OPTIMIZATION OF BROACHING TOOL DESIGN

by

UTKU KÖKTÜRK

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabanci University
July 2004

OPTIMIZATION OF BROACHING TOOL DESIGN

APPROVED BY:

Associate Prof. Dr. Erhan Budak ………………………….

(Thesis Advisor)

Assistant Prof. Dr. Cem Güneri ………………………….

Assistant Prof. Dr. İsmail Lazoğlu ………………………….

Assistant Prof. Dr. Tonguç Ünlüyurt ………………………….

Associate Prof. Dr. Yusuf Z. Menceloğlu

DATE OF APPROVAL: ………………………….

ACKNOWLEDGMENTS

First, I would like to extend my sincere gratitude to Associate Prof. Dr. *Erhan Budak* for his patience, guidance and encouragement throughout these two years.

I owe many thanks to my parents for always being there when I need them. I thank my friends, flat-mate *Ahmet Bulut,* and sweet girlfriend *Ozlem Sinat* for their patience and emotional supports.

I wish to thank my office mates *Pinar Yilmaz, Mehmet Kayhan* and *Omer Erhun Kundakcioglu* for their friendships and motivation. I also would like to thank my roommate *Selim Yannier, Emre Tavsancil, Onur Cotur* and *Metin Berke Baspinar* who made my stay at Sabanci University pleasurable while I was away from home.

ABSTRACT

Broaching is a commonly used machining operation in manufacturing of variety of internal or external complex features. High quality surfaces can be generated with high productivity if proper conditions are used. The main disadvantage of broaching is that it is not possible to change any of the cutting parameters but the cutting speed during production. That is because all machining parameters, except cutting speed, are built into broaching tools which makes tool design the most important aspect of broaching. In this thesis, a procedure for the optimization of broaching tools is presented.

First, the mechanics of the broaching process and general properties of the broach tools are explained. Important design parameters and the effects of them on the broaching process are demonstrated. Most broaching tools have several tool segments with different profiles. One of the critical factors in the design of these tools is the assignment of segment profiles which determine the relative amounts of material removal rate in each section. Several alternatives are tried for optimization of section geometries and their effects are demonstrated by simulations. The objective function of the optimization problem and the constraints due to machine, tool and part limitations are presented. A heuristic optimization algorithm is developed, and demonstrated by examples. It is also shown that by using the algorithm developed the production time can be reduced due to shortened tool length. The simulation program developed is also explained and demonstrated.

ÖZET

Broşlama iç ve dış birçok karmaşık profilin üretiminde sıkça kullanılan bir talaşlı imalat yöntemidir. Uygun şartlarda kesim yapıldığında yüksek verimlilikte kaliteli yüzeylerin eldesi mümkündür. Broşlamanın en büyük dezavantajı, üretim sırasında kesme hızı dışında hiçbir parametrenin değiştirilememesidir. Bunun sebebi kesme hızı dışındaki tüm parametrelerin broş tığının dizaynı ile belirlenmesidir ve bu da tığın dizaynını broşlamanın en önemli safhası haline getirir. Bu tezde tığ dizaynının optimizasyonu için geliştirilmiş bir prosedür açıklanmıştır.

İlk olarak, broşlama işleminin mekanik özellikleri ve bir broş tığının genel yapısı anlatılmıştır. Dizayn için önemli parametreler ve bunların broşlama işlemi üzerindeki etkileri gösterilmiştir. Broş tığlarının çoğu farklı geometride birkaç kısımdan oluşurlar. Dizayn işleminin en kritik noktalarından biri her bir kısımda kesilecek malzeme hacmini belirleyecek olan bölüm geometrilerinin saptanmasıdır. Bölüm geometrilerinin optimizasyonu amacıyla birçok farklı seçenek denenmiş ve bunların etkileri simülasyonlar ile gösterilmiştir. Optimizasyon probleminin hedefi ve makine, tığ ve kesilecek parçadan kaynaklanan sınırlamalar ortaya konmuştur. Buluşsal bir optimizasyon algoritması geliştirilmiş ve örneklerle açıklanmıştır. Bu algoritma yardımıyla tığ boyunun ve dolayısıyla üretim zamanının kısaldığı ortaya konmuştur. Ayrıca geliştirilen simulasyon programı da gösterilmiş ve açıklanmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

OPTIMIZATION OF BROACHING TOOL DESIGN

by
UTKU KÖKTÜRK

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabanci University
July 2004

OPTIMIZATION OF BROACHING TOOL DESIGN

APPROVED BY:

Associate Prof. Dr. Erhan Budak …………………………….
(Thesis Advisor)

Assistant Prof. Dr. Cem Güneri …………………………….

Assistant Prof. Dr. İsmail Lazoğlu …………………………….

Assistant Prof. Dr. Tonguç Ünlüyurt …………………………….

Associate Prof. Dr. Yusuf Z. Menceloğlu

DATE OF APPROVAL: …………………………….

ACKNOWLEDGMENTS

First, I would like to extend my sincere gratitude to Associate Prof. Dr. *Erhan Budak* for his patience, guidance and encouragement throughout these two years.

I owe many thanks to my parents for always being there when I need them. I thank my friends, flat-mate *Ahmet Bulut,* and sweet girlfriend *Ozlem Sinat* for their patience and emotional supports.

I wish to thank my office mates *Pinar Yilmaz, Mehmet Kayhan* and *Omer Erhun Kundakcioglu* for their friendships and motivation. I also would like to thank my roommate *Selim Yannier, Emre Tavsancil, Onur Cotur* and *Metin Berke Baspinar* who made my stay at Sabanci University pleasurable while I was away from home.

ABSTRACT

Broaching is a commonly used machining operation in manufacturing of variety of internal or external complex features. High quality surfaces can be generated with high productivity if proper conditions are used. The main disadvantage of broaching is that it is not possible to change any of the cutting parameters but the cutting speed during production. That is because all machining parameters, except cutting speed, are built into broaching tools which makes tool design the most important aspect of broaching. In this thesis, a procedure for the optimization of broaching tools is presented.

First, the mechanics of the broaching process and general properties of the broach tools are explained. Important design parameters and the effects of them on the broaching process are demonstrated. Most broaching tools have several tool segments with different profiles. One of the critical factors in the design of these tools is the assignment of segment profiles which determine the relative amounts of material removal rate in each section. Several alternatives are tried for optimization of section geometries and their effects are demonstrated by simulations. The objective function of the optimization problem and the constraints due to machine, tool and part limitations are presented. A heuristic optimization algorithm is developed, and demonstrated by examples. It is also shown that by using the algorithm developed the production time can be reduced due to shortened tool length. The simulation program developed is also explained and demonstrated.

ÖZET

Broşlama iç ve dış birçok karmaşık profilin üretiminde sıkça kullanılan bir talaşlı imalat yöntemidir. Uygun şartlarda kesim yapıldığında yüksek verimlilikte kaliteli yüzeylerin eldesi mümkündür. Broşlamanın en büyük dezavantajı, üretim sırasında kesme hızı dışında hiçbir parametrenin değiştirilememesidir. Bunun sebebi kesme hızı dışındaki tüm parametrelerin broş tığının dizaynı ile belirlenmesidir ve bu da tığın dizaynını broşlamanın en önemli safhası haline getirir. Bu tezde tığ dizaynının optimizasyonu için geliştirilmiş bir prosedür açıklanmıştır.

İlk olarak, broşlama işleminin mekanik özellikleri ve bir broş tığının genel yapısı anlatılmıştır. Dizayn için önemli parametreler ve bunların broşlama işlemi üzerindeki etkileri gösterilmiştir. Broş tığlarının çoğu farklı geometride birkaç kısımdan oluşurlar. Dizayn işleminin en kritik noktalarından biri her bir kısımda kesilecek malzeme hacmini belirleyecek olan bölüm geometrilerinin saptanmasıdır. Bölüm geometrilerinin optimizasyonu amacıyla birçok farklı seçenek denenmiş ve bunların etkileri simülasyonlar ile gösterilmiştir. Optimizasyon probleminin hedefi ve makine, tığ ve kesilecek parçadan kaynaklanan sınırlamalar ortaya konmuştur. Buluşsal bir optimizasyon algoritması geliştirilmiş ve örneklerle açıklanmıştır. Bu algoritma yardımıyla tığ boyunun ve dolayısıyla üretim zamanının kısaldığı ortaya konmuştur. Ayrıca geliştirilen simulasyon programı da gösterilmiş ve açıklanmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

Broaching is one of the most important machining operations which has a high production rate and capable of producing one-of-a-kind parts. Both external and internal profiles can be produced by broaching no matter whether they are complex or not. Noncircular holes, keyways, fir-tree profiles are some of the examples of the profiles that can be machined by this method.

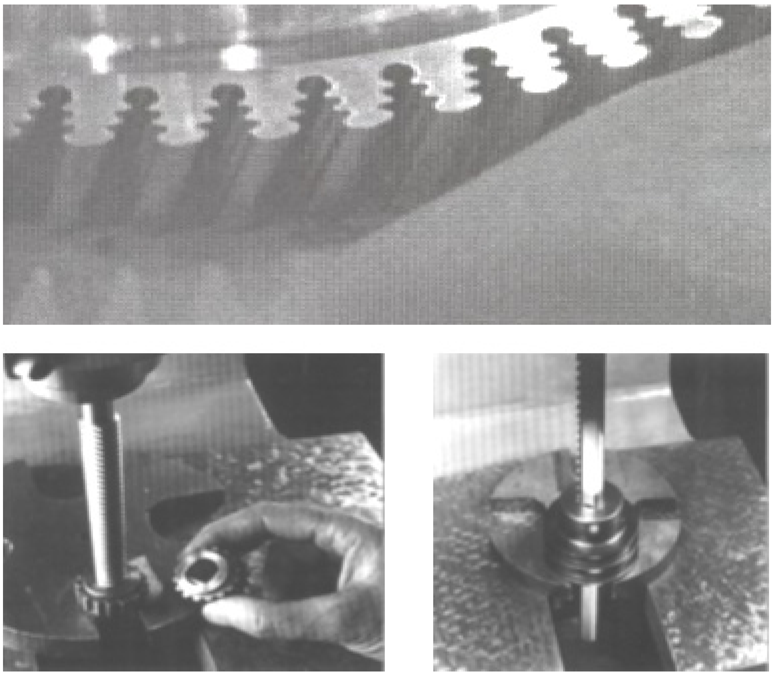


Figure 1-1: Some broached profiles.

Broaching is different than the other machining processes with respect to motion at the time of production that all operation is performed by the linear motion of the tool. The broach tool is like a straight stick on which the teeth are arranged as following each other. The geometry of the teeth are slightly different than each other and that difference makes the cutting performance possible while the tool is moving linearly on or in the fixed workpiece.

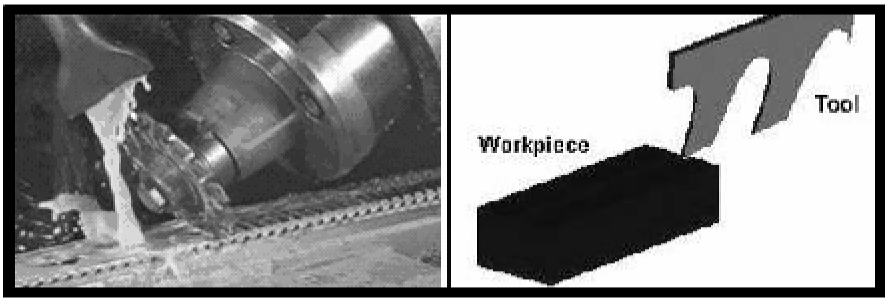


Figure 1-2: Broaching a part.

Tooling is the heart of any broaching process. That is because after the tool is produced the only parameter which can be changed during production is the cutting speed. All other cutting parameters depend on the tool design. Broach teeth are generally grouped in three main sections along the tool length which are roughing, semi-finishing and finishing sections. The first tooth of the roughing section is generally the smallest tooth on the tool. The subsequent teeth are larger in size and that increase in size includes the first finishing tooth. The tooth rise which means the size difference of the following tooth has higher values in the roughing section where it has smaller values along the semi-finishing section and generally all finishing teeth are the same size.

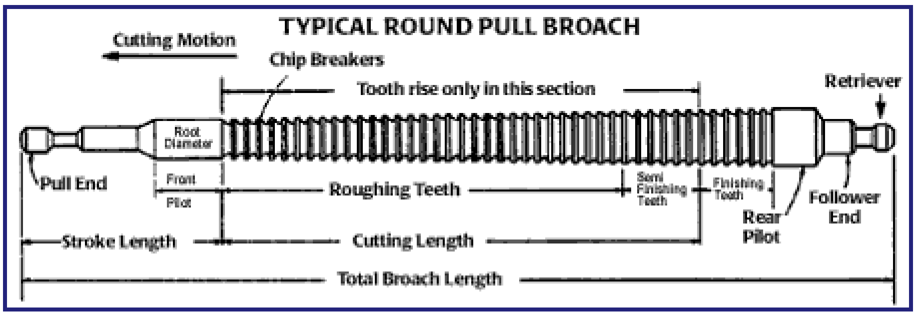


Figure 1-3: General tool view.

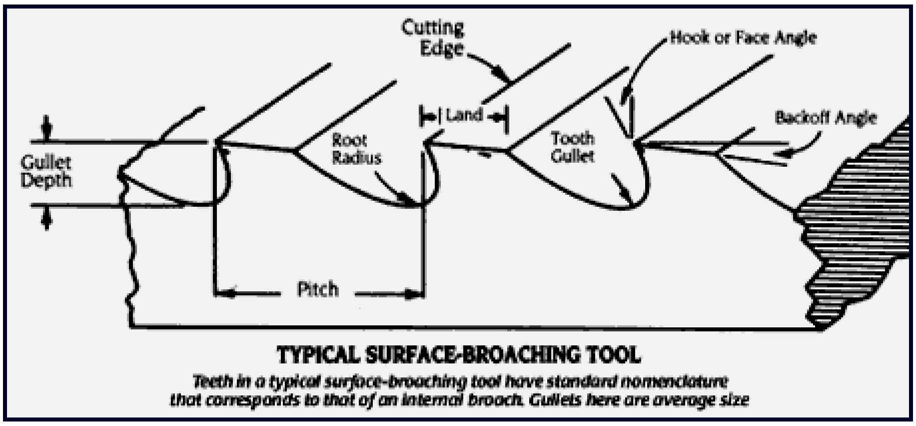


Figure 1-4: A surface broach tool.

Advantages of the broaching process are high productivity, high surface quality, low necessity for skilled labor, ability to cut complex geometries at one stroke and ability to cut noncircular internal profiles easily. But a good performance is directly based on the selection of the proper cutting conditions and for that reason the tool design has a great importance in broaching. Because all of the process parameters except the cutting speed are determined by the tool geometry.

1.1 Literature Survey

Machining has a very important place among the production processes. The fundamentals of machining processes including optimization of the parameters have been investigated in many studies. Here a brief review will be given. A more detailed review can be found in [3, 12, 23, 24, 41, 46 and 47].

Merchant [31] modeled the orthogonal cutting by assuming the cutting zone as a thin plane. Palmer and Oxley [36] explained the physics of the chip removal process and formulated basic mechanics in orthogonal cutting. Barrow, Graham, Kurimoto and Leong [6] investigated the stress distribution on the rake face in orthogonal machining. Chiffre [13] formulated the mechanics of the cutting fluid action in orthogonal cutting. Bailey [5] presented the details of the friction on the rake face and the flank face during the orthogonal cutting processes. As another type of cutting process the oblique cutting has been studied by different researchers [8, 35 and 41]

Altintas [3], Trent and Wright [47], Boothroyd and Knight [7], Kalpakjian and Schmid [23 and 24], Stephenson and Agapiou [43], Childs, Maekava, Obikava and Yanane [12] and Tlusty [46] have given detailed information about the metal cutting processes and mechanics. They presented the general principles of machining operations and the process. As it can be seen from these references metal cutting is a very complex process involving deformation of materials at extreme strain, temperature and friction conditions.

One of the most important aspects of machining is the chip geometry. Fang, Jawahir and Oxley [15, 16, 17 and 22] have developed a new slipline theory to understand the mechanics of chip formation. They investigated different configurations such as limited tool chip contact length or tool edge with a radius. They also used vectors and some special matrix operators for solution of the resulting equations. Flank contact or third deformation zone is another critical part of machining process. Albrecht

[2] studied the ploughing process during chip formation, and its effects on the chip curling and cutting forces.

The optimization of the process parameters is very important to obtain the maximum performance in machining. Different methods and theories have been used to optimize the machining operations such as turning, milling, boring, grinding and broaching. Meng, Arsecularatne and Mathew [29] tried to find the optimum cutting conditions in turning using the minimum cost or maximum production rate as the objective function which are also common objective functions. They developed the equations for the objective functions and the constraints based on the machining theories starting with the optimum cutting speed. They also checked the values of the variables according to the constraints and then modified the parameters to stay in the feasible region. Challa and Benna [11] tried to find the best combination using the properties of tools, machines and other materials. Erol and Ferrell [14] used fuzzy quality function and transformed qualitative data into quantitative data in order to find the optimum solution among a finite number of alternatives. Lee and Tarng [27] used polynomial networks which can learn the relationships between the cutting parameters and cutting performance for optimizing the production rate and cost in multistage turning operations. Stephenson and Agapiou [43] investigated the optimization problem from the economics side. They explained the problem by using general equations applicable to all machining processes like turning, milling etc. and explained different types of optimization techniques. Hagglund [10] worked on turning operation optimization. He demonstrated a new procedure for optimizing turning operations, and claimed that this general method can be applied to other processes if Taylor tool life equation is used. Baek, Ko and Kim [4] tried to optimize the feedrate for the best surface roughness value. They created a model in order to simulate the surface roughness. Then for a given surface roughness constraint, they determined the optimum feedrate for maximizing material removal rate.

Genetic algorithms, fuzzy methods and probabilistic approaches have been widely used in the optimization of the machining processes. Rao and Hati [20] determined the optimum cutting conditions by using both deterministic and probabilistic approaches. In the deterministic model, they created the objective function according to important objectives such as cost of production per piece, production rate and profit. Then, they created a starting vector which is feasible based on the given constraints, and found the best solution by iteration. They also solved the same problem with the probabilistic method, and compared the results. Shin and Joo [42] also used an iterative model. They neglected some of the variables and divided constraints into two groups as roughing and finishing to simplify the problem. Their starting point was the tool life and thus they determined the parameters using a tool life equation, the constraints and an iterative solution. Khan, Prosad and Singh [25] compared genetic algorithm, simulated annealing algorithm and continuous simulated annealing algorithm by applying these algorithms to different optimization models developed by different researchers. Saravanan, Asokan and Sachidanandam [40] used genetic algorithms to find optimum cutting conditions in surface grinding operations. They choose some of the variables as optimization variables and used binary coding to represent them. Alberti and Perrone [1] dealt with multipass machining operations. They modeled the problem with probobilistic fuzzy algorithm and constraint relaxation. Then they tried to optimize the model by using genetic algorithms. Rao and Chen [37] too, used both probability and fuzzy theories together for optimizing the cutting conditions. They assumed that the random variables have a normal distribution where it is assumed that the fuzzy parameters have a linear probobilistic distribution. Another person who used the fuzzy theories is Lin [28]. Lin used weighted max-min and fuzzy goal programming methods to optimize multi-objective problems. Iwata, Murotsu, Iwatsubo and Fujii [21] used volume of material machined per unit tool wear, and production cost per component as objective functions. They used probabilistic approaches and converted all of the probabilistic constraints into deterministic form.

When we review the literature for broaching, it is seen that the number of references is so limited despite its advantages and importance. Monday [32] wrote the only book on broaching. He presented the broaching process geometry and parameters in detail. Although it is an old reference it continues to be an important one. Terry, Karni and Huang [45] presented the factors that affect productivity in broaching. They explained the design constraints, their importance and how they are selected. Finite element analysis was used to predict the tooth deflection and experimental data is used to create the general rules for designing. Sutherland, Salisbury, Hoge [44] worked on the force modeling in broaching process. They determined forces in cutting gear broaching using an oblique model. They created two sub models in creating the main mechanistic model. These sub models were the tool-work contact area and chip load-cutting force relationship. Gilormini [18] also analyzed the cutting forces in broaching operations in which the tool consists of one section. Celik, Korbahti and Kucur [10] explained a software that they developed for the prediction of the cutting forces in order to increase the productivity of solid pull broaches. Kokmeyer [26] gave examples of different applications and works of broaching. Sajeev, Vijayaraghavan and Rao [38 and 39] investigated the effects of broaching parameters on the tool and work piece deflections and the final shape of the broached geometry. Budak [9] evaluated the fir-tree broaching tools used for waspaloy turbine discs based on the force and power monitoring systems. He showed that the force distribution on the broaching tool sections is not uniform and concluded that the models could be used to design tools with more uniform force distribution, and shorter in length. After that Ozturk [33 and 34] developed a model to simulate the broaching process. He studied fir-tree profiles, simulated the broaching process forces and the tool stresses to improve the tool design.

1.2 Problem Definition

After a broaching tool is designed and manufactured, none of the process parameters, except the speed, can be modified during the process. That is why tool design is the most important stage for broaching processes. Optimization in broaching means the design of the best tool for the target objective(s). The objective in this study is to decrease the production time. Thus the best designed tool is the shortest possible tool for a given cutting speed.

There is not enough literature about the optimization of the tool design in broaching, in fact only very few have been found. Furthermore the design in industry is known to be performed based on experience. The selection of the tool parameters are not conducted based on the process mechanics and engineering rules. The problem is quite a complex problem, and there is no possibility to find out if the design is the optimal one, or how close it is to the optimal. All possible combinations must be tried in order to find the optimal design which is impractical. An algorithm is needed to optimize the tool design or evaluate an existing design.

The difficulty of developing an optimization algorithm for the tool design is the complexity of the problem. There are many parameters which must be considered and they are interrelated. Furthermore, there are also some geometrical constraints depending on the application. This dynamic structure of the problem increases the number of feasible solutions, and complicates the determination of the optimum one. However, that is not the only problem that causes complexity. Because the geometry to be broached is generally complex, it is necessary to divide into several sections and the parameters and the relationship between them should be decided for each section.

In broaching, only the profile of the last tooth, i.e. the part geometry, and the cutting length, i.e. the machine raw length, are given at the beginning of a process. Generally three main sections are used in broaching which are roughing, semi-finishing and finishing sections. The profile of the finishing section is same as the profile to be cut and the semi-finishing section is generally almost the same. The roughing section design can be more complex. The same profile can be cut with just one roughing section or it could be divided into number of sub-roughing sections. The profile of these sections and the volume removed by each of them are the main decision variables. Some geometrical constraints can automatically be added to the problem according to the application, and these constraints can be used to find a starting point or personal constraints can be used. Selection and design of the sections is one of the most complicated parts.

In summary, optimization problem in broaching is a difficult problem to solve. There are many variables and the sensitivity of the results to any change in any variable is high. Thus, most of the common algorithms cannot be used or are not efficient to optimize the tool design. That is why a new heuristic method is developed in this study.

1.3 Methodology

The physics of broaching must be understood well in order to optimize the tool design. All of the optimization parameters should be defined clearly and the effects of each of them on the objective function should be demonstrated. General rules of the process and the main assumptions must be noted.

In order to understand the physics of broaching completely, the process should be modeled. Force, stress and other important parameters must be defined analytically and tooth profile must be analyzed in detail. The force model is the first step as it is the main parameter. After that, a general tooth stress model will be chosen for the broach tool. This model must be suitable enough to use for all of the possible tooth profiles. Furthermore, analytic models will be developed for all other important parameters of the process and the relations between these parameters will be presented.

Accuracy of the models used is crucial. Effects of each variable on the process must be understood well in order to be capable of doing something to improve it. Because it is impossible to see the effects of each variable on the process in real life, a simulation program will be needed and these models will be used to develop this simulation program Thus, as the next step, a simulation program will be written by Visual Basic. The program must be user friendly and have the capability of simulating complex geometries such as fir-tree profiles. This simulation program will be used to see the effects of each variable on the results. The results will be analyzed and information obtained from the results will be discussed.

Results of the simulations will give us detailed information about broaching and the tool design parameters. These will be used to develop an algorithm for the optimization of tool design. In order to create an algorithm, first an objective function will be chosen. Then, the main constraints will be identified. Main constraints are the common constraints which can be used for all profiles. Also, there are some special constraints which depend on the geometry to be cut. These geometrical constraints and the selection criteria for them will also be presented. At this point, the designer may decide to add extra constraints that are not compulsory but useful to get the desired force or stress distributions among the sections.

The logic of the algorithm is simple. Number of feasible solutions is so many for any broaching process that it is not practical to try all of them. Furthermore, it is quite difficult to determine if the solution is optimum or how close it is to the optimum in an experience based design. That's why a different approach is used. The algorithm will start with the shortest tool by using maximum tooth rise and minimum pitch values for the given material and the geometry and check the constraints one by one. The necessary modifications will be done, and the results will be simulated to check the solutions. In conclusion, the solution will be best possible solution, or at least it will be known how close it is to the optimum by the help of the algorithm.

CHAPTER 2 MECHANICS OF BROACHING

In this chapter the general properties of a broach tool and the basic principles of the process will be discussed. Broach tools are different than the tools used in other machining processes such as milling, turning, grinding, etc. A detailed explanation of the tool is necessary in order to understand the optimization algorithm. Also force, stress, power, tool life and chatter in broaching will be reviewed. Furthermore, general chip geometry and chip formation basics will be discussed with application to broaching.

2.1 General Tool Geometry in Broaching

A broach is a long and straight tool with multiple teeth located on it. The teeth follow each other and each one is slightly different in geometry from the one in front of it. The cutting is performed due to that difference. Each tooth removes only a small amount of material, and the total depth of cut is distributed over all the teeth.

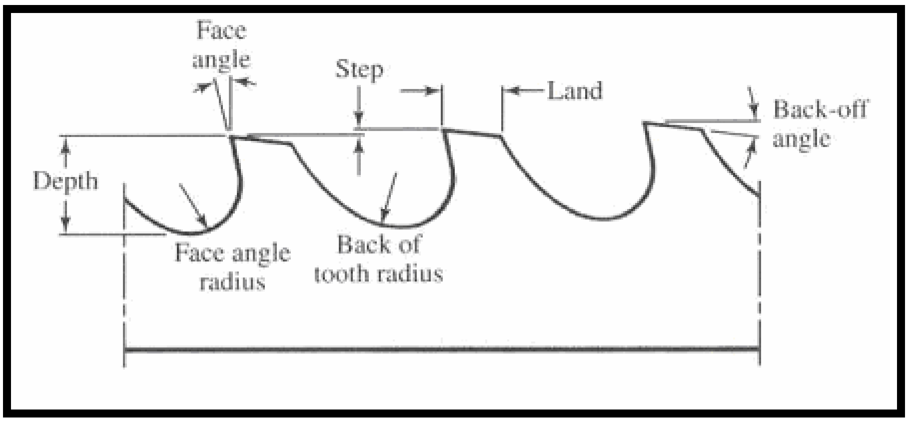


Figure 2-1: Broach tool geometry.

The general geometry of a broach tool can be seen in Figure 2-1. The linear distance between successive cutting edges is called the pitch. The pitch value determines the number of teeth in cut and the length of tool. Because of the process dynamics it is preferable to cut with at least two teeth in cut. [30 and 33]. This prevents the tool from drifting or chattering.

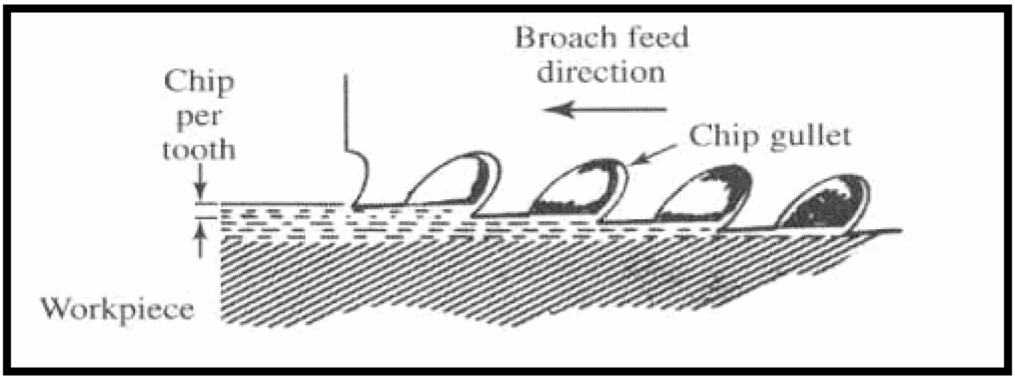


Figure 2-2: Chip formation in broaching.

The space between two following teeth is called the gullet space. Figure 2-2 shows the chip formation in the gullet space. As different from other processes each tooth of the tool enters the cutting zone just for once at each stroke of the tool. Each tooth enters the zone, cuts the workpiece until the end of the cutting length and then leaves the workpiece. The chip cut by the tooth is captured in the gullet space until the tooth finishes its cutting performance as seen in Figure 2-3. Insufficient chip space will cause the chips to pack between the teeth and may cause the teeth to break or lower the surface quality. To prevent that kind of results the ratio of the chip volume cut by the tooth to the volume of the gullet space should be no larger than 0,35 [32, 33 and 34]. That ratio is especially important when the cutting length is high or internal broaching is done.

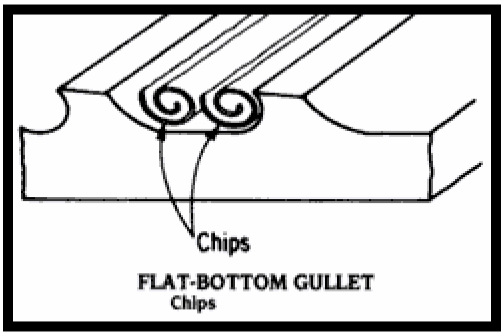


Figure 2-3: Chips in gullet space.

The general gometry of the broach tool can be used to find the gullet volume in order to check its ratio to the cut chip volume by current tooth. The parameters can be seen in Figure 2-4.

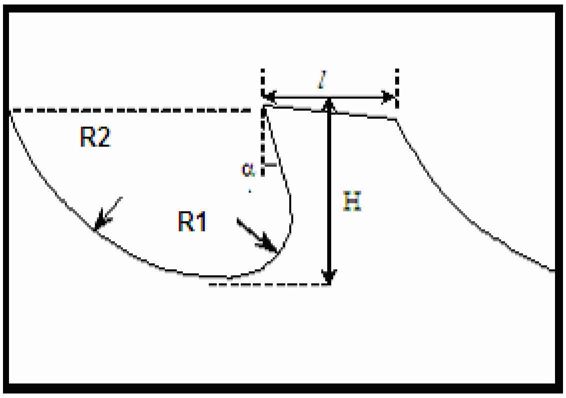


Figure 2-4: General geometry parameters of a broach tool.

As Ozturk [33 and 34] proposes the gullet area is:

$$Gullet\ area = 0.9456(p-l)^{0.816} H^{1.14} R_1^{0.026} R_2^{-0.0891} \alpha^{0.0388} \quad (2.1)$$

Gullet volume can be found by multiplying that area with the tooth width, bottom length of the tooth. In the equation p is the pitch length.

The rake angle, α, is choosen according to the material to be cut, usually between 0º and 20º. The clerance angle which can also be called as the back-off angle is the angle between a surface parallel to the ground and the flank face which is the top face of the tooth as seen in Figure 2-1. Clereance angle has a range of 1º-4º and usually smaller in the finishing sections. Larger back-off angles are selected at the roughing sections because small angles may cause rubbing, pushing the chip into the workpiece instead of cutting, during the cutting [24].

2.2 Forces in Broaching

The prediction of the forces that occur during cutting is very important to simulate the broaching process. It is impossible to calculate and simulate the other important variables such as power requirement and tooth stress without the force information. Consequently, no optimization algorithm can be developed. Just like all other machining processes both orthogonal and oblique cutting techniques can be used in broaching.

The general way of calculating the forces in machining operations is formulated in Equation 2.2. In this equation, K_j is the cutting force coefficient of force F_j, component j of the resultant force, b is the width of cut and t is the uncut chip thickness.

$$F_j = K_j bt \tag{2.2}$$

Furthermore each force can be calculated as the sum of two components. One of these components is the cutting force component and the other is the edge force component:

$$F_j = F_{jc} + F_{je} \tag{2.3}$$

and

$$F_{jc} = K_{jc} bt \tag{2.4}$$

$$F_{je} = K_{je} b \tag{2.5}$$

These equations can be used to determine the cutting forces in the broaching processes.

2.2.1 Forces in Orthogonal Cutting

In orthogonal cutting the velocity vector of the tool movement is normal to the cutting edge. The teeth on an orthogonal broach can be seen in Figure 2-5.

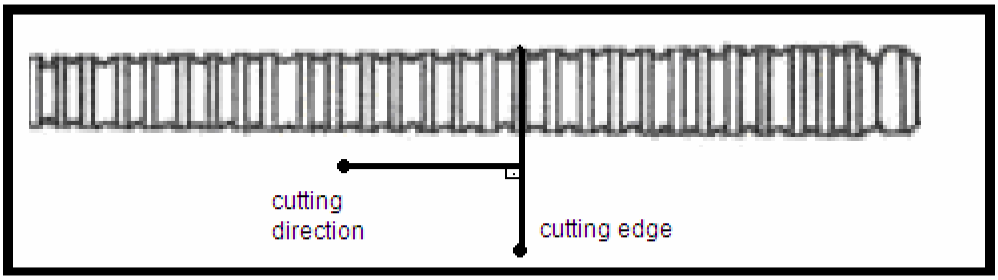


Figure 2-5: Orthogonal broach tool.

There are two components of the total force per tooth in orthogonal broaching. One of them is the F_t, the tangential force, in the opposite direction of cutting action. The other is the feed force, F_f, which is in the direction normal to the feed force and from the tooth cutting edge towards the tool body. The forces can be better seen in Figure 2-6.

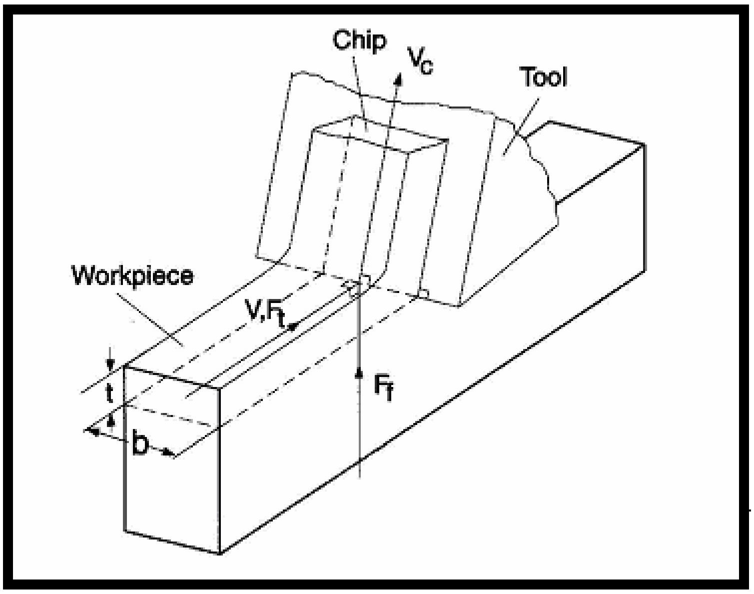


Figure 2-6: Forces in orthogonal cutting [3].

Both tangential and the feed forces can be found by using the Equations 2.3, 2.4 and 2.5 as long as the coefficients K_{tc}, K_{te} ,K_{fc} and K_{fe} are known. These coefficients can be found from experimental data [3 and 33] or analytically calculated as follows:

$$K_t = \left[\tau_s \frac{\cos(\beta - \alpha)}{\sin(\phi)\cos(\phi + \beta - \alpha)} \right]$$
$$K_f = \left[\tau_s \frac{\sin(\beta - \alpha)}{\sin(\phi)\cos(\phi + \beta - \alpha)} \right] \qquad (2.6)$$

where K_t and K_f are the cutting force coefficients in the cutting and feed (normal) directions, τ_s is the shear stress in the shear plane. $\emptyset$, β and α are the shear, friction and rake angles, respectively. Note that there is not an accurate model for edge forces which are to be determined always experimentally. General chip formation geometry can be seen in Figure 2-7.

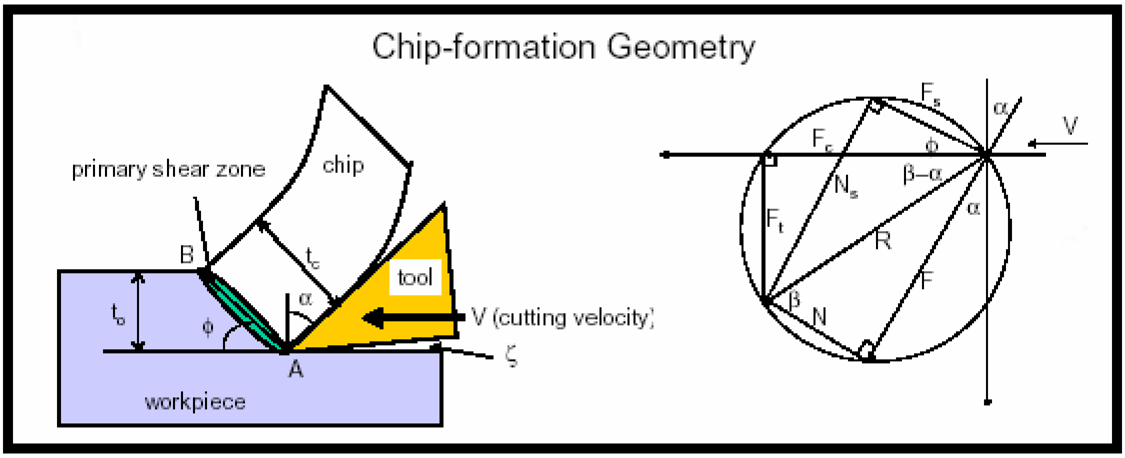


Figure 2-7: Chip formation geometry.

When the feed and tangential forces are found, the total force can be calculated easily as in Equation 2.7:

$$F = \sqrt{F_t^2 + F_f^2} \qquad (2.7)$$

2.2.2 Forces in Oblique Broaching

Oblique cutting is the machining technique in which the velocity vector of the tool movement is not normal to the cutting and there is an inclination angle *i* between them. The general geometry of the oblique cutting and the teeth positions on an oblique broach can be seen in Figure 2-8.

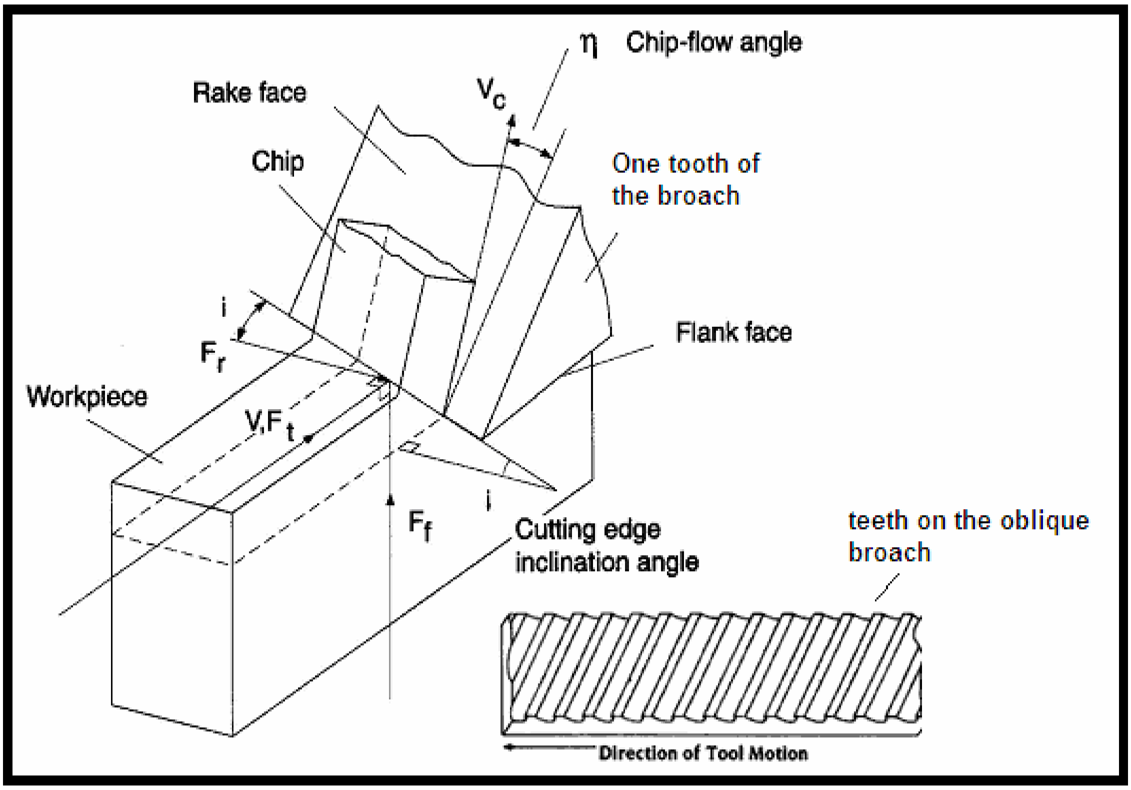


Figure 2-8: Oblique cutting and tool geometry.

As seen in Figure 2-8, there is an extra force named radial force, F_r, in oblique cutting because of the oblique angle. The tangential and feed forces generally do not change so much but because of the new force component the total force increases. However, because the force and energy per unit cutting edge length decrease the tool life is improved [35]. But, the cost of the broach tool increases. The same method as in the orthogonal cutting can be used to find the forces in oblique broaching. In order to find the force coefficients, the oblique cutting model can be used [3, 8]:

$$
\begin{aligned}
K_{tc} &= \frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) + \tan i \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}} \\
K_{fc} &= \frac{\tau_s}{\sin\phi_n \cos i} \frac{\sin(\beta_n - \alpha_n)}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}} \\
K_{rc} &= \frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n)\tan i - \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}
\end{aligned}
\tag{2.8}
$$

where τ_s is the shear stress, $\O_n$ is the shear angle, β_n is the friction angle, η_n is the chip flow angle and α_n is the rake angle in oblique broaching. The total force per tooth is calculated like in orthogonal cutting:

$$
F = \sqrt{F_t^2 + F_f^2 + F_r^2} \tag{2.9}
$$

2.2.3 Comparison of the Total Forces in Broaching

The total forces found in section 2.2.1 and 2.2.2 are the total force per tooth. The total force during the cutting process, F_{total} is the total of the forces acting on the teeth in the cutting zone. It is easy to determine it in orthogonal broaching, where each tooth enters the cutting zone and leaves at once. Thus, the total force on the system can be found by calculating the forces acting on each tooth in the cutting zone and then by summing them. This can be formulated in Equation 2.10 [33] as follows:

$$
\begin{aligned}
F_{ttotal} &= \sum_{i=1}^{m} \left(K_{tc} t_i b_i + K_{te} b_i \right) \\
F_{ftotal} &= \sum_{i=1}^{m} \left(K_{fc} t_i b_i + K_{fe} b_i \right)
\end{aligned}
\tag{2.10}
$$

Here m is the number of simultaneously cutting teeth which can be determined as [33]:

$$m = ceil(\frac{w}{p}) \qquad (2.11)$$

In Equation 2.11, w is the length of cut and p is the pitch length. Important point which should be taken into consideration is that the number of teeth in cut should be an integer for orthogonal cutting. So if the result is not an integer value it should be rounded to the nearest bigger integer [33].

In oblique cutting, however, the teeth enter the cutting zone in a more smooth way because of the inclination angle. At a given time some part of a given tooth may be in cut where the other part may not have entered the zone, or gone out already. The result of that situation can be seen in the final force graphics. These graphics are the results of the simulation program written in Visual Basic. The experimental data taken from UBC [48] and Ozturk [33 and 34] are used to find the cutting force coefficients for different tool parameters for waspaloy material which is commonly used for turbine discs.

cutting speed(m/min)	3,3528	3,3528	3,3528	3,3528	3,3528	3,3528
rake angle (degree)	4	6	8	10	12	14
Ktc (N/mm^2)	6190	5454	5507	5010	5387	4679
Kfc (N/mm^2)	3407	3275	3311	3242	3036	2345
Kte (N/mm)	80	87	79	78	61	76
Kfe (N/mm)	113	102	88	74	70	86
Tangential edge force (N)	119	131	119	117	92	114
Feed edge force (N)	170	153	133	111	105	129
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	13	14	15	17	18	20
Friction angle (degree)	31	36	37	42	41	40
Average shear stress (Mpa)	1200	1044	1132	1074	1255	1228
cutting speed(m/min)	4,572	4,572	4,572	4,572	4,572	4,572
rake angle (degree)	4	6	8	10	12	14
Ktc (N/mm^2)	5422	5543	5086	4776	4695	4446
Kfc (N/mm^2)	2393	2819	2501	2253	2168	2178
Kte (N/mm)	80	78	72	72	70	90
Kfe (N/mm)	122	82	82	84	77	75
Tangential edge force (N)	120	117	108	107	105	136
Feed edge force (N)	183	124	122	127	115	112
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	16	19	20	18	19	22
Friction angle (degree)	28	33	35	35	37	40
Average shear stress (Mpa)	1244	1051	1438	1186	1213	1215
cutting speed(m/min)	6,096	6,096	6,096	6,096	6,096	6,096
rake angle (degree)	4	6	8	10	12	14
Ktc (N/mm^2)	5667	5494	5033	5130	5014	4199
Kfc (N/mm^2)	3342	3437	2274	2826	2986	2209
Kte (N/mm)	76	83	74	73	59	74
Kfe (N/mm)	83	86	90	82	49	70
Tangential edge force (N)	114	125	111	110	89	111
Feed edge force (N)	125	130	135	123	74	105
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	15	14	17	20	20	22
Friction angle (degree)	32	40	39	39	43	42
Average shear stress (Mpa)	1113	1035	1179	1294	1271	1152

Table 2-1: Experimental data [33, 34 and 48].

The experimental data in Table 2-1 shows cutting coefficients for different cutting conditions in orthogonal cutting. The workpiece is waspaloy and a HSS-T steel is used to cut the part. It has been demonstrated that the orthogonal data could be used in the oblique force analysis with satisfactory results [3, 8, 9].

cutting speed(m/min)	3,3528	3,3528	3,3528	3,3528	3,3528	3,3528
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	119	131	119	117	92	114
Feed edge force (N)	170	153	133	111	105	129
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	13	14	15	17	18	20
Friction angle (degree)	31	36	37	42	41	40
Average shear stress (Mpa)	1200	1044	1132	1074	1255	1228
Kt (N/mm^2) (orthogonal)	6067	5344	5357	4816	5281	4623
Kf (N/mm^2) (orthogonal)	3131	3099	2991	2962	2889	2282
cutting speed(m/min)	4,572	4,572	4,572	4,572	4,572	4,572
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	120	117	108	107	105	136
Feed edge force (N)	183	124	122	127	115	112
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	16	19	20	18	19	22
Friction angle (degree)	28	33	35	35	37	40
Average shear stress (Mpa)	1244	1051	1438	1186	1213	1215
Kt (N/mm^2) (orthogonal)	5456	4157	5426	4681	4629	4386
Kf (N/mm^2) (orthogonal)	2416	2103	2786	2191	2134	2150
cutting speed(m/min)	6,096	6,096	6,096	6,096	6,096	6,096
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	114	125	111	110	89	111
Feed edge force (N)	125	130	135	123	74	105
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	15	14	17	20	20	22
Friction angle (degree)	32	40	39	39	43	42
Average shear stress (Mpa)	1113	1035	1179	1294	1271	1152
Kt (N/mm^2) (orthogonal)	5154	5199	5098	5092	5074	4208
Kf (N/mm^2) (orthogonal)	2739	3453	3010	2804	3032	2217

Table 2-2: Analytically calculated force coefficients for orthogonal cutting.

cutting speed(m/min)	3,3528	3,3528	3,3528	3,3528	3,3528	3,3528
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	119	131	119	117	92	114
Feed edge force (N)	170	153	133	111	105	129
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	13	14	15	17	18	20
Friction angle (degree)	31	36	37	42	41	40
Average shear stress (Mpa)	1200	1044	1132	1074	1255	1228
Oblique angle (degree)	15	15	15	15	15	15
Chip flow angle (degree)	15	15	15	15	15	15
Kt (N/mm^2) (Oblique)	6217	5477	5485	4914	5393	4715
Kf (N/mm^2) (Oblique)	3188	3135	3021	2963	2900	2291
Kr (N/mm^2) (Oblique)	664	446	431	275	353	335
cutting speed(m/min)	4,572	4,572	4,572	4,572	4,572	4,572
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	120	117	108	107	105	136
Feed edge force (N)	183	124	122	127	115	112
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	16	19	20	18	19	22
Friction angle (degree)	28	33	35	35	37	40
Average shear stress (Mpa)	1244	1051	1438	1186	1213	1215
Oblique angle (degree)	15	15	15	15	15	15
Chip flow angle (degree)	15	15	15	15	15	15
Kt (N/mm^2) (Oblique)	5583	4248	5535	4787	4731	4467
Kf (N/mm^2) (Oblique)	2468	2131	2812	2218	2156	2155
Kr (N/mm^2) (Oblique)	705	428	499	448	413	322
cutting speed(m/min)	6,096	6,096	6,096	6,096	6,096	6,096
rake angle (degree)	4	6	8	10	12	14
Tangential edge force (N)	114	125	111	110	89	111
Feed edge force (N)	125	130	135	123	74	105
Average chip ratio	0	0	0	0	0	0
Shear angle (degree)	15	14	17	20	20	22
Friction angle (degree)	32	40	39	39	43	42
Average shear stress (Mpa)	1113	1035	1179	1294	1271	1152
Oblique angle (degree)	15	15	15	15	15	15
Chip flow angle (degree)	15	15	15	15	15	15
Kt (N/mm^2) (Oblique)	5277	5315	5205	5189	5154	4275
Kf (N/mm^2) (Oblique)	2784	3464	3024	2814	3017	2212
Kr (N/mm^2) (Oblique)	542	317	366	376	271	268

Table 2-3: Analytically calculated force coefficients for oblique cutting.

As seen in Table 2-2 and Table 2-3 the tangential anf feed force coefficients are slightly increasing with the oblique angle. Naturally, this will cause an increase in force results. Furthermore, radial force coefficient K_r is not zero any more. The radial force coefficient value increases with the oblique angle which as a result will increase the resultant force.

In order to see the difference in the total forces for oblique and orthogonal broaching a tooth profile that is shown in Figure 2-9 is used. The geometry to be cut by this tooth profile is in Figure 2-10.

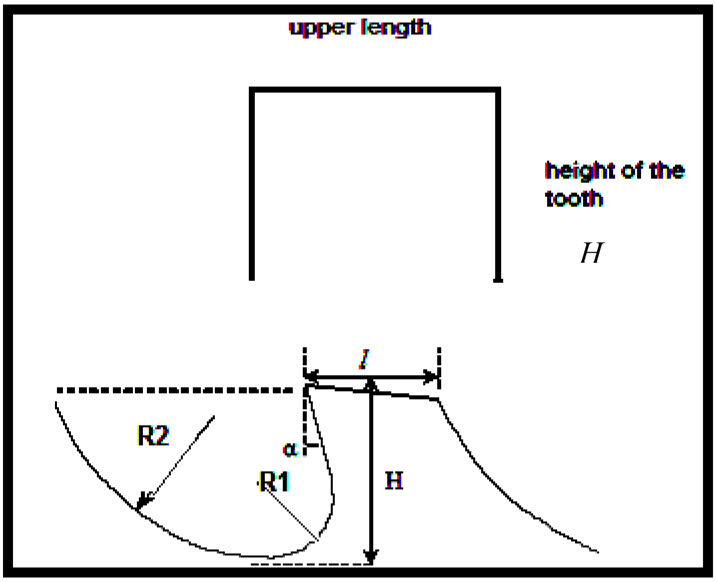


Figure 2-9: The tooth geometry selected for the tests.

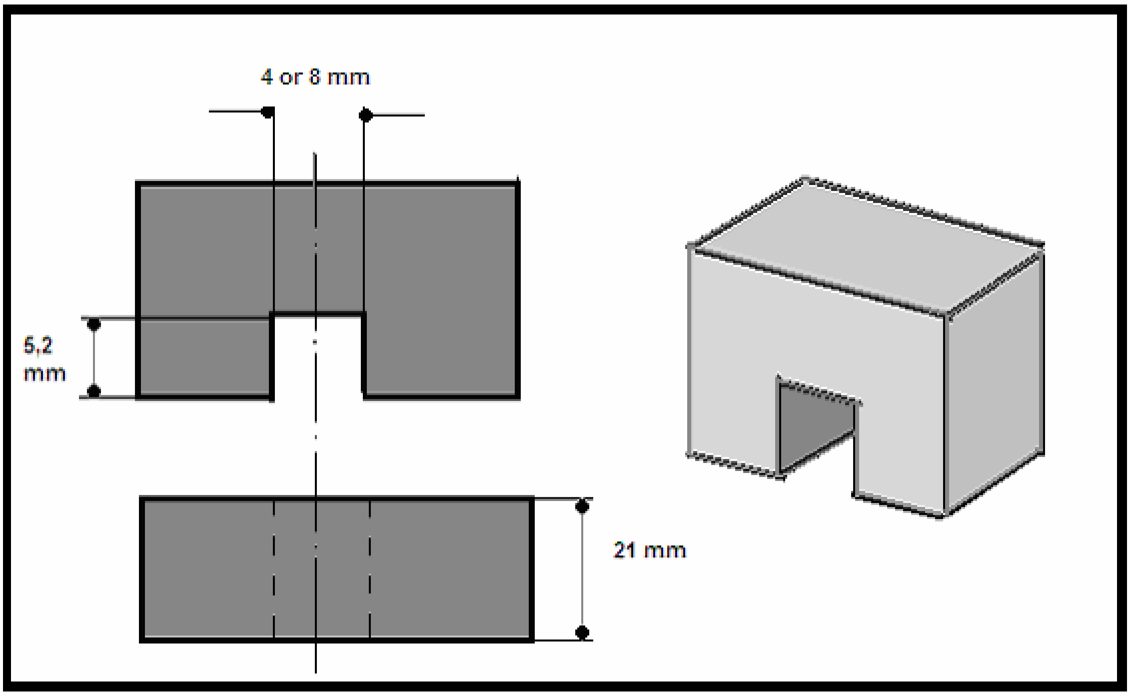


Figure 2-10: Geometry to be cut.

For broaching of this geometry in Figure 2-10, a 20 teeth tool with different geometries are used with different configurations. The geometries used for each test are in (Table 2-4).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
no. of teeth	20	20	20	20	20	20	20	20	20
height of the first tooth	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm	4 mm
upper length of the first tooth	4 mm	4 mm	8 mm	4 mm	4 mm	8 mm	4 mm	4 mm	8 mm
base length of the first tooth	4 mm	4 mm	8 mm	4 mm	4 mm	8 mm	4 mm	4 mm	8 mm
velocity	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s	55,88 mm/s
raise on the upper surface	0,06 mm	0,06 mm	0,06 mm	0,06 mm	0,06 mm	0,06 mm	0,06 mm	0,06 mm	0,06 mm
rake angle	12 deg.	12 deg.	12 deg.	12 deg.	12 deg.	12 deg.	12 deg.	12 deg.	12 deg.
land	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm	2,9176 mm
R1	4,98 mm	4,98 mm	4,98 mm	4,98 mm	4,98 mm	4,98 mm	4,98 mm	4,98 mm	4,98 mm
R2	6,5 mm	6,5 mm	6,5 mm	6,5 mm	6,5 mm	6,5 mm	6,5 mm	6,5 mm	6,5 mm
pitch	5 mm	10 mm	10 mm	5 mm	10 mm	10 mm	5 mm	10 mm	10 mm
oblique angle	15 deg.	15 deg.	15 deg.	30 deg.	30 deg.	30 deg.	0 deg.	0 deg.	0 deg.

Table 2-4: Test matrix.

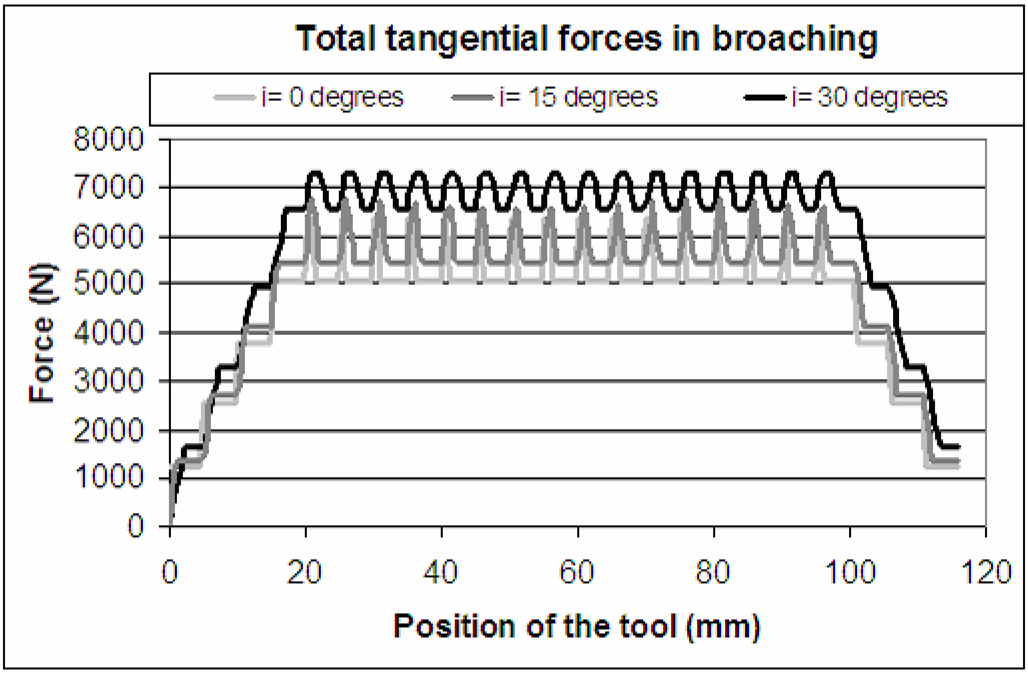


Figure 2-11: Total tangential forces in broaching with different oblique angles.

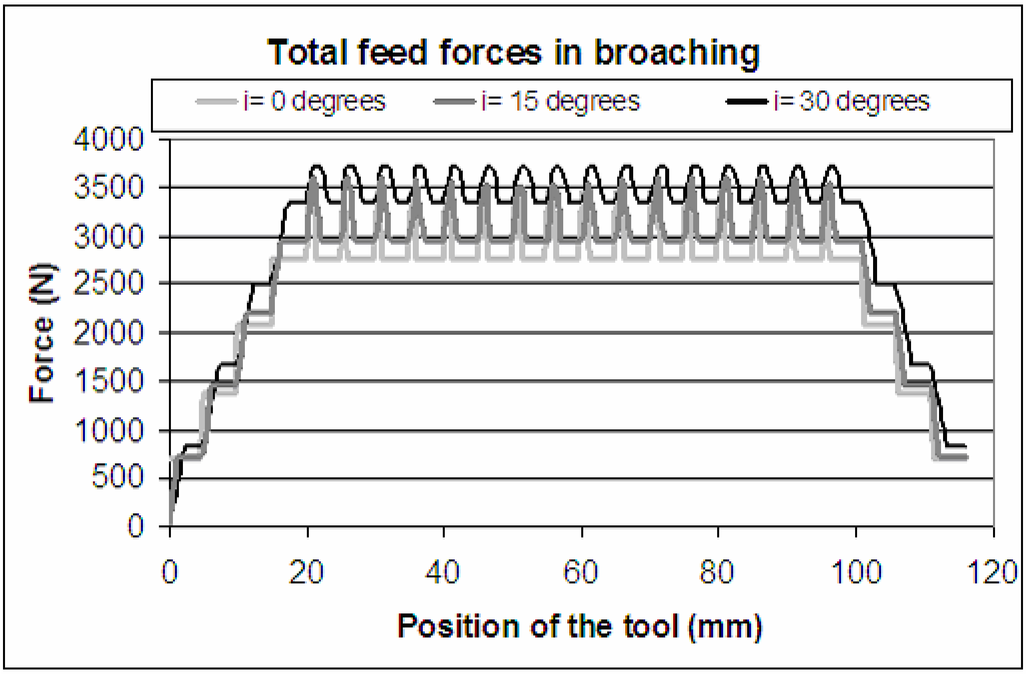


Figure 2-12: Total feed forces in broaching with different oblique angles.

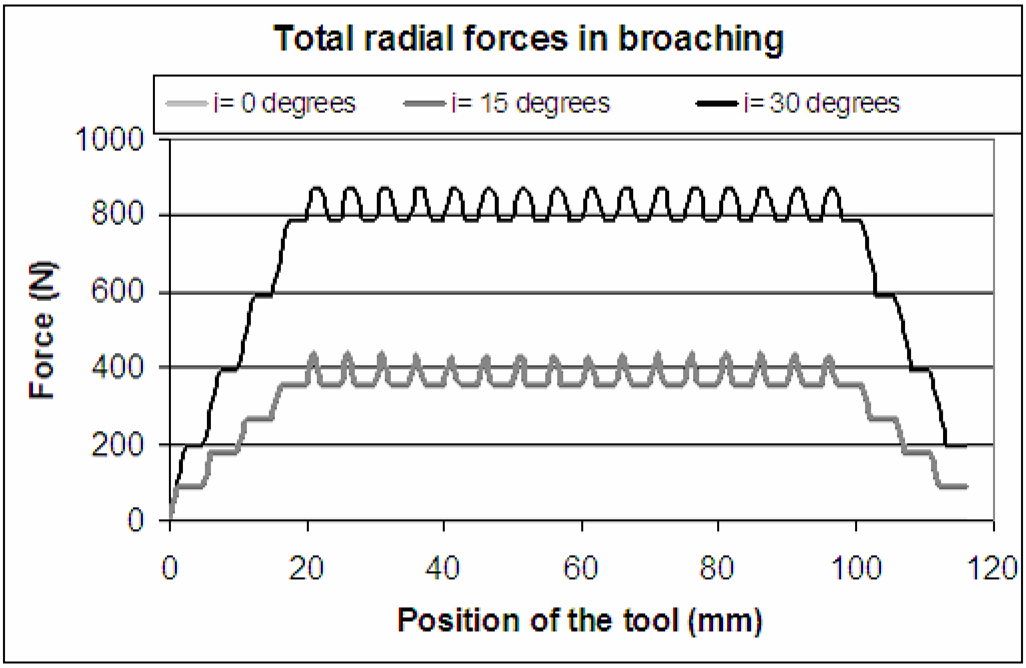


Figure 2-13: Total radial forces in broaching with different oblique angles.

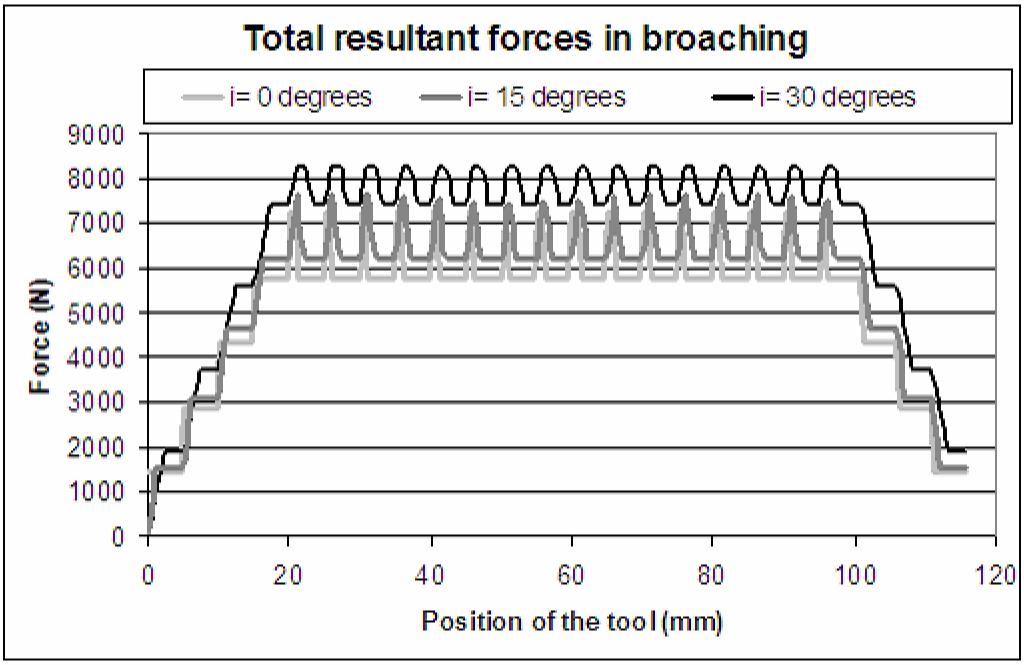


Figure 2-14: Total resultant forces in broaching with different oblique angles.

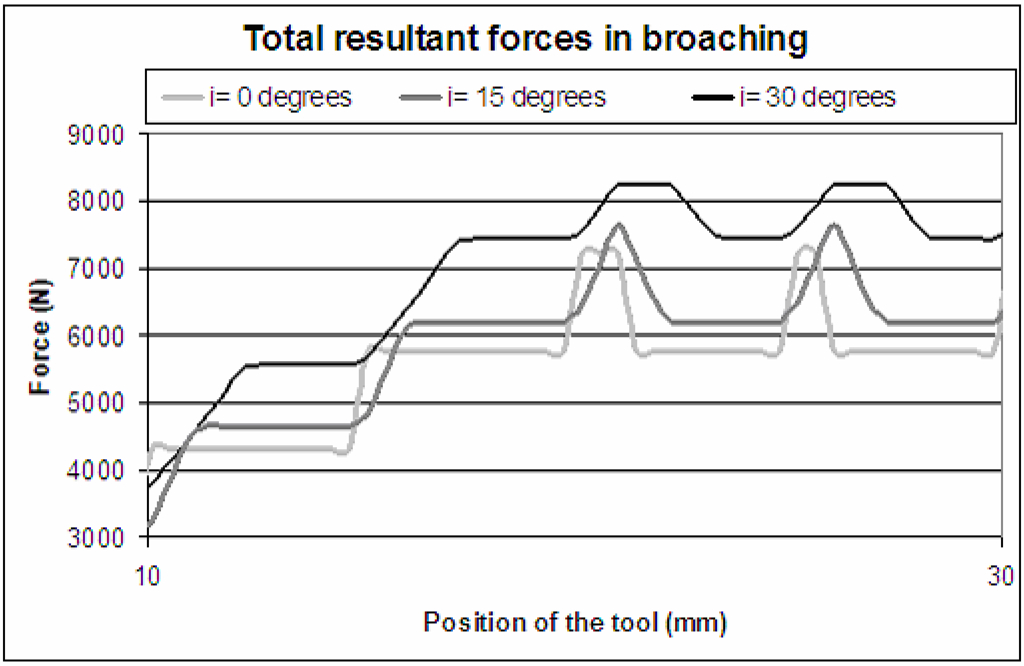


Figure 2-15: Enlarged view of resultant forces in broaching with different oblique angles.

As seen in the figures (Figure 2-11, Figure 2-12, Figure 2-13, Figure 2-14 & Figure 2-15) the radial forces increase with the increasing oblique angle. Also the force variation is much more smooth with oblique broaching (Figure 2-15). That is because the cutting teeth do not enter the cutting zone at once in oblique broaches. Generally, the resultant force per tooth values are greater in oblique cutting. The reason for this increase is the increasing force coefficients. The experimental data showed that the feed and tangential force coefficients are increasing for our process with increasing oblique angle. That variation is quite small but effective. The cutting edge length also increases, and so does the chip width. However, the main reason for the resultant force to increase is the radial force in oblique broaching. Oblique angle creates a new force component, the radial force, and this force increases with increasing inclination angle. Figure 2-16 and Table 2-5 show the force per tooth value variations with oblique angle.

Oblique angle (Degrees)	Tangential force per tooth (N)	Feed force per tooth (N)	Radial force per tooth (N)	Resultant force per tooth (N)
0	1373	751	0	1565
15	1452	795	97	1658
30	1737	904	212	1970

Table 2-5: Force per tooth values for different oblique angles.

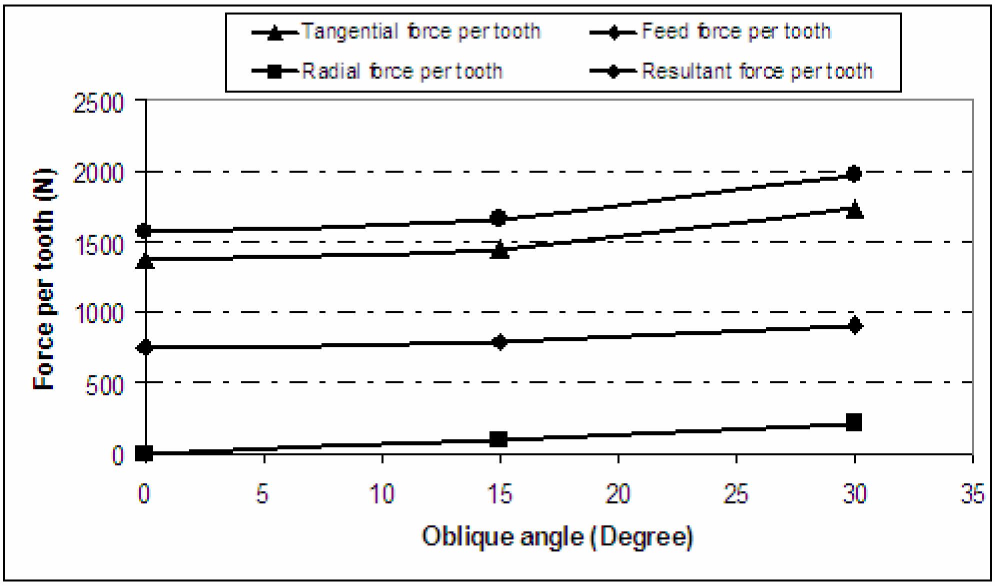


Figure 2-16: Force per tooth values for different oblique angles.

As expected, higher force per tooth values cause higher total forces as shown in figures (Figure 2-11, Figure 2-12, Figure 2-13, Figure 2-14 & Figure 2-15). In industry, orthogonal broaching is more common than the oblique one due to the simplicity of the tool for both manufacturing and resharpening. Orthogonal process will be considered in the rest of the study.

2.3 Tooth Stress Model

Stress on broaching teeth is the other important constraint which must be taken into consideration. For a successful operation, each tooth should be strong enough to withstand the force applied on it as the result of the cutting operation. In addition there must be some safe margin for the increased stress due to tool wear. Broach tooth geometries vary depending on the part and application. Since it is very impractical to determine the stress for each tooth using a method such as FEA for each tooth profile during the simulation and optimization, it was decided to use a general profile which can be a representative geometry for most of the broaching applications. Ozturk [33 and 34] proposed a profile shown in Figure 2-17.

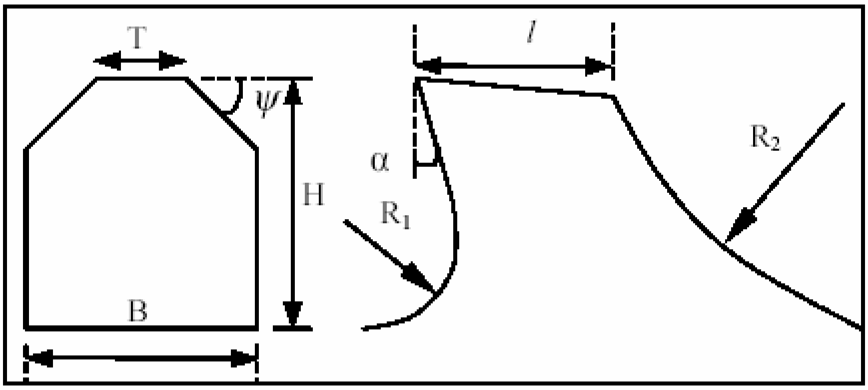


Figure 2-17: Tooth profile for stress calculations.

He used FEA for the stress calculation by distributing the cutting forces of the tooth. He repeated FEA for many different geometry parameters and developed the following equations by numerical methods:

$$\sigma_t = F(1.3H^{0.374} B^{-1.09} T^{0.072} \psi^{0.088} R_1^{-0.082} l^{0.356}) \quad (2.12)$$

where F is total cutting force applied on the tooth and the results are realistic over 90%.

2.4 Broaching Power

Total power needed in the system can be found by using the total tangential force and the cutting velocity as in Equation 2.13.

$$Power_{total} = F_{ttotal} v \qquad (2.13)$$

where v is the cutting speed.

2.5 Chip Flow

Chips produced in metal cutting have generally no commercial value. But the types of chips produced and the chip formation process is highly important because of the effect of that process on metal cutting mechanics and quality of the work. Besides, the results of researches in chip mechanics provide us information about the general mechanics of the machining.

Chips are unwanted items which must be removed from the work zone. But in broaching the chips do not leave the cutting zone as long as the teeth are in cut. That is why chip formation mechanics is important in broaching. Although there are different useful methods to predict the chip geometry, there is not a theory that can be directly used for broaching. The chip breaker theory can be used to predict the chip radius in broaching. In this section the similarity of broach tooth geometry with an attached obstruction type chip breaker will be presented and the chip radius will be tried to be predicted using this theory. If it is assumed that there is an attached obstruction type chip breaker like in Figure 2-18 the equation for the chip radius is given as [7].

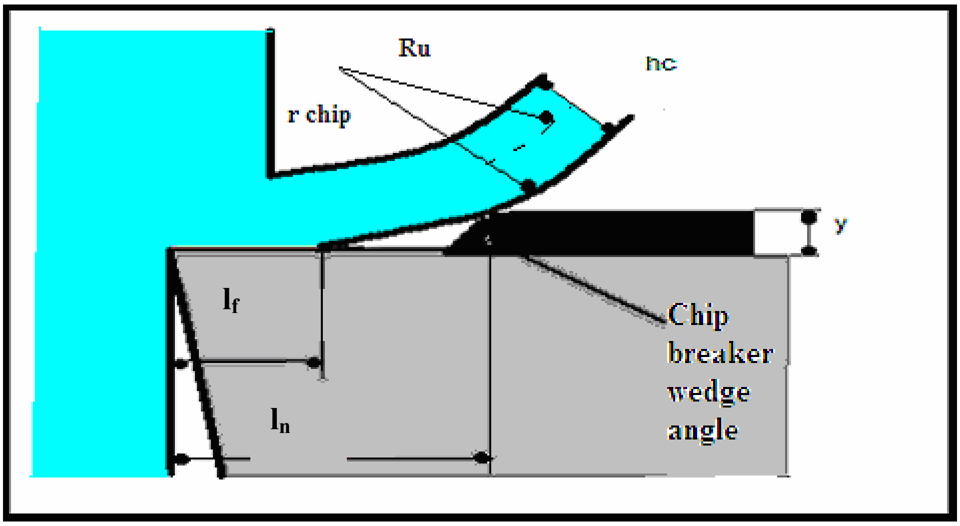


Figure 2-18: Attached obstruction type chip breaker.

$$r_{chip} = \left[\left(l_n - l_f \right) - \left(y \cot \sigma \right) \right] \cot \frac{\sigma}{2} \tag{2.14}$$

where σ is the chip-breaker wedge angle, y is the chip breaker height and l_f and l_n are the contact length and the chip breaker distance, respectively, as shown in Figure 2-18.

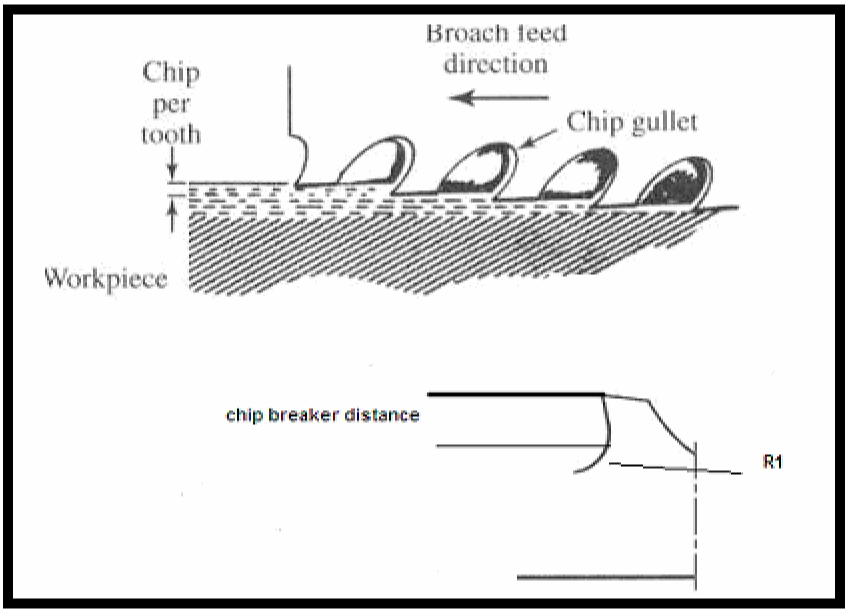


Figure 2-19: Similarity of broach tooth with attached obstruction type chip breaker.

Figure 2-19 shows the similarity of broach tooth geometry with attached type chip breaker. It is assumed that the curve with a radius of *R1* at the end of the rake face behaves like an attached obstruction type chip breaker and *y* is equal to *R1*. Also the chip breaker wedge angle is assumed as 45º because of the curved structure of the tooth bottom. Another important parameter needed to find the chip radius using Equation 2.14 is the chip breaker distance which can be found as follows:

$$l_n = H / \cos(\alpha) \tag{2.15}$$

In Equation 2.15 *H* is the tooth height and *α* is the rake angle of the tooth. Chip geometry is tried to be predicted for different tooth geometries using the assumptions and equations given. Experimental data given in Table 2-1 [33, 34 and 48] is used for the calculations. These data give enough information about the chip cutting geometry such as shear angle (*Ø*), friction angle (*β*), average shear stress (*τ*), average chip ratio, cutting force coefficients for given rake angles and cutting speeds. Contact length of the chip, l_f, may be calculated as follows [3]:

$$lf = a = \frac{h \sin\left(\phi + \beta - \alpha\right)}{\sin\phi \cos\beta} \tag{2.16}$$

In Equation 2.16 *h* is the uncut chip thickness and *α* is the rake angle. Average chip radius *(R_u)* is predicted by using these data. *R1* and *H* are kept constant. Also uncut chip thickness has a constant value of 0,05588 mm in the sample calculations given in the following. Average chip ratio is the ratio of uncut chip thickness to the cut chip thickness (*hc)* value and used to find the cut chip thickness. Cut chip thickness value is used in finding R_u from "*r chip"* values which are the outer radius of the chips as seen in Figure 2.18 and calculated as follows:

$$R_u = r_{chip} - \frac{hc}{2} \tag{2.17}$$

Test results are shown in Table 2.6.

Cutting velocity (m/min)	3,3528	3,3528	3,3528	3,3528	3,3528	3,3528
Rake angle(degrees)	4	6	8	10	12	14
Ktc	6189,93	5454,23	5506,79	5010,12	5387,3	4678,96
Kfc	3406,86	3275,01	3310,78	3242,31	3036,36	2345,22
Kte	79,59	87,42	79,43	77,93	61	75,69
Kfe	113,11	101,82	88,43	73,88	69,74	85,94
Fte	119,39	131,13	119,15	116,89	91,5	113,54
Ffe	169,678	152,74	132,65	110,82	104,62	128,91
Average chip ratio	0,24	0,24	0,26	0,29	0,3	0,35
Shear angle	13,41	13,5	14,88	16,54	17,54	20,25
Frriction angle	31,3	36,11	37,18	41,59	40,68	40,27
Shear stress	1200,21	1044,24	1132,2	1074,23	1255,14	1227,8
Cuttingvelocity(mm/sec)	55,88	55,88	55,88	55,88	55,88	55,88
Contact length	0,183922	0,204366	0,18993	0,195434	0,176529	0,153536
Chip breaker distance	4,009768	4,022033	4,03931	4,061706	4,089362	4,122455
Uncut chip thickness	0,05588	0,05588	0,05588	0,05588	0,05588	0,05588
Chip breaker height	1,98	1,98	1,98	1,98	1,98	1,98
r chip	4,456267	4,43652	4,513083	4,553865	4,666273	4,801673
Cut chip thickness	0,232833	0,232833	0,214923	0,19269	0,186267	0,159657
Ru	4,33985	4,320103	4,405622	4,457521	4,573139	4,721845
Tooth height	4	4	4	4	4	4
R1	1,98	1,98	1,98	1,98	1,98	1,98
Cutting velocity (m/min)	4,572	4,572	4,572	4,572	4,572	4,572
Rake angle(degrees)	4	6	8	10	12	14
Ktc	5421,61	5542,91	5086,47	4775,93	4695,48	4446
Kfc	2393,08	2819,16	25,,,53	2253,08	2167,74	2177,91
Kte	79,8	78,2	72,13	71,53	70,23	90,48
Kfe	122,15	82,46	81,63	84,41	76,61	74,71
Fte	119,69	117,3	108,19	107,29	105,35	135,72
Ffe	183,23	123,69	122,44	126,61	114,92	112,07
Average chip ratio	0,29	0,35	0,35	0,31	0,33	0,37
Shear angle	15,7	18,84	20,49	18,45	19,36	21,77
Frriction angle	27,88	32,83	35,18	35,08	36,75	40,11
Shear stress	1244,49	1051,25	1437,82	1185,75	1213,19	1215,04
Cuttingvelocity(mm/sec)	76,2	76,2	76,2	76,2	76,2	76,2
Contact length	0,148852	0,14731	0,14439	0,148603	0,146431	0,146124
Chip breaker distance	4,009768	4,022033	4,03931	4,061706	4,089362	4,122455
Uncut chip thickness	0,05588	0,05588	0,05588	0,05588	0,05588	0,05588

Chip breaker height	1,98	1,98	1,98	1,98	1,98	1,98
r chip	4,540931	4,574267	4,623027	4,666925	4,738936	4,819569
Cut chip thickness	0,19269	0,159657	0,159657	0,180258	0,169333	0,151027
Ru	4,444586	4,494438	4,543199	4,576796	4,654269	4,744055
Tooth height	4	4	4	4	4	4
R1	1,98	1,98	1,98	1,98	1,98	1,98
Cutting velocity (m/min)	6,096	6,096	6,096	6,096	6,096	6,096
Rake angle(degrees)	4	6	8	10	12	14
Ktc	5666,54	5493,56	5033,31	5129,84	5013,63	4199,4
Kfc	3341,91	3436,88	2274,49	2826,36	2985,64	2208,96
Kte	76,26	83,47	73,79	73,07	59,14	74,08
Kfe	83,21	86,41	89,85	82	49,08	69,95
Fte	114,39	125,21	110,69	109,61	88,71	111,13
Ffe	124,82	129,61	134,77	123	73,62	104,92
Average chip ratio	0,26	0,25	0,3	0,33	0,34	0,38
Shear angle	15,14	14,32	17,24	19,61	19,85	22,06
Frriction angle	31,99	39,59	38,56	38,84	42,86	41,78
Shear stress	1112,59	1034,73	1178,7	1293,92	1271,01	1152,06
Cuttingvelocity(mm/sec)	101,6	101,6	101,6	101,6	101,6	101,6
Contact length	0,17246	0,217562	0,178623	0,159975	0,173756	0,152483
Chip breaker distance	4,009768	4,022033	4,03931	4,061706	4,089362	4,122455
Uncut chip thickness	0,05588	0,05588	0,05588	0,05588	0,05588	0,05588
Chip breaker height	1,98	1,98	1,98	1,98	1,98	1,98
r chip	4,483937	4,404664	4,540382	4,63947	4,672967	4,804216
Cut chip thickness	0,214923	0,22352	0,186267	0,169333	0,164353	0,147053
Ru	4,376475	4,292904	4,447248	4,554803	4,59079	4,73069
Tooth height	4	4	4	4	4	4
R1	1,98	1,98	1,98	1,98	1,98	1,98

Table 2-6: R_u values for different rake angle and cutting speed values.

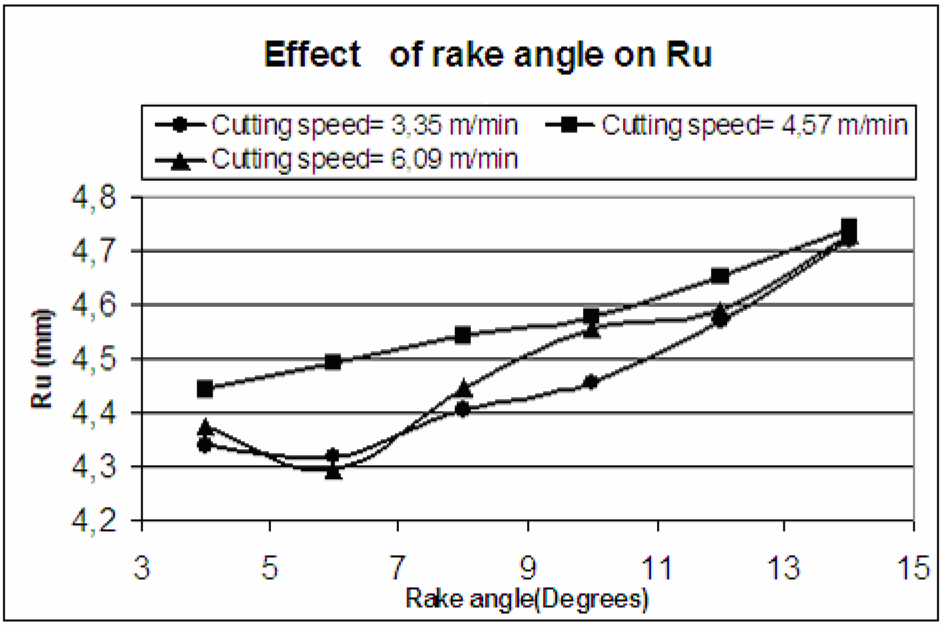


Figure 2-20: Effects of rake angle on R_u for a constant speed.

Results in Figure 2-20 show that the chip radius increases with increasing rake angle. This is an expected result. Bigger rake angle means a larger area for the chip to move. Thus, the chip can have a larger radius. Also a larger rake angle reduces the cutting forces which allows the chip to flow more freely across the rake surface.

It will also be useful to check the effects of uncut chip thickness on R_u. Test matrix in Table 2-7 is used to see the effects of uncut chip thickness on chip radius. Again experimental data from UBC and Ozturk [33, 34 and 48] are used. Cutting speed, *R1,* tooth height and rake angle values are kept constant.

Cutting velocity (m/min)	3,3528	3,3528	3,3528	3,3528	3,3528	3,3528
Rake angle(degrees)	4	4	4	4	4	4
Ktc	6189,93	6189,93	6189,93	6189,93	6189,93	6189,93
Kfc	3406,86	3406,86	3406,86	3406,86	3406,86	3406,86
Kte	79,59	79,59	79,59	79,59	79,59	79,59
Kfe	113,11	113,11	113,11	113,11	113,11	113,11
Fte	119,39	119,39	119,39	119,39	119,39	119,39
Ffe	169,678	169,678	169,678	169,678	169,678	169,678
Average chip ratio	0,24	0,24	0,24	0,24	0,24	0,24
Shear angle	13,41	13,41	13,41	13,41	13,41	13,41
Frriction angle	31,3	31,3	31,3	31,3	31,3	31,3
Shear stress	1200,21	1044,24	1132,2	1074,23	1255,14	1227,8
Cuttingvelocity(mm/sec)	55,88	55,88	55,88	55,88	55,88	55,88
Contact length	0,115198	0,148111	0,181025	0,213939	0,246852	0,279766
Chip breaker distance	4,009768	4,009768	4,009768	4,009768	4,009768	4,009768
Uncut chip thickness	0,035	0,045	0,055	0,065	0,075	0,085
Chip breaker height	1,98	1,98	1,98	1,98	1,98	1,98
r chip	4,62218	4,54272	4,463259	4,383798	4,304338	4,224877
Cut chip thickness	0,145833	0,1875	0,229167	0,270833	0,3125	0,354167
Ru	4,549264	4,44897	4,348676	4,248382	4,148088	4,047794
Tooth height	4	4	4	4	4	4
R1	1,98	1,98	1,98	1,98	1,98	1,98

Table 2-7: Variation of *Ru* with different uncut chip thickness.

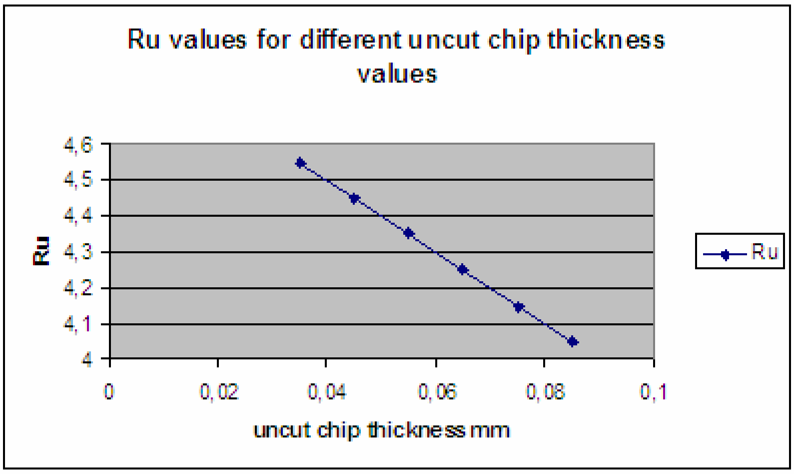


Figure 2-21: R_u for different uncut chip thickness.

In Figure 2-21, it is shown that the R_u decreases with increasing uncut chip thicknessin nearly a linear fashion. Trim and Boothroyd had the same results for the 85/15 brass chip. When all other parameters (cutting speed, rake angle, R1, uncut chip thickness) are kept constant, as the case in Table 2-7, the chip radius follows an increasing trend with the increasing tooth height. That is an expected result because when the tooth height increases the distance of the chip breaker increases, and so does the radius. We can see the effects of tooth height on R_u in Figure 2-22.

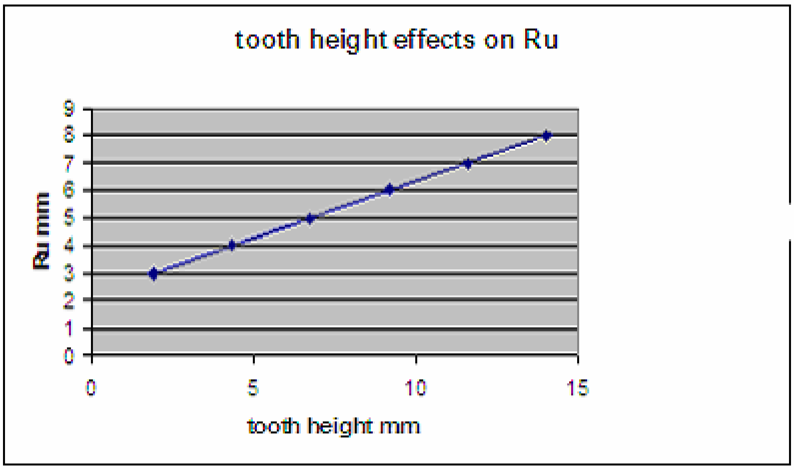


Figure2-22: Tooth height effects on *Ru*.

In this section, chip radius in broaching was analyzed and predicted. It is assumed that the tooth behaves as if there is an attached obstruction type chip breaker because of the face angle radius (*R1*). However, the chip is assumed to have a free space to move when these equations are used as shown in Figure 2-18. In broaching, on the other hand, the gullet bottom applies a force on chip which probably will cause the chip to have a smaller radius. This force and closed gullet volume are ignored during the chip radius calculations.

CHAPTER 3 OPTIMIZATION METHODOLOGY

3.1 Tool Design Optimization Parameters

In Chapter 2 the general properties of the broaching process and the equations which are used for simulation were reviewed. The main objective in this thesis is to produce the shortest total tool length in order to reduce the production time. Thus, the main parameters for our target are the pitch, number of the teeth per section, and total number of sections. In this chapter important broaching variables that are used to develop an optimization algorithm for broaching process will be explained. Simulations done for describing the effects of these variables will be presented and the results will be discussed. After that, the new method developed to optimize the tool design will be demonstrated.

3.1.1 General Tool and Tooth Geometry Variables

There are different variables that should be considered in the optimization of broach tools. These variables are interrelated, and the governing equations are implicit and nonlinear. That forces us to understand the variables and the relations between them very well. The general tool geometry variables such as land, gullet radius, rake angle and the back off angle are the parameters that create the tool geometry. In this thesis, these parameters are selected according to the common values that are used in industry. These variables are important for the cutting performance of the tools. Further research in order to optimize these variables may be done in a later study.

Pitch length is the main tool geometry variable which is going to be analyzed in detail. Pitch is the distance between two successive teeth, and it determines the number of teeth in the cut at a time. Smaller pitch would reduce the tool length at the cost of increased total broaching force. Gullet volume is the other important value determined by the pitch. The equations used to determine these values were explained in Chapter 2.

The profile of the tooth geometry is one of the most important variables.The profile means the shape the tooth creates while it passes through the work piece. The profile is selected according to the part geometry to be cut. Profile of the first tooth, variation of the profile from tooth to tooth and the tooth rise values that create the change along the tool axis are the important parameters to be determined. Tooth rise and the geometric properties of the tooth give us the chip thickness and chip width as seen in Figure 3-1. Just like the other machining processes, in broaching the chip geometry affects the cutting process strongly. The total force, total power and the stress are directly related to the chip geometry to be cut. However, in this thesis different methods are used to find the force and stress. Real geometry is used while determining the forces. The real lengths of the cutting edges are found and the forces are calculated by using these edge lengths and tooth rises on these edges. Stress calculation, on the other hand is done by approximation. Each tooth is approximated by the general tooth geometry explained in Section 2.3 in order to use the general stress equations. The profile of the tooth gives us the profile parameters such as tooth height (H), tooth width (B) and angle of side face (Ψ). Tooth height, tooth width and other general tooth geometry parameters such as the angle of the side face, rake angle, land length are necessary to find stress values. Also, the cut chip volume is important to check if there is enough gullet volume and chip geometry properties are necessary to control the chip flow. Gullet volume calculation was explained in Chapter 2. Chip volume can be determined from the total cutting edge length and the rise of the tooth.

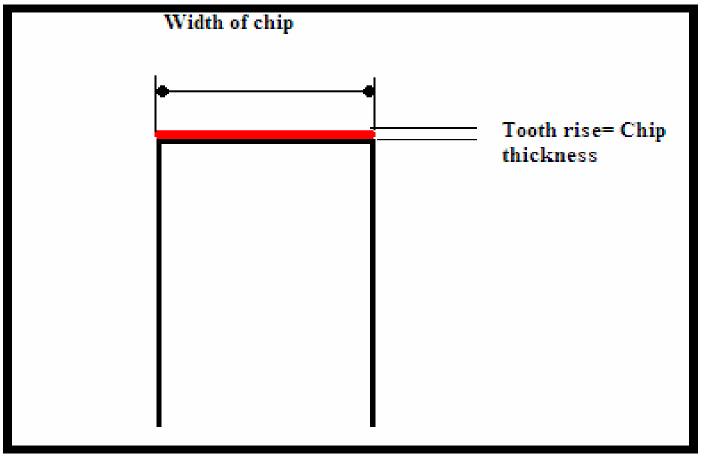


Figure 3-1: Determination of chip thickness and chip width.

As mentioned before, the tooth geometry is slightly different from a tooth to the next one. In this study, this change in geometry is grouped into three main groups which will be called tooth change options. These three main options can be seen in Figure 3-2.

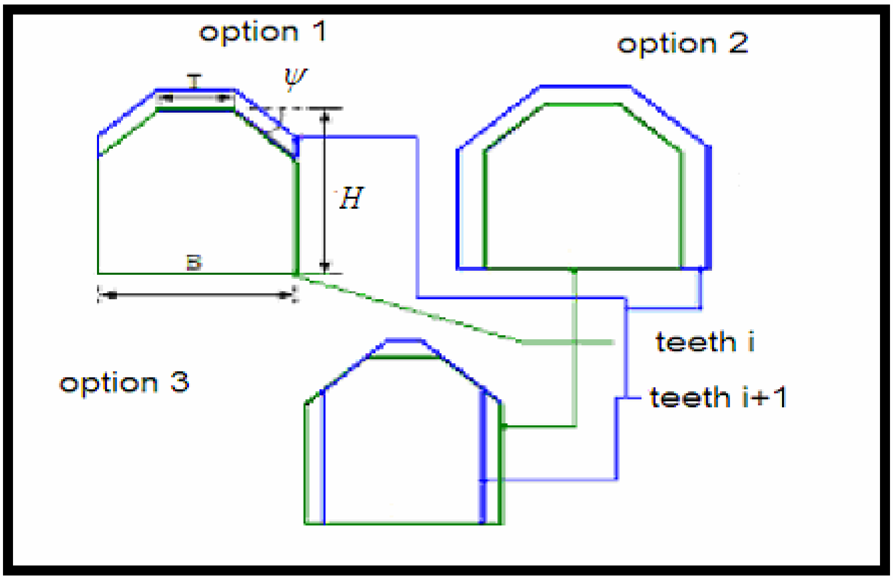


Figure 3-2: Tooth rise options.

In option 1, the cutting length is kept constant. In the second option, the cutting length and width can be controlled by selecting proper values of rise on the top and the side. In option 3, the side length is kept constant where the top decreases. The best stress control is in option 2 with relatively small rise on the side so that the effect of increasing height is compensated with increasing bottom width.

3.1.2 Cutting Speed

Cutting speed is the only cutting parameter which can be changed after a broach tool is manufactured. It may be thought that it is possible to increase the speed during production in order to reduce the cycle time. However, it is well established that the tool life exponentially decreases with the cutting speed. Considering long set up and resharpening times, as well as high broach tool costs, one should determine an economically feasible cutting speed. These speeds are usually determined through experience in production for each material/part. In addition, cutting speed is one of the parameters that affect the chip generation and its geometry as well as the cutting parameters such as cutting force coefficients. The cutting coefficients affect the total cutting forces. Because of all these reasons, the cutting speed should be determined separately from the tool design.

3.1.3 Dividing the Geometry into Sections

The optimization of the broaching process is complicated due to several reasons. First of all, the parameters explained above are interrelated, thus modification of one would affect others. For example, if the pitch is decreased, the number of simultaneously cutting teeth may increase resulting in higher cutting force and power. This in turn may require lower rise to be used. Combination of these may result in a shorter or longer broach section depending on the other parameters and the constraints. This is only for a single section. Considering that for complex geometries like a fir-tree there are multiple broach sections with different profiles, the selection of number of sections and properties of each section make the optimization process are further complicated. The volume to be broached must be distributed among broaching sections, and there is large number of feasible solutions. However, each section selection would affect the rest of the tools, both in profile and in cutting parameters.

Number of sections and their respective profiles are very important decisions in broach tool design. This fundamental decision affects the cost of tooling, process cycle time, surface quality etc. There are almost infinite possibilities for sectional selections. Therefore, there is a need for a method for this selection. As an example, consider the geometry shown in Figure 3-3. There are two basic methods for distribution of the material volume to be machined among the sections: height divisions or width divisions. They have different implications in terms of the process. First of all, in height divisions the tooth stresses are much lower due to the fact that each section starts with the shortest possible height which increases as much as needed to remove the material for that section. Tooth height is one of the most important factors affecting the tooth stress. In width divisions, on the other hand, the tooth height may become too large causing high tooth stress. For the example shown in Figure 3-3, in width division method, in some sections the width and total cutting length do not vary while the height of the tooth increases resulting in high stress values. But in height division method, the cutting length decreases as the teeth become higher which decreases the cutting force, and as a result the stress decreases. Therefore, height division is more efficient way of dividing the sections.

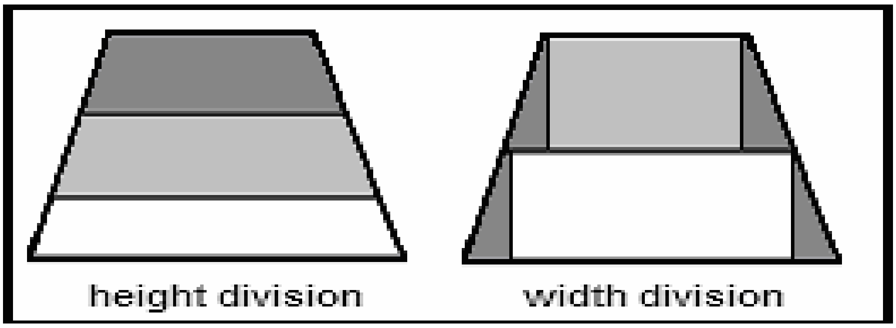


Figure 3-3: Volume divisions for the geometry to be broached.

3.2 Simulation of the Process and Simulation Results

Broaching is an expensive process. It is difficult to investigate the effects of each parameter on the process in real life. So, a simulation program has been written in Visual Basic in order to see the effects of the design parameters on the results. The program outputs are force components F_t, F_f, and the resultant force, stress, power and the chip-gullet volume ratio. The program is going will be explained in detail in Chapter 4.

3.2.1 Effects of Pitch

Pitch is the distance between two following teeth. So, pitch length directly affects both the number of simultaneously cutting teeth and the gullet volume. Number of simultaneously cutting teeth was given in Chapter 2. When the pitch increases, the number of simultaneously cutting teeth decreases. The change in pitch has no effect on the tooth profile and uncut chip volume, and so the force applied on each tooth are not changed. Thus, the total broaching force and power of the system decrease because of decreasing number of simultaneously cutting teeth. The available chip space also increases with increasing pitch which can clearly be seen in Figure 2-4 and understood by Equation 2.1. In order to see the effects of pitch on force, stress and chip-gullet volume ratio some simulations are performed. A simple geometry is chosen like in Figure 3-3. The geometry is 28mm high, bottom width is 63mm and top width is 21mm. this is quite bigger than the geometries cut in industry so the force results are huge. A geometry big like this is chosen to be able to try different modifications and see the effects of variables more clearly. Material to be cut is waspaloy. A tool with just one section is used. The tooth rise values are at their maximum values for waspaloy (0,06mm) and tooth rise option 2 is preferred. Cutting speed is 55mm/sec, rake angle is 12º, back-off angle is 2º, R2 is 7,95mm and R1 is 1,98mm. The effects of the pitch on stress, gullet volume and resultant force values can be seen in Figure 3-4, Figure 3-5 and Figure 3-6. Stress results give the maximum stress and this logic will be used in all stress analysis in the thesis. The maximum stress point on tooth is explained in Chapter 4.

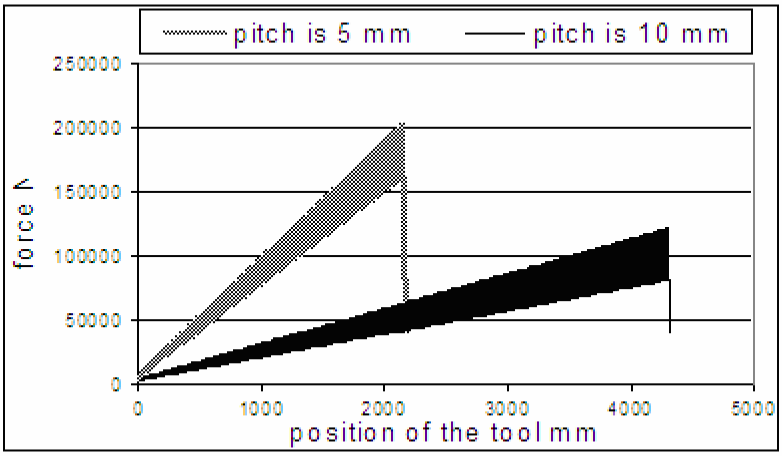


Figure 3-4: Effect of the pitch on the resultant force for a one-section tool.

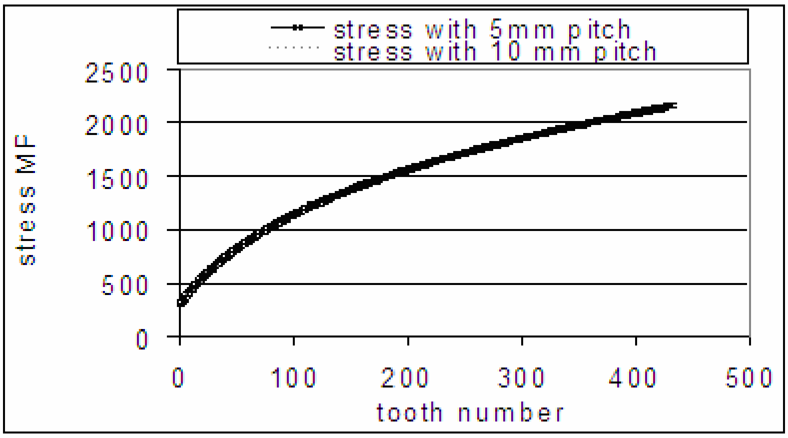


Figure 3-5: Effect of the pitch on tooth stress for a one-section tool.

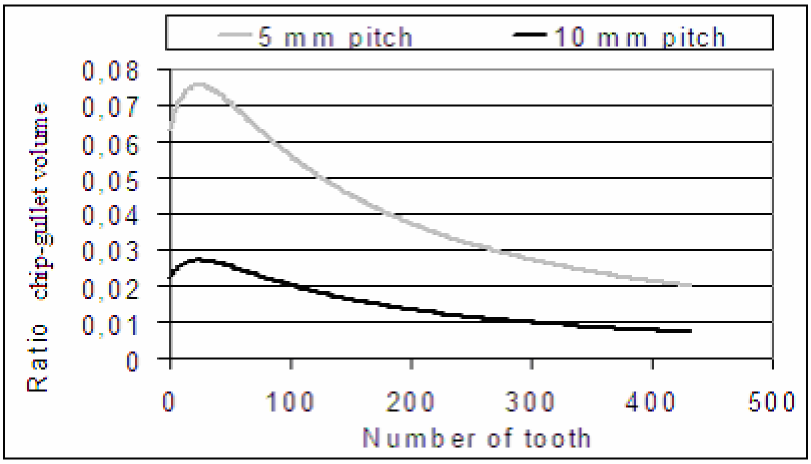


Figure 3-6: Effects of the pitch on chip-gullet volume ratio for one-section tool.

In Figure 3-4, it can be seen that the resultant force decreases with the increasing pitch. That decrease is because of the decrease in the number of simultaneously cutting teeth. As expected, the total tool length increases with pitch which can also be seen from the figure. Figure 3-5 shows that the tooth stresses are not affected with changing pitch. This is also to be expected as per tooth forces are not affected by the pitch. Figure 3-6 shows the effect of the pitch on chip-gullet volume ratio. Increased pitch allows more gullet space, thus lower volume ratio. These figures are for a tool with one section.

3.2.2 Tooth Rise

Tooth rise is the geometrical difference of each tooth from the previous one as seen in Figure 3-1 and Figure 3-2. The tooth rise defines the uncut chip thickness in broaching. An increase in the tooth rise will increase the force per tooth as natural. If pitch is kept constant this increase in force per tooth also increases total force and total power on the system. Change in force affects the tooth stress. However, the stress variation is also related with the tooth rise type. For example same amount of increase in force causes a larger increase in stress when tooth change option 3 is chosen instead of option 2. Furthermore, since the rise increases the tooth height, the stress increases even more than the force with increased rise. Same geometry in Section 3.2.1 is cut in order to investigate the effects of tooth rise on process. The tool geometries used are given in Table 3-1.

	Tool 1		Tool 2	
Section number	1	2	1	2
Rise on top side (mm)	0,035	0,108	0,065	0,108
Rise on the side edge (mm)	0,021	0,065	0,039	0,065
Bottom width of the first tooth(mm)	21	24	21	24
Top width of the first tooth(mm)	21	21	21	21
Angle (mm)	37	37	37	37
Rake angle (degrees)	12	12	12	12
Height of the first tooth (mm)	2	2	2	2
Land (mm)	3	3	3	3
Back-off angle (degrees)	2	2	2	2
R1 (mm)	2	2	2	2
R2 (mm)	8	8	8	8
Pitch (mm)	5	5	5	5
Number of teeth	800	258	431	258
Cutting speed (mm/sec)	50	50	50	50
Total tool length (mm)	5285		3440	

Table 3-1: Tool parameters used to see the effects of tooth rise.

Figure 3-7 shows the geometrical meanings of the parameters in Table 3-1.

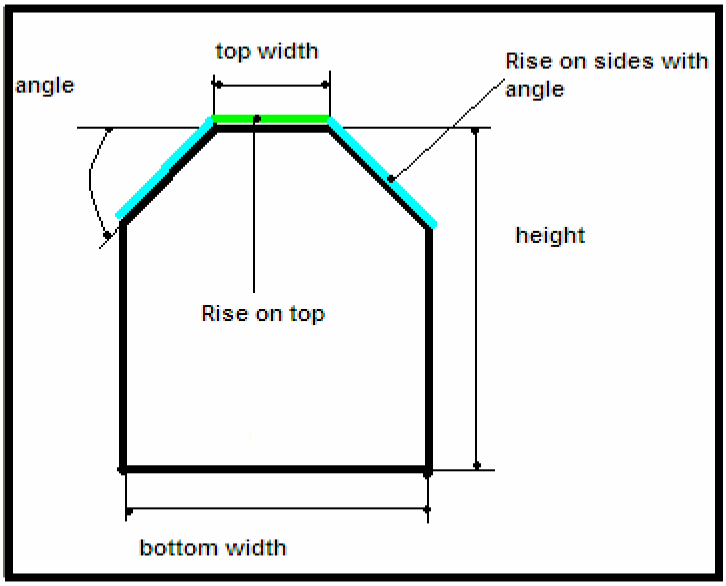


Figure 3-7: Tooth geometrical parameters.

Two different tools both with two sections are used. Tooth rise option 1 is used for the first sections and option 2 is used for the second sections. As shown in Table 3-1 the tooth rise is increased in the first section of the second tool. Other parameters are kept constant. As a result of increased tooth rise, number teeth in section decreases and the total tool length gets shorter.

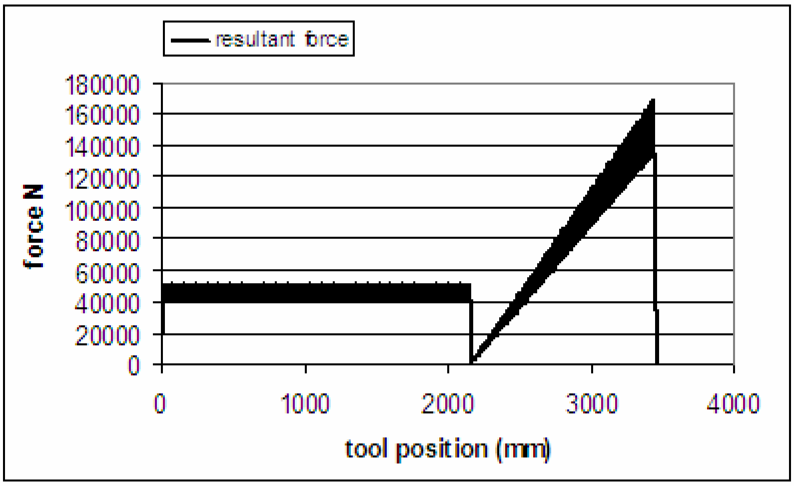


Figure 3-8: Resultant force values for *Tool 2*.

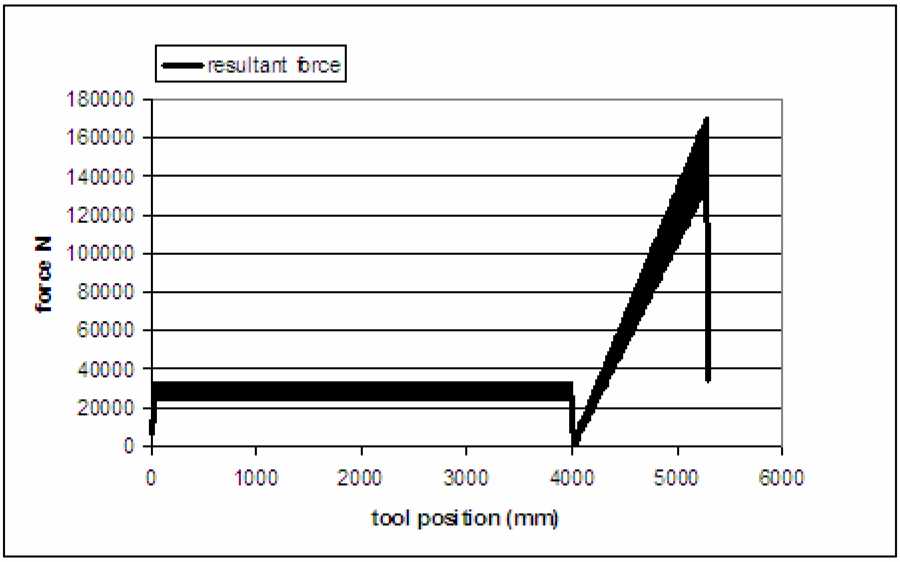


Figure 3-9: Resultant force values for *Tool 1*.

As seen in Figure 3-8 and Figure 3-9, the force in the first section of *Tool 1* is nearly half of the force in the first section of *Tool 2*. Besides, the first section of *Tool 1* is nearly two times longer than the first section of *Tool 2* which is because of the increasing number of teeth. Figure 3-10 shows the tooth stress on these tools.

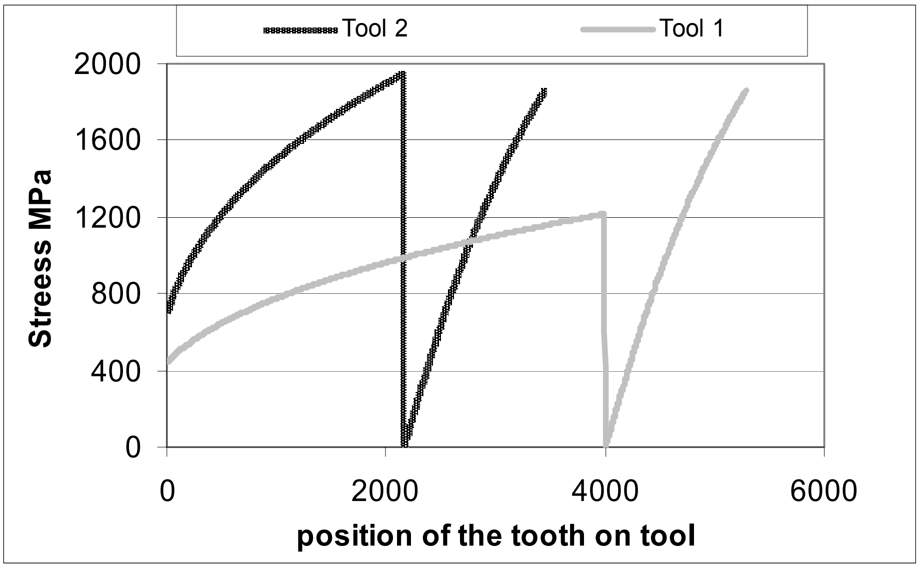


Figure 3-10: Stress per tooth values for *Tool 1* and *Tool 2.*

Figure 3-10 shows that there are more teeth in the first section of the tool with 0,035 mm rise. That results in longer tool. But decreasing force also decrease the tooth stress.

3.2.3 Tooth Width and Tooth Height

Tooth height and tooth width were explained in previous sections. Tooth height is the *height* parameter in Figure 3-7 where tooth width is the *bottom width.* Height and width of a tooth determine its general structure with land length if the tooth is assumed as a beam. Ozturk [33 and 34] proposed a general stress equation for broach tooth but this equation is based on the calculation of stress of a beam. So, tooth stress is directly related with the tooth width and tooth height parameters. The increase in the tooth height increases the stress while an increase in the tooth width affects the stress in opposite way. That is an expected result that same force is more effective on a longer beam where its effect decreases with increasing width of the beam. On the other hand, a wider tooth means a longer cutting edge which as a result means increased chip width. So, the force applied on the tooth increases with the increasing width of the tooth. However, if decreasing rate of the stress is higher than the increasing rate of force with increasing tooth width the stress may decrease instead of increasing. A proper ratio between the change of height and width values also gives the same result.

3.2.4 Cutting Length and Tooth Profile Options

Cutting length determines the chip width. Force per tooth values increase with increasing cutting length because of increasing chip width. Increasing force per tooth increases tooth stress and total resultant forces. Decreasing cutting length affects the process oppositely. This direct relationship between the cutting length and force makes this parameter important for the cutting process. If both force applied on tooth and the tooth height increase at the same time, tooth stress will be huge. As explained in Section 3.2.3 stress can be decreased by increasing tooth width. Type of the change in tooth geometry is important for stress control. Three main tooth geometry change options were presented in Figure 3-2. Selection of the right option will be helpful to keep the tooth stress under control. Different simulations are performed to see the effects of selecting different options. Figure 3-11 and Figure 3-12 show the effects of cutting length on total resultant force and tooth profile change options on tooth stress. Same geometry used in the previous simulations is cut. All geometrical variables, tooth rise parameters, cutting lengths and the rate of change in cutting length are same for both of the tools. Tools are four-section tools. Option 2 is used in all sections of one of the tools and so the tooth bottom width increases while moving to the end of the tool. The other tool is designed using option 3 and that causes a decreasing tooth bottom width while going to the end of the tool.

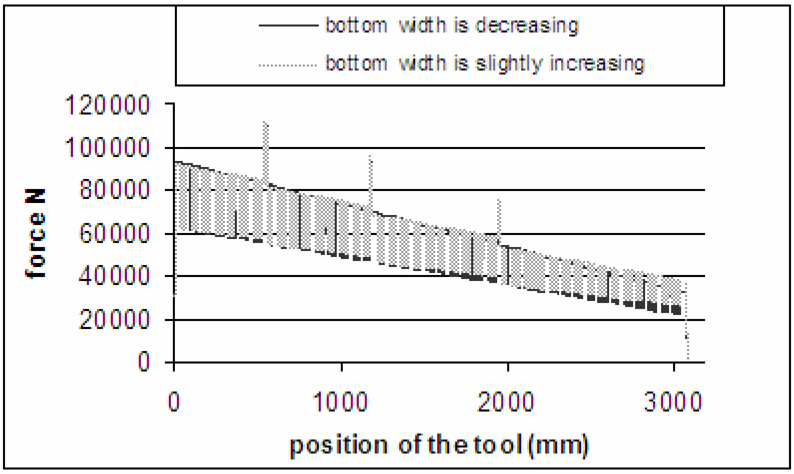


Figure 3-11: Effect of decreasing cutting length on total resultant forces.

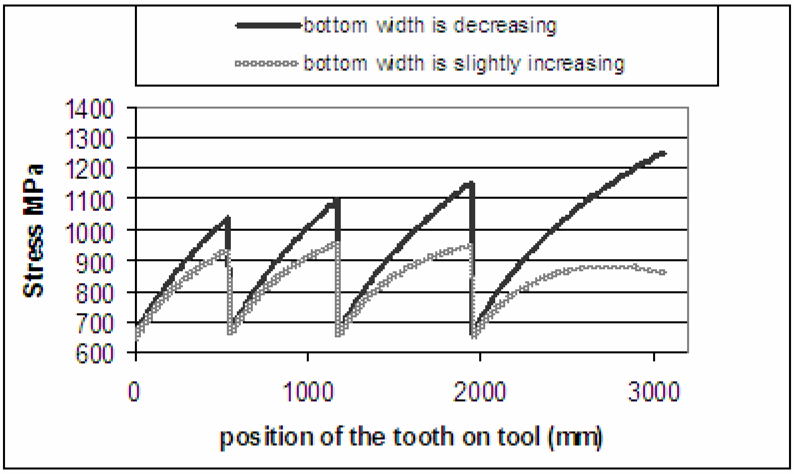


Figure 3-12: Effect of different tooth profile change options on stress.

As shown in Figure 3-11 decreasing cutting length decreases the resultant force. Figure 3-12 shows the stress per tooth corresponding to the forces in Figure 3-12. Although the broaching forces in Figure 3-11 are same the stress values are different as shown in Figure 3-12 due to different bottom widths of the teeth.

In conclusion, it can be said that, cutting length determines the chip width and so the broaching forces. Stress is also affected by the cutting length. Increasing cutting forces and tooth height may cause high tooth stress and should be controlled. Selection of proper tooth profile option can be useful to keep stress under control.

3.2.5 Number of Sections and Dividing the Geometry into Sections

Creating the target geometry in broaching is performed by selecting the right tooth profile and changing this profile slowly. These small geometrical differences between following teeth are called tooth rise. Profile of the each tooth is slightly different from the previous one and last tooth has the same profile with the geometry to be cut. Cutting action, also, is performed as a result of these geometrical differences. An important point is that the differences between successive teeth should be same. This is mainly to make the tool design and manufacturing easier. Broached profiles are generally noncircular holes or complex geometries like fir-tree profiles. Complex geometries are divided into simple sub geometries in order to simplify the tool design manufacturing. Dividing into sections is a necessity for complex geometries. Minimum number of sections is generally determined by the geometry to be cut. Sections for a fir-tree profile are shown in Figure 3-13.

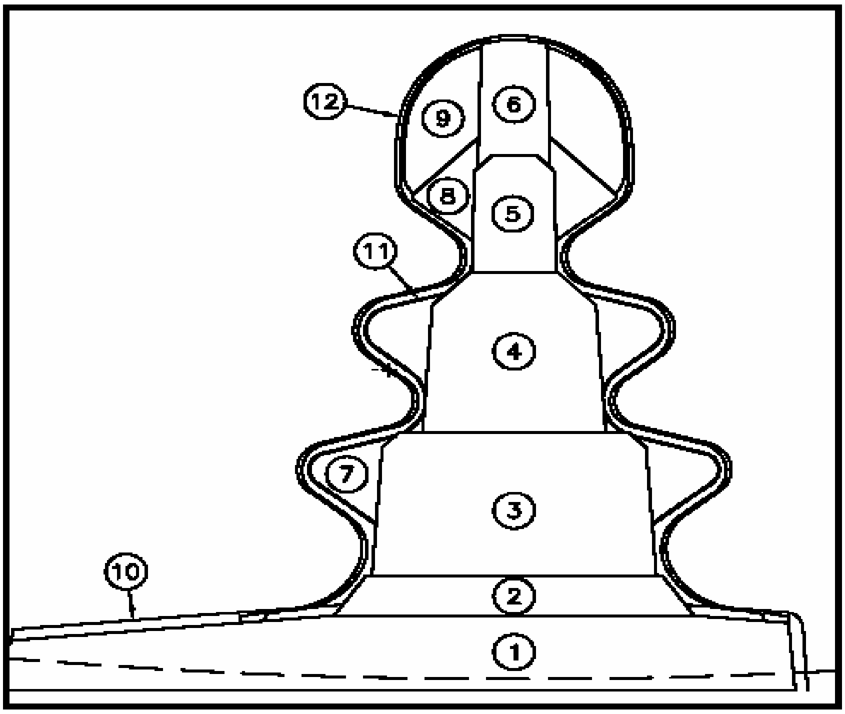


Figure 3-13: Dividing a fir-tree profile into sections.

Also, force and stress can be controlled by dividing the geometry into sections. As mentioned, tooth stress increases as the height of the tooth increases. With a new section the height starts from the beginning and the tooth height is again at its minimum value. Force and stress control can be explained better using Figure 3-14. In Figure3-14 same geometry is cut in different ways. In Figure 3-14-a the geometry is assumed as just one section and divided into two sections in Figure 3-14-b by height division. *Tooth rise 1* and *tooth rise 2* values are equal. As seen from the figure also *cutting length 1* and *cutting length 2* are the same. So, the acting forces on both teeth are the same. However, as a result of the section division the *tooth height 2* is smaller than *tooth height 1* and so is the stress of the second tooth. (Figure 3-14-c) gives an idea about force control by dividing the geometry into sections. Force can be decreased by different methods. Decreasing tooth rise or cutting length will decrease the force. Here tooth rise is kept constant but first section is again divided into sub sections by width division which provides a decrease in the cutting length. So the force decreases. However decreasing force does not mean a decrease in the tooth stress. Because, as shown in the figure, also the tooth width decreases and so the stress should be controlled.

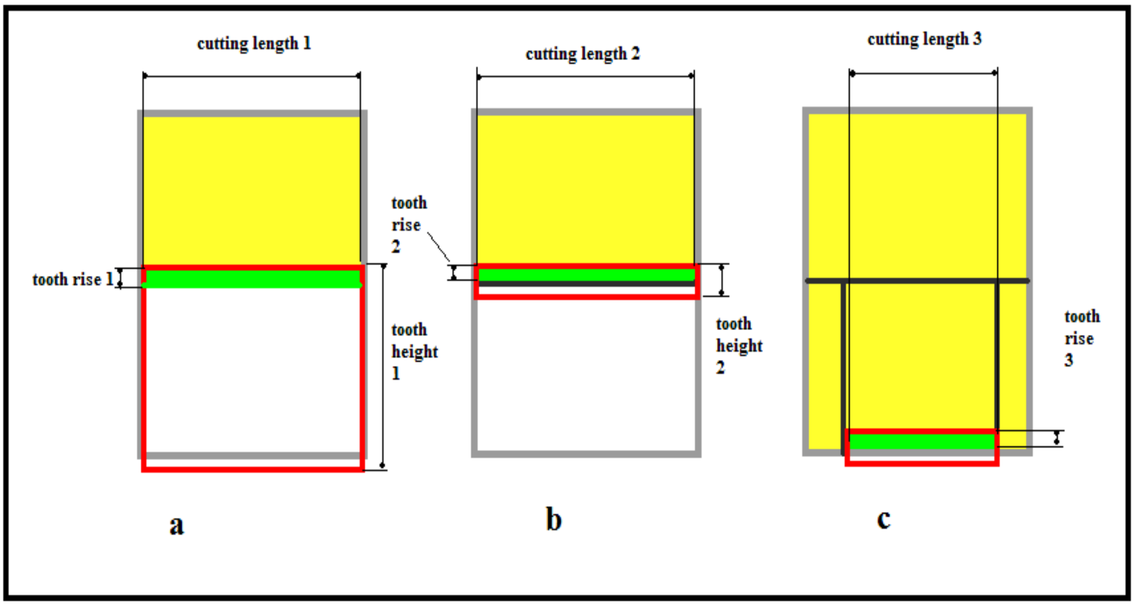


Figure 3-14: Dividing geometry into sections.

As mentioned before, section division methods are grouped into two main groups as height division and width division (Figure 3-3). The properties of these two methods were discussed. Thus, in this section the effects of these methods on force and stress results will be presented.

Height division does not have very much effect on force results. Because, generally, cutting length is not affected so much by the height division. But the tooth stress decreases as a result of decreasing tooth height. Same geometry used in previous simulations is used again. First, geometry is divided into three sections and then 4 sections. Tooth rise is taken as maximum. Pitch in all sections is 5mm and land is 3mm. R1 is 1,98mm, R2 is 7,5mm. Rake angle is taken as 12º where back-off angle is 2º for all sections. The height of the first tooth of each section is 2mm and the cutting speed is 55mm/sec. Tooth profile used in both four-section division and three-section divisions is similar. Results are in Figure 3-15 and Figure 3-16.

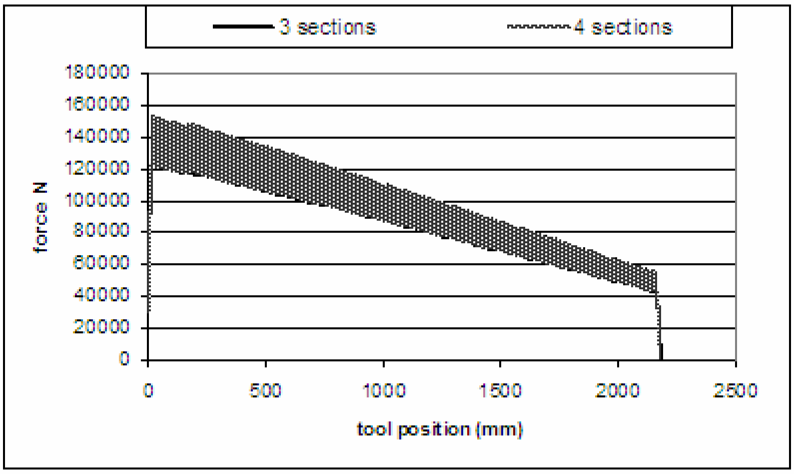


Figure 3-15: Effects of number of section on resultant forces when height division is done.

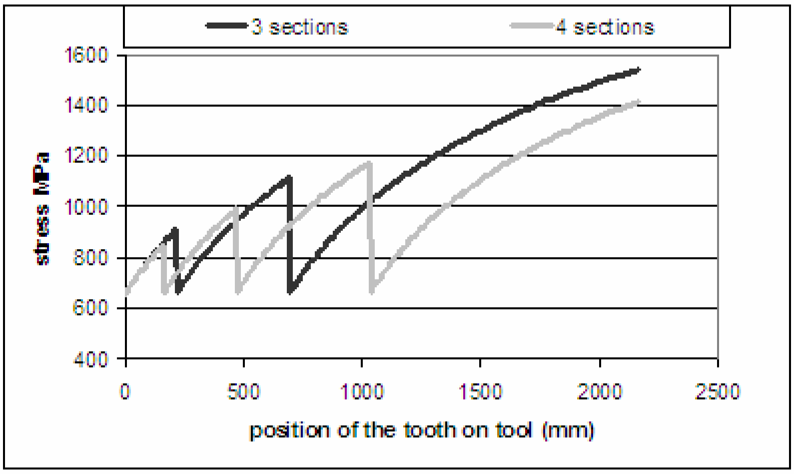


Figure 3-16: Effects of number of section on tooth stress when height division is done.

In each section a part of the volume is removed. Stress can be controlled by adjusting the volume ratio removed in each section. In each section equal volumes can be removed or there can be a ratio between the volumes (Figure 3-17). For example if the volume removed in first section is *V,* the second section will remove also a volume of *V* for equal volumes. The volume removed in the second section will be *2V* and the volume removed in the third section will be *3V* for linearly increasing volumes. Volumes removed in sections may linearly decrease, exponentially increase, exponentially decrease or other combinations can be tried. When height division is preferred, the ratio between the volumes cut by each sections does not affect the forces so much. Because, as explained before, height division does not affect the cutting length. Heights of the sections change with chip thickness and width but different tooth geometry (different tooth height, tooth width etc.) which, as a result, affect the stress values (Figure 3-17). Increase in the height of the section means an increase in the maximum height of the tooth in that section because maximum tooth height in a section is determined by the section height. If the other geometrical parameters of a tooth are kept constant while its height is increasing, and the same force is applied, the stress is expected to be higher. As explained before, force per tooth values are not affected by the change in ratio when height division is performed since the cutting length remains almost the same

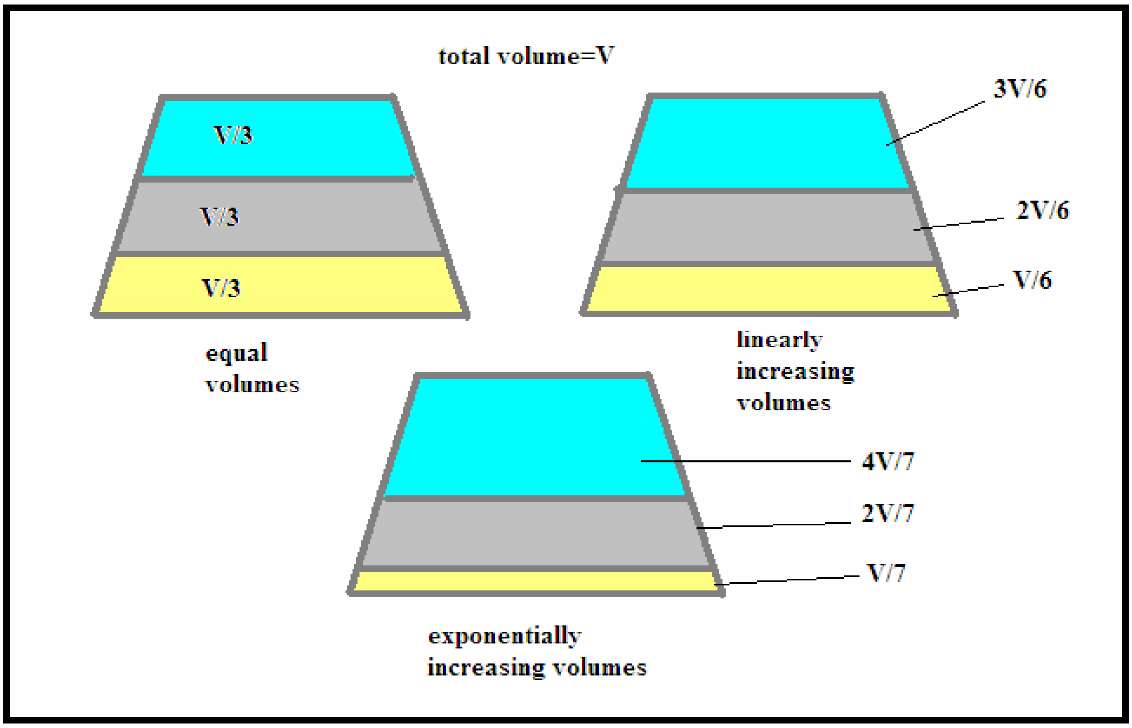


Figure 3-17: Volume ratio between sections.

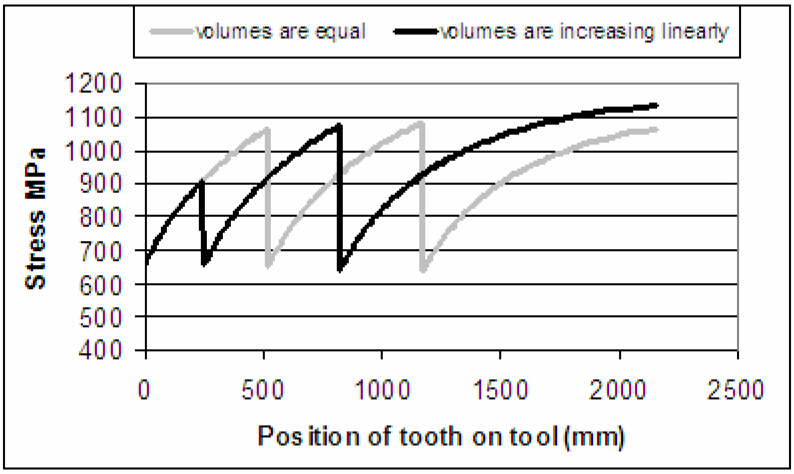


Figure 3-18: Effects of section volume ratios on tooth stress when height division is done.

In Figure 3-18, it is seen that when the volumes of the sections are following a linearly increasing trend, higher stresses occur towards the end of the tool when compared with a tool which is divided into three sections with equal volumes because of changing section heights.

Stress is a more serious problem when width division is preferred. Smaller tooth widths cause higher tooth stress even when less force is applied on the tooth. In order to prevent the high stress, maximum tooth height or force applied on tooth may be decreased. Keeping the section heights shorter will be useful to decrease the maximum tooth height. Besides, force can be adjusted by tooth rise. Same geometry in previous simulations is divided into four sections by both height and width division methods. Tooth rise is always taken as maximum. Other parameters such as land, pitch, R1, R2, rake angle, clearance angle, height of the first tooth of each section are kept constant. Simulations showed that maximum value of tooth stress is higher in width division even for less force (Figure 3-19 and Figure 3-20).

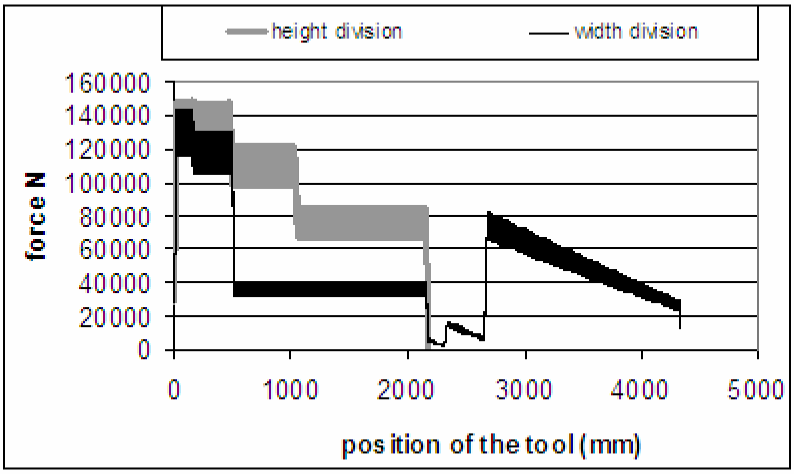


Figure 3-19: Effects of section division methods on resultant forces for four-section tools.

As mentioned, height division is a better choice if the geometry forces or other constraints do not cause problems. Width division allows higher tooth rise but tooth stress must be controlled. Volume ratios between sections affect the force and stress and must be decided according to the process.

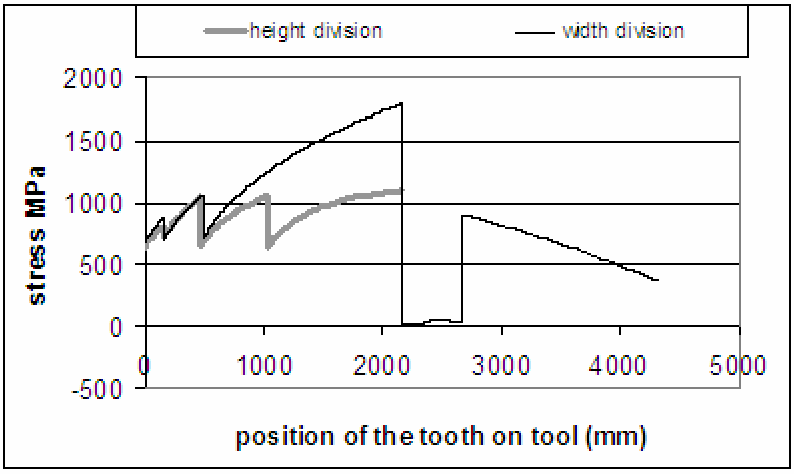


Figure 3-20: Effects of section division methods on tooth stress for four-section tools.

3.3 Optimization algorithm

3.3.1 Objective Function

Target of the optimization algorithm is to obtain the shortest tool length. Mathematical definition for the objective function can be given as follows:

$$Min \quad L \tag{3.1}$$

In Equation 3.1, L is the total tool length. Ozturk [33 and 34] suggests another variable as the objective function of the optimization in broaching. He used material removal rate as the objective function, and tried to maximize the material removal rate:

$$Max \quad MRR = \frac{w\sum_{i:1}^{N_s} t_i b_i n_i}{w + \sum_{i:1}^{N_s} (n_i - 1) p_i} V \tag{3.2}$$

where MRR is the material production rate, V is the cutting speed, w is the cutting depth (part thickness, length of cut), t_i is the chip thickness, b_i is the chip width, p_i is the pitch for the i^{th} teeth, N_s is the number of sections and n_i is the number of cutting teeth in section i. The tool length can be expressed as follows:

$$L = \sum_{i=1}^{N_s} (n_i - 1) p_i \tag{3.3}$$

which shows that minimizing the length or maximizing the material removal rate are equivalent. Because V is the cutting speed defined as a constant value respectively. Also the other statement used as numerator is the total volume to be cut and determined by the geometry to be cut and the length of cut.

3.3.2 Constraints

3.3.2.1 Total Tool Length

A broaching machine has a certain maximum tool length it can accommodate. Tool design must be done according to this and the tool must be shorter than the maximum ram length of the machine, L_{ram}.

$$L \leq L_{ram} \tag{3.4}$$

3.3.2.2 Chip Space

As mentioned in Chapter 2, chips cannot leave the cutting zone as long as the tooth is active. The cut chip is kept in the gullet, until the tooth leaves the cutting zone. The ratio of the cut chip volume and the gullet volume in which the chip is kept must be smaller than a certain number which is recommended as 0.35 by Monday [32].

$$\frac{V_{cutchip}}{V_{gullet}} \leq 0.35 \tag{3.5}$$

where $V_{cutchip}$ is the volume of the chip cut by one tooth and V_{gullet} is the gullet volume for the same tooth. The calculation of the gullet area can be found in Chapter 2. Gullet volume can be calculated by multiplying the gullet area with the tooth width w [33 and 34]:

$$V_{Gullet,i} = 0.9456w(p_i - l_i)^{0.816} H_i^{1.14} R_{1i}^{0.026} R_2 i^{-0.0891} A_i^{0.0388} \tag{3.6}$$

3.3.2.3 Chip Load

Chip load, i.e. tooth rise, has an upper limit to prevent chipping, and a lower limit to prevent rubbing [33 and 34].

$$t_{\min} \le t_i \le t_{\max} \tag{3.7}$$

3.3.2.4 Total Cut Volume

Total cut chip volume must be equal to the volume of the geometry to be cut.

3.3.2.5 Maximum Pitch Length

Because of some dynamic problems during the process, generally at least 2 teeth should be cutting at the same time. Thus, the pitch length has an upper limit which is determined by the length of cut as seen in Equation 3.8.

$$pitch \le \frac{length\ of\ cut}{2} \tag{3.8}$$

3.3.2.6 Pitch and Other Geometrical Features

As it can be seen obviously from the general tooth views (Figure 1-3, Figure 1-4, Figure 2-1 and Figure 2-4), pitch length should be longer than the land length for creating a gullet volume. Besides, as the pitch changes other geometrical values such as gullet radius and tooth height should be modified because of the machinability constraints. These constraints can be stated as in Equation 3.9 [33].

$$
\begin{aligned}
&H_i = c_{1i} p_i \\
&R_{1i} = c_{2i} p_i \\
&R_{2i} = c_{3i} p_i \\
&l_i = a_i p_i \\
&\text{and} \\
&a_i > 1
\end{aligned}
\tag{3.9}
$$

The c_{ji}; $j=1, 2, 3$; are selected according to the smooth chip flow and good machining. The selection of *a* constraint is a part of the optimization algorithm and the optimum design is found after trying different *a* values.

3.3.2.7 Tooth Stress

Stress on any tooth, S_i, should be less than the permissible stress value. Permissible stress depends on the tool material, and the stress per tooth is determined by the geometry of each tooth. The calculation of the stress was explained in the previous chapters.

$$S_i \leq \textit{permissible stress} \tag{3.10}$$

3.3.2.8 Power

In Chapter 2, the total power in broaching, $Power_{total}$, was formulated (Equation 2.13). The system power should not exceed the maximum machine power.

$$Power_{total} \leq \textit{Available machine power} \tag{3.11}$$

3.3.2.9 Special Constraints

Manufacturer or the user may require some special properties on broach tools such as volume ratio between sections, increasing, decreasing or constant broaching force patterns, less stress at the finishing section etc. These should be taken into consideration while defining the sections and tooth rise options.

3.3.2.10 Geometry Constraints

The profile to be cut is one of the main parameters of the tool design. Minimum number of roughing sections and the section geometries depend on the final geometry. For example, a simple geometry may be cut by a tool with just one section, but a fir-tree profile generally needs more sections. Figure 3-21 shows possible divisions for fir-tree profiles.

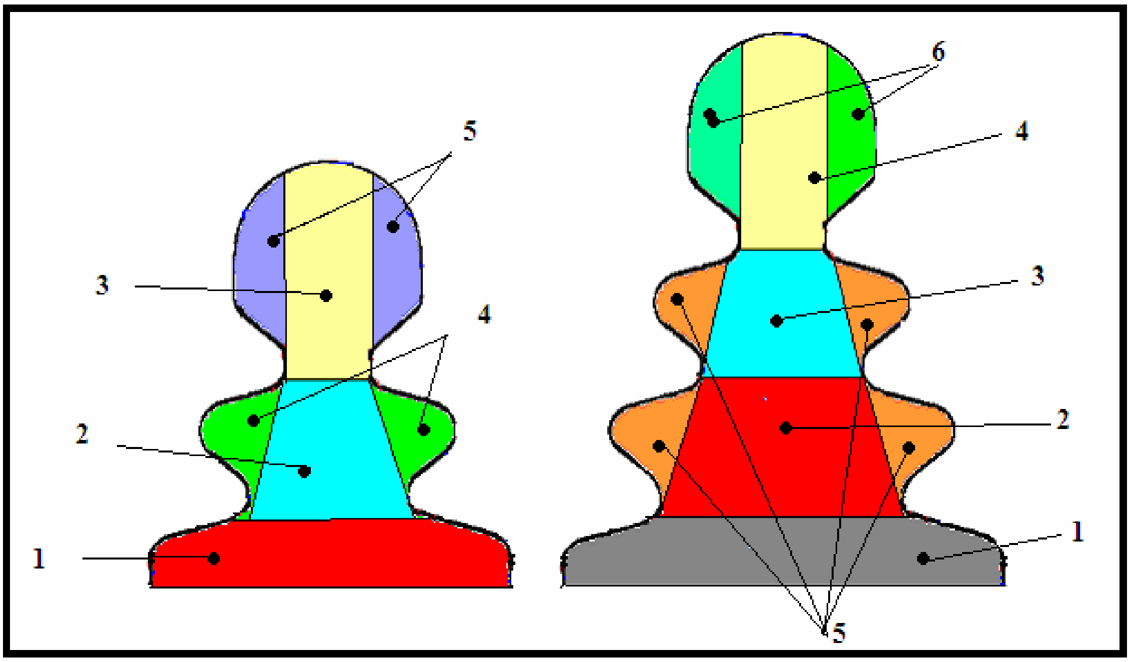


Figure 3-21: Dividing fir-tree profiles into sections.

Sections shown in the figure are not the only geometries. These are just possible ways of dividing the geometry into sections.

3.3.3 Optimization Algorithm

The main purpose of the optimization procedure is to obtain the minimum total tool length. There are many feasible solutions, and there is not a straightforward method to find the optimal one. One obvious way to achieve that is to use the minimum possible number of sections, maximum chip thickness with minimum pitch. The solution is started with the minimum possible tool length using the maximum allowable chip thickness and minimum pitch without violating the main constraints such as power, gullet area, tooth stress etc. The minimum possible number of sections is used as a start. This means that, if it is geometrically possible, the initial solution contains only one section. However, depending on the workpiece geometry, this may not be possible in which case the solution is started with minimum possible number of sections. The section profiles are selected based on the work geometry as explained in previous sections. Once the sections are defined, each section is optimized separately. When a constraint violation is encountered, the rise is reduced and the pitch is increased. For example, for waspaloy material, the maximum and the minimum chip thickness are set to 0,065 mm and 0,012 mm, respectively based on the production data [33 and 34].

For constraint checks, the calculations such as force and stress are carried out for the first tooth of each section using the equations given in Chapter 2. These can be repeated for the rest of the teeth which would take time in simulations. An alternative method is to model the stress based on the variations of the tooth geometry with respect to the first tooth. Simulations have been carried out to determine the following equations for stress predictions

$$\begin{aligned}
C_{\%s} &= 0,0059C_{\%b}^{\;2} - 1,1811C_{\%b} + 6,8643 \\
C_{\%s} &= C_{\%f} \\
C_{\%s} &= 0,3709C_{\%h} + 0,0017 \\
C_{\%s} &= 0,0002C_{\%t}^{\;2} - 0,072C_{\%t} - 0,0832
\end{aligned} \tag{3.12}$$

where $C_{\%s}$ is the percentage variation of the tooth stress, $C_{\%b}$ is the percentage change in the tooth bottom width, $C_{\%h}$ is the percentage change in the tooth height and $C_{\%t}$ is the percentage change in the tooth top width.

The algorithm starts with possible minimum number of sections, minimum number of teeth per sections, i.e. with maximum tooth rise, and minimum pitch value. Then, these parameters are modified according to the constraints. As a result, the solution which is almost optimal is found. In the following, the optimization algorithm is explained step by step.

Step 1: (Cutting speed selection) First, the cutting speed must be selected. A proper cutting speed is selected based on the material and the economical tool life considering tool set up time, batch sizes etc.

Step 2: (Max. and min. number of cutting teeth) In broaching, the experience and the analysis suggest that there must be at least one cutting tooth at a time in order to reduce the dynamic affects of tooth impact on the part. This means that:

$$pitch_{\max} = \frac{lengthofcut}{2} \tag{3.13}$$

From the geometry of the tool:

$$\min.pitch = a \times land \tag{3.14}$$

where a is a constant which is greater than 1.

By using the maximum and minimum pitch values from above equations, we can determine the maximum and minimum number of teeth in the cutting process, $m_{\max}$ and $m_{\min}$, respectively.

Step 3: (Tooth rise option selection.) Option 2 shown in Figure 3.2 is the best choice if there is no geometrical limitations. That is because the increase in the bottom width compensates the increase in height.

Step 4: (Definition of the geometry) Height and width values of the geometry are defined.

Step 5: (Number of simultaneously cutting teeth) The number of simultaneously cutting teeth, $m_{pm,}$ is an important factor which directly affect the total cutting force and power, as well as the pitch of the tool. m_{pm} can be determined based on the maximum available power on the machine for the cutting speed used. The part of the tool that has the maximum cutting area must be found out first which is needed to determine the maximum cutting force per tooth. The maximum possible chip thickness, or rise, is used in force calculations. Then, m_{pm} can be determined as follows:

$$\text{int}\left(\frac{F_{total\,\max}}{F_{\max\,pp}}\right) = m_{pm} \tag{3.15}$$

where F_{maxpp} is the maximum calculated cutting force on a tooth and $F_{total\max}$ is the maximum possible cutting force, i.e. force available on the ram for a particular cutting speed.

Step 6: (Selection of the number of simultaneously cutting teeth) m_{pm} found in step 5 is chosen as the number of teeth in cut if it is greater than or equal to m_{min} or smaller than or equal to m_{max}. determined in step 2. If the force constraint allows cutting with more than m_{max},, then m_{pm} is taken as m_{max}, and we proceed to step 8. But if the force constraint requires m_{pm} to be smaller than m_{min} then m_{min} is chosen as m_{pm}, and we proceed to step 7 for a modification.

Step 7: (Modification of the rise) In step 6, it was found that the force constraint required the cutting teeth number to be less than m_{min}. But, because of the pitch length constraint the minimum number of cutting teeth is m_{min}. Thus, m_{min} is to be selected as m_{pm}. However, when this modification is done, the force per tooth must be decreased in order to remain within force constraint limits. That can be done by decreasing the chip area per teeth. Hence, the tooth rise is decreased. We may proceed to step 8 with the new values. However, we may also try width division for this section which is another way of decreasing the chip area per tooth

Step 8: (Pitch limits) Minimum and maximum possible pitch values are determined based on the simultaneously cutting teeth determined in Step 6.

Step 9: (Graphs) The graphs that show stress, gullet-chip volume ratio and force variations are drawn. These variations are also expressed in terms of best-fit equations.

Step10: (Gullet-chip volume ratio control) Chip-to-gullet volume indicates the space availability for the chips in the gullet. Monday [32] recommends this ratio to be less that 0.35 for good chip control. The volume ratio for the first tooth is checked. If there is no problem with the ratio, we directly proceed to step 11. But if the ratio is bigger than 0.35 then modifications must be done. First, the pitch is increased step by step until it reaches the value of maximum pitch corresponding to m_{pm} and each time graphs in step 9 are updated. If the pitch modification is not enough to reduce the volume ratio to the acceptable levels, then the height modification starts each time turning back to step 9.

Step 11: (Stress control) Tooth stress is checked. If it is higher than the acceptable stress level, then the rise is decreased.

Step 12: (Number of teeth) From the force and stress variation graphs in step 9, maximum force level for each section is identified. Of course, it would be very much desirable to maintain uniform stress and force within a section, and also throughout the whole cycle. However, this is usually not possible due to the constraints.

The number of the total teeth for a section is selected according to the force, stress and volume ratio predictions, and the geometry to be cut. The objective is to reach the maximum allowable force level, but if that is not possible a new reachable maximum force level is selected. Based on this analysis, a section may be divided into several subsections. Then, each subsection is analyzed and designed separately.

After a section is designed completely, the machined part geometry is checked to see if it has reached to its final form. If there is more material to be removed, we go back to step 4 to design the next broach section. If all cutting is over, the final design is used for simulations.

There are some special cases which may need additional steps or rules as they may yield better results. For example, if we need to use a small rise within a section because of the constraints, a width division option in that section may produce better results. The tooth rise option 1 is used for that new section, and the same steps are followed step by step starting from step 4. This additional step is shown as *Add. 1* in Figure 3-22 and Figure 3-23 which demonstrate the flowchart of the optimization algorithm.

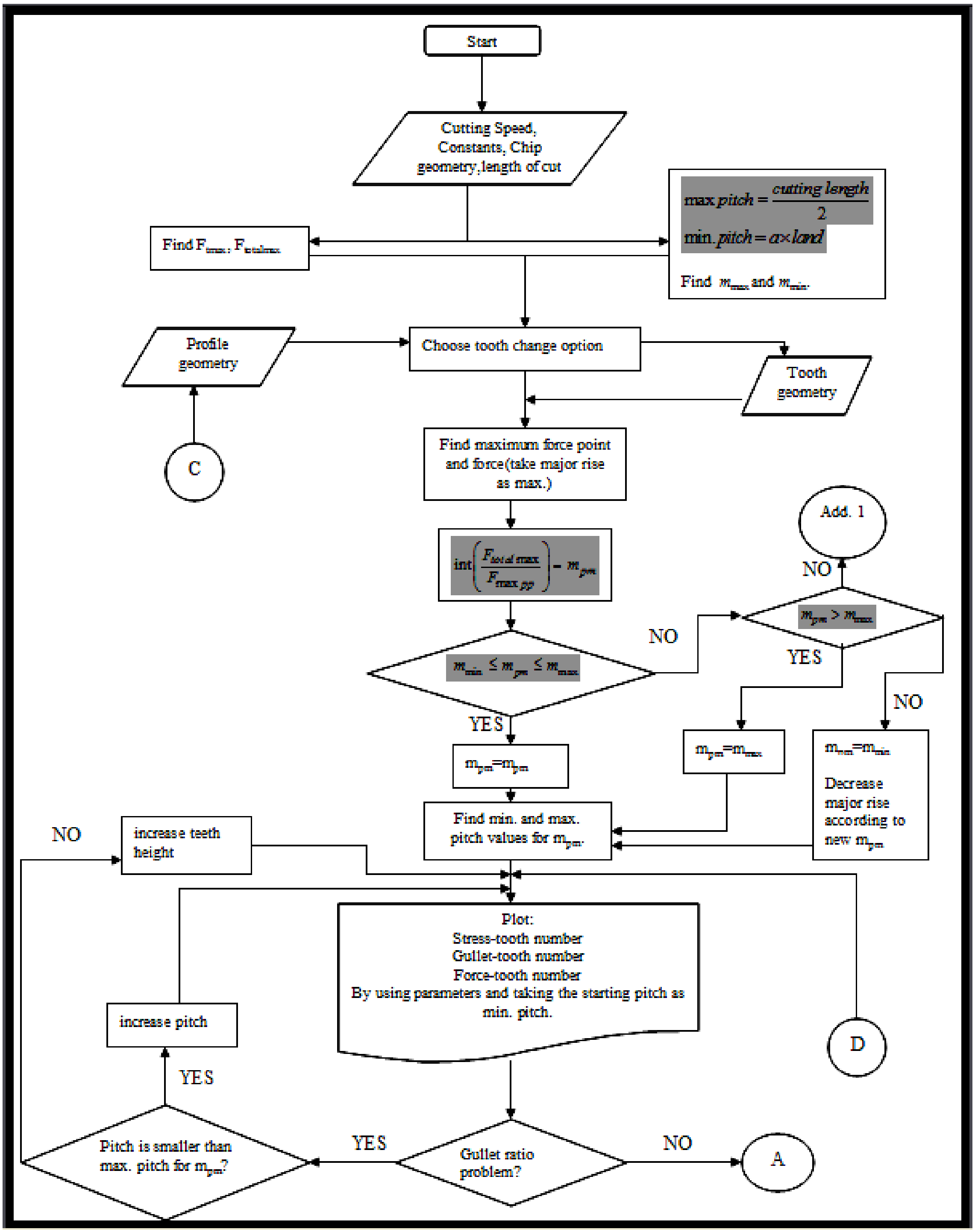


Figure 3-22: Algorithm flow chart (Part 1).

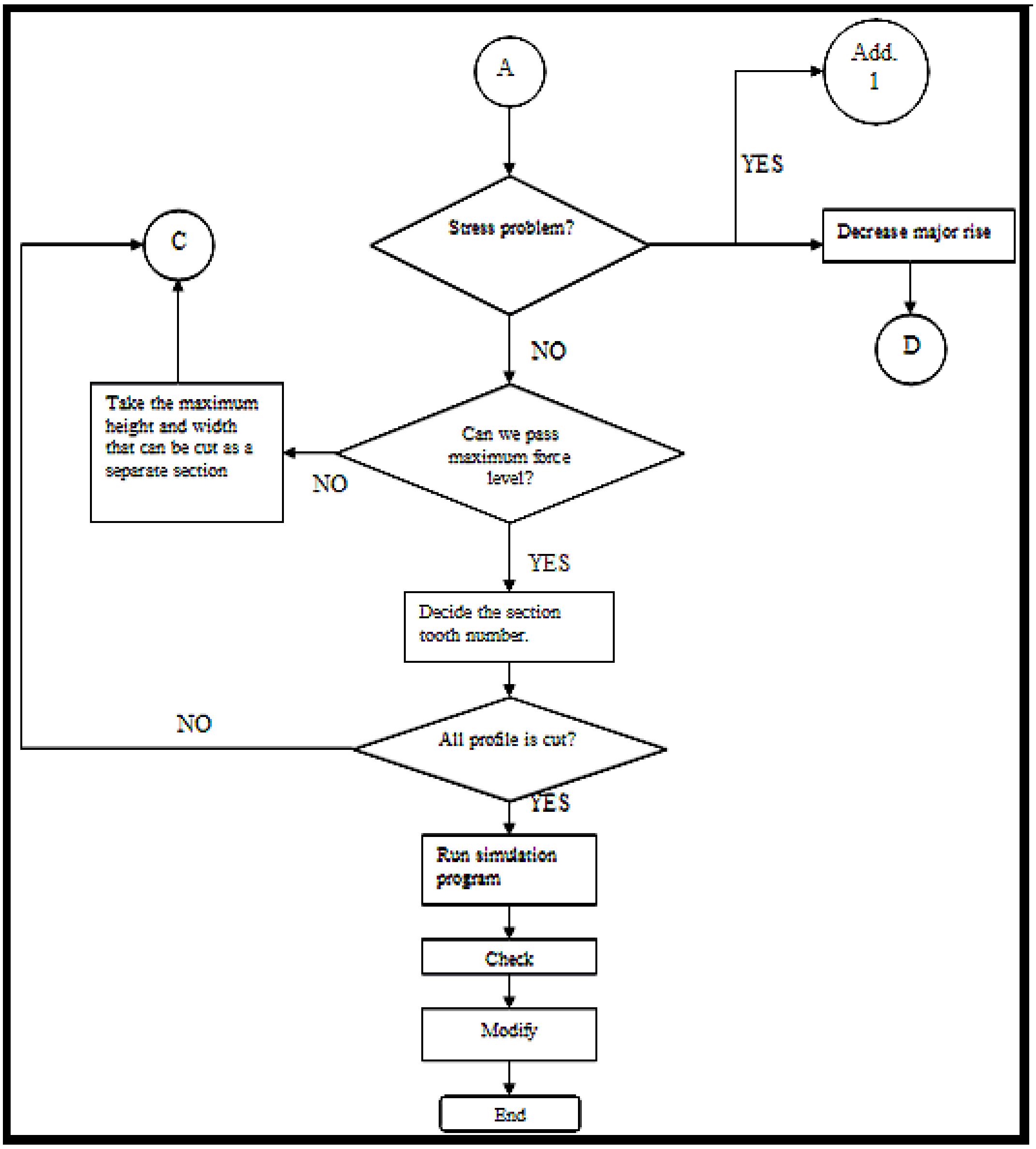


Figure 3-23: Algorithm flow chart (Part 2).

3.3.4 Numerical Example

The method and the program are demonstrated on an example application. The geometry to be cut has a top width of 21 mm and bottom width of 63 mm with 28 mm height. The depth of the workpiece to be cut is 21 mm. The material is waspaloy, and the tool is HSS-T material. The tooth land of 3 mm and a rake angle of 12 degrees are used. The back off angle chosen is 2 degrees. R1 is 1,98 mm and R2 is 7,95 mm. The cutting speed is selected as 55 mm/sec. Figure 3-24 indicates the target geometry. Selected geometry is much bigger than the actual geometries used in industry. This geometry is selected to be able to try more options at once with maximum tooth rise. So the forces are huge. But the effects of variables on the results are same.

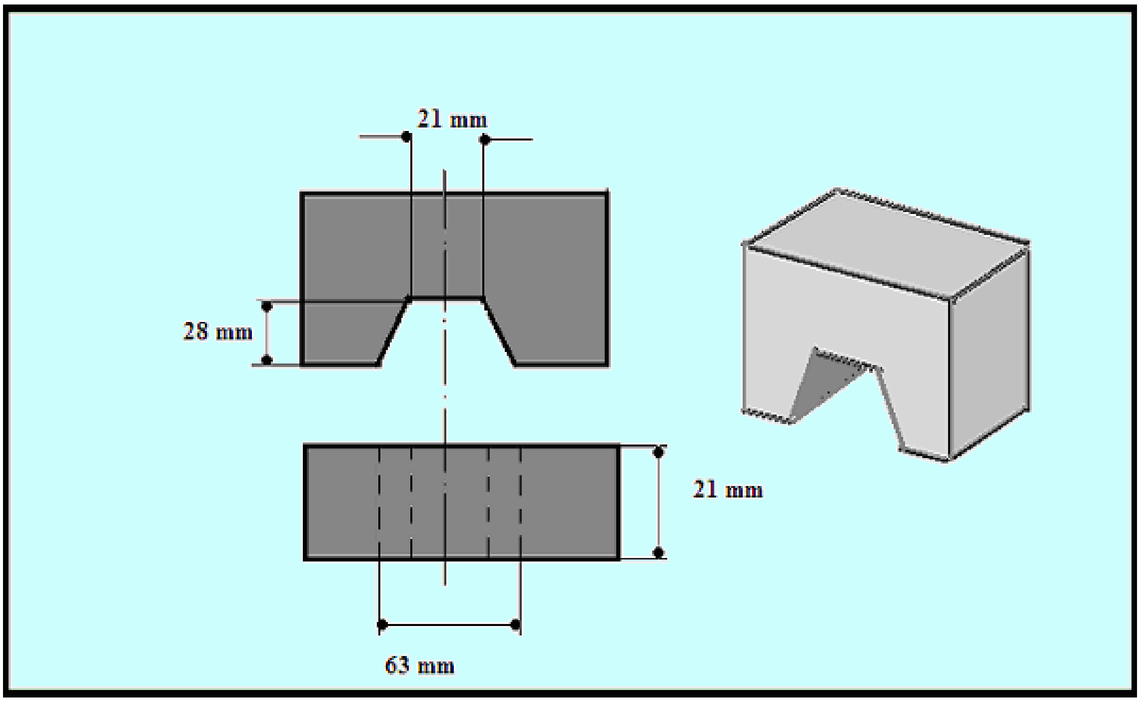


Figure 3-24: Target geometry to be cut.

In the simulations, the maximum force constraint of 150000 N, and the maximum stress constraint of 1200 MPa are chosen. First, section and tool parameters were assigned in a random manner, using intuition. This is done to demonstrate the effectiveness of the method for which the results will also be presented. By running the computer program using various geometric parameters, the best solution obtained was 3 sections with total tool length of 2155 mm.

Now, the method is applied in a systematical manner. Since the geometry is simple, there is no natural geometrical constraint. As there are no geometrical constraints, the height division is done. The algorithm is applied using given force, stress, gullet-chip volume ratio and other practical constraints. The pitch is taken as at least 1.5 times of the tool land (a=1.5). Maximum cutting tooth number is 5. The other parameters are given in Table 3-2. The simulated total force and stress are shown in Figure 3-25 and Figure 3-26. For this geometry and given constraints, this is the best solution. Some modifications can be done based on different requirements. Also, some extra constraints such as number of sections, section volume, heights or different tooth rise values can be asked for based on practical and quality considerations. Obviously, these may increase the tool length.

section no	1	2
pitch	5,25	4,5
tooth no.	30	401
top rise	0,065	0,0649
first teeth height	2	2
side rise	0	0
R1	1,98	1,98
R2	5,25	4,5
land	3	3
rake angle	12	12
back off angle	2	2
section length	152,25	1800
section division	height	
tooth change option	option 2	option 2
tool length	1952,25 mm	

Table 3-2: Parameters that give the best tool.

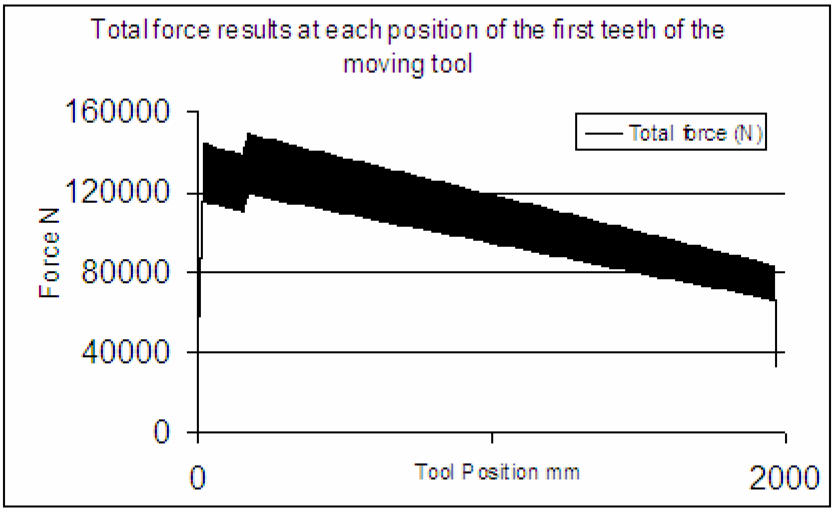


Figure 3-25: Force results of the solution.

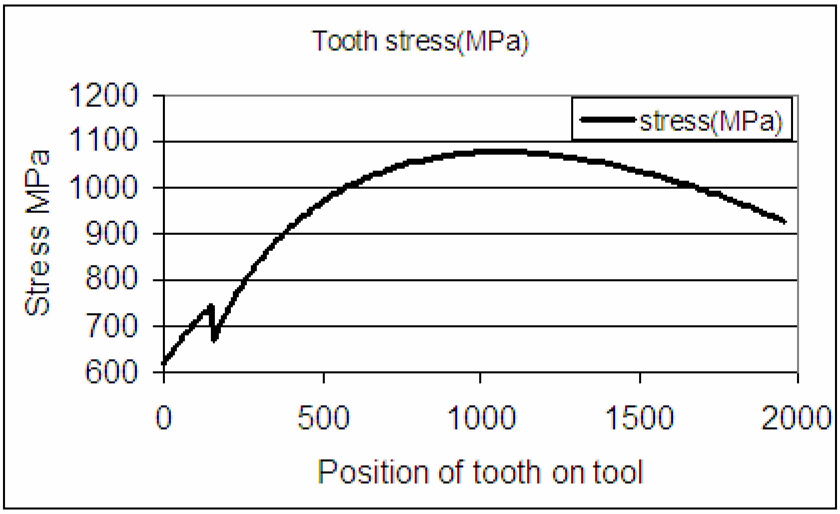


Figure 3-26: Stress results of the solution.

CHAPTER 4 COMPUTER IMPLEMENTATION

Manufacturing of broach tools is a difficult and expensive process. Thus, it is not practical to manufacture new tools to see the effects of design parameters on cutting process. That is why a simulation software has been written in order to simulate the force, stress and power in broaching. The program has been written by using Visual Basic and formulations explained in the previous chapters were used. Program can be used to simulate a broaching process with given data, but not the optimization. In this chapter the program will be explained in detail.

Simulation of broaching forces and stress are performed separately. Because, the force simulation is based on the total forces and power of the system and the stress simulation depends on the force per tooth. Broaching forces are calculated for different positions of the tool. Tool position is determined by the x-axis coordinate of the first tooth. Tool moves from the starting point to ending point step by step. Figure 4-1 shows the starting and the ending points of the simulation. These steps are so small and called as increments. The increments are determined by the length of cut, *lc,* as shown in Equation 4.1.

$$increment = \frac{l_c}{100} \tag{4.1}$$

At each step the coordinate of each tooth is updated. Coordinate of a tooth determines if it is active or not. Total tangential, feed and resultant forces and power of the system is calculated using this data.

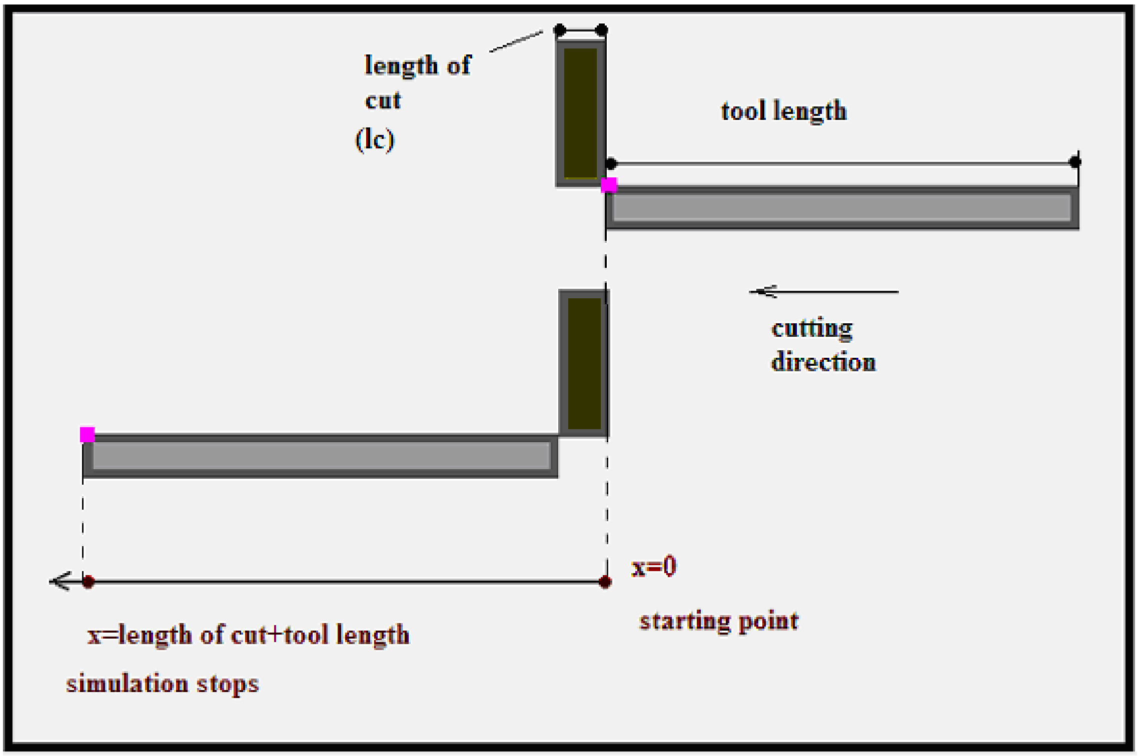


Figure 4-1: Simulation starting and ending points.

Tool movement can be followed on the output file during the simulation. The output file is an excel sheet and the tangential force, feed force, resultant force and the power in the system is given at each increment. Program starts to give the results at the time when the first tooth of the tool enters the cutting zone and stops when the last tooth leaves it. An output file example is demonstrated in Figure 4-2.

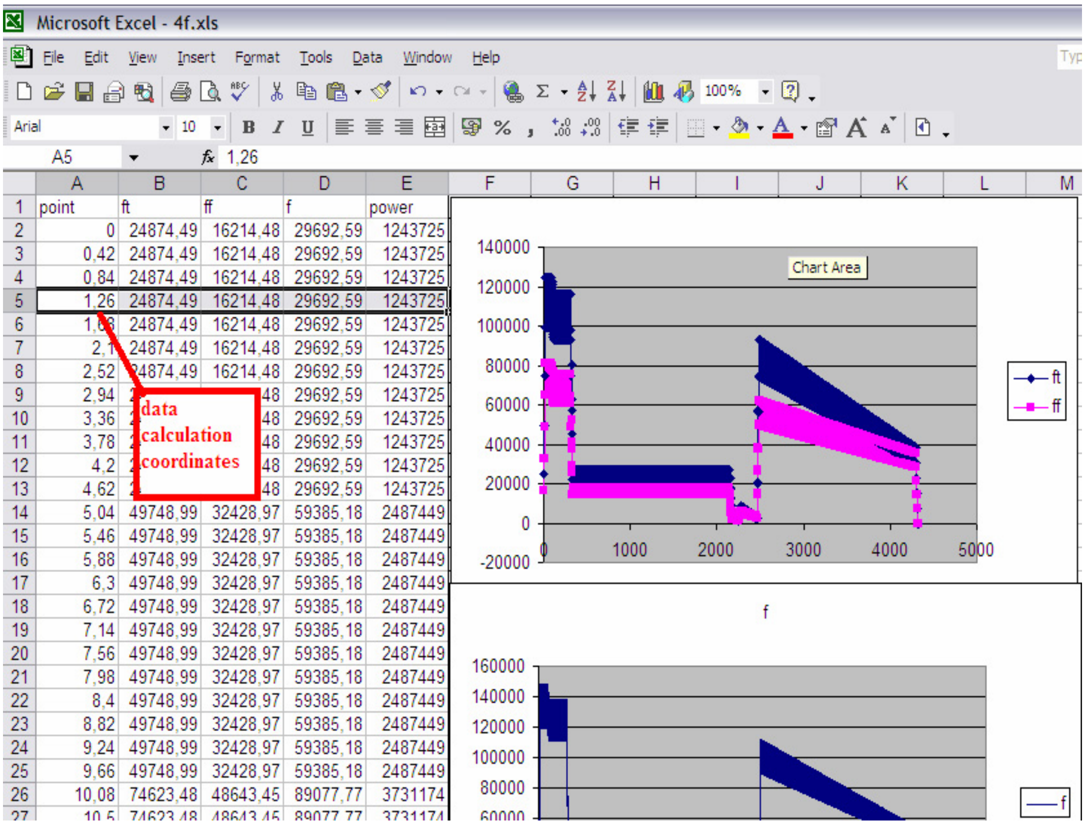


Figure 4-2: An example of force and power output file.

Logic of stress simulation is different. First, force acting on each tooth is found using the tooth geometry and tooth rise data. Tooth geometry is approximated to the general tooth profile by the program for stress calculation. Tooth stress and gullet-chip volume ratio and force per tooth are calculated for all of the teeth. Stress found by the program is the maximum stress acting on the tooth. So the force found by the program by stress calculation may be different than the total force acting on that tooth. Figure 4-3 shows the maximum stress point. The cutting edges named "*not active*" are the edges that are in fact cutting the workpiece. However because of the tooth geometry the force acting on these edges has no significant effect on the maximum stress. As shown in the figure the stress on the maximum stress point is mainly because of the forces acting on the edges named "*active*" edges. This should be taken into consideration during force and stress calculations and data should be entered to the program according to that. So the geometry can be changed during force or stress simulation.

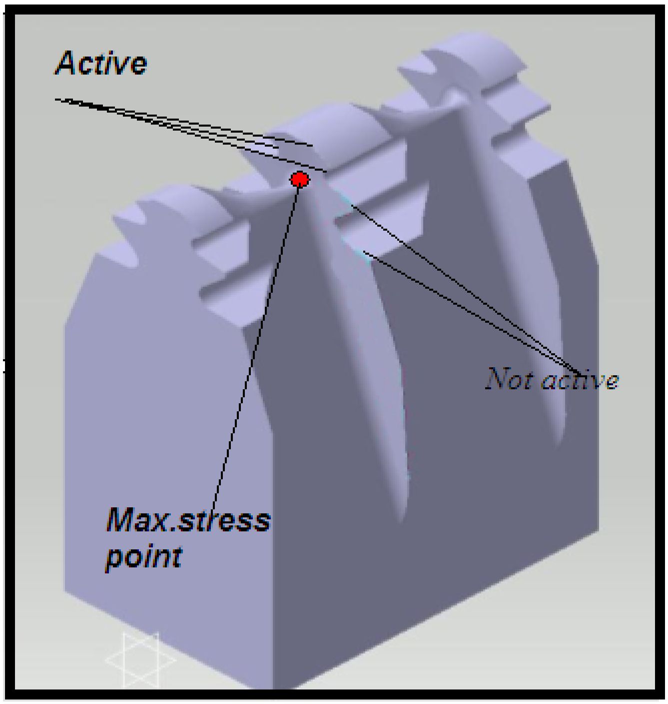
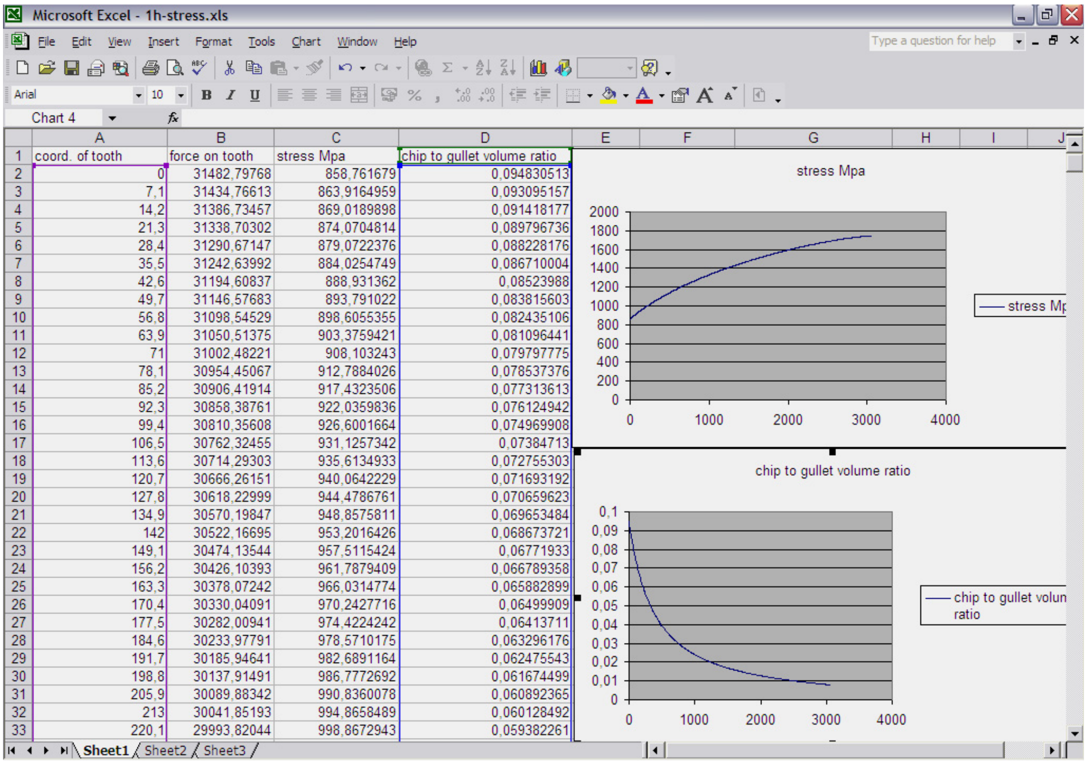


Figure 4-3: Maximum stress point.

Output file is again an excel sheet but this time the teeth are defined according to their positions on the tool (Figure 4-4).



	A	B	C	D
1	coord. of tooth	force on tooth	stress Mpa	chip to gullet volume ratio
2	0	31482,79768	858,761679	0,094830513
3	7,1	31434,76613	863,9164959	0,093095157
4	14,2	31386,73457	869,0189898	0,091418177
5	21,3	31338,70302	874,0704814	0,089796736
6	28,4	31290,67147	879,0722376	0,088228176
7	35,5	31242,63992	884,0254749	0,086710004
8	42,6	31194,60837	888,931362	0,08523988
9	49,7	31146,57683	893,791022	0,083815603
10	56,8	31098,54529	898,6055355	0,082435106
11	63,9	31050,51375	903,3759421	0,081096441
12	71	31002,48221	908,103243	0,079797775
13	78,1	30954,45067	912,7884026	0,078537376
14	85,2	30906,41914	917,4323506	0,077313613
15	92,3	30858,38761	922,0359836	0,076124942
16	99,4	30810,35608	926,6001664	0,074969908
17	106,5	30762,32455	931,1257342	0,07384713
18	113,6	30714,29303	935,6134933	0,072755303
19	120,7	30666,26151	940,0642229	0,071693192
20	127,8	30618,22999	944,4786761	0,070659623
21	134,9	30570,19847	948,8575811	0,069653484
22	142	30522,16695	953,2016426	0,068673721
23	149,1	30474,13544	957,5115424	0,06771933
24	156,2	30426,10393	961,7879409	0,066789358
25	163,3	30378,07242	966,0314774	0,065882899
26	170,4	30330,04091	970,2427716	0,06499909
27	177,5	30282,00941	974,4224242	0,06413711
28	184,6	30233,97791	978,5710175	0,063296176
29	191,7	30185,94641	982,6891164	0,062475543
30	198,8	30137,91491	986,7772692	0,061674499
31	205,9	30089,88342	990,8360078	0,060892365
32	213	30041,85193	994,8658489	0,060128492
33	220,1	29993,82044	998,8672943	0,059382261

Figure 4-4: Stress and chip-gullet volume ratio output file.

It is quite easy to use the program. In the following sections data input to the program and some properties are going to be explained.

4.1 General Properties Window

General properties window is the opening page of the program. General variables such as cutting force constants K_{tc}, K_{te}, K_{fc}, and K_{fe} are the inputs. Also total tool length, cutting speed and the length of cut data are entered to the program at this step. This window is also the gate to the section properties. As shown in Figure 4-5, the program is capable of simulating the broaching process with a tool at most 20 sections. Units of the data are given in Table 4-1.

Parameter	unit
Ktc	N/mm2
Kte	N/mm
Kfc	N/mm2
Kfe	N/mm
total length of tool	mm
length of cut	mm
cutting speed	mm/sec

Table 4-1: Units for the general property data.

After the necessary data are entered the calculation of the stress and force values are done by clicking on the “Calculate” menu and selecting the variable to simulate.

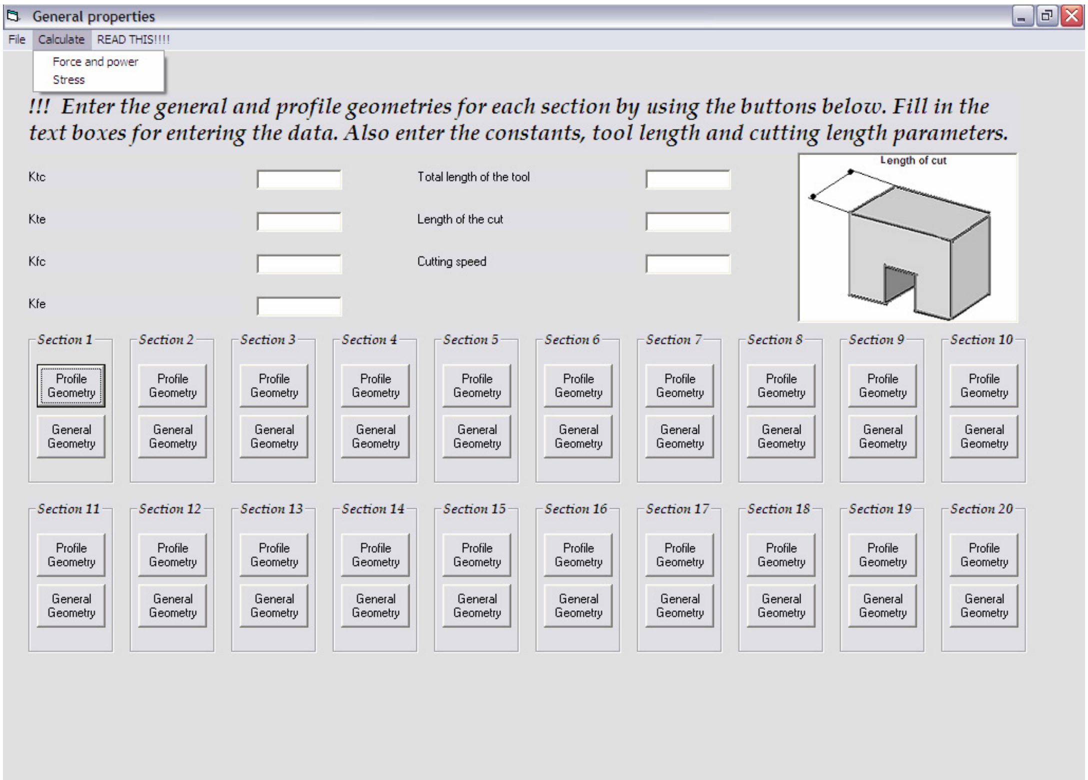


Figure 4-5: General properties window.

4.2 Profile Geometry Window

Data of the tooth profile of each section is entered in this page. There are 11 main tooth profile examples which can be used to describe the tooth profile and the geometry changes within the current section. Help menu “What is?” can be used to check which profile is your tooth profile and what each variable means.

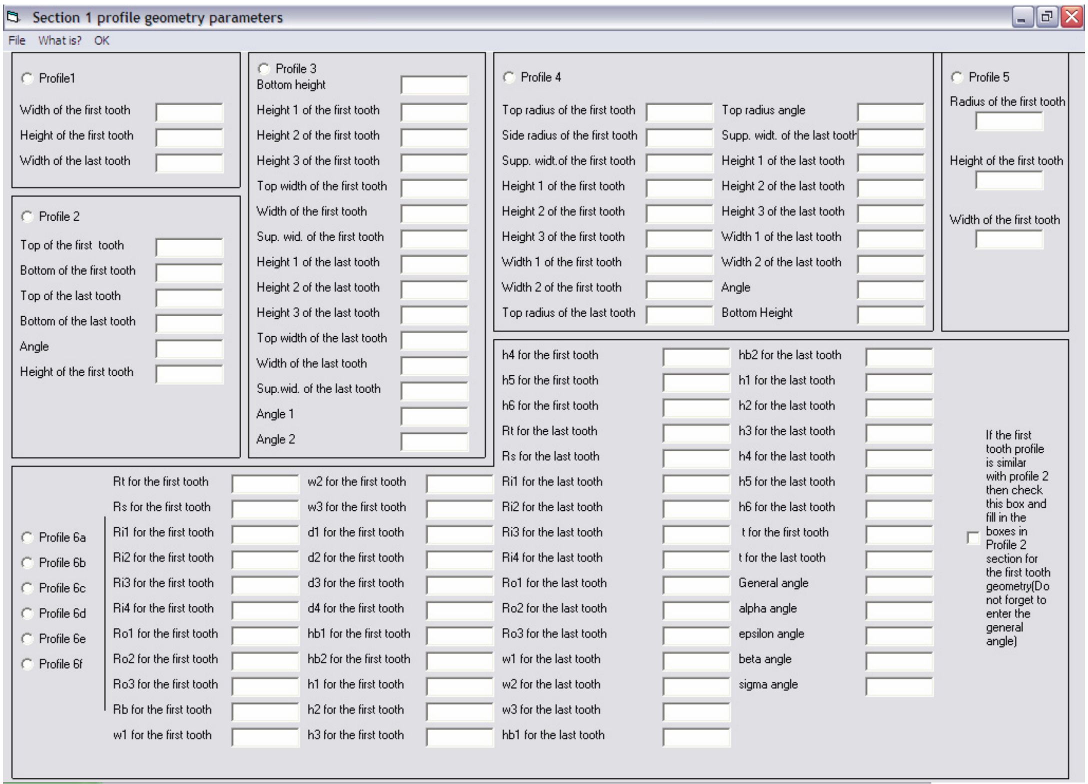


Figure 4-6: Profile geometry window.

Figure 4-6 shows the general view of the profile geometry window. At first it may seem crowded, however the user needs to enter only the necessary data for his/her section tooth profile. For example, when the user chooses profile 6d, the other data which are not necessary become gray in color and only the necessary parameters remain white as in Figure 4-7.

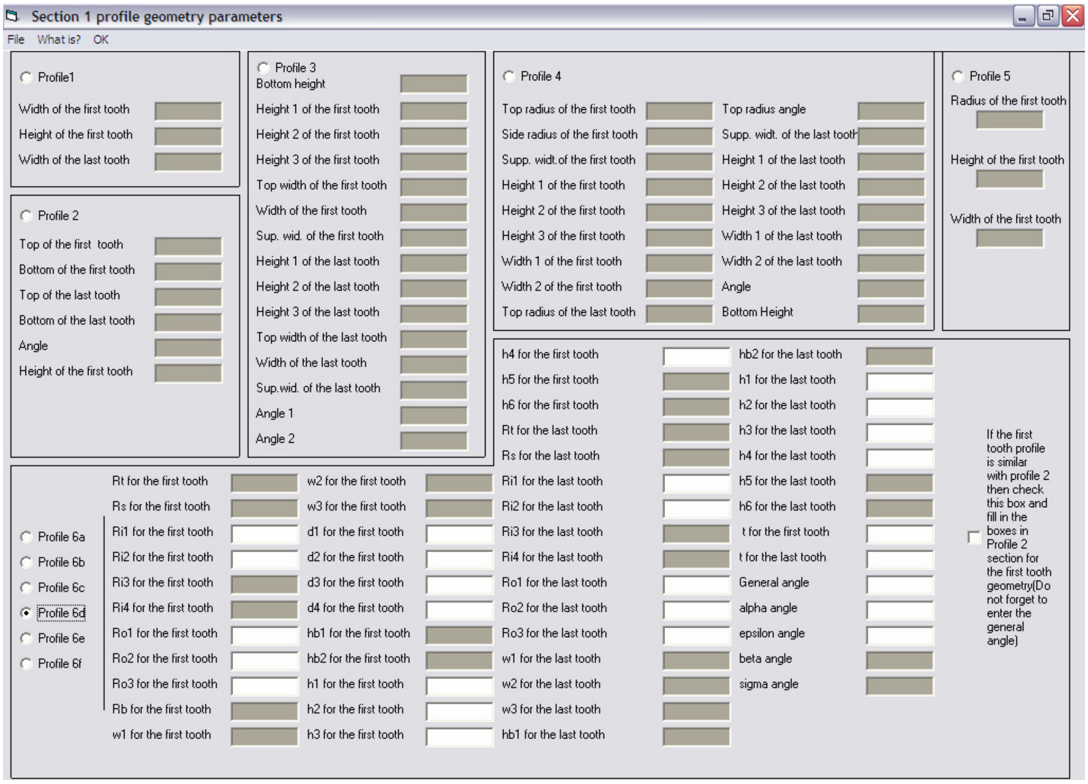


Figure 4-7: Profile geometry window when Profile 6d is chosen.

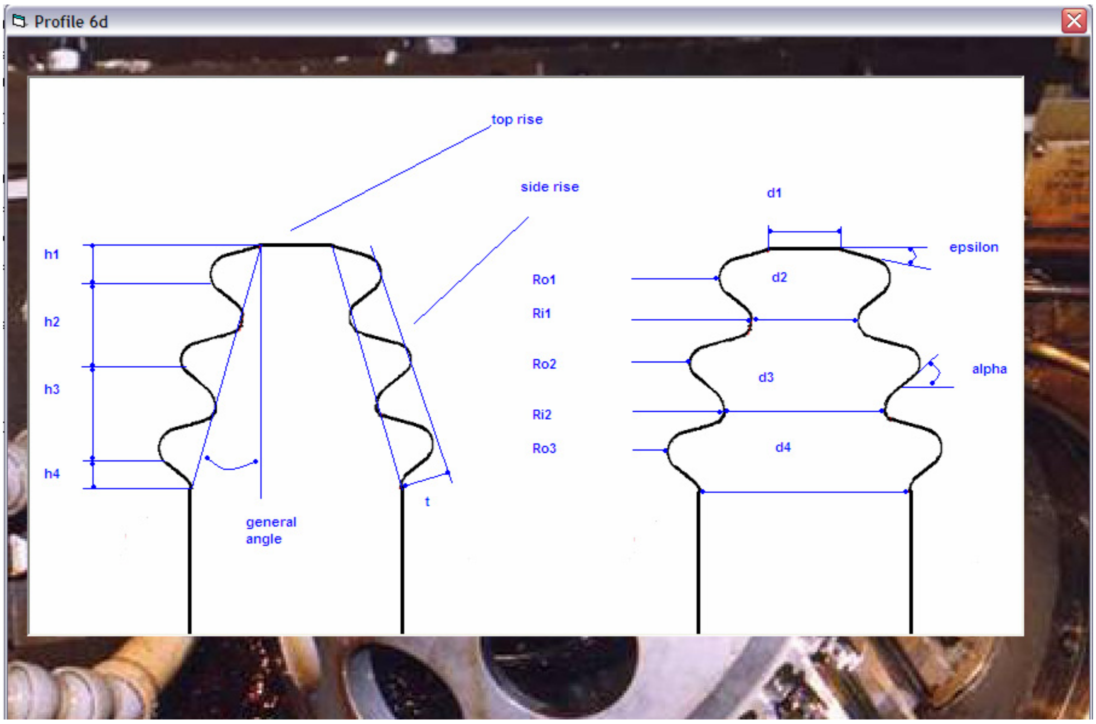


Figure 4-8: Help window for profile 6d.

As mentioned before "What is?" part on the menu bar is used to get help about the profile geometry selection and descriptions. Figure 4-8 is an example for the help windows in "What is?" menu. Figure 4-9 shows examples for different profile help windows.

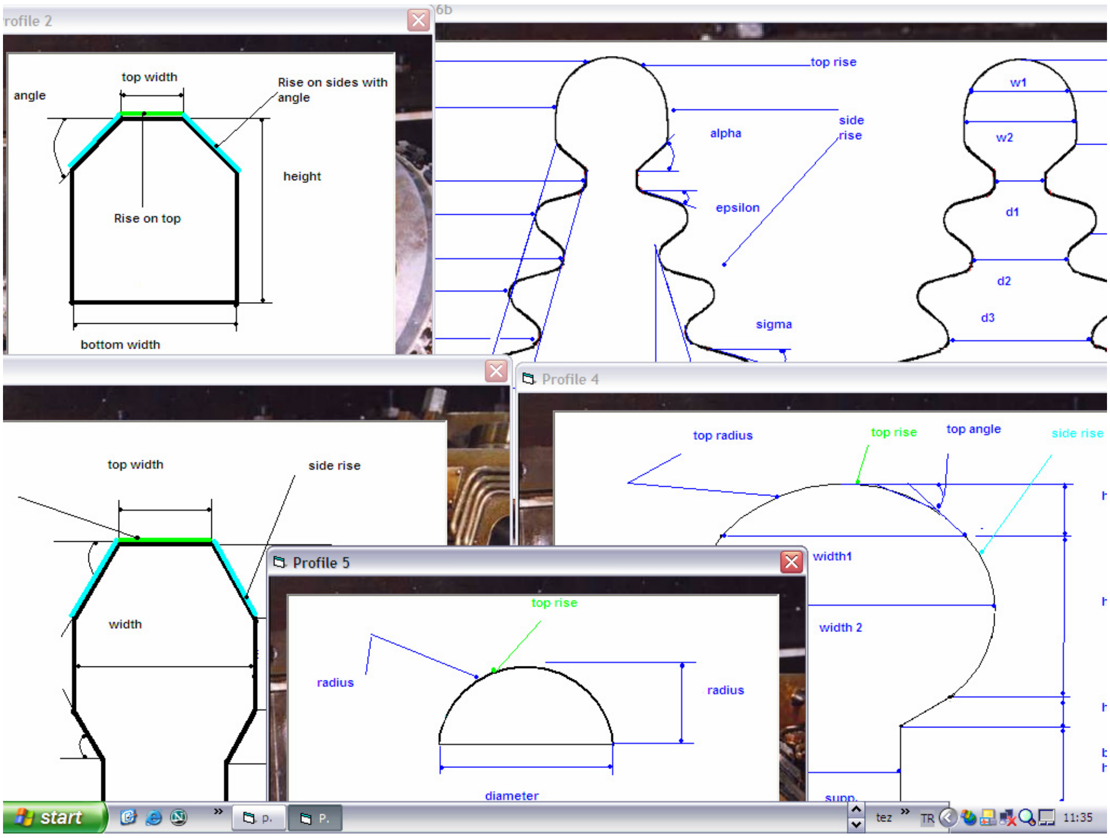


Figure 4-9: A group of help window examples.

SI units have been used in the program.

4.3 General geometry window

General geometry window is an interface used to enter the general parameters for each section such as rake angle, pitch, R1, R2, land, tooth rise and back-off angle. Most of the data are general geometry data for the section geometry. Previously cut width is used for finding the actual cutting length of a tooth.

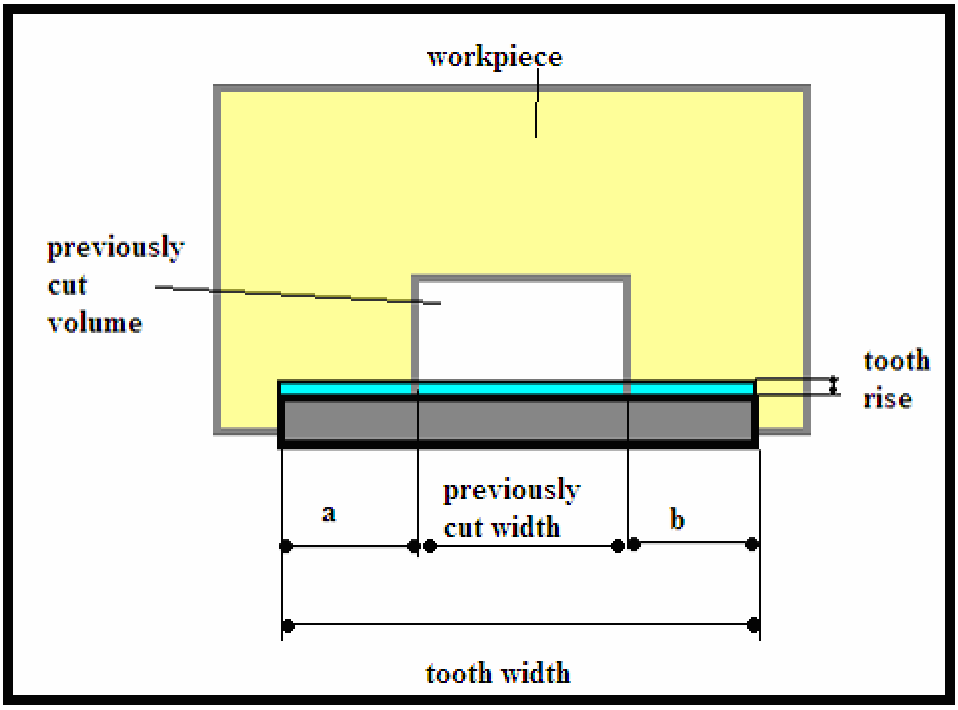


Figure 4-10: Previously cut volume.

Figure 4-10 shows an example of the effect of previously cut volume on the cutting process. As shown in the figure a volume is cut by previous sections of the tool. If this part is not taken into consideration the program calculates the broaching forces assuming the chip width is equal to the tooth width. However, real chip width is $a+b$ as shown in the figure. Previously cut width is necessary for calculating the broaching forces accurately. Figure 4-11 shows the general view of the general geometry window.

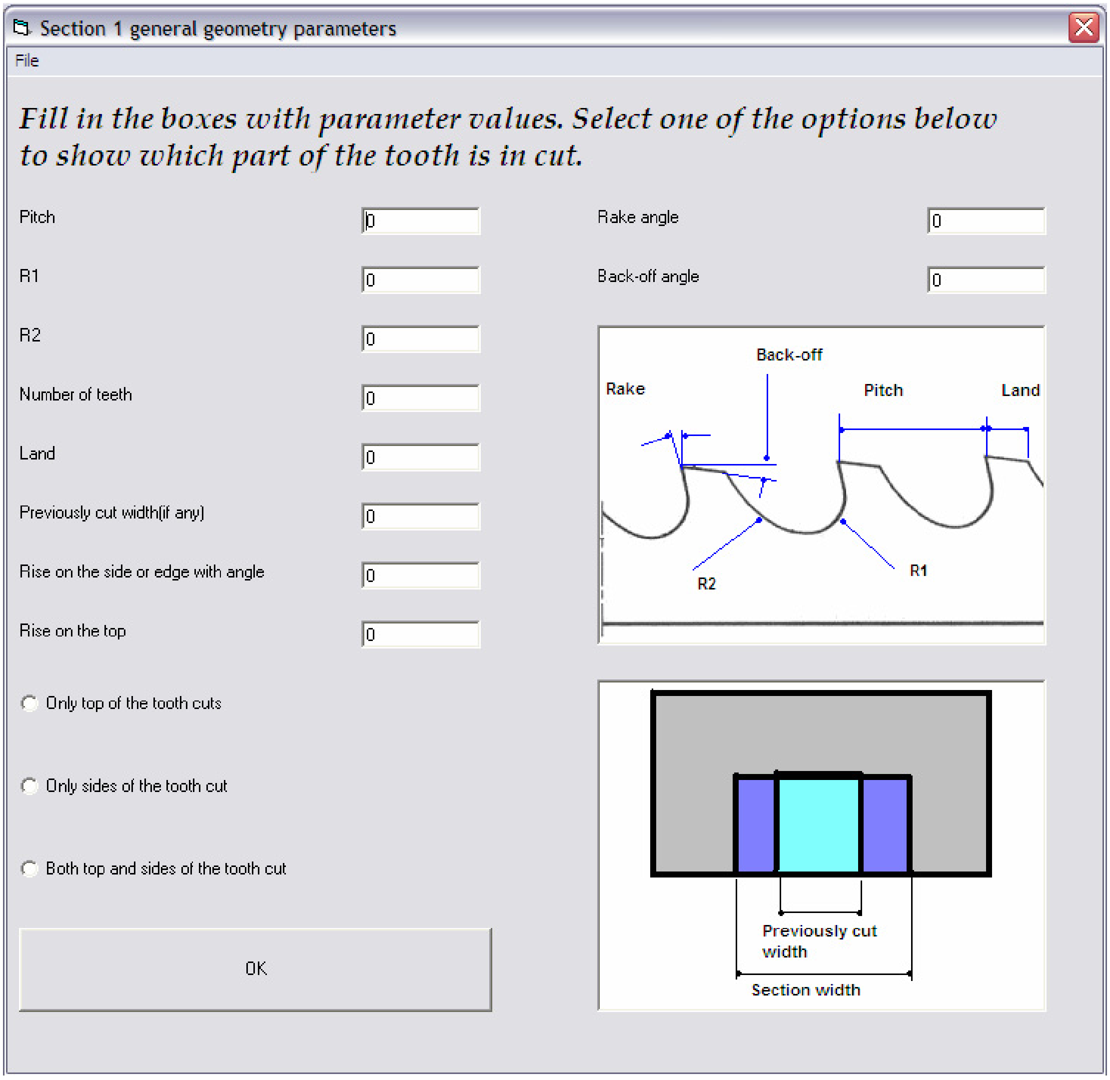


Figure 4-11: General geometry window.

CHAPTER 5 DISCUSSION AND CONCLUSION

Broaching is a widely used process in industry for machining non-circular holes and complex geometries such as fir-tree profiles. High productivity and quality are the main advantages of the broaching process. The main disadvantage of broaching is the low flexibility. Cutting speed is the only cutting parameter which can be modified during production. All other cutting conditions are set by the tool geometry. Thus, tool design is extremely important for broaching.

Broach tool design optimization is a quite complex problem to. There are many variables which are also interrelated. Sensitivity of the problem is quite high and conventional optimization methods cannot be applied. Furthermore, there are many feasible solutions, and it is difficult to judge if the solution is really the optimum one. The broaching tool should be as short as possible for optimum design which minimizes the production time. Force and stress values should be kept under the limits and all dynamic, practical and geometrical constraints must be satisfied. In this study, a new optimization algorithm is developed for designing the shortest possible tool to cut any geometry with given constraints.

Logic of the algorithm is straightforward. However, it becomes more complicated during the application, because of the complicated structure of the problem itself. Many simulations have been done and the effects of tooth rise, pitch, method of dividing the geometry into sections, type of tooth geometry change are investigated. The results are discussed, and the best options for the optimum solution are determined. Algorithm starts with the shortest tool for a given cutting speed, and the geometry is divided into minimum possible number of sections. Each section is optimized separately, and if necessary divided into sub-sections during the solution. Tooth rise is maximized and pitch is taken as small as possible. Each constraint is checked, and variables are modified according to the constraints. At last the design is examined by the simulation program and results are discussed. New modifications are done if necessary.

It takes shorter time to find a solution by the algorithm presented here than trying different alternatives randomly. The best part of this algorithm is that it is possible to know how close our solution is to the optimum one. However, only the main variables are considered during the optimization procedure. The remaining parameters are determined based on the common values used in industry. As a future work, the algorithm may be extended to consider all of the parameters. Also, improvements can be done in the simulation program. The program may be more user friendly and the algorithm may be implemented to the simulation program.

In this thesis, a new algorithm for shortest tool design to broach any given geometry is presented. This thesis may be a resource for studies about broaching and broach tool design optimization.

REFERENCES

1. Alberti, N., Perrone, G., 1999, Multipass machining optimization by using fuzzy possibilistic programming and genetic algorithms, Proc. Instn. Mech. Engrs., 213/B: 261-273.

2. Albrecht, P., 1960, New developments in the theory of the metal cutting process- Part1- The ploughing process in metal cutting, Transactions of ASME-Journal of Engineering for Industry, November:348-358.

3. Altintas, Y., 2000, Manufacturing automation: metal cutting mechanics, machine tool vibrations and CNC design, Cambridge University Press.

4. Baek, D.K., Ko, T.J., Kim, H.S., 2001, Optimization of feedrate in face milling operation using a surface roughness model, International Journal of Machine Tools&Manufacture, 41: 451-462.

5. Bailey, J.A., 1975, Friction in metal machining- Mechanical aspects, Wear, 31/2: 243-275.

6. Barrow, G., Graham, W., Kurimoto, T. and Leong, Y.F., 1982, Determination of rake face stress distribution in orthogonal machining, Int. J. Mach. Tool Des. Res., 22/1: 75-85.

7. Boothroyd, G. and Knight, W.A., 1989, fundamentals of machining and machine tools 2nd edition, Marcel Dekker, New York, USA.

8. Brown, R.H. and Armarego, E.J.A., 1964, Oblique machining with a single cutting edge, Int. J. Mach. Tool Des. Res., 4:9-25.

9. Budak,E., 2001, Broaching process monitoring, Proceedings of Third International Conference on Metal Cutting and High Speed Machining, Metz-France, 251-260.

10. Celik, K.F., Korbahti, B. and Kucur, M., Computer aided design application for optimum broach design.

11. Challa, K., Berra, P.B., 1976, Automated planning and optimization of machining processes: A systems approach, Comp&Indus. Eng., 1: 35-46.

12. Childs, T.H.C., Maekawa, K., Obikawa, T. and Yamane, Y., 2000, Metal Machining- theory and applications, Arnold, Hodder Headline Group, Redwood Books Ltd.

13. De Chiffre, L., 1977, Mechanics of metal cutting and cutting fluid action, Int. J. Mach. Tool Des. Res., 17: 225-234.

14. Erol, I., Ferrell, W.G., 2003, A methodology for selection problems with multiple conflicting objectives and both qualitative and quantitative criteria, Int. J. Production Economics, 86/3:187-199.

15. Fang, N., 2003, Slip-line modeling of machining with a rounded-edge tool—Part I: new model and theory. Journal of the Mechanics and Physics of solids, 51: 715-742.

16. Fang, N., 2003, Slip-line modeling of machining with a rounded-edge tool—Part II: analysis of the size efect and the shear strain-rate . Journal of the Mechanics and Physics of solids, 51: 743-762.

17. Fang, N., Jawahir, I.S. and Oxley, P.L.B. 2001, A universal slip-line model with non-unique solutions for machining with curled chip formation and a restricted contact tool. International Journal of Mechanical Sciences, 43: 557-580.

18. Gilormini, P., Felder, E., 1984, A comparative analysis of three machining processes: broaching, tapping and slotting, Annals of the CIRP, 33/1: 19-22.

19. Hagglund, S., 2003, New procedure for optimizing cutting data for general turning, Proc. Instn. Mech. Engrs., 217/B: 349-362.

20. Hati, S.K., and Rao, S.S., 1976, Determination of optimummachining conditions-Deterministic and probabilistic approaches, Transactions of ASME journal of Enigineering for Industry, February:354-359.

21. Iwata, K., Murotsu, Y., Iwatsubo, T. and Fujii, S., 1972, A probabilistic approach to the determination of the optimum cutting conditions, Journal of Engineering for Industry, November: 1099-1107.

22. Jawahir, I. S. And Fang, N. 2002, Analytical predictions and experimental validation of cutting force ratio, chip thickness, and chip back-flow angle in restricted contact machining using the universal slip-line model. International Journal of Machine Tools & Manufacture ,42: 681–694

23. Kalpakjian, S. and Schmid, S.R., 2003, Manufacturing processes for engineering materials 4th edition, Prentice Hall, USA.

24. Kalpakjian, S. and Schmid, S.R., 2001, Manufacturing engineering and technology 4th edition, Prentice Hall, USA.

25. Khan, Z., Prasad, B. and Singh, T., 1997, Machining condition optimization by genetic algorithms and simulated annealing, Computers Ops. Res., 24/7:647-657.

26. Kokmeyer, E., 1984, Better broaching operations, Society of Manufacturing Engineers.

27. Lee, B.Y., Tarng, Y.S., 2000, Cutting parameter selection for maximizing production rate or minimizing production cost in multistage turning operations, Journal of Materials Processin Technology, 105: 61-66.

28. Lin, C.C., 2004, A weighted max-min model for fuzzy goal programming, Fuzzy Sets and Systems, 142/3: 407-420.

29. Meng, Q., Arsecularatne, J.A. and Mathew, P., 2000, Calculation of optimum cutting conditions for turning operations using a machining theory, International Journal of Machine Tools&Manufacture, 40:1709-1733.

30. Metal Cutting Tool Institute, 1971, Metal cutting tool handbook, New York, USA.

31. Merchant, M.E., 1945, Mechanics of metal cutting process, J. Appl. Phys. 16:318-324,

32. Monday, C., 1960, Broaching, The Machinery Publishing Co., London.

33. Ozturk, O., 2003, Modelling of Broaching Process, M.Sc. Thesis, Industrial Engineering, Sabanci University, Istanbul, Turkey.

34. Ozturk, O. And Budak, E., November 2003, Modeling of Broaching Process for Improved Tool Design, ASME International Mechanical Engineering Conference and Exposition, , Washington D.C., IMECE 2003, IMECE-42304.

35. Pal, A.K. and Koenigsberger, F., 1968, Some aspects of the oblique cutting process, Int. J. Mach. Tool Des. Res., 8:45-57.

36. Palmer, W.B. and Oxley, P.L.B., 1959, Mechanics of orthogonal machining, Proc. Instn. Mech. Engrs., 173/24:623-638.

37. Rao, S.S., Chen, L., 2000, Determination of optimal machining conditions: A coupled uncertainty model, Transactions of the ASME, 122: 206,214.

38. Sajeev, V., Vijayaraghavan, L., Rao, U.R.K., 2000, effect of tool-work deflections on the shape of a broached hole, International Journal of Mechanical Engineering Education, 28/1: 88-92.

39. Sajeev, V., Vijayaraghavan, L., Rao, U.R.K., 2000, Analysis of the effects of burnishing in internal broaching, International Journal of Mechanical Engineering Education, 28/2 :163-173.

40. Saravanan, R., Asokan, P., Sachidanandam, M., 2002, A multi-objective genetic algorithm approach for optimization of surface grinding operations, International Journal of Machine Tools&Manufacture, 42: 1307-1334.

41. Shaw, M.C., Cook, N.H. and Smith, P.A., 1962,The mechanics of three-dimentional cutting operations, Transactions of ASME, August: 1055-1064.

42. Shin, Y.C. and Joo, Y.S., 1992, Optimization of machining conditions with practical constraints, Int. J. Prod. Res., 30/12:2907-2919.

43. Stephenson, D.A., Agapiou, J.S., 1997, Metal cutting theory and practice, Marcel Dekker, New York, USA.

44. Sutherland, J.W., Salisbury, E.J., Hoge, F.W., 1997, A model for the cutting force system in the gear broaching process, Int. J. Mach. Tools Manufact., 47/10: 1409-1421.

45. Terry, W.R., Karni, R., Huang, Y.R., 1992, Concurrent tool and production system design for a surface broach cutting tool-a knowledge based systems approach, Int. J. Prod. Res., 30/2:219-240.

46. Tlusty, G., 2000, Manufacturing processes and equipment, Prentice Hall, USA.

47. Trent, E.M. and Wright, P.K., 2000, Metal Cutting, Butterworth-Heinemann.

48. UBC-MAL

REFERENCES

1. Alberti, N., Perrone, G., 1999, Multipass machining optimization by using fuzzy possibilistic programming and genetic algorithms, Proc. Instn. Mech. Engrs., 213/B: 261-273.

2. Albrecht, P., 1960, New developments in the theory of the metal cutting process-Part1- The ploughing process in metal cutting, Transactions of ASME-Journal of Engineering for Industry, November:348-358.

3. Altintas, Y., 2000, Manufacturing automation: metal cutting mechanics, machine tool vibrations and CNC design, Cambridge University Press.

4. Baek, D.K., Ko, T.J., Kim, H.S., 2001, Optimization of feedrate in face milling operation using a surface roughness model, International Journal of Machine Tools&Manufacture, 41: 451-462.

5. Bailey, J.A., 1975, Friction in metal machining- Mechanical aspects, Wear, 31/2: 243-275.

6. Barrow, G., Graham, W., Kurimoto, T. and Leong, Y.F., 1982, Determination of rake face stress distribution in orthogonal machining, Int. J. Mach. Tool Des. Res., 22/1: 75-85.

7. Boothroyd, G. and Knight, W.A., 1989, fundamentals of machining and machine tools 2nd edition, Marcel Dekker, New York, USA.

8. Brown, R.H. and Armarego, E.J.A., 1964, Oblique machining with a single cutting edge, Int. J. Mach. Tool Des. Res., 4:9-25.

9. Budak,E., 2001, Broaching process monitoring, Proceedings of Third International Conference on Metal Cutting and High Speed Machining, Metz-France, 251-260.

10. Celik, K.F., Korbahti, B. and Kucur, M., Computer aided design application for optimum broach design.

11. Challa, K., Berra, P.B., 1976, Automated planning and optimization of machining processes: A systems approach, Comp&Indus. Eng., 1: 35-46.

12. Childs, T.H.C., Maekawa, K., Obikawa, T. and Yamane, Y., 2000, Metal Machining- theory and applications, Arnold, Hodder Headline Group, Redwood Books Ltd.

13. De Chiffre, L., 1977, Mechanics of metal cutting and cutting fluid action, Int. J. Mach. Tool Des. Res., 17: 225-234.

14. Erol, I., Ferrell, W.G., 2003, A methodology for selection problems with multiple conflicting objectives and both qualitative and quantitative criteria, Int. J. Production Economics, 86/3:187-199.

15. Fang, N., 2003, Slip-line modeling of machining with a rounded-edge tool—Part I: new model and theory. Journal of the Mechanics and Physics of solids, 51: 715-742.

16. Fang, N., 2003, Slip-line modeling of machining with a rounded-edge tool—Part II: analysis of the size efect and the shear strain-rate . Journal of the Mechanics and Physics of solids, 51: 743-762.

17. Fang, N., Jawahir, I.S. and Oxley, P.L.B. 2001, A universal slip-line model with non-unique solutions for machining with curled chip formation and a restricted contact tool. International Journal of Mechanical Sciences, 43: 557-580.

18. Gilormini, P., Felder, E., 1984, A comparative analysis of three machining processes: broaching, tapping and slotting, Annals of the CIRP, 33/1: 19-22.

19. Hagglund, S., 2003, New procedure for optimizing cutting data for general turning, Proc. Instn. Mech. Engrs., 217/B: 349-362.

20. Hati, S.K., and Rao, S.S., 1976, Determination of optimummachining conditions-Deterministic and probabilistic approaches, Transactions of ASME journal of Enigineering for Industry, February:354-359.

21. Iwata, K., Murotsu, Y., Iwatsubo, T. and Fujii, S., 1972, A probabilistic approach to the determination of the optimum cutting conditions, Journal of Engineering for Industry, November: 1099-1107.

22. Jawahir, I. S. And Fang, N. 2002, Analytical predictions and experimental validation of cutting force ratio, chip thickness, and chip back-flow angle in restricted contact machining using the universal slip-line model. International Journal of Machine Tools & Manufacture ,42: 681–694

23. Kalpakjian, S. and Schmid, S.R., 2003, Manufacturing processes for engineering materials 4^{th} edition, Prentice Hall, USA.

24. Kalpakjian, S. and Schmid, S.R., 2001, Manufacturing engineering and technology 4^{th} edition, Prentice Hall, USA.

25. Khan, Z., Prasad, B. and Singh, T., 1997, Machining condition optimization by genetic algorithms and simulated annealing, Computers Ops. Res., 24/7:647-657.

26. Kokmeyer, E., 1984, Better broaching operations, Society of Manufacturing Engineers.

27. Lee, B.Y., Tarng, Y.S., 2000, Cutting parameter selection for maximizing production rate or minimizing production cost in multistage turning operations, Journal of Materials Processin Technology, 105: 61-66.

28. Lin, C.C., 2004, A weighted max-min model for fuzzy goal programming, Fuzzy Sets and Systems, 142/3: 407-420.

29. Meng, Q., Arsecularatne, J.A. and Mathew, P., 2000, Calculation of optimum cutting conditions for turning operations using a machining theory, International Journal of Machine Tools&Manufacture, 40:1709-1733.

30. Metal Cutting Tool Institute, 1971, Metal cutting tool handbook, New York, USA.

31. Merchant, M.E., 1945, Mechanics of metal cutting process, J. Appl. Phys. 16:318-324,

32. Monday, C., 1960, Broaching, The Machinery Publishing Co., London.

33. Ozturk, O., 2003, Modelling of Broaching Process, M.Sc. Thesis, Industrial Engineering, Sabanci University, Istanbul, Turkey.

34. Ozturk, O. And Budak, E., November 2003, Modeling of Broaching Process for Improved Tool Design, ASME International Mechanical Engineering Conference and Exposition, , Washington D.C., IMECE 2003, IMECE-42304.

35. Pal, A.K. and Koenigsberger, F., 1968, Some aspects of the oblique cutting process, Int. J. Mach. Tool Des. Res., 8:45-57.

36. Palmer, W.B. and Oxley, P.L.B., 1959, Mechanics of orthogonal machining, Proc. Instn. Mech. Engrs., 173/24:623-638.

37. Rao, S.S., Chen, L., 2000, Determination of optimal machining conditions: A coupled uncertainty model, Transactions of the ASME, 122: 206,214.

38. Sajeev, V., Vijayaraghavan, L., Rao, U.R.K., 2000, effect of tool-work deflections on the shape of a broached hole, International Journal of Mechanical Engineering Education, 28/1: 88-92.

39. Sajeev, V., Vijayaraghavan, L., Rao, U.R.K., 2000, Analysis of the effects of burnishing in internal broaching, International Journal of Mechanical Engineering Education, 28/2 :163-173.

40. Saravanan, R., Asokan, P., Sachidanandam, M., 2002, A multi-objective genetic algorithm approach for optimization of surface grinding operations, International Journal of Machine Tools&Manufacture, 42: 1307-1334.

41. Shaw, M.C., Cook, N.H. and Smith, P.A., 1962,The mechanics of three-dimentional cutting operations, Transactions of ASME, August: 1055-1064.

42. Shin, Y.C. and Joo, Y.S., 1992, Optimization of machining conditions with practical constraints, Int. J. Prod. Res., 30/12:2907-2919.

43. Stephenson, D.A., Agapiou, J.S., 1997, Metal cutting theory and practice, Marcel Dekker, New York, USA.

44. Sutherland, J.W., Salisbury, E.J., Hoge, F.W., 1997, A model for the cutting force system in the gear broaching process, Int. J. Mach. Tools Manufact., 47/10: 1409-1421.

45. Terry, W.R., Karni, R., Huang, Y.R., 1992, Concurrent tool and production system design for a surface broach cutting tool-a knowledge based systems approach, Int. J. Prod. Res., 30/2:219-240.

46. Tlusty, G., 2000, Manufacturing processes and equipment, Prentice Hall, USA.

47. Trent, E.M. and Wright, P.K., 2000, Metal Cutting, Butterworth-Heinemann.

48. UBC-MAL