OPTIMIZATION OF BROACHING TOOL DESIGN

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Abstract
Broaching is a very common manufacturing process for the machining of internal or external complex shapes into parts. Due to the process geometry, broaching tool is the most critical parameter of the broaching process. Therefore, optimal design of the tools is needed in order to improve the productivity of the process. In this paper, a methodology is presented for optimal design of the broaching tools by respecting the geometric and physical constraints. The method has also been implemented on a computer code.

1 INTRODUCTION

Broaching is commonly used for machining of internal or external complex profiles that are difficult to generate by other machining processes such as milling and turning. Originally, broaching was developed for noncircular internal profiles and keyways. The process is very simple, and decreases the need for talented machine operator while providing high production rate and quality. Because of the straight noncircular motion, very high quality surface finish can be obtained. In addition, roughing and finishing operations can be completed in one pass reducing total cycle time. The main disadvantage of broaching is the inflexibility of the process in terms of process parameters. In broaching, all machining conditions, except the speed, are defined by the tool geometry, and thus, once a tool is designed it is impossible to change any process parameters such as depth of cut or chip thickness. This makes tool design the most important aspect of the broaching process. For improved productivity and part quality with reduced process cost, broach tools must be designed properly. In this paper, an approach for optimal design of broaching tools is presented with applications. This approach can be used for optimal design of broaching tools for a given part geometry and material.

The optimization procedure has to respect the physical and process constraints. In broaching, usually the profile to be machined into the part is specified. However, it is possible to generate the same profile using many different combinations of broach sections with different tool geometries. Therefore, first of all, the number of sections and the basic tooth profile for each section have to be selected. In addition, tool geometry and parameters, such as tooth rise, pitch etc. for each section has to be defined. Considering the number of possibilities, there is a need for a practical method for optimal design of broaching tools which is the topic of this paper.

Optimization of machining processes has been the topic of many studies for a long time, starting with pioneering works of F. Taylor. Turning was the process under consideration in most of these studies due to its wide use and simpler geometry. Since the relationship between the cutting speed and tool wear was known, i.e. Taylor's tool life equation, the most common purpose of these studies was the optimization of the cutting speed. Stephenson and Agapiou [1] give the general principles of economics in machining, and explain process optimization using common methods. Many different methods were employed, from genetic algorithms or combination genetic algorithms with fuzzy approaches [2, 3] to simulated annealing [4]. Also, iterative methods [5], or combinatorial methods that use databases [6], have also been used. Combinations of different approaches have also been utilized with a mixture of fuzzy basics [7]. Erol and Ferrel [8] also used fuzzy methods among many others. In most of these studies, the mechanics of the process such as forces, deflections, vibrations etc., other than tool wear, were not included in the analysis.

Although there have been many studies on various machining processes, there has been only a few on broaching. The book by Monday [9] is perhaps the most comprehensive source on broaching. The broaching technology including tooling and machines is reviewed, and critical aspects of the process are analyzed. Kokmeyer [10] edited collection of works on broaching demonstrating the effectiveness of the process. Gilormini et al. [11] analyzed the cutting forces on a single broaching section, and compared them to the process forces in slotting and tapping. Sutherland, Salisbury and Hoge [12] presented a mechanistic model for force predictions in gear broaching. Terry, Kami and Huang [13] presented a knowledge based system for optimal design of broaching tools. Sanjeev et al. [14,15] used FEA to analyze the effects of burnishing. Budak [16] evaluated the fir-tree broaching tools used for waspaloy turbine discs based on the force and power monitoring system results. He demonstrated that for most of the tools analyzed, the load distribution among the broaching sections were quite non uniform resulting in uneven wear, potential quality problems and overloaded sections. He also suggested that the process models can be used to improve the load distribution which may result in shorter tool length, and thus lower cycle time. Following with this idea, Budak and Ozturk [17] presented a model for simulation of the broaching process which can be used for improved tool design. They considered fir-tree broaching as it represents one of the most complex broaching processes due to the geometry and difficult-to-cut work material, waspaloy.

In this paper, an optimization method is presented for broach tool design based on the previously developed process and structural models. The paper is organized as follows. The optimization procedure together with the constraints are explained in the second section. The computer implementation is presented in section 3. The procedure is demonstrated on a tool design application. The paper is concluded by the overview of the optimization procedure and the future work.

2 BROACHING PROCESS OPTIMIZATION

2.1 Broaching variables

There are several important variables that must be considered in the optimization of broaching tools. They strongly affect the process mechanics and the machined part quality. These variables are interrelated, and the governing equations are implicit and nonlinear. Thus, they cannot be optimized in a straightforward manner. In this section, the important variables considered in broach tool design will be briefly reviewed.

There are several limitations related to tool stress, force, power or part quality that will be considered in the optimization process. The difficulty of the optimization procedure for broaching is the number of feasible solutions for a given part geometry. Figure 1 shows general broaching tool geometry. In broaching, the material is removed by successive cutting teeth on a broach tool section. There may be more than one section in a tool set which is moved through the work in a linear motion. Increased size or rise of the tooth with respect to the previous one defines the chip thickness. Similar to other machining processes, chip thickness affects the cutting process strongly, and thus has to be selected properly. 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. Another important variable is the gullet space between the teeth, which depends on the tooth height and land, root radius and gullet depth. Chip-to-gullet space ratio is important for chip storage during broaching, and thus it must be maintained at a certain acceptable level.
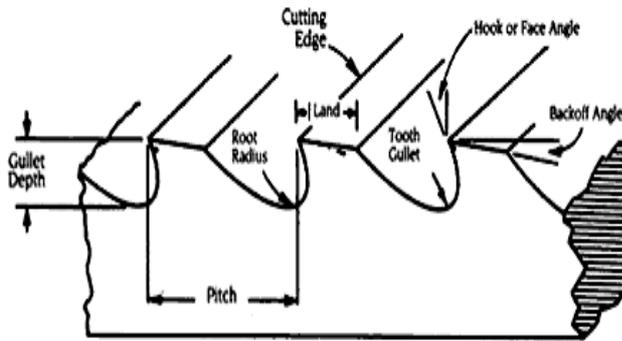

Figure 1: General broach tool geometry.

The optimization of the broaching process is complicated due to several reasons. First of all, all of these parameters are interrelated, thus modification of one would affect others strongly. 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 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 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. This is a unique optimization problem which cannot be addressed using the common methods. This partially explains why this problem has never been attacked in the literature before. The approach used for this purpose will be presented in the following sections of the paper.

2.2 Objective function

The objective function is based on the maximum production rate, or the material removal rate (MRR). The MRR depends on the cycle time, and thus the stroke, or tool length, and the cutting speed. In broaching, an economical cutting speed is usually selected for an application based on machinability of the material, tool setup time and wear rate. Therefore, the cutting speed will be assumed as given and will be left out of the optimization process. Thus, the only way to minimize the production time is by using the shortest possible total tool length.

$$Min \quad L \tag{1}$$

or as Ozturk stated [17]:

$$Max \quad MRR = \frac{w \sum_{i:1}^{N_s} t_i b_i n_i}{w + \sum_{i:1}^{N_s} (n_i - 1) p_i} V \tag{2}$$

where *MRR* is the material production rate, *V* is the cutting speed, *w* is the cutting depth, t_i is the chip thickness, b_i is the chip width, p_i is the pitch for the ith teeth, N_s is the number of sections and n_i is the number of cutting teeth. The tool length can be expressed as follows:

$$L = \sum_{i:1}^{N_s} (n_i - 1) p_i \tag{3}$$

which shows that minimizing the length or maximizing the material removal rate are equivalent. There are many constraints due to the physics of metal cutting, machine and geometrical limitations, which are interrelated. These make the optimization problem complicated which will be explained in the following sections.

2.3 Constraints

Ozturk [17] presented the important constraints for the broaching process. There are power, force and tool length constraints for a given machine; tool stress, cutting force, chip load, tooth geometry, maximum number of cutting teeth etc. constraints as summarized in the following.

Force model

The broaching force is one of the fundamental parameters affecting the process, and needs to be modeled. The broaching forces in two fundamental directions can be given as [21]:

$$F_t = \sum_{i=1}^{m} \left(K_{tc} t_i b_i + K_{te} b_i \right)$$

$$F_f = \sum_{i=1}^{m} \left(K_{fc} t_i b_i + K_{fe} b_i \right) \tag{4}$$

where *m* is the number of simultaneously cutting teeth, t_i and b_i are uncut chip thickness and width of cut for the cutting teeth *i*, respectively. K_c and K_e represent the cutting and the edge force coefficients, respectively, in the tangential and the normal directions.

Broaching processes can be in orthogonal or oblique cutting modes based on the tooth geometry, i.e. whether there is an inclination or helix angle between the normal to the cutting speed direction and the cutting edge. In this study, orthogonal cutting process is assumed for simplicity. In addition to the well known differences in the cutting process mechanics between two cutting modes, such as the chip flow angle, oblique cutting may present some

advantages. In orthogonal cutting, each tooth enters and exits the cut instantaneously, which results in sudden increases and decreases in the total cutting force. The oblique angle spreads the entry and exit over a longer cutting distance, hence the sudden changes in cutting forces are eliminated. This can also be modeled and simulated similar to the force simulations for helical end milling processes, provided that the oblique force coefficients are known. The cutting force coefficients for oblique cutting can be determined from [21].

$$K_{tc} = \frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) + \tan i \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}$$

$$K_{fc} = \frac{\tau_s}{\sin\phi_n \cos i} \frac{\sin(\beta_n - \alpha_n)}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}} \quad (5)$$

$$K_{rc} = \frac{\tau_s}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) \tan i - \tan\eta \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \sin^2\beta_n}}$$

In equation 5, the force coefficients for tangential, feed and radial forces are calculated by using shear stress (τ_s), shear angle (ϕ_n), rake angle (α_n), friction coefficient (β_n), oblique angle (i), and chip flow angle (η).

The power of the broaching machine is one of the constraints, which can easily be determined once the cutting force is known.

Tooth Stress

The maximum stress on a broaching tooth may be one of the constraints as it may cause tooth breakage. In general, broaching teeth have complex geometry and it is not possible to model the stresses analytically. Finite element analysis (FEA) can be used to determine the stresses, however considering great variety of the tooth profiles the procedure needs to be simplified. In order to model the stress on a tooth, Ozturk [17] developed a general equation for the tooth stress based on FEA. He used the tooth form shown in figure 2 due to general shape which can be used to represent variety of broach tool forms.
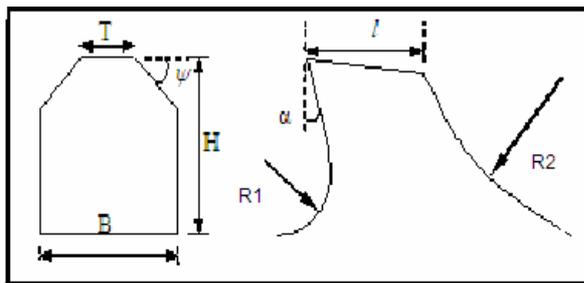

Figure 2: General tooth profile used to find stress.

It was demonstrated [17] that even for complex geometries such as fir-tree forms this representation results in good predictions for the stress:

$$\sigma_t = F(1.3H^{0.374} B^{-1.09} T^{0.072} \psi^{0.088} R_1^{-0.082} l^{-0.356}) \quad (6)$$

There are other constraints related to the geometry and the cutting performance of the process as presented by Ozturk. One of them is related to the chip space in the tool gullet area. The gullet area was also formulated [17] as a function of the tool geometry and will be used in this study as well. Another requirement, but not an absolute constraint, is related to the variation of the cutting force from section to section as well as within a particular section. If this variation is minimized, the sudden jumps in the cutting forces would be eliminated which would reduce tool wear and quality problems.

2.4 Broach tool sections

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. 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 on 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 tooth height which increases as much as needed to remove the material for that section. As shown in equation 6, the tooth stress increases with height and decreases with the width. 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, 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 stresses. 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.
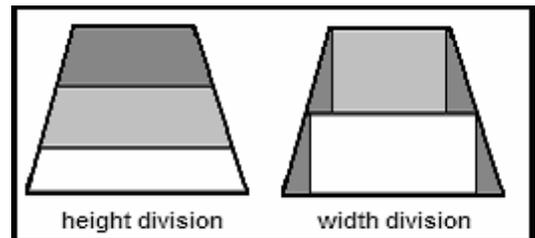

Figure 3: Volume divisions for the geometry.

2.5 Tooth rise options

In broaching, material removal is facilitated by increasing the size of a tooth with respect to the previous one since there is no feed motion as in other machining operations. This enlargement can be achieved in several ways. Figure 4 shows different rise choices for a sample profile. 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.
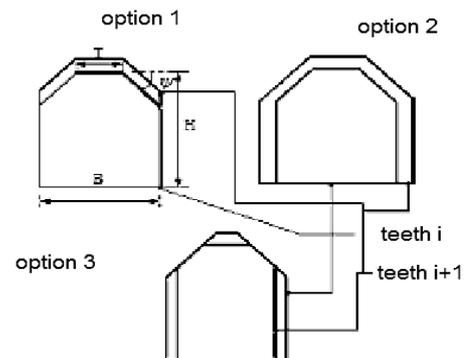

Figure 4: Tooth rise options.

2.6 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 section 2.4. 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 [17].

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 section 2.3. 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

$$C_{\%s} = 0,0059C_{\%b}^{2} - 1,1811C_{\%b} + 6,8643$$
$$C_{\%s} = C_{\%f}$$
$$C_{\%s} = 0,3709C_{\%h} + 0,0017 \qquad (7)$$
$$C_{\%s} = 0,0002C_{\%t}^{2} - 0,072C_{\%t} - 0,0832$$

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:

$$\max pitch = \frac{cutting\ length}{2} \qquad (8)$$

From the geometry of the tool:

$$\min.pitch = a \times land \qquad (9)$$

where a is a constant which 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 4 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 is 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:

$$int\left(\frac{F_{total\,max}}{F_{max\,pp}}\right) = m_{pm} \qquad (9)$$

where F_{maxpp} is the maximum calculated cutting force on a tooth and $F_{totalmax}$ 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 [9] 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.

3   COMPUTER IMPLEMENTATION

The models and algorithms developed are being implemented in computer program for practical use. The program will have two main functions when completed: Simulation of an existing broaching tool and optimal tool design for a specified work geometry, material, machine etc. The first, i.e. the simulation, part of the program has been completed and will be briefly described here. The program can be used to simulate the process with up to 20 tool sections. First of all, the geometry of the each section is entered. The window which is used to enter the general properties for each section can be seen in figure 5. In order to make this simple and fast, some common geometry templates are used in the input section of the program. Using there templates even very complex profiles such as fir-tree can be entered easily. Some profile examples can be seen in figure 6.
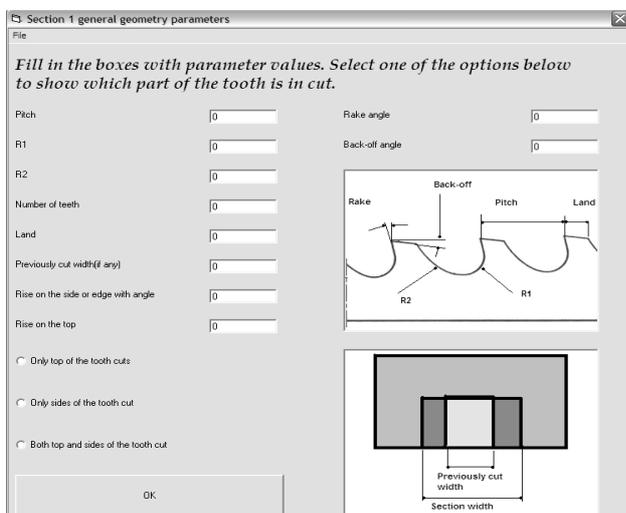
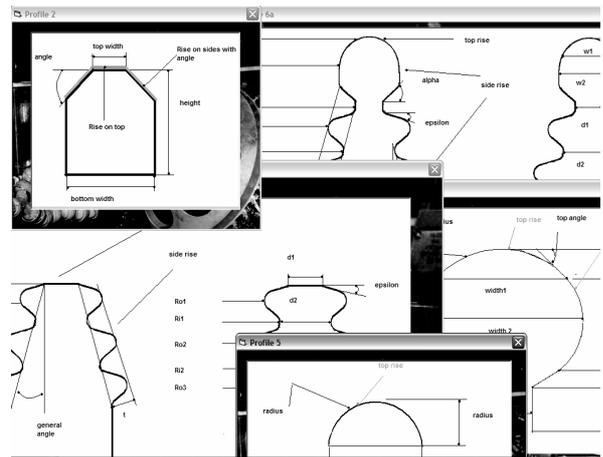Figure 5: General section properties window.

Figure 6: A group of help window examples.

Cutting force and tooth stress are simulated and displayed in the program.

4   APPLICATION

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.

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 1. The simulated total force and stress are shown in figure 7 and figure 8. 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.

5   CONCLUSIONS

Broaching is a common machining process. The quality and the productivity in this process heavily depend on the tool design which defines the cutting conditions. A procedure is described for optimal design of the broach tools. The shortest possible broach tool is designed by considering the geometrical and physical constraints. This procedure can be used in optimal design of broaching tools. The results indicate that the procedure proposed here may yield to much shorter tool lengths than the ones designed intuitively.

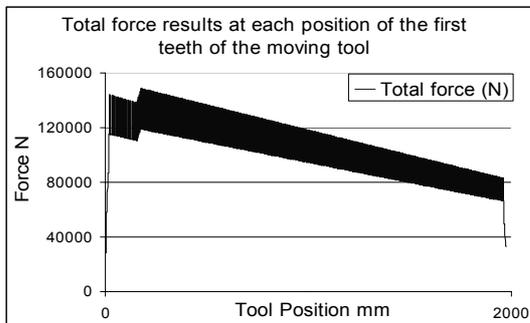| section no	1	2
pitch	5,25	4,5
tooth no.	30	401
top rise	0,065	0,0649
first teeth height	2	2
side rise	0	0
R1	1,98	1,98
R2	5,25	4,5
land	3	3
rake angle	12	12
back off angle	2	2
section length	152,25	1800
section division	height	
tooth change option	option 2	option 2
tool lenght	1952,25 mm	

Table 1: Parameters that give the best tool.
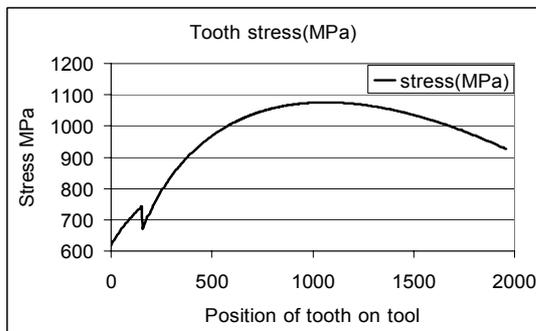

Figure 7: Force results of the solution.

Figure 8: Stress results of the solution.

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