tours can be calculated as Equation (4.14). The summarized version of the number of tours can be seen in Equation (4.15).

$$\left(\frac{D}{2}-\frac{D_2}{2}\right).\frac{3}{2}.\frac{1}{3}-\frac{D_2\delta}{2}=n_{D2}D_2\delta \tag{4.14}$$

$$\mathbf{n_{D2}}=\left(\left(\frac{D}{2}-\frac{D_2}{2}\right).\frac{3}{2}.\frac{1}{3}-\frac{D_2\delta}{2}\right).\frac{1}{D_2\delta} \tag{4.15}$$

The total path length for the tool D_2 can be calculated as Equation (4.16).

$$\mathbf{L_{D2total}}=D_2\delta+3\sqrt{3}D_2\delta+\lfloor n_{D2}\rfloor 2D_2\delta+\sum_{k=1}^{n_{D2}}(2k+1)\,D_2\delta 3\sqrt{3}+(n_{D2}-$$

nD22D2δ+nD2−nD23D2−D223 (4.16)

The flow chart of choosing the right tool path length depending on the relation between the tool sizes can be seen in Figure 4.17.

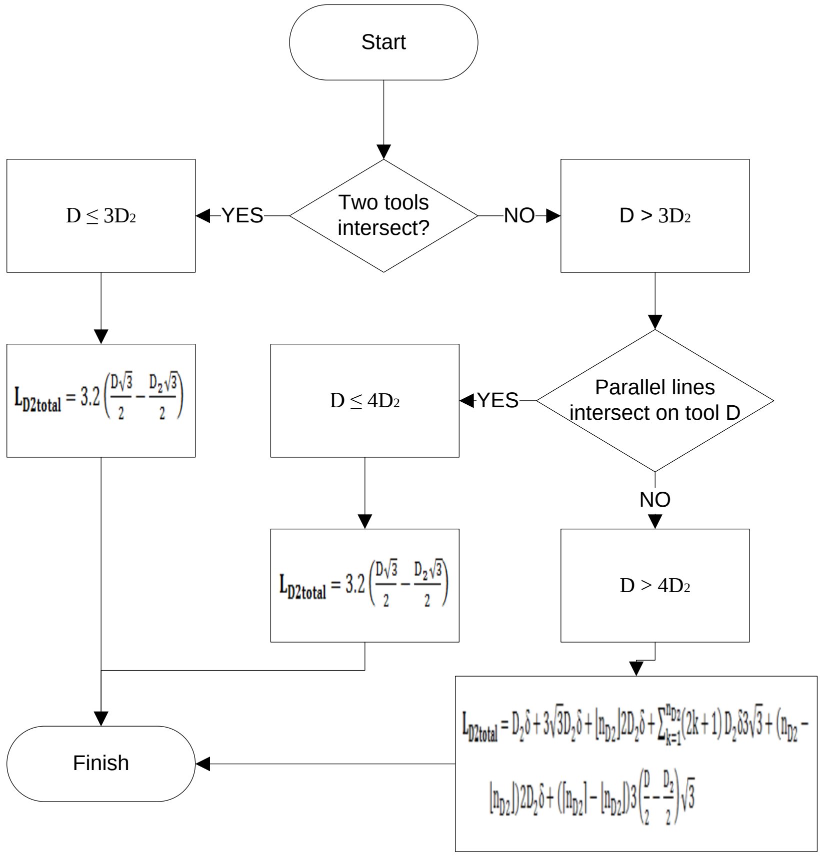


Figure 4.17 Flow chart to choose tool path length depending on the cases

4.2.1.3 Pocketing with the smallest Diameter D_3 after machining with D_2

After machining with the tool D_2, there can be some parts that are still not machined with the tool D_2 which are located on the corners of the pocket. Thus, the relations of the tools D_2 and D are examined in order to create a strategy to machine these parts of the pocket. There are cases that affect the strategies. The first case is that the tool with diameter D_3 can intersect at least one point with the tool D_2 at the corner of the pocket (Figure 4.13) meaning that $D_2 \leq 3D_3$.

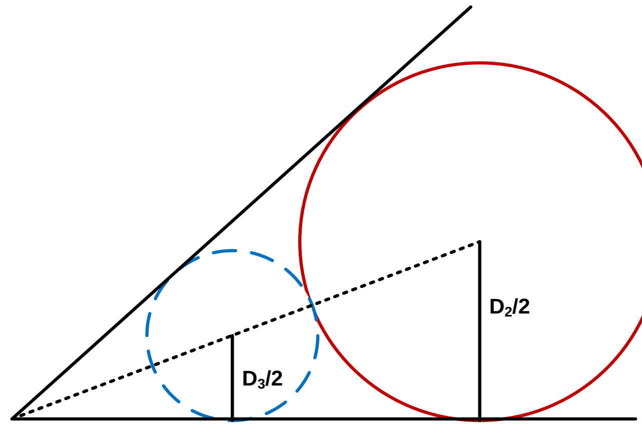


Figure 4.18 Representation of the intersection of the Tools D_2 and D_3

In order to intersect the larger tool D_2 (Figure 4.18) and the tool having the same diameter with the corner diameter, we need the following Equation (4.17). The total tool path length can be calculated as Equation (4.18).

$$D_2 = D_3 + \frac{D_3}{2} + \frac{D_2}{2} \tag{4.17}$$

$$\mathbf{L}_{\mathbf{D_3 total}} = 3.2\left(\frac{\mathrm{D_2}\sqrt{3}}{2} - \frac{D_3\sqrt{3}}{2}\right) \tag{4.18}$$

If $D_2 > 3D_3$ meaning that these two tools cannot intersect to each other, therefore there are some cases that the tool D_3 can machine the part with the one tour. If $D_2 \geq 4\mathrm{D}_3$ showing that they cannot intersect, and then the tool moves only one tour with the edge length $\frac{\mathbf{D_2}\sqrt{3}}{2} - \frac{\mathrm{D_3}\sqrt{3}}{2}$. Thus, the tool path length of D_2 can be seen in Equation (4.19).

$$L_{D3total} = 3.2\left(\frac{\mathbf{D_2}\sqrt{3}}{2} - \frac{D_3\sqrt{3}}{2}\right) \tag{4.19}$$

If $D_2 < 4D_3$, then on the corner, we create a triangle. First tour will be with the edge length $\sqrt{3}D_3\delta$. The height of the triangle ABC is $\left(\frac{D_2}{2} - \frac{D_3}{2}\right).\frac{3}{2}$. The number of tours can be calculated as in Equation (4.20). The simplified version of the number of tours can be seen in Equation (4.21).

$$\left(\frac{D_2}{2} - \frac{D_3}{2}\right).\frac{3}{2}.\frac{1}{3} - \frac{D_3\delta}{2} = n_{D3}D_3\delta \tag{4.20}$$

$$\mathbf{n_{D3}} = \left(\left(\frac{D_2}{2} - \frac{D_3}{2}\right).\frac{3}{2}.\frac{1}{3} - \frac{D_3\delta}{2}\right).\frac{1}{D_3\delta} \tag{4.21}$$

The total path length calculation for the tool D_2 can be expressed as Equation (4.22).

$\mathbf{L_{D3total}} = D_3\delta + 3\sqrt{3}D_3\delta + \lfloor n_{D3} \rfloor 2D_3\delta + \sum_{k=1}^{n_{D3}}(2k+1)\, D_3\delta 3\sqrt{3} + (n_{D3} -$
nD32D3δ+nD3−nD33D22−D323 (4.22)

4.2.2 Multi-Tool Multi-Pass Problem

The algorithm of the multi tool, multi pass is combined version of the multi tool one pass and one tool multi pass. The tool path lengths for each tool ought to be calculated for each pass. The number of the pass can be calculated as Equation (4.23).

$$\boldsymbol{n} = d/a_p \tag{4.23}$$

Our aim is to minimize the total production time of one triangular pocket for each tool. Hence, the objective function of the problem can be thought as Equation (4.24). The actual machining time is expressed in Equation (4.25). For each tool, the optimization is done separately. The reason is that the cutting speeds differ with the changes on the parameters. For each tool, there is an optimal cutting speed different from other tools' optimal values. Since the feed value changes depending on the tool diameters and the tool path lengths alters with the change on the used combinations of the tools.

$$\boldsymbol{T_{tot}} = T_m + \frac{T_r T_m}{T} + T_a + T_c \tag{4.24}$$

$$\boldsymbol{T_m} = \frac{L_{stotal}}{v}.n \tag{4.25}$$

The objective function can be written as Equation (4.26).

$$\boldsymbol{T_{tot}} = \frac{L_{total}\pi D}{f1000Vz}.n + \frac{T_r}{T}.\frac{L_{total}\pi D}{f1000Vz} + T_h \tag{4.26}$$

4.3 Software to Solve the Mathematical Model of the Equilateral Triangle Pocket

The aim of the software is to find the optimal cutting speed while minimizing the production time at the given region. The algorithm starts with the given equilateral triangular pocket information containing edge length and the total depth of the pocket. Then, the available tool diameters will be determined. From the obtained tool diameters, some of them cannot be used. The reason is that some of them cannot fit into the pocket or create the first tour. Thus, some of them are eliminated by the user. The software works for single tool single pass, single tool multi pass, multi tool single pass and multi tool multi pass problems. The parameters are given by the user to the software and the module is run. Each combination of the tools is considered. For each combination, the appropriate mathematical model is run. Then, the cutting speed value is optimized for each mathematical model and found the optimal solutions for each tool of a given combination. The flow chart (Figure 4.19) summarizes the algorithm of the software and the procedure to find the optimal cutting speed.

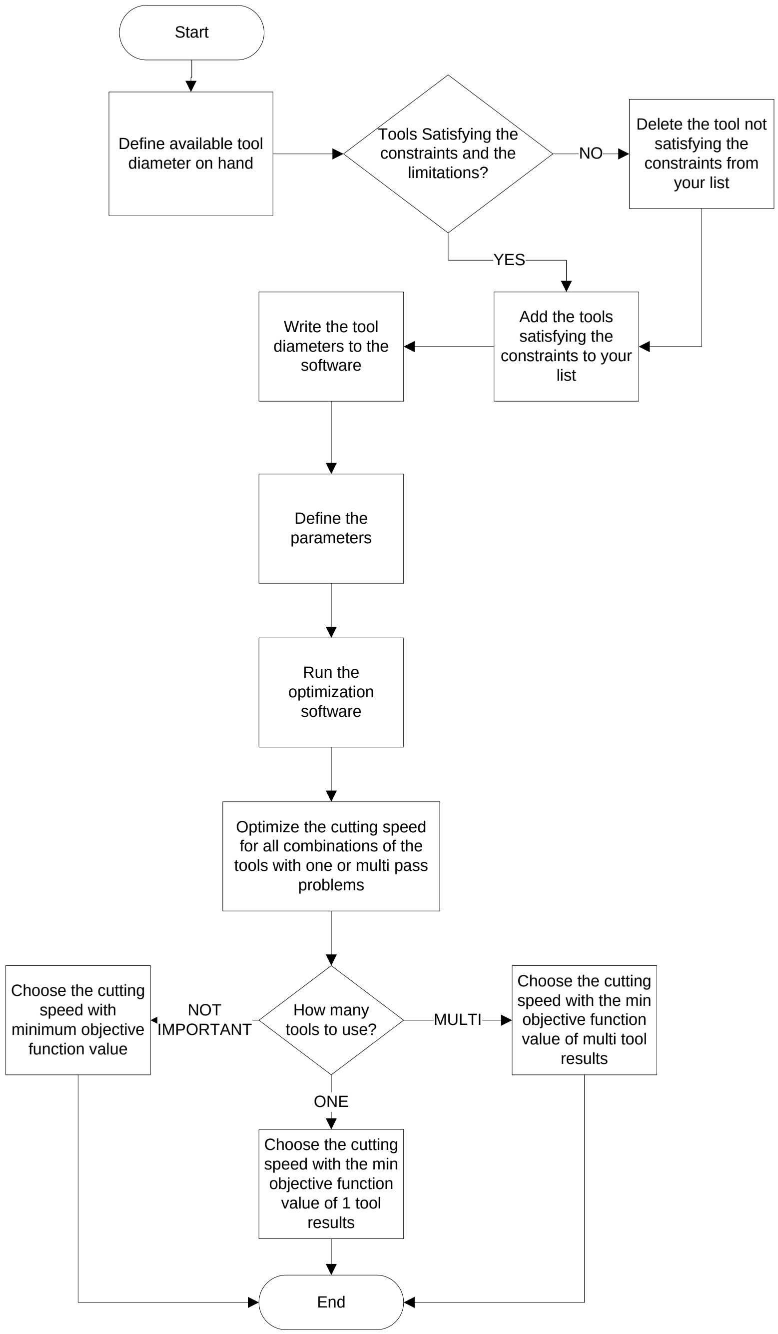


Figure 4.19 Flow Chart of the decision processes

For our study, the used tool life equation can be seen in Equation (4.27). The tool life is dependent on tool diameter, cutting speed, feed per tooth, axial and radial depth of cut.

$$\boldsymbol{T} = \frac{(19.15).10^4\left(\frac{D}{8}\right)^{1.08}}{V^{1.3417}(1000.f)^{0.4653}(1000.a_p)^{0.1491}(100.a_e/D)^{0.7017}} \tag{4.27}$$

When the software starts, it starts with the input screen which can be seen in Figure 4.20. This screen is used to enter inputs to the system. Column A represents the parameters. Column C, D and E are used to run the optimization. Column F, G, H, I, J are used for writing the outputs of the optimization. After finishing the experiments, the data is deleted so as not to confuse the user. Column O is to write the diameters which are wanted to be examined. The sequence can be in any order since it is sequenced from largest to smallest at the column P by the software. Column Q shows the feed per tooth values of the tools which is dependent on the tool diameters. The manufacturer catalogue values of the tool are considered (Figure 4.21). It is realized that there is a polynomial relationship between tool diameter and the feed per tooth. Figure 4.21 shows the fitted line and its relations. The tool diameters are starting from 0.3 mm and the last tool diameter is 4 mm. In the Figure 4.20, the pink highlighted cells represent the input data given by the user of the software.

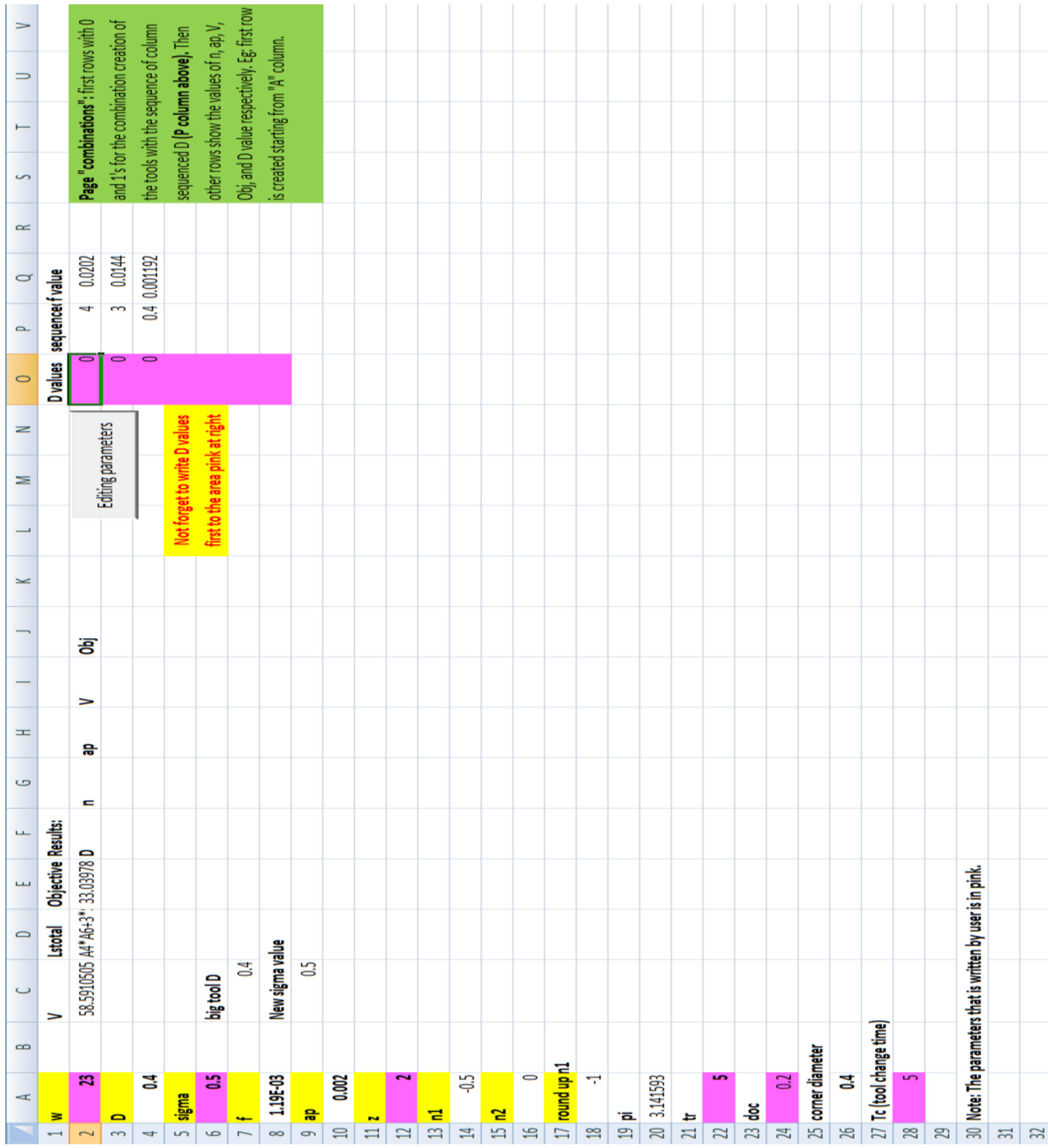


Figure 4.20 Main Screen of the Software

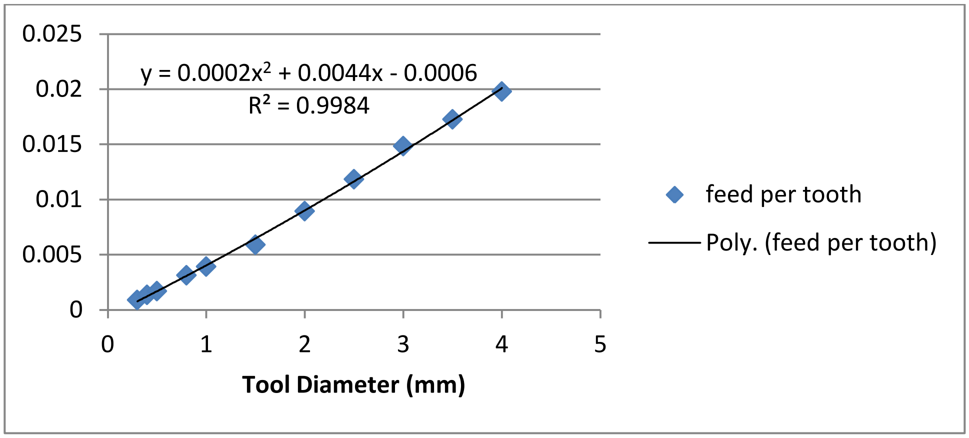


Figure 4.21 Plot of the feed per tooth from the book values [42]

First of all, the usable tool diameters are written at Column O and after writing the usable tools, the parameter values are written by clicking the Editing parameters button. The pop up window appears, which can be seen in Figure 4.22**.** In this screen, the parameters of the model is given by the user which are edge length of the pocket, immersion ratio, number of tooth of the tools, tool replacement time, total depth of cut, and finally tool change time.

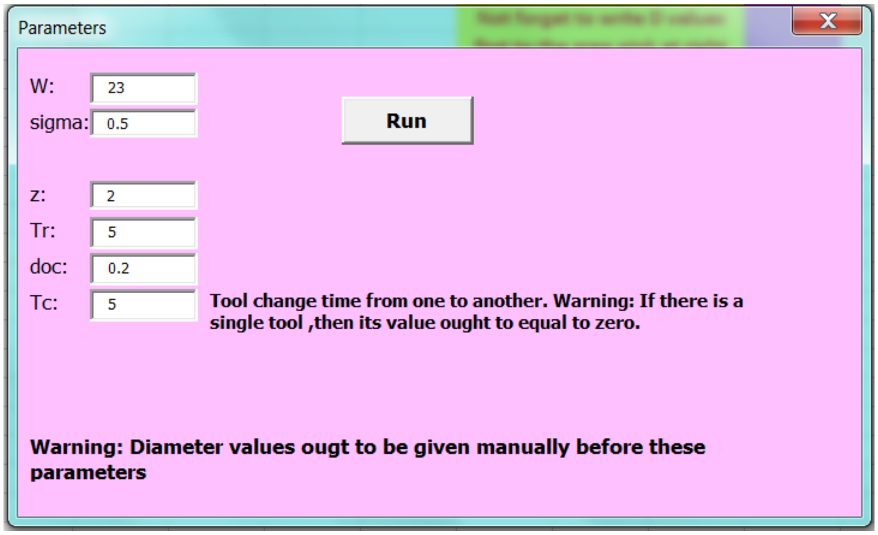


Figure 4.22 Screen to write the inputs of the problem to the software

It is important to note that the diameters should be written before editing the parameters. The parameters that are determined by the user are w, δ, z, T_r, doc, T_c . The meanings of the symbols are edge length, immersion ratio, number of tooth, tool replacement rime, total axial depth of cut and tool change time for tools having different diameter sizes respectively. When there is a single tool, then the tool replacement time becomes zero and it should be written by the user. These given data is entered into the system. By the module, the diameters are sequenced from the descending order. The smallest one is taken as a corner radius of the pocket. The reason is that the corner is wanted to be made as sharpest as possible.

After clicking the Run button, the module starts to create the combinations of the tools. First, it is known that the smallest one is used at each combinations of the tools in order to create sharp corner. However, which tool combinations ought to be chosen so as to minimize the total production time of the pocket is not known. Thus, different combinations of the tools are examined. While machining the pocket, the tools are used from largest to smallest. If the smaller tool is used first, then the larger tool cannot be used because there will not be an area that it can cut or fit. The combination algorithm's working principle can be summarized in a given example. It is assumed in the example we have three tools with the given sequence D>D1>D2. The corner diameter equals to D2. Thus, it will be used in all the experiments. Thus, the module creates the table as in Table 3.

Table 3. Example of creating combinations with tools D, D_1 and D_2

D	**D1**	**D2**
0	0	1
0	1	1
1	0	1
1	1	1

The rows represent the experiment's properties and 1 at each row shows that the tool will be used and 0 represents not using the tool in the experiment. The number of the combinations can be found by $2^{number\ of\ tools-1}$.

After creating the combinations by the module, the number of the experiments is known. Hence, it starts from the upper experiment to lower. The first experiment is by using the tool D_2 only.

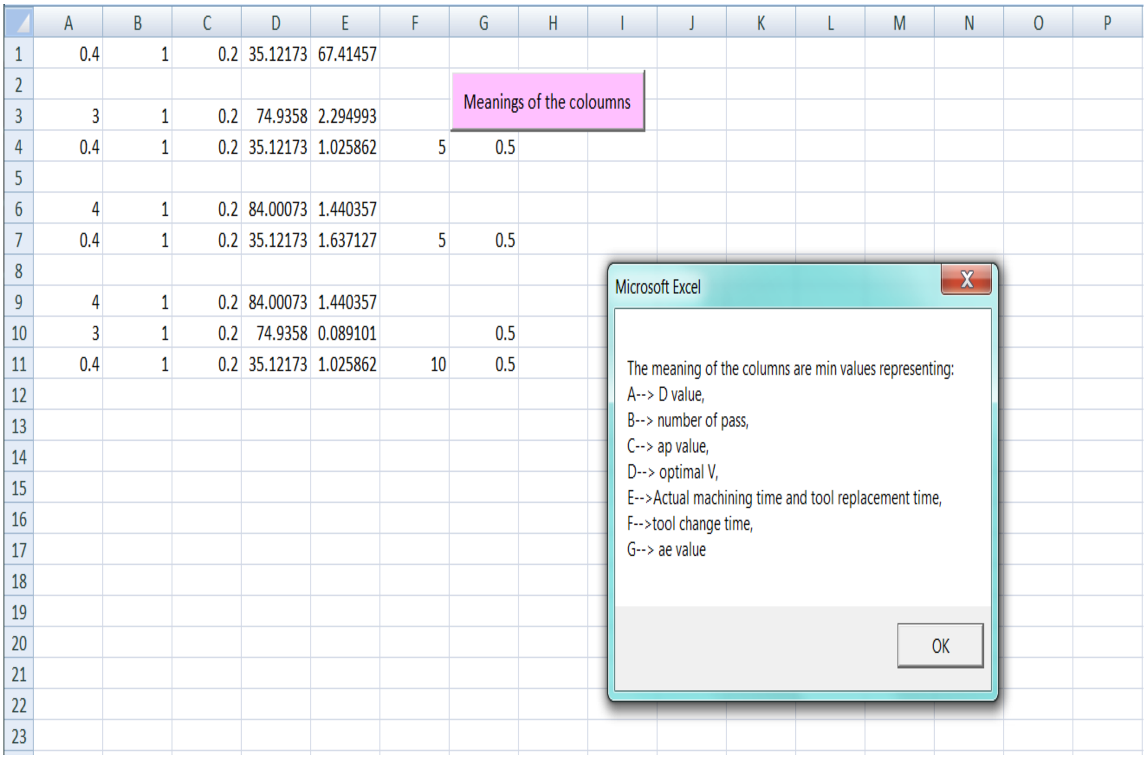
The total depth of the cut is thought as fix and the axial immersion amount is changed by considering different number of passes. By considering different number of passes, the software is run. First, the axial depth of the cut equals to the total depth of cut and the number of pass is increased by one until reaching the number 100. By the given inputs, the number of passes are changed from 1 to 100. The number 100 can be changed to any number that is wanted to be examined.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	0	0	1																			
2	0	1	1																			
3	1	0	1																			
4	1	1	1																			
5																						
6	0.4	1	0.2	35.12173	67.41457		3	1	0.2	74.9358	2.294993		0.4	1	0.2	35.12173	1.025862		4	1	0.2	84.00073
7	0.4	2	0.1	38.09304	125.012		3	2	0.1	80.93637	4.249703		0.4	2	0.1	37.93415	1.899617		4	2	0.1	90.72719
8	0.4	3	0.066667	39.90411	179.3414		3	3	0.066667	84.66632	6.093702		0.4	3	0.066667	39.68234	2.723884		4	3	0.066667	94.90835
9	0.4	4	0.05	41.22903	231.6531		3	4	0.05	87.41709	7.869294		0.4	4	0.05	40.9716	3.517574		4	4	0.05	97.99188
10	0.4	5	0.04	42.28177	282.5144		3	5	0.04	89.61162	9.595695		0.4	5	0.04	42.00016	4.289275		4	5	0.04	100.4519
11	0.4	6	0.033333	43.15913	332.249		3	6	0.033333	91.44575	11.28388		0.4	6	0.033333	42.8598	5.043894		4	6	0.033333	102.5079
12	0.4	7	0.028571	43.91352	381.066		3	7	0.028571	93.02575	12.94093		0.4	7	0.028571	43.60033	5.784596		4	7	0.028571	104.279
13	0.4	8	0.025	44.57663	429.111		3	8	0.025	94.41645	14.57179		0.4	8	0.025	44.25214	6.513591		4	8	0.025	105.8379
14	0.4	9	0.022222	45.16914	476.4912		3	9	0.022222	95.66038	16.1801		0.4	9	0.022222	44.83516	7.232502		4	9	0.022222	107.2324
15	0.4	10	0.02	45.70533	523.2884		3	10	0.02	96.787	17.76862		0.4	10	0.02	45.3632	7.942571		4	10	0.02	108.4953
16	0.4	11	0.018182	46.19548	569.5674		3	11	0.018182	97.81758	19.33955		0.4	11	0.018182	45.84622	8.64478		4	11	0.018182	109.6505
17	0.4	12	0.016667	46.64727	615.3804		3	12	0.016667	98.768	20.89468		0.4	12	0.016667	46.29167	9.33992		4	12	0.016667	110.7159
18	0.4	13	0.015385	47.06655	660.7705		3	13	0.015385	99.65046	22.43545		0.4	13	0.015385	46.70527	10.02864		4	13	0.015385	111.7051
19	0.4	14	0.014286	47.45793	705.7737		3	14	0.014286	100.4745	23.96309		0.4	14	0.014286	47.0915	10.7115		4	14	0.014286	112.6288
20	0.4	15	0.013333	47.82508	750.4208		3	15	0.013333	101.2478	25.47864		0.4	15	0.013333	47.45394	11.38895		4	15	0.013333	113.4957
21	0.4	16	0.0125	48.17098	794.7379		3	16	0.0125	101.9766	26.983		0.4	16	0.0125	47.7955	12.0614		4	16	0.0125	114.3126
22	0.4	17	0.011765	48.49809	838.7481		3	17	0.011765	102.6659	28.47694		0.4	17	0.011765	48.11859	12.72919		4	17	0.011765	115.0853
23	0.4	18	0.011111	48.80844	882.4712		3	18	0.011111	103.3201	29.96114		0.4	18	0.011111	48.4252	13.39263		4	18	0.011111	115.8187
24	0.4	19	0.010526	49.10378	925.9251		3	19	0.010526	103.9428	31.4362		0.4	19	0.010526	48.71704	14.05198		4	19	0.010526	116.5167
25	0.4	20	0.01	49.38555	969.1254		3	20	0.01	104.5369	32.90265		0.4	20	0.01	48.99552	14.70748		4	20	0.01	117.1827
26	0.4	21	0.009524	49.65503	1012.086		3	21	0.009524	105.1053	34.36097		0.4	21	0.009524	49.26189	15.35935		4	21	0.009524	117.8198
27	0.4	22	0.009091	49.91329	1054.82		3	22	0.009091	105.65	35.8116		0.4	22	0.009091	49.51722	16.00778		4	22	0.009091	118.4305
28	0.4	23	0.008696	50.16128	1097.339		3	23	0.008696	106.1732	37.25491		0.4	23	0.008696	49.76243	16.65294		4	23	0.008696	119.0169
29	0.4	24	0.008333	50.39985	1139.652		3	24	0.008333	106.6766	38.69126		0.4	24	0.008333	49.99834	17.29499		4	24	0.008333	119.5812
30	0.4	25	0.008	50.6297	1181.77		3	25	0.008	107.1616	40.12098		0.4	25	0.008	50.22567	17.93408		4	25	0.008	120.1249
31	0.4	26	0.007692	50.8515	1223.701		3	26	0.007692	107.6297	41.54435		0.4	26	0.007692	50.44506	18.57032		4	26	0.007692	120.6496
32	0.4	27	0.007407	51.06583	1265.453		3	27	0.007407	108.082	42.96165		0.4	27	0.007407	50.65707	19.20386		4	27	0.007407	121.1566
33	0.4	28	0.007143	51.27319	1307.034		3	28	0.007143	108.5197	44.37313		0.4	28	0.007143	50.86221	19.83479		4	28	0.007143	121.6473

Figure 4.23 Combinations Sheet

At the Combinations Sheet, we can see the combinations table at the top left corner (Figure 4.23) and the results of the optimization for each run can be seen. On the example, assuming that we have 3 tools with D>D1>D2, the column A to E represents the first experiment of the smallest tool with the combination 001. Then, from G to K column, it is for the run of the second smallest tool D1. From column M to Q, it represents the D2's run for the second experiment. All the 1 values at the table at the left corner examined one by one and the results are pasted to the below in a sequence. For instance, from G to K column, they shows diameter, number of pass, axial depth of cut, cutting speed and the summation of actual machining time, and tool replacement time, respectively.

After finishing all the experiments for number of passes from 1 to 100, the software finds the minimum time for each experiment. The outputs are shown in the Results sheet (Figure 4.24). The meaning of the columns are diameter, number of pass, ap value, optimal cutting speed, summation of actual machining time and tool replacement time, tool change time and the immersion ratio for the smaller tools, respectively. There is one line gap to separate the experiments from each other.



	A	B	C	D	E	F	G
1	0.4	1	0.2	35.12173	67.41457		
2							
3	3	1	0.2	74.9358	2.294993		
4	0.4	1	0.2	35.12173	1.025862	5	0.5
5							
6	4	1	0.2	84.00073	1.440357		
7	0.4	1	0.2	35.12173	1.637127	5	0.5
8							
9	4	1	0.2	84.00073	1.440357		
10	3	1	0.2	74.9358	0.089101		0.5
11	0.4	1	0.2	35.12173	1.025862	10	0.5

Figure 4.24 Results sheet of the software

From the Figure 4.24 and Table 4, it can be realized that the suitable combination which gives the minimum time is with the combinations of 4 and 0.4 mm tools. The total time of the third experiment is 8.08 min. The summary of the results can be seen in Table 4. From the given table, it can be said that the min time of production can be satisfied when only two tools with diameters 4, 0.4 mm are used with the one pass and for the diameter 4, the optimal cutting speed is 84 m/min and for the tool having diameter 0.4 mm, the optimal cutting speed equals to 35.12. However, if the tool change time equals to zero meaning that the automated machined are used, the tools with the diameters 4, 3, and 0.4 mm will give the minimum time of production.

Table 4. Summary of the results sheet

Experiment number	D (mm)	number of pass	ap (mm)	Immersion ratio	V (m/min)	Total machining time + Tool rep. time	Tool change time	Total production time (min)
1	0.4	1	0.2	0.5	35.12	67.41		**67.41**
	3	1	0.2	0.5	74.94	2.29		
2	0.4	1	0.2	0.5	35.12	1.03	5	**8.32**
	4	1	0.2	0.5	84.00	1.44		
3	0.4	1	0.2	0.5	35.12	1.64	5	**8.08**
	4	1	0.2	0.5	84.00	1.44		
	3	1	0.2	0.5	74.94	0.09		
4	0.4	1	0.2	0.5	35.12	1.03	10	**12.56**

When the objective function is considered as finding the total production cost of one pocket which includes total cost of tools, machining cost, tool change cost, and tool replacement cost. It is assumed that the tool's cost can be calculated with the Equation (4.27). The values of the diameters 0.4 and 4 mm are found in the booklet and it is assumed that there is a linear trend. Thus, the cost of tool having diameter 0.4 mm equals to 50$ and 4 mm tool's cost equals to 25$. The other tools cost changes with the linear trend. The cost of using machine is assumed as 15$/hour (co). The tool change cost can be calculated with the Equation (4.28). Thus, the results of the given example can be seen in Table 5. It can be realized that using all the tools are less costly but it takes longer time to produce the pocket. Hence, depending on the preference of the user the best combination can be chosen.

$$Tool\ cost = -6.9444D + 52.778 \qquad (4.27)$$

$$Tool\ change\ cost = co.T_c(number\ of\ different\ tools\ used - 1) \qquad (4.28)$$

Table 5. Summary of the cost of the problem

Experiment number	D (mm)	Total Cost of tools ($)	Machining cost ($)	Tool change cost ($)	Tool replacement cost ($)	Total production cost ($)
1	**0.4**	593.09	2.03	0	14.83	**609.94**
2	**3**	7.24	0.29	1.25	0.28	**18.35**
	0.4	9.03	0.03		0.23	
3	**4**	3.04	0.21	1.25	0.15	**19.47**
	0.4	14.40	0.05		0.36	
4	**4**	3.04	0.21	2.5	0.15	**15.49**
	3	0.28	0.01		0.01	
	0.4	9.03	0.03		0.23	

4.5 Summary of Findings

In this chapter, first, literature survey on triangular pocket machining problems is presented. Machining of the sharp corner equilateral triangle pocket is taken as a problem. For the multi-tool multi-pass problem, the decision procedure is expressed. The tool path length calculations and the mathematical model are presented. The corner machining is described in details. The pockets are machined with different tool combinations and found the optimal cutting speed for each tool and the optimal combinations of the tools are found by using the software program. It is realized that for the given example using largest tool and then the smallest tool gives the shortest production time; however, it is more costly than using all three of the tools for the production. Hence, it can be said that there can be some tradeoffs between time and cost of production.

An important feature of the software is that, for different diameters, the optimal production time is found by considering different number of passes, and the different combinations of the tools. All the combinations of the tools are examined. The results of the experiments can be seen one by one. Micro milling process planning for multiple tool cases can be made through the developed model.

Chapter 5

A 2.5 D Micro Milling Application: Fabrication of Micro Needle Arrays

In some cases, depending on the finish goods properties, some islands can be created on the work pieces that are the parts not machined with the cutting tools. One of the examples of it can be seen on the roughing processes of the pyramid (Figure 5.1). On each layer of the production, different sizes of islands are created in order to create the pyramid.

In this chapter, the multi-pass problem with different size of islands is studied. In each pass of the tool, different size of square islands are created. Thus, the mathematical model is defined and to find the total tool path length, the calculation strategy is presented. The tool path generation strategy for the roughing processes are defined. First of all, the literature about the micro needle is summarized. Then, the tool path generation strategies for the layers and the mathematical model to calculate the length of it are defined.

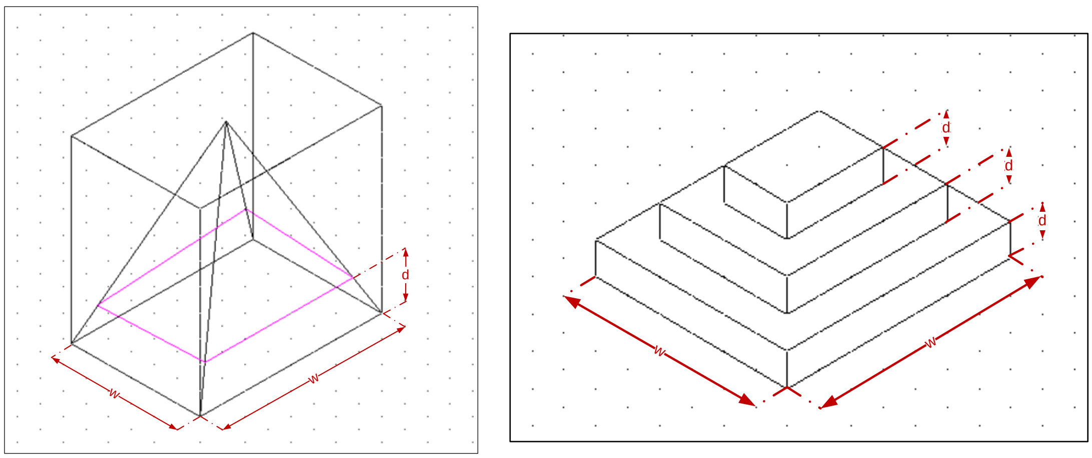


Figure 5.1 Representation of the micro needles and its layers after the roughing process

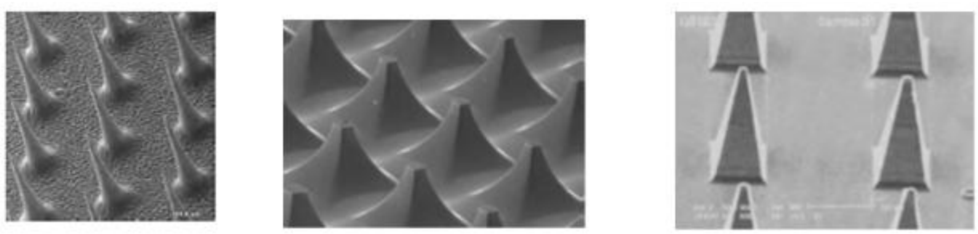
5.1 Literature Review

In the thesis of Roxhed, the research about the micro needles as a drug delivery system is given. The roles of the micro needles are discussed in detail. Different micro needle types and the applications are mentioned.[43]

It is mentioned that to penetrate the skin layer, different types of the micro needles are used. Because of being short, these needles do not reach to the nerve-rich regions of the skins. Thus, the insertion is weak and painless. Unlike traditional transdermal patches, these days, the micro needles based patches enable to offer delivering any macro molecular drugs like vaccines and insulin and patient friendly drug administration system with less involvement of the professional. [43]

The MEMS (Microelectromechanical Systems) are "devices with sub-millimeter features". They can be used as a variety of sensors to control fluid eg. flows, pressure.[43]

In the literature, there are different types of micro needles for different purposes, solid micro needles, hollow type micro needles (Figure 5.2). One of the examples is the hollow micro needle which is used for drug delivery system (Figure 5.3). For the painless transfer of liquid, it is important to fabricate the hollow micro needle as sharp as possible and mechanically strong. Thus, the study of Gardeniers et al. presents the improved design and fabrication process of the hollow micro needles. [44]



(a) (b) (c)

Figure 5.2 (a) Transdermal drug delivery application [43, 45] (b) Used to scrape the skin to deliver DNA vaccine [43, 46] (c) 250 µm polymer microneedles being tested for vaccine delivery [43, 47]

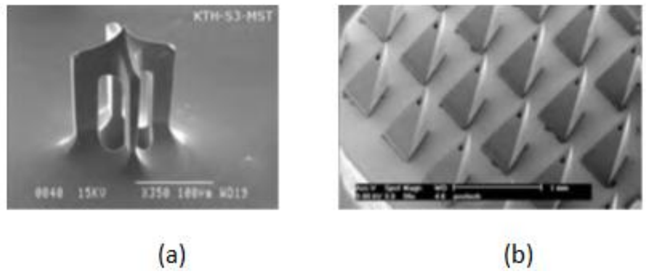


Figure 5.3 (a) Hollow type silicon micro needle [43, 48] (b) polymethyl methacrylate micro needle [43, 49]

Roxhed et al. also study the hollow type micro needles. They machine the sharp micro needles and form the patch-like drug delivery system (Figure 5.4). With the finger force, the needles can be attached to the skin and it is electrically controlled with low-cost dosing and actuation unit. [50]

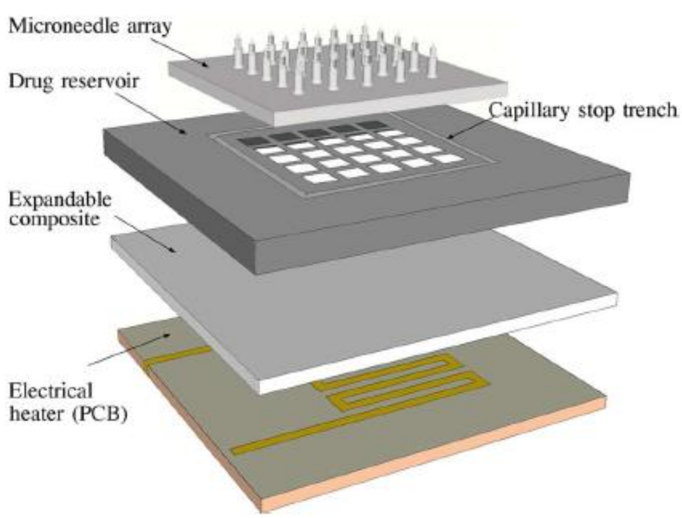


Figure 5.4 View of the micro needle drug delivery system [50]

The other application of the micro needles is to enhance the brightness of LCD's, personal TVs and camcorders. Thus, the plastic micro pyramids are used for this purpose. [51] The shapes of the pyramids can be seen in Figure 5.5.

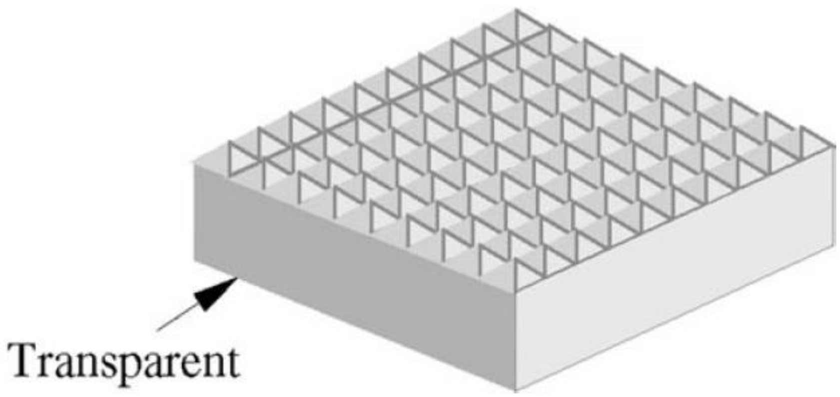


Figure 5.5 Micro pyramids illustration [51]

5.2 Mathematical Modeling

In order to machine the micro needle, first of all, the tool path generation strategy is defined and then the tool path length is calculated by using this strategy. After that, the mathematical model is defined.

As an assumption, single tool diameter is used for the roughing processes. Only roughing processes are taken into consideration. In order to generalize and understand the production strategy, it is started from the bottom level with the depth of cut d and it goes to upper layers with d amount thickness. The layer by layer production is considered and the pyramid is considered as right angle pyramid; hence, the layers will be created upward. The distances between the layers are about d which equals to the depth of cut at each layer. The 3D representation of the layers can be seen in Figure 5.6

and the front view can be seen in Figure 5.7. The other assumptions of the problem are that the axial depth of cut is considered as constant for all passes equivalent to d. The number of passes, m (h/d), is an integer number. Moreover, the optimization is considered for 100% immersion case and on air movements are ignored while writing the objective function.

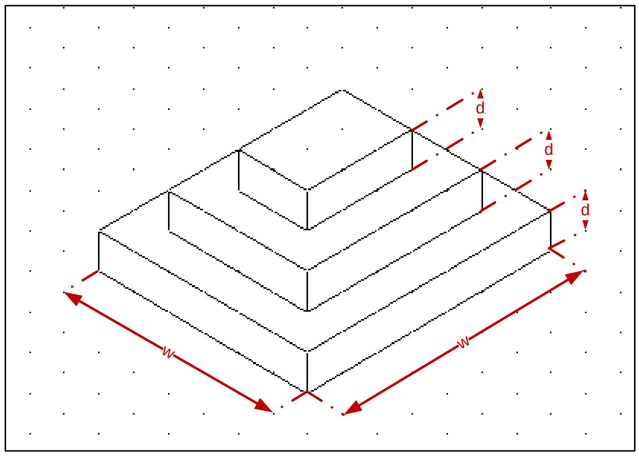


Figure 5.6 Layers of the micro needle

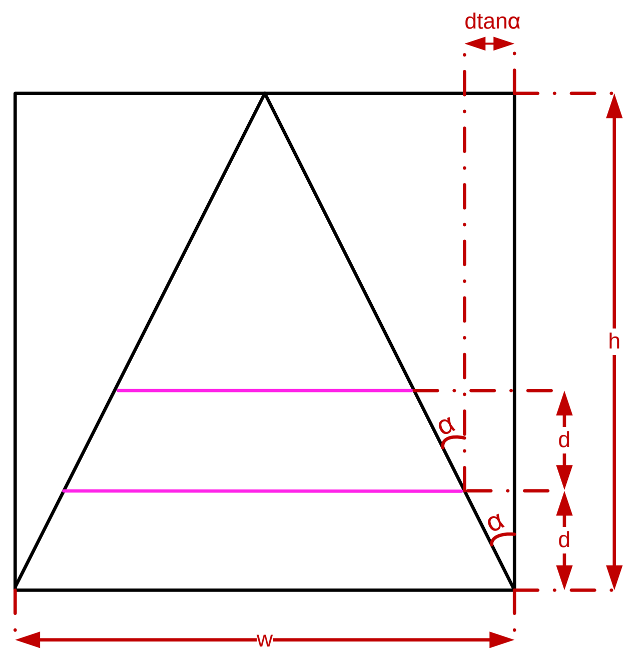


Figure 5.7 Front view of the micro needle

The additional notations and the changes to the expressions given on the Chapter 3 with their units and their illustrations can be listed as:

$D: diameter\ of\ tool\ (mm)$

$w: island\ edge\ length\ (mm)$

$a: pocket\ edge\ length\ (mm)$

$h: height\ of\ the\ pyramid\ (mm)$

$k: length\ of\ the\ tool\ cutting\ edge\ (mm)$

$d: axial\ depth\ of\ cut\ (mm)$

$m: number\ of\ passes\ to\ manufacture\ the\ whole\ pyramid\ (m = h/d)$

$n_i: number\ of\ tours\ for\ pass\ i, i = 1, \dots, m$

The objective is to minimize the total production time. The aim is to cut the material as fast as possible by considering the tool life, machine properties, and satisfying the properties of the pyramid. After the rough cut operation, there will be the finishing operation; hence, it is important to have fewer materials to be processed in final operation so as to focus more on the quality of the product.

The total production time can be calculated as the summation of machining time to produce one part (T_m), material handling including setup (T_h), and tool replacement time per part (T_r / n_p).

Tool handling time is constant; hence, it is not considered while optimizing the problem. Furthermore, n_p equals to tool life (T) divided into machining time (T_m). The extended Taylor's tool life equation given in the paper of Armarego et al. for end milling is generalized and the used tool life equation can be seen in Equation (5.1). [1]

$$T = \frac{C}{V^{\alpha} f^{\beta} {a_p}^{\gamma} {a_e}^{\varepsilon}} \tag{5.1}$$

There is m (h/d) number of passes to produce the pyramid which gives the number of layers. Hence, the total tool path length while machining the layers can be calculated by considering the layers individually. It is started from bottom island to create. In the last pass, the island's edge length is $w - 2mdtan\alpha$, and in the first pass the edge length of the island becomes w.

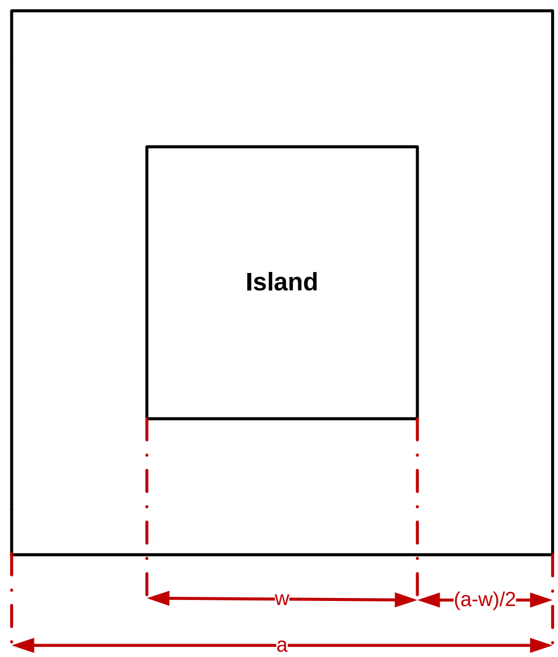


Figure 5.8 Up view of the lowest layer

The first layer's representation can be seen in Figure 5.8. The first tour's tool path is shown in Figure 5.9. In the first tour of the tool, tool path length can be calculated as $4(a - D) + D\sqrt{2}$. The edge length of the square path is$(a - D)$. The length of tool movement to inward through the island in order to create the second tour is about $D\sqrt{2}$. The inward movement of the tool can be seen in Figure 5.10. The second tour of the tool equals to $4(a - 3D) + D\sqrt{2}$ and its representation can be seen in Figure 5.11.

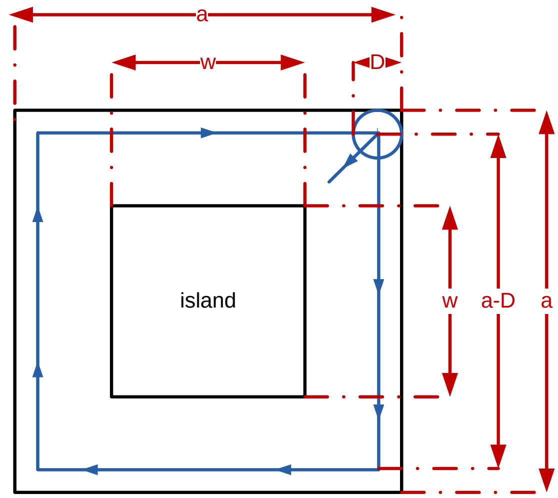


Figure 5.9 First tour of the tool

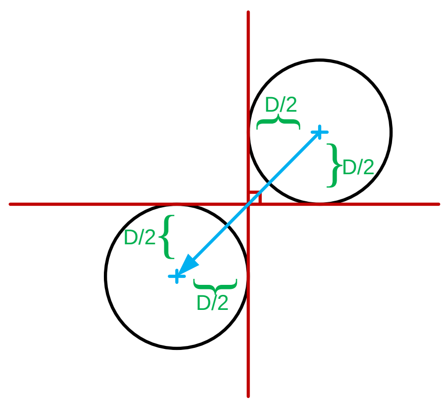


Figure 5.10 Movement of the tool from corner to inside

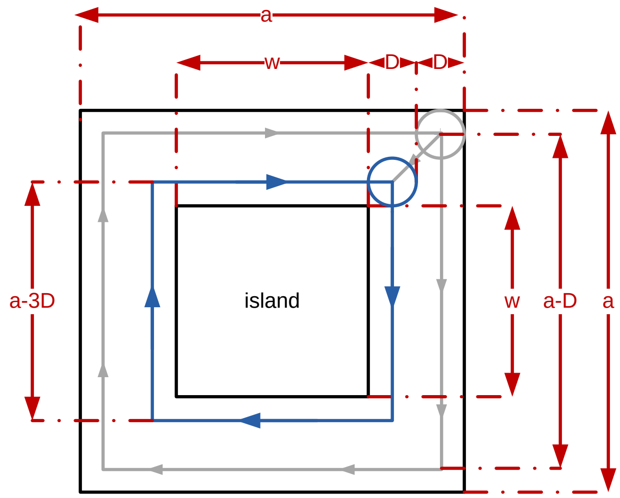


Figure 5.11 Second tour of the tool

The generalized form of the tool path for one pass can be expressed with these formulas. The calculation of the number of tours can be seen in Equation (5.2). The total tool path length for the first pass can be calculated as shown in Equation (5.3).

$$\boldsymbol{n_1} = \frac{\left(\frac{a}{2}-\frac{w}{2}-D\right)}{D} \tag{5.2}$$

$$\boldsymbol{L_{total1}} = (\lfloor n \rfloor)D\sqrt{2} + \sum_{i=1}^{\lfloor n \rfloor} 4(a-(2i-1)D) + (n-\lfloor n \rfloor)D\sqrt{2} + 4(w+D)(\lceil n \rceil - \lfloor n \rfloor) \tag{5.3}$$

The tool moves inward $D\sqrt{2}$ amount in each tour and creates a square path. If the number of tour is the decimal number, then the last tour cannot be machined with 100% immersion. Thus, the last tour's tool path length can be calculated as $(n-\lfloor n \rfloor)D\sqrt{2}+$

$4(w + D)(\lceil n \rceil - \lfloor n \rfloor)$. The tool moves inward less than $D\sqrt{2}$. The representation of the last tour can be seen in Figure 5.12.

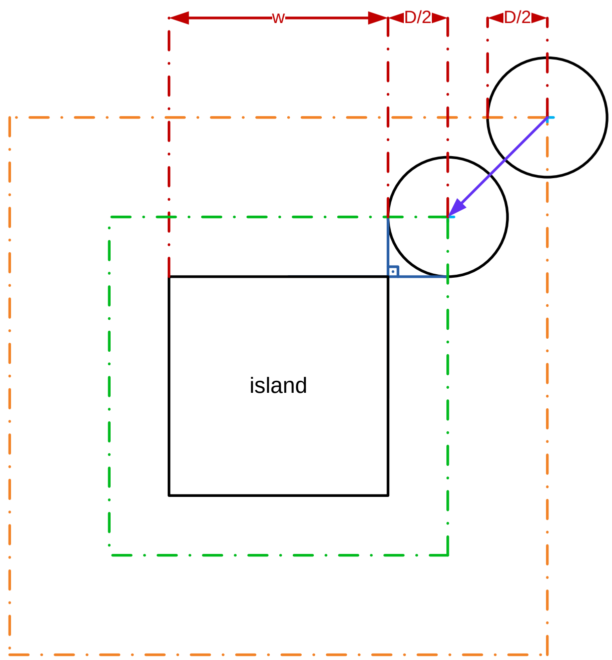


Figure 5.12 Last tour of the tool

After finishing to machine the first layer, the tool moves rapidly to the corner of the pocket. Then, it starts to machine the second layer. The representation of the second layer can be seen in Figure 5.13.

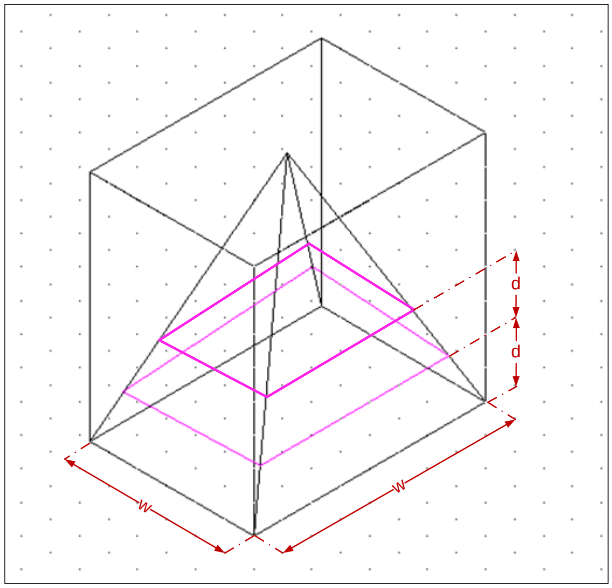


Figure 5.13. 3D view of the second pass

The island edge length from each side will decrease dtanα amount. Hence, the island edge length of the second pass becomes $w - 2dtan\alpha$ (Figure 5.14).

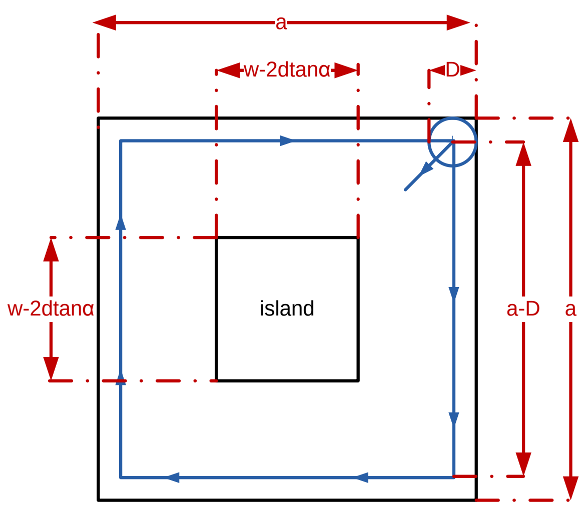


Figure 5.14 Second layer's first tour

In the first tour of the second pass, the tool path length is $4(a-D)+D\sqrt{2}$. The second tour of the tool equals to $(a-3D)+D\sqrt{2}$, which are same as the first pass' first and second tour. The generalized formula for the tour can be expressed as Equation (5.4) and the total tool path length can be written as in Equation (5.5). In each tour, the tool moves inward $D\sqrt{2}$ amount. Then, the square tool path is created. If n is the decimal number, last tour will be created with less than 100% immersion. $4(w-2d\tan\alpha+D)(\lceil n\rceil-\lfloor n\rfloor)$ part of the Equation (5.5) is for the case of number of tours being decimal number. The representation of the last tour can be seen in Figure 5.15.

$$\boldsymbol{n_2} = \frac{\left(\frac{a}{2}-\frac{w-2dtan\alpha}{2}-D\right)}{D} \tag{5.4}$$

$$\boldsymbol{L_{total2}} = (\lfloor n\rfloor)D\sqrt{2}+\sum_{i=1}^{\lfloor n\rfloor}4(a-(2i-1)D)+(n-\lfloor n\rfloor)D\sqrt{2}+4(w-2d\tan\alpha+ D(n-n) \tag{5.5}$$

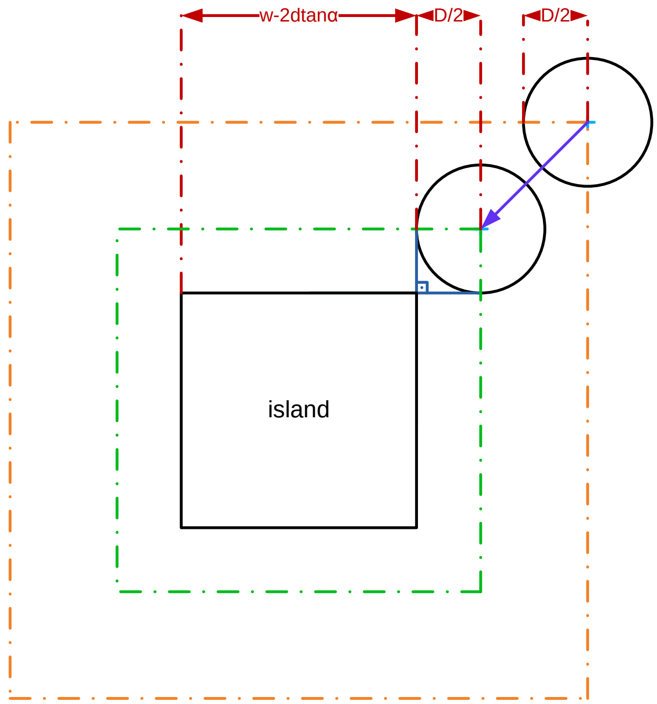


Figure 5.15 Last tour of the second pass

The tour numbers for pass j can be defined as Equation (5.6).

$$\boldsymbol{n_j} = \frac{\left(\frac{a}{2} - \frac{w-2(j-1)dtan\alpha}{2} - D\right)}{D}, j = 1,2 \ldots, m \tag{5.6}$$

The generalized tool path length for pass j can be seen in Equation (5.7). For each pass, the total tool path length of the pass is calculated.

$$\boldsymbol{L_{total}} = \sum_{j=1}^{m}\Big[\big(\lfloor n_j \rfloor D\sqrt{2}\big) + \sum_{i=1}^{\lfloor n_j \rfloor}(4(a-(2i-1)D) + +\big(n_j - \lfloor n_j \rfloor\big)D\sqrt{2} + 4w-2j-1d\tan\alpha+Dnj-nj \quad (5.7)$$

The actual machining time is obtained by dividing tool path length into cutting speed (Equation (5.8)) and the total production time can be calculated by the summation of the actual machining time, tool replacement time and material handling time, which can be seen in Equation (5.9). The constraints and the limitations of the problem are that the first tour of the first pass is created which can be seen in inequality (5.10). The tool ought to fit the area between the island and the edge of the whole pocket. Furthermore, the tool cutter should be equal or larger than the axial depth of cut in order to cut the material (5.11). Number of pass is the integer number (5.12). Inequalities (5.13) and (5.14) represent the limitation of the machine.

$$\boldsymbol{T_m} = \frac{L_{total}}{v} \quad (5.8)$$

$$\boldsymbol{T_{tot}} = T_m + \frac{T_r T_m}{T} + T_h \quad (5.9)$$

$$\frac{a-w}{2} - D \geq D \quad (5.10)$$

$$d \leq k \quad (5.11)$$

$$m \ is \ integer \quad (5.12)$$

$$V_0 \leq V \leq V_1 \quad (5.13)$$

$$f_0 \leq f \leq f_1 \quad (5.14)$$

Thus, in this problem, the only decision variable is the cutting speed and it is known that the objective function is coercive, continuous and differentiable. First, it is thought that the problem does not have any constraints. Then, by taking the first derivative of the objective function we can find the optimal cutting speed. After finding the optimal cutting speed, it is checked whether the given constraints can be satisfied. If the constraint of the cutting speed is not satisfied, for the corner values of the constraint the total production time is calculated.

5.3 Summary of Findings

In this chapter, first, the literature review about the micro needle is given. In the literature, different type of the micro needles are defined; however, there is no study on manufacturing optimization of the micro needles. A milling strategy to produce micro needles is proposed and the tool path length formulation is given. With this algorithm, lengthy micro needle array machining can be optimized. However, some other milling strategies considering the structure of micro needles must be further developed. It is left as a future study.

Chapter 6

Conclusion and Future Work

In this thesis, the single and multi tool cases for single and multi pass milling problems are examined and micro milling of basic types of the pockets are studied in detail. For the single tool case, the objective function of the problem is considered as the minimum total production time and the cutting speed is considered as an independent variable. Another objective is also defined which is related to machining of a complete pocket with a single tool. Therefore, milling optimization is adapted to specific needs of micro milling process. It is shown that complex shaped 2D molds can be modeled by using the proposed mathematical models without having to use any computer aided manufacturing (CAM) software. For the multiple tool case, first the combinations of the tools are created and the optimal cutting speeds and the total production times for each combination are calculated. A software module is developed which helps to calculate the total production time and investigate different alternative solutions to the problem. The cost of the production is also investigated. By using illustrative example, it is realized that the time and the cost problems can give different solutions. Hence, depending on the expectations of the user of the model, different alternatives can be chosen. For the complex shaped 2.5D pockets, the micro needle production is taken into consideration. The objective is to minimize the total production time of one micro needle. As a strategy, layer by layer production of the micro needle is considered. It is shown that 2D pocket modeling can be extended to 2.5D pocket milling cases.

As a future work, the pocketing strategies can be improved for different shapes of pockets. In this thesis, simple constraints are used. Physics of the process including tool and workpiece material properties can be included in the optimization algorithm. Tool life equation is important in terms of optimization of cutting speed and other machining parameters. However, obtaining a reliable tool life equation requires a lot of experimentation and tool life is rarely deterministic. Therefore, probabilistic approaches for tool life and surface quality prediction can be considered.

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Appendix

Appendix 1: Results of two circular pocket's cutting speed change analysis

V (m/min)	Total production time (min)	Machining time (min)	Tool replacement time (min)	Tool life (min)
20	0.3616	0.2492	0.1125	11.0797
21	0.3517	0.2373	0.1143	10.3776
22	0.3427	0.2265	0.1162	9.7497
23	0.3346	0.2167	0.1180	9.1852
24	0.3273	0.2077	0.1197	8.6754
25	0.3207	0.1993	0.1214	8.2130
26	0.3147	0.1917	0.1230	7.7920
27	0.3092	0.1846	0.1246	7.4073
28	0.3041	0.1780	0.1262	7.0545
29	0.2995	0.1719	0.1277	6.7301
30	0.2953	0.1661	0.1292	6.4308
31	0.2914	0.1608	0.1306	6.1540
32	0.2878	0.1557	0.1320	5.8974
33	0.2845	0.1510	0.1334	5.6589
34	0.2814	0.1466	0.1348	5.4367
35	0.2785	0.1424	0.1361	5.2293
36	0.2759	0.1384	0.1375	5.0353
37	0.2734	0.1347	0.1388	4.8536
38	0.2712	0.1311	0.1400	4.6830
39	0.2691	0.1278	0.1413	4.5226
40	0.2671	0.1246	0.1425	4.3716
41	0.2653	0.1216	0.1437	4.2291
42	0.2636	0.1187	0.1449	4.0946
43	0.2620	0.1159	0.1461	3.9673
44	0.2605	0.1133	0.1472	3.8468
45	0.2591	0.1107	0.1484	3.7325
46	0.2578	0.1083	0.1495	3.6241
47	0.2566	0.1060	0.1506	3.5210
48	0.2555	0.1038	0.1517	3.4229
49	0.2544	0.1017	0.1527	3.3295
50	0.2535	0.0997	0.1538	3.2405
51	0.2526	0.0977	0.1548	3.1555
52	0.2517	0.0958	0.1559	3.0744
53	0.2509	0.0940	0.1569	2.9968
54	0.2502	0.0923	0.1579	2.9226
55	0.2495	0.0906	0.1589	2.8515

V (m/min)	Total production time (min)	Machining time (min)	Tool replacement time (min)	Tool life (min)
56	0.2489	0.0890	0.1599	2.7834
57	0.2483	0.0874	0.1608	2.7181
58	0.2477	0.0859	0.1618	2.6554
59	0.2472	0.0845	0.1627	2.5952
60	0.2467	0.0831	0.1637	2.5373
61	0.2463	0.0817	0.1646	2.4817
62	0.2459	0.0804	0.1655	2.4281
63	0.2455	0.0791	0.1664	2.3765
64	0.2452	0.0779	0.1673	2.3269
65	0.2449	0.0767	0.1682	2.2789
66	0.2446	0.0755	0.1691	2.2327
67	0.2444	0.0744	0.1700	2.1881
68	0.2441	0.0733	0.1708	2.1451
69	0.2439	0.0722	0.1717	2.1035
70	0.2437	0.0712	0.1725	2.0633
71	0.2436	0.0702	0.1734	2.0244
72	0.2434	0.0692	0.1742	1.9867
73	0.2433	0.0683	0.1750	1.9503
74	0.2432	0.0673	0.1758	1.9150
75	0.2431	0.0664	0.1766	1.8808
76	0.2430	0.0656	0.1774	1.8477
77	0.2430	0.0647	0.1782	1.8156
78	0.2429	0.0639	0.1790	1.7844
79	0.2429	0.0631	0.1798	1.7542
80	0.2429	0.0623	0.1806	1.7248
81	0.2429	0.0615	0.1814	1.6963
82	0.2429	0.0608	0.1821	1.6686
83	0.2429	0.0600	0.1829	1.6417
84	0.2430	0.0593	0.1836	1.6155
85	0.2430	0.0586	0.1844	1.5901
86	0.2431	0.0579	0.1851	1.5653
87	0.2431	0.0573	0.1858	1.5412
88	0.2432	0.0566	0.1866	1.5178
89	0.2433	0.0560	0.1873	1.4949
90	0.2434	0.0554	0.1880	1.4727
91	0.2435	0.0548	0.1887	1.4510

V (m/min)	Total production time (min)	Machining time (min)	Tool replacement time (min)	Tool life (min)
92	0.2436	0.0542	0.1894	1.4299
93	0.2437	0.0536	0.1901	1.4093
94	0.2438	0.0530	0.1908	1.3892
95	0.2440	0.0525	0.1915	1.3696
96	0.2441	0.0519	0.1922	1.3505
97	0.2443	0.0514	0.1929	1.3319
98	0.2444	0.0509	0.1936	1.3137
99	0.2446	0.0503	0.1942	1.2959
100	0.2447	0.0498	0.1949	1.2786
101	0.2449	0.0493	0.1956	1.2616
102	0.2451	0.0489	0.1962	1.2450
103	0.2453	0.0484	0.1969	1.2288
104	0.2454	0.0479	0.1975	1.2130
105	0.2456	0.0475	0.1982	1.1975
106	0.2458	0.0470	0.1988	1.1824
107	0.2460	0.0466	0.1995	1.1676
108	0.2462	0.0461	0.2001	1.1531
109	0.2464	0.0457	0.2007	1.1390
110	0.2467	0.0453	0.2013	1.1251
111	0.2469	0.0449	0.2020	1.1115
112	0.2471	0.0445	0.2026	1.0982
113	0.2473	0.0441	0.2032	1.0852
114	0.2475	0.0437	0.2038	1.0724
115	0.2478	0.0433	0.2044	1.0599
116	0.2480	0.0430	0.2050	1.0477
117	0.2482	0.0426	0.2056	1.0357
118	0.2485	0.0422	0.2062	1.0239
119	0.2487	0.0419	0.2068	1.0124
120	0.2490	0.0415	0.2074	1.0011
121	0.2492	0.0412	0.2080	0.9900
122	0.2494	0.0408	0.2086	0.9792
123	0.2497	0.0405	0.2092	0.9685
124	0.2499	0.0402	0.2098	0.9580
125	0.2502	0.0399	0.2103	0.9478
126	0.2505	0.0396	0.2109	0.9377
127	0.2507	0.0392	0.2115	0.9278

V (m/min)	Total production time (min)	Machining time (min)	Tool replacement time (min)	Tool life (min)
128	0.2510	0.0389	0.2120	0.9181
129	0.2512	0.0386	0.2126	0.9085
130	0.2515	0.0383	0.2132	0.8992
131	0.2518	0.0380	0.2137	0.8900
132	0.2520	0.0378	0.2143	0.8809
133	0.2523	0.0375	0.2148	0.8721
134	0.2526	0.0372	0.2154	0.8633
135	0.2529	0.0369	0.2159	0.8548
136	0.2531	0.0366	0.2165	0.8464
137	0.2534	0.0364	0.2170	0.8381
138	0.2537	0.0361	0.2176	0.8299
139	0.2540	0.0359	0.2181	0.8219
140	0.2542	0.0356	0.2186	0.8141
141	0.2545	0.0353	0.2192	0.8063
142	0.2548	0.0351	0.2197	0.7987
143	0.2551	0.0349	0.2202	0.7912
144	0.2554	0.0346	0.2208	0.7839
145	0.2556	0.0344	0.2213	0.7766
146	0.2559	0.0341	0.2218	0.7695
147	0.2562	0.0339	0.2223	0.7625
148	0.2565	0.0337	0.2228	0.7556
149	0.2568	0.0334	0.2233	0.7488
150	0.2571	0.0332	0.2239	0.7421
151	0.2574	0.0330	0.2244	0.7355
152	0.2577	0.0328	0.2249	0.7290
153	0.2579	0.0326	0.2254	0.7226
154	0.2582	0.0324	0.2259	0.7163
155	0.2585	0.0322	0.2264	0.7102
156	0.2588	0.0319	0.2269	0.7041
157	0.2591	0.0317	0.2274	0.6980
158	0.2594	0.0315	0.2279	0.6921
159	0.2597	0.0313	0.2284	0.6863
160	0.2600	0.0311	0.2288	0.6805
161	0.2603	0.0310	0.2293	0.6749
162	0.2606	0.0308	0.2298	0.6693
163	0.2609	0.0306	0.2303	0.6638

V (m/min)	Total production time (min)	Machining time (min)	Tool replacement time (min)	Tool life (min)
164	0.2612	0.0304	0.2308	0.6584
165	0.2615	0.0302	0.2313	0.6530
166	0.2618	0.0300	0.2317	0.6477
167	0.2621	0.0298	0.2322	0.6425
168	0.2624	0.0297	0.2327	0.6374
169	0.2627	0.0295	0.2332	0.6324
170	0.2630	0.0293	0.2336	0.6274
171	0.2633	0.0291	0.2341	0.6225
172	0.2635	0.0290	0.2346	0.6176
173	0.2638	0.0288	0.2350	0.6128
174	0.2641	0.0286	0.2355	0.6081
175	0.2644	0.0285	0.2360	0.6034
176	0.2647	0.0283	0.2364	0.5988
177	0.2650	0.0282	0.2369	0.5943
178	0.2653	0.0280	0.2373	0.5898
179	0.2656	0.0278	0.2378	0.5854
180	0.2659	0.0277	0.2382	0.5811
181	0.2662	0.0275	0.2387	0.5768
182	0.2665	0.0274	0.2391	0.5725
183	0.2668	0.0272	0.2396	0.5683
184	0.2671	0.0271	0.2400	0.5642
185	0.2674	0.0269	0.2405	0.5601
186	0.2677	0.0268	0.2409	0.5561
187	0.2680	0.0267	0.2414	0.5521
188	0.2683	0.0265	0.2418	0.5481
189	0.2686	0.0264	0.2423	0.5442
190	0.2689	0.0262	0.2427	0.5404
191	0.2692	0.0261	0.2431	0.5366
192	0.2695	0.0260	0.2436	0.5329
193	0.2698	0.0258	0.2440	0.5292
194	0.2701	0.0257	0.2444	0.5255
195	0.2704	0.0256	0.2449	0.5219
196	0.2707	0.0254	0.2453	0.5183
197	0.2710	0.0253	0.2457	0.5148
198	0.2713	0.0252	0.2461	0.5113
199	0.2716	0.0250	0.2466	0.5079
200	0.2719	0.0249	0.2470	0.5045

Appendix 2: Results of square pocket's cutting speed change analysis

V (m/min)	Total production time (min)	Total machining time (min)	Tool replacement time (min)	Tool life (min)
20	3.8142	2.6282	1.1860	11.0797
21	3.7090	2.5030	1.2060	10.3776
22	3.6145	2.3892	1.2253	9.7497
23	3.5294	2.2854	1.2440	9.1852
24	3.4524	2.1901	1.2623	8.6754
25	3.3825	2.1025	1.2800	8.2130
26	3.3189	2.0217	1.2973	7.7920
27	3.2609	1.9468	1.3141	7.4073
28	3.2078	1.8773	1.3305	7.0545
29	3.1591	1.8125	1.3466	6.7301
30	3.1144	1.7521	1.3623	6.4308
31	3.0732	1.6956	1.3776	6.1540
32	3.0353	1.6426	1.3927	5.8974
33	3.0002	1.5928	1.4074	5.6589
34	2.9678	1.5460	1.4218	5.4367
35	2.9378	1.5018	1.4360	5.2293
36	2.9099	1.4601	1.4498	5.0353
37	2.8841	1.4206	1.4635	4.8536
38	2.8601	1.3832	1.4769	4.6830
39	2.8378	1.3478	1.4900	4.5226
40	2.8171	1.3141	1.5030	4.3716
41	2.7978	1.2820	1.5157	4.2291
42	2.7798	1.2515	1.5283	4.0946
43	2.7630	1.2224	1.5406	3.9673
44	2.7474	1.1946	1.5527	3.8468
45	2.7328	1.1681	1.5647	3.7325
46	2.7192	1.1427	1.5765	3.6241
47	2.7065	1.1184	1.5881	3.5210
48	2.6947	1.0951	1.5996	3.4229
49	2.6836	1.0727	1.6109	3.3295
50	2.6733	1.0513	1.6221	3.2405
51	2.6637	1.0307	1.6331	3.1555
52	2.6548	1.0108	1.6440	3.0744
53	2.6465	0.9918	1.6547	2.9968
54	2.6387	0.9734	1.6653	2.9226
55	2.6315	0.9557	1.6758	2.8515

V (m/min)	Total production time (min)	Total machining time (min)	Tool replacement time (min)	Tool life (min)
56	2.6248	0.9386	1.6861	2.7834
57	2.6185	0.9222	1.6963	2.7181
58	2.6127	0.9063	1.7065	2.6554
59	2.6074	0.8909	1.7165	2.5952
60	2.6024	0.8761	1.7263	2.5373
61	2.5978	0.8617	1.7361	2.4817
62	2.5936	0.8478	1.7458	2.4281
63	2.5897	0.8343	1.7554	2.3765
64	2.5861	0.8213	1.7648	2.3269
65	2.5829	0.8087	1.7742	2.2789
66	2.5799	0.7964	1.7835	2.2327
67	2.5772	0.7845	1.7927	2.1881
68	2.5748	0.7730	1.8018	2.1451
69	2.5726	0.7618	1.8108	2.1035
70	2.5706	0.7509	1.8197	2.0633
71	2.5689	0.7403	1.8286	2.0244
72	2.5674	0.7300	1.8373	1.9867
73	2.5660	0.7200	1.8460	1.9503
74	2.5649	0.7103	1.8546	1.9150
75	2.5640	0.7008	1.8631	1.8808
76	2.5632	0.6916	1.8716	1.8477
77	2.5626	0.6826	1.8800	1.8156
78	2.5621	0.6739	1.8883	1.7844
79	2.5619	0.6654	1.8965	1.7542
80	2.5617	0.6570	1.9047	1.7248
81	2.5617	0.6489	1.9128	1.6963
82	2.5618	0.6410	1.9208	1.6686
83	2.5621	0.6333	1.9288	1.6417
84	2.5624	0.6258	1.9367	1.6155
85	2.5629	0.6184	1.9445	1.5901
86	2.5635	0.6112	1.9523	1.5653
87	2.5642	0.6042	1.9600	1.5412
88	2.5650	0.5973	1.9677	1.5178
89	2.5659	0.5906	1.9753	1.4949
90	2.5669	0.5840	1.9829	1.4727
91	2.5680	0.5776	1.9904	1.4510

V (m/min)	Total production time (min)	Total machining time (min)	Tool replacement time (min)	Tool life (min)
92	2.5692	0.5713	1.9978	1.4299
93	2.5704	0.5652	2.0052	1.4093
94	2.5718	0.5592	2.0126	1.3892
95	2.5732	0.5533	2.0199	1.3696
96	2.5746	0.5475	2.0271	1.3505
97	2.5762	0.5419	2.0343	1.3319
98	2.5778	0.5364	2.0414	1.3137
99	2.5795	0.5309	2.0485	1.2959
100	2.5812	0.5256	2.0556	1.2786
101	2.5830	0.5204	2.0626	1.2616
102	2.5849	0.5153	2.0695	1.2450
103	2.5868	0.5103	2.0764	1.2288
104	2.5887	0.5054	2.0833	1.2130
105	2.5907	0.5006	2.0901	1.1975
106	2.5928	0.4959	2.0969	1.1824
107	2.5949	0.4912	2.1036	1.1676
108	2.5970	0.4867	2.1103	1.1531
109	2.5992	0.4822	2.1170	1.1390
110	2.6015	0.4778	2.1236	1.1251
111	2.6037	0.4735	2.1302	1.1115
112	2.6060	0.4693	2.1367	1.0982
113	2.6084	0.4652	2.1432	1.0852
114	2.6108	0.4611	2.1497	1.0724
115	2.6132	0.4571	2.1561	1.0599
116	2.6156	0.4531	2.1625	1.0477
117	2.6181	0.4493	2.1689	1.0357
118	2.6206	0.4455	2.1752	1.0239
119	2.6232	0.4417	2.1815	1.0124
120	2.6257	0.4380	2.1877	1.0011
121	2.6283	0.4344	2.1939	0.9900
122	2.6309	0.4308	2.2001	0.9792
123	2.6336	0.4273	2.2062	0.9685
124	2.6363	0.4239	2.2124	0.9580
125	2.6389	0.4205	2.2184	0.9478
126	2.6417	0.4172	2.2245	0.9377
127	2.6444	0.4139	2.2305	0.9278

V (m/min)	Total production time (min)	Total machining time (min)	Tool replacement time (min)	Tool life (min)
128	2.6471	0.4107	2.2365	0.9181
129	2.6499	0.4075	2.2424	0.9085
130	2.6527	0.4043	2.2484	0.8992
131	2.6555	0.4012	2.2543	0.8900
132	2.6583	0.3982	2.2601	0.8809
133	2.6612	0.3952	2.2660	0.8721
134	2.6640	0.3923	2.2718	0.8633
135	2.6669	0.3894	2.2775	0.8548
136	2.6698	0.3865	2.2833	0.8464
137	2.6727	0.3837	2.2890	0.8381
138	2.6756	0.3809	2.2947	0.8299
139	2.6785	0.3782	2.3004	0.8219
140	2.6815	0.3755	2.3060	0.8141
141	2.6844	0.3728	2.3116	0.8063
142	2.6874	0.3702	2.3172	0.7987
143	2.6904	0.3676	2.3228	0.7912
144	2.6934	0.3650	2.3283	0.7839
145	2.6964	0.3625	2.3338	0.7766
146	2.6994	0.3600	2.3393	0.7695
147	2.7024	0.3576	2.3448	0.7625
148	2.7054	0.3552	2.3502	0.7556
149	2.7084	0.3528	2.3556	0.7488
150	2.7115	0.3504	2.3610	0.7421
151	2.7145	0.3481	2.3664	0.7355
152	2.7176	0.3458	2.3717	0.7290
153	2.7206	0.3436	2.3771	0.7226
154	2.7237	0.3413	2.3824	0.7163
155	2.7268	0.3391	2.3876	0.7102
156	2.7298	0.3369	2.3929	0.7041
157	2.7329	0.3348	2.3981	0.6980
158	2.7360	0.3327	2.4033	0.6921
159	2.7391	0.3306	2.4085	0.6863
160	2.7422	0.3285	2.4137	0.6805
161	2.7453	0.3265	2.4188	0.6749
162	2.7484	0.3245	2.4240	0.6693
163	2.7515	0.3225	2.4291	0.6638

V (m/min)	Total production time (min)	Total machining time (min)	Tool replacement time (min)	Tool life (min)
164	2.7546	0.3205	2.4341	0.6584
165	2.7578	0.3186	2.4392	0.6530
166	2.7609	0.3166	2.4442	0.6477
167	2.7640	0.3148	2.4493	0.6425
168	2.7671	0.3129	2.4543	0.6374
169	2.7703	0.3110	2.4592	0.6324
170	2.7734	0.3092	2.4642	0.6274
171	2.7765	0.3074	2.4691	0.6225
172	2.7797	0.3056	2.4741	0.6176
173	2.7828	0.3038	2.4790	0.6128
174	2.7860	0.3021	2.4839	0.6081
175	2.7891	0.3004	2.4887	0.6034
176	2.7922	0.2987	2.4936	0.5988
177	2.7954	0.2970	2.4984	0.5943
178	2.7985	0.2953	2.5032	0.5898
179	2.8017	0.2936	2.5080	0.5854
180	2.8048	0.2920	2.5128	0.5811
181	2.8080	0.2904	2.5176	0.5768
182	2.8111	0.2888	2.5223	0.5725
183	2.8143	0.2872	2.5270	0.5683
184	2.8174	0.2857	2.5317	0.5642
185	2.8206	0.2841	2.5364	0.5601
186	2.8237	0.2826	2.5411	0.5561
187	2.8269	0.2811	2.5458	0.5521
188	2.8300	0.2796	2.5504	0.5481
189	2.8332	0.2781	2.5551	0.5442
190	2.8363	0.2766	2.5597	0.5404
191	2.8395	0.2752	2.5643	0.5366
192	2.8426	0.2738	2.5688	0.5329
193	2.8457	0.2723	2.5734	0.5292
194	2.8489	0.2709	2.5779	0.5255
195	2.8520	0.2696	2.5825	0.5219
196	2.8552	0.2682	2.5870	0.5183
197	2.8583	0.2668	2.5915	0.5148
198	2.8615	0.2655	2.5960	0.5113
199	2.8646	0.2641	2.6005	0.5079

Appendix 3: Comparison chart of tool life and the total production time of the whole pocket (1 square and 2 circular pocket production)

V (m/min)	Tool life (min)	Total production time of whole pocket (min)	V (m/min)	Tool life (min)	Total production time of whole pocket (min)
20	11.0797112	4.1758	65	2.27894863	2.8278
21	10.3776438	4.0606	66	2.2327407	2.8245
22	9.749714	3.9572	67	2.18814362	2.8216
23	9.1852324	3.8640	68	2.14507844	2.8189
24	8.67542908	3.7797	69	2.10347116	2.8165
25	8.21304642	3.7032	70	2.06325234	2.8143
26	7.79203054	3.6336	71	2.0243568	2.8124
27	7.40729472	3.5701	72	1.98672326	2.8108
28	7.05453604	3.5119	73	1.95029409	2.8093
29	6.73009188	3.4586	74	1.91501504	2.8081
30	6.4308266	3.4097	75	1.88083497	2.8071
31	6.15404124	3.3646	76	1.84770566	2.8062
32	5.89740103	3.3230	77	1.81558163	2.8056
33	5.65887673	3.2847	78	1.7844199	2.8051
34	5.43669693	3.2492	79	1.75417985	2.8047
35	5.22930884	3.2163	80	1.72482307	2.8046
36	5.03534604	3.1858	81	1.69631318	2.8046
37	4.8536017	3.1576	82	1.66861576	2.8047
38	4.68300623	3.1313	83	1.64169816	2.8050
39	4.52260859	3.1069	84	1.61552941	2.8054
40	4.37156053	3.0842	85	1.59008014	2.8059
41	4.22910323	3.0630	86	1.56532245	2.8066
42	4.09455599	3.0433	87	1.54122983	2.8073
43	3.96730656	3.0250	88	1.51777706	2.8082
44	3.84680287	3.0079	89	1.49494018	2.8092
45	3.7325459	2.9919	90	1.47269636	2.8103
46	3.62408357	2.9770	91	1.45102385	2.8115
47	3.5210054	2.9631	92	1.42990195	2.8128
48	3.42293789	2.9502	93	1.40931091	2.8141
49	3.32954053	2.9381	94	1.3892319	2.8156
50	3.24050229	2.9268	95	1.36964692	2.8171
51	3.15553849	2.9163	96	1.35053882	2.8187
52	3.07438817	2.9065	97	1.3318912	2.8204
53	2.99681168	2.8974	98	1.31368839	2.8222
54	2.92258856	2.8889	99	1.29591539	2.8240
55	2.8515157	2.8810	100	1.27855786	2.8259
56	2.78340569	2.8736	101	1.26160209	2.8279
57	2.71808537	2.8668	102	1.24503493	2.8299
58	2.65539448	2.8604	103	1.2288438	2.8320
59	2.59518453	2.8546	104	1.21301663	2.8342
60	2.53731773	2.8491	105	1.19754186	2.8364
61	2.48166609	2.8441	106	1.1824084	2.8386
62	2.42811056	2.8395	107	1.16760561	2.8409
63	2.37654024	2.8352	108	1.15312326	2.8433
64	2.32685176	2.8313	109	1.13895156	2.8457

V (m/min)	Tool life (min)	Total production time of whole pocket (min)	V (m/min)	Tool life (min)	Total production time of whole pocket (min)
110	1.12508108	2.8481	160	0.68053835	3.0022
111	1.11150276	2.8506	161	0.67487309	3.0056
112	1.09820791	2.8531	162	0.66928962	3.0090
113	1.08518814	2.8557	163	0.66378629	3.0124
114	1.07243542	2.8583	164	0.65836145	3.0158
115	1.05994198	2.8610	165	0.65301353	3.0192
116	1.04770038	2.8636	166	0.64774097	3.0227
117	1.03570343	2.8663	167	0.64254226	3.0261
118	1.02394422	2.8691	168	0.63741595	3.0295
119	1.01241607	2.8719	169	0.63236059	3.0329
120	1.00111256	2.8747	170	0.6273748	3.0364
121	0.99002749	2.8775	171	0.62245722	3.0398
122	0.9791549	2.8804	172	0.61760652	3.0432
123	0.96848901	2.8833	173	0.61282141	3.0467
124	0.95802427	2.8862	174	0.60810064	3.0501
125	0.9477553	2.8891	175	0.60344298	3.0535
126	0.93767692	2.8921	176	0.59884722	3.0570
127	0.92778412	2.8951	177	0.59431221	3.0604
128	0.91807206	2.8981	178	0.58983681	3.0639
129	0.90853607	2.9012	179	0.58541989	3.0673
130	0.89917162	2.9042	180	0.58106038	3.0708
131	0.88997435	2.9073	181	0.57675722	3.0742
132	0.88094003	2.9104	182	0.57250938	3.0777
133	0.87206457	2.9135	183	0.56831584	3.0811
134	0.86334401	2.9166	184	0.56417562	3.0845
135	0.85477452	2.9198	185	0.56008776	3.0880
136	0.84635241	2.9229	186	0.55605131	3.0914
137	0.83807407	2.9261	187	0.55206537	3.0949
138	0.82993603	2.9293	188	0.54812903	3.0983
139	0.82193492	2.9325	189	0.54424141	3.1018
140	0.81406747	2.9357	190	0.54040167	3.1052
141	0.80633053	2.9389	191	0.53660896	3.1087
142	0.79872102	2.9422	192	0.53286246	3.1121
143	0.79123598	2.9455	193	0.52916139	3.1156
144	0.7838725	2.9487	194	0.52550494	3.1190
145	0.77662781	2.9520	195	0.52189237	3.1224
146	0.76949918	2.9553	196	0.51832292	3.1259
147	0.76248397	2.9586	197	0.51479587	3.1293
148	0.75557963	2.9619	198	0.51131049	3.1328
149	0.74878368	2.9652	199	0.50786609	3.1362
150	0.7420937	2.9685			
151	0.73550735	2.9719			
152	0.72902235	2.9752			
153	0.7226365	2.9786			
154	0.71634764	2.9819			
155	0.71015369	2.9853			
156	0.70405261	2.9887			
157	0.69804243	2.9920			
158	0.69212123	2.9954			
159	0.68628715	2.9988			