ABSTRACT

High productivity and high quality can be achieved in broaching if the process is applied properly. Roughing, semi-finishing and finishing can be performed in one stroke of the tool increasing productivity and reducing set-up time. Furthermore, high quality surface finish can be obtained due to straight motion of the tool. One big disadvantage of broaching is that all process parameters, except cutting speed, are built into broaching tools. Therefore, it is not possible to modify cutting conditions during the process once the tool is manufactured. Improved design of broaching tools needs detailed modeling and analysis of the broaching process. In this paper, tool optimization method and process models are presented. Cutting forces, tooth stresses, part deflections are modeled and analyzed using cutting models and FEA. The results of the analysis are summarized in analytical forms so that they can be used for other applications although turbine disc broaching is considered as the application which is one of the most complex broaching operations. Application of the model for improved and optimized tool design are demonstrated by examples.

INTRODUCTION

Broaching is commonly used in industry for machining of variety of external or internal features such as keyways, noncircular holes, fir-tree slots on turbine discs etc. Broaching can offer very high productivity and part quality when the conditions are selected properly. It has several advantages over other machining processes most important of them being roughing and finishing of a complex form on a part can be completed in one stroke instead of many passes with another process such as milling. Also, straight and non-rotating tool motion results in good surface finish without feed marks. However, achieving high quality and productivity continuously in production needs a well-designed process. In broaching, all process parameters except cutting speed are defined by the cutting tool. Therefore, it is not possible to modify cutting conditions after cutters are manufactured unlike other machining processes where depth-of-cut or feedrate can be changed easily. This makes tool design the single most important aspect of broaching. In this paper, the constraints on the process and simulation of broaching will be presented with applications to machining of fir tree forms on turbine discs which is regarded as one of the most difficult broaching operations due to complex geometry, very tight tolerances and difficult-to-machine work material.

Figure 1: The broaching of fir-tree forms on a turbine disc.

Fig. 1 shows broaching of a turbine disc on a horizontal broaching machine. There are multiple broaching tool segments with different profiles as shown in Fig. 2.
The tooth rise-per-tooth determines the chip thickness which is different for each segment. In general, there is more than one tooth in-cut depending on the pitch of the cutter. Different profiles, rise-per-tooth and pitch results in variations in the total chip area, and thus cutting forces in a broaching cycle. This causes fluctuations in the load applied on the part and the fixture, and their deflections, cutting tooth stress and uneven wear of cutting teeth. Uneven load distribution will be shown by monitoring results in the paper. Proper design of broaching tools is necessary to improve the process for better quality and improved productivity. A modeling and simulation procedure which can be used for improved tool design will also be demonstrated by examples.

Although widely used in industry, there is very limited literature on broaching. The book by Monday [1] presents the technology of broaching machines, processes and tools in a detailed manner. Although this is relatively an old reference, most of the material in the book still applies to current broaching operations. Collection of the works edited by Kokmeyer [2] has several different broaching applications in industry demonstrating the effectiveness of the process. Terry et al. [3] presented a knowledge based system approach that can be used in design of broaching tools. Gilormini et al. [4] analyzed the cutting forces on a single broaching section compared them with the forces in tapping and slotting. Sutherland et al. [5] demonstrated the application of a mechanistic force model to gear machining. In one of the recent works, Sajeev et al. [6] presented the finite element analysis results for the effects of burnishing in broaching. Last section of a broach set usually burnishes the surface to improve surface finish and surface integrity. The analysis done by Sajeev et al. [6] is interesting to understand the mechanics of this process. Taricco [7] presented the tool wear affects on the surface integrity of the broached slots which increases the risk of high tensile stresses on the surface. Also, monitoring results are very helpful for identification of the possible improvements on the tool design [8].

In this paper, first of all the evaluation of existing broach cutters will be done through monitoring results. The constraints for optimization of broaching tools will be identified and analytical models will be presented. This will be followed by simulation results and suggestions for improvements on the tool design.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$F_t$</td>
<td>Tangential cutting force (N)</td>
</tr>
<tr>
<td>$F_f$</td>
<td>Feed force (N)</td>
</tr>
<tr>
<td>$F$</td>
<td>Total cutting force (N)</td>
</tr>
<tr>
<td>$G$</td>
<td>Oriented transfer function in chip thickness direction</td>
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<tr>
<td>$GA$</td>
<td>Gullet area (mm²)</td>
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<td>$L_{ram}$</td>
<td>Available ram length of the machine (mm)</td>
</tr>
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<td>$L$</td>
<td>Total length of the broach (mm)</td>
</tr>
<tr>
<td>$P$</td>
<td>Power (Watt)</td>
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<tr>
<td>$R$</td>
<td>Gullet radius (mm)</td>
</tr>
<tr>
<td>$T$</td>
<td>Tool life (min)</td>
</tr>
<tr>
<td>$V$</td>
<td>Cutting Speed (m/min)</td>
</tr>
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<td>$b_i$</td>
<td>Width of cut for tooth $i$ (mm)</td>
</tr>
<tr>
<td>$b_{lim}$</td>
<td>Limit for the width of cut (mm)</td>
</tr>
<tr>
<td>$fp$</td>
<td>Maximum allowed force variation percentage</td>
</tr>
<tr>
<td>$l$</td>
<td>Land length (mm)</td>
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<tr>
<td>$m$</td>
<td>Total number of teeth in-cut</td>
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<tr>
<td>$n$</td>
<td>Number of teeth in $i^{th}$ section</td>
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<tr>
<td>$p$</td>
<td>Pitch in section $i$ (mm)</td>
</tr>
<tr>
<td>$t$</td>
<td>Uncut chip thickness for teeth in section $i$ (mm)</td>
</tr>
<tr>
<td>$w$</td>
<td>Part thickness (mm)</td>
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<td>Rake angle of the tooth</td>
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<tr>
<td>$\sigma_t$</td>
<td>Tooth Stress (MPa)</td>
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<tr>
<td>$\delta_i^p$</td>
<td>Deflection due to tooth $i$ at position $x$ when it is at $x$</td>
</tr>
<tr>
<td>$\delta_i^e$</td>
<td>Deflection due to tooth $j$ at position $x$ when it is at $z$ distance away from $x$</td>
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<tr>
<td>$\delta_x$</td>
<td>Total deflection at position $x$</td>
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**1 EVALUATION OF AN EXISTING BROACH TOOL DESIGN**

Force and power monitoring systems have been installed on production broach machines in order to monitor tool wear, detect breakage and assess tool design [8]. Piezo-electric force sensors were placed and preloaded under the base block...
beneath the indexer unit on which the part is clamped as shown in Fig. 1. Broaching forces have two components: tangential or main cutting force in the cutting direction and passive or radial force in the normal direction. Because of the non-symmetrical geometry, the off-axis effects of the forces, i.e. moments, are not eliminated. As a result, the force sensor outputs depend on both force components as well as the part, tool and fixture geometry. Therefore, these forces cannot be used for the analysis of the process, but they may be suitable for monitoring. They are used to obtain reference forces which are compared with broaching forces during production in order to identify variations due to wear and breakage. However, in order to evaluate broach tool designs, power monitors were used to obtain a better indication of main cutting forces. Power monitors provide useful information about cutting force distribution on cutting teeth and among broaching sections as shown by Fig. 3. Note that the power consumption is low due to very slow cutting speed (3 m/min). Fluctuations in the cutting power are due to the variations of broaching forces from section to section. The data show that the cutting forces are distributed quite unevenly among broach sections.

Figure 3: Power-monitoring data showing broaching force fluctuations.

Also, the forces are surprisingly high in the finishing sections which may cause excessive part deflections. Improper distribution of broaching forces may cause uneven wear of the sections, tooth breakage due to overloading, quality problems due to part deflections, and longer cycle times due to unnecessarily long sections which are underloaded. A modeling approach will be presented in the next section in order to overcome these problems by improving the tool design.

2 OPTIMIZATION OF BROACHING TOOLS

The improvement of the process and tool design can be achieved through modeling. In order to achieve the desired productivity, predictive models are very important. As in other operations, higher productivity and lower cost are the objectives. In broaching, there are several constraints which can be summarized as tooth breakage, machine power, ram length of the machine and part quality. These constraints will be discussed in detail, however a force model is presented first as it will be needed in constraint formulations.

2.1 Broaching Forces

In general, broaching is an orthogonal cutting process. In some cases, cutting teeth may have an inclination angle to provide a smooth entry and exit to and from the cut making the process oblique. Cutting force coefficients are needed for force calculation. The data from other cutting processes cannot be used for broaching due to extremely small cutting speeds. They could be calibrated using mechanistic force models [9-10] which need force measurements. However, instrumentation of broaching machines is very difficult, as they do not have tables for clamping a dynamometer. Orthogonal cutting tests were performed using broaching cutting conditions on a lathe. HSS-T cutting tools were used to machine Waspaloy material. Cutting conditions such as depth of cut, cutting speed and rake angle were chosen such that the broaching conditions are obtained. The cutting coefficients are identified from cutting force and chip thickness measurements[11]. The cutting coefficients for 12° rake angle are obtained as in Table 1.

| \( K_{tc} \) (MPa) | 5387 |
| \( K_{te} \) (N/mm) | 61 |
| \( K_{fc} \) (MPa) | 3036 |
| \( K_{fe} \) (N/mm) | 70 |

Table 1: Experimental Cutting Coefficients.

where \( K_{tc} \) and \( K_{fc} \) are cutting force coefficients in the cutting and feed (normal) directions, and \( K_{te} \) and \( K_{fe} \) are the edge cutting force coefficients[11].

Total broaching forces in both directions can be determined by multiplying the cutting force coefficients with the total chip area, and the edge cutting coefficients by width of cut:

\[
F_i = \sum_{i=1}^{m} (K_{tc}t_i b_i + K_{te}b_i) \\
F_f = \sum_{i=1}^{m} (K_{fc}t_i b_i + K_{fe}b_i)
\]

(1)

where \( m \) is the total number of teeth in-cut, \( t_i \) and \( b_i \) are uncut chip thickness and width of cut for the tooth \( i \). \( m \) depends on the cutter pitch and the part thickness whereas width of cut is determined by the periphery of the tooth which is in-cut.

2.2 Ram Length

The total length of the broach sections cannot be higher than the machine’s ram length. This can be expressed by the following equation
\[ \sum_{i=1}^{N} (n_i - 1) p_i \leq L_{\text{ram}} \]  \hspace{1cm} (2)

where \( N \) is the number of broach sections, \( n_i \) is the number of teeth in \( i^{th} \) section, \( p_i \) is the pitch and \( L \) is the total length of the ram. One of the most important aspects of the optimization is to reduce the total length of a broach set, and make it even shorter than the available length on the machine. This would reduce the tool cost and machining time.

### 2.3 Tool life

Tool life in any cutting operation depends on cutting conditions, primarily on the speed. The Taylor tool life equation relates the tool life to the cutting speed \( V \) by

\[ T_i = \frac{k}{V^c} \]  \hspace{1cm} (3)

where \( T_i \) is the tool life for cutting speed of \( V \). \( k \) and \( c \) are empirical constants. Increased speed may reduce cutting time, but it increases the tool wear resulting in lower tool life. This is very important for broaching as worn tools may cause serious quality issues, and set-up times are usually very high.

Therefore, optimal tool life should be determined. This can only be done by evaluating the available production data as wear tests are time consuming and costly. Usually 2000 inches (50 m.) cutting length is recommended for tool life in broaching. It should probably be longer in case of fir-tree broaching considering the number of sections and long set-up times.

### 2.4 Broach Tool Stress

Broaching forces can be quite high due to large width of cuts which may be required for a given profile. High forces may cause tooth breakage, thus tooth stresses must be calculated during tool design. Tooth stress analysis can be performed using the Finite Element Analysis (FEA). Broach tooth profiles can have variety of different complex shapes which makes the stress analysis time consuming as analysis of each profile needs to be performed separately. In order to simplify the modeling, a generalized tooth geometry has been used in FEA as shown in Fig. 4. The cutting forces in tangential and feed direction were distributed at the cutting edges of the tooth in a uniform manner. The maximum stresses in the tooth body were determined using the FEA as shown in Fig. 5. High stresses at the edges due to very small radius will be discussed in section 2.8. By varying the geometric parameters and repeating FEA, the following equation has been determined for the maximum stress in the tooth by curve-fitting:

\[ \sigma_i = F(1.3H^{0.374}B^{-1.09}T^{0.072}\psi^{0.088}R_i^{-0.082}l^{-0.356}) \]  \hspace{1cm} (4)

where dimensions are in (mm), \( \psi \) is in degrees and \( \sigma \) is in (MPa). In the third direction, a standard clearance angle of 2° is used for fir-tree broaches. The general form shown in Fig. 4 is also a valid representation for more complex tooth-forms such as a fir-tree. This was checked by comparing results from FEA and Eq. (4).

### 2.5 Machine Power

The power available on the machine ram could impose a limitation on the broaching process. This will be formulated in the following.

\[ P = F_i V = \sum_{i=1}^{m} t_i b_i K_i V \]  \hspace{1cm} (5)

where the number of teeth in-cut \((m)\) can be expressed in terms of part thickness \((w)\) and the pitch \((p)\)

\[ m = \frac{w}{p} \]  \hspace{1cm} (6)

Note that \( m \) is integer and should always be rounded to nearest upper value. Substituting (6) into (5) and assuming that the chip thickness and the width of cut are the same on the simultaneously cutting teeth, the following is obtained:

\[ P = \frac{wbK_i V}{p} \]  \hspace{1cm} (7)
Eq. (7) can be used to determine limitations on $t$, $V$ and $p$ due to power constraint as expressed in the following:

$$t \leq \frac{Pp}{bwK_tV}$$

$$V \leq \frac{Pp}{btwK_t}$$

$$p \leq \frac{btwK_tV}{P}$$

(8)

The broach length constraint due to ram length, as given in 2.2 is always present which has to be included in this analysis as well. However, for a simple case where there is only one broach section, the formulation can be simplified as follows. If the total stock which needs to be removed from the surface is $s$, for constant rise per tooth ($t$), the necessary number of teeth on the cutter is

$$N = s / t$$

(9)

The total length of the broach is

$$L = N \cdot p = \frac{s \cdot p}{t}$$

(10)

From which the chip thickness in terms of other parameters is obtained as

$$t = \frac{sp}{L}$$

(11)

Substituting (11) into (7):

$$P = \frac{bwsK_tV}{L}$$

(12)

Similar to Eq. (8), the limitations on the maximum stock size and velocity can be determined in terms of the broaching system parameters:

$$s \leq \frac{LP}{bwK_tV}$$

$$V \leq \frac{LP}{bwsK_t}$$

(13)

2.6 Part Quality

The form errors left on the surface are considered as the measure of part quality. They increase with cutting loads resulting from high rise per tooth, high number of teeth in-cut or worn cutting teeth. The force and part deflection models can be used in order to check for this constraint. As a result, the chip load or number of teeth in-cut may be modified. This can be expressed as follows.

$$F_q / k_q = \delta_q$$

or

$$\frac{K_q t_m}{k_q} \sum_{i=1}^{m} b_i \leq \delta_{allowea}$$

(14)

where $k_q$, $K_q$, $\delta_q$ are the stiffness, cutting force coefficient and deflection in the direction of interest, i.e. tangential ($t$) or feed (or passive) ($f$), respectively. $b_i$ is the width of cut for tooth $i$, $\delta_{allowea}$ in the maximum deflection allowed which is dictated by part tolerances. Since fir-tree is the application, it is approximated according to the analyses below.

$$F_q / k_q = \delta_q$$

$$\frac{K_q t_m}{k_q} \sum_{i=1}^{m} b_i \leq \delta_{allowea}$$

(14)

Therefore, the geometry shown in Fig. 7 can be used as the generalized geometry. $B$, $T$, $H$ and $W$ can be determined from the real tooth profile as shown in Fig. 6. The radial forces cause the part deflections and they are represented by the normalized line force $K$, which can be determined from the cutting coefficients as follows:

$${\begin{array}{c|c|c|c|c}
  \text{Tangent to curl 2} & \text{Tangent to curl 3} \\
  \hline
  \text{FEA} & \text{Formula} & \text{Error} & \text{FEA} & \text{Formula} & \text{Error} \\
  \hline
  \text{Case 1} & 0.184 & 0.191 & 8% & 0.165 & 0.16 & 3% \\
  \text{Case 2} & 0.184 & 0.194 & 7% & 0.184 & 0.176 & 4% \\
\end{array}}$$

Table 2: Fir-tree approximation comparison.

The complex form of the fir-tree needs to be simplified so that the resulting equations can be applied to other geometries. The approximation shown Fig. 6 is used in the analysis. First, the accuracy of the trapezoidal approximation is checked using FEA which is given in Table 2. As it can be seen from the table, the approximation is quite acceptable and representing a fir-tree by drawing a tangent line to curl 3 is better than curl 2.
where \( t \) is the chip thickness. The total force can then be determined by multiplying \( K_f \) by chip thickness \( t \).

Similar to the tooth stress analysis, the geometric parameters have been varied in the FEA, and the following resulting equation has been determined through curve-fitting for the prediction of deflection at a point \((x)\) when the force, i.e. cutting tooth, is at the same position as shown in Fig.7:

\[
\delta_{i,x} = \frac{K_f f_s t}{1000} \left(0.0265 w^{-0.45} T^{-0.608} B^{-1.834} H^{1.81} t_r^{0.968}\right) \tag{16}
\]

where all dimensions are in (mm). \( r_i \) is defined as follows

\[
\begin{align*}
  r_i &= 1 - \frac{x}{w} \quad \text{if} \quad r_i < 0.5 \\
  r_i &= \frac{x}{w} \quad \text{if} \quad r_i \geq 0.5
\end{align*}
\]

If multiple teeth are in-cut at the same time, the deflection caused by one of the cutting at the position where the other tooth is contact with the material is approximated as:

\[
\delta_{j,x} = \frac{K_f f_s t}{1000} \left(0.0055 w^{-1.35} T^{-0.259} B^{-1.81} H^{2.47} r_j^{-1.16}\right) \tag{17}
\]

\( \delta_{j,x} \) represents the deflection caused by tooth \( j \) at position \( x \) when it is at a distance \( p \) from \( x \) (mm) where \( r_j=p/w \). This is necessary to determine the deflections and surface errors in case multiple teeth are in-cut. Using super positioning of deflections caused by all teeth, the total deflection of the part during cutting is determined. Note that fixture stiffness must be measured if it is significant. The total deflection at a point can be calculated as:

\[
\delta_x = \delta_{i,x} + \sum_{j=1}^{m} \delta_{j,x} \quad (mm) \quad j=1:m \tag{18}
\]

Figure 7: Generalized part geometry used in deflection analysis.

2.7 Chatter Stability

Chatter vibrations may develop and result in poor surface finish in broaching. It could be an important limitation particularly in case of highly flexible parts and fixtures. Broaching is an orthogonal cutting process, and thus standard cutting stability model [11] can be used for determining the limiting width of cut which dictates the allowable number of teeth in-cut. The chatter stability limit for the width of cut in orthogonal cutting is given by [12]

\[
b_{\text{lim}} = \frac{1}{2\text{Re}[G] K_f} \tag{19}
\]

where \( G \) is the oriented transfer function in the chip thickness direction. In broaching, the total width of cut must be smaller than the stability limit:

\[
\sum_{i=1}^{m} b_i \leq b_{\text{lim}} \tag{20}
\]

The width of cut is usually the same for successive broaching teeth:

\[
b_i \leq \frac{b_{\text{lim}}}{m} \quad \text{or} \quad m \leq \frac{b_{\text{lim}}}{b_i} \quad (i=1:n) \tag{21}
\]

2.8 Chip Space

Chip jam is a common problem in broaching. Broach chips can be very short depending on the thickness of the part. If there is not enough curvature in the chip they may get stuck on the surface. This is usually overcome by using a brush mounted over the ram. Another problem is the chip space. If there is not enough space in the gullet, chips may get stuck in that space and cause jamming. The space in the gullet has to be checked for sufficient chip room. For this purpose, an equation is developed for the gullet area as follows:

\[
GA = 0.9456(p - l)^{0.816} H^{1.14} R_1^{0.026} R_2^{-0.089} \alpha^{0.038} \tag{22}
\]

where all dimensions are in (mm) and \( \alpha \) is in (deg) (Fig. 8). The chip space to chip volume ratio is recommended as 24 by Monday [1].
2.9 Tooth Chipping

The edge stresses are not considered in the tooth breakage as they mainly cause edge chipping. Chipping is usually related to the chip thickness, thus there is a limit for maximum rise per tooth:

$$t \leq t_{\text{max}}$$  \hspace{1cm} (23)

where $t_{\text{max}}$ depends on the tool and work material. In waspaloy broaching practice it is about 0.0025" (0.065 mm) with HSS tools.

2.10 Rubbing

Rubbing is undesired in cutting as it reduces tool life and results in poor surface finish. It can be eliminated by increasing clearance angle and chip thickness and reducing edge hone radius. For the cutting tool geometry used in a broaching application, the minimum chip thickness that can be removed without rubbing presents a constraint on the chip thickness as

$$t \geq t_{\text{min}}$$  \hspace{1cm} (24)

In our case it is taken as 0.0005" (0.012 mm).

2.11 Force Fluctuation within a section

The broaching forces fluctuate as the teeth enter and exit in and out of the cut. Force fluctuations cause changes in the deflections of the part and the fixture causing reduction in the effective clearance angle and decreasing tool life. The fluctuations can be reduced by selecting the pitch properly:

$$p = \frac{w}{m}$$  \hspace{1cm} (25)

where $m$ is the number of teeth in-cut. This way the entry and exit to and from the cut are synchronized reducing fluctuations. Note that zero fluctuation is very difficult to achieve as the exiting and entering teeth will be either in the cut together momentarily or one will exit and the other enter immediately. In both cases there will be some force fluctuation, however its amplitude and the period could be reduced by properly selecting the pitch.

2.12 Force Fluctuations from section to section

Broaching forces are in general different for each section based on the cutting conditions. This may result in high variations in the force causing increased wear and poor quality. The force fluctuation from section to section should be minimized:

$$|F_{i+1} - F_i| \leq \Delta F_{\text{max}} \quad (i=1, N-1)$$  \hspace{1cm} (26)

or,

$$\frac{|F_{i+1} - F_i|}{F_i} \times 100 \leq fp \quad (i=1, N-1)$$  \hspace{1cm} (27)

where $F_i$ is the broaching force in the $i^{th}$ broach section, $\Delta F_{\text{max}}$ is the maximum allowed force variation and $fp$ is the maximum allowed force variation percentage.

2.13 Manufacturability of broaching tool

The manufacturability of broach tools may impose other constraints. Since most of the sections are manufactured by standard tools, an extraordinary design will be time consuming and will lead to increased cost. For example a broach design with variable pitch or rise in the same section may suppress chatter, improve surface finish and tool life, but it may also increase manufacturing and resharpening cost. For most of the tools, the gullet radius ($R_1$) in a section is the same for easy grinding of the tool. For this reason, it is important to consider manufacturability of the improved tool design before it is implemented.

3 SIMULATION OF BROACHING PROCESS

A computer program has been developed in Matlab® in order to simulate the process and improve the tool design. The simplified algorithm of the program is shown on Fig. 9. The inputs to the program are the material characteristics, tool and part geometry. The simulation is carried out in time domain where the broach tool is advanced into the material using small increments. There are two modes in the program. In the simple mode, the effects of deflections on cutting force calculations are neglected (Rigid Model) whereas in the iterative mode, the deflection effects are included (Flexible Model). The deflections affect the forces on the first few teeth after which the forces stabilize.

4 EXAMPLE APPLICATION

4.1 Existing Tool

The simulations have been carried out for the HSS-T tool shown in Fig. 2 to machine the work piece made out of a nickel alloy (waspaloy). Experimental cutting coefficients obtained in Table 1 are used for cutting force predictions. The variations of predicted force components in a complete broaching cycle are shown in Fig. 10. As in the power monitoring data (Fig. 3), high fluctuations are present in broaching forces as well. The bold line in Fig. 11 is the process power read from Fig. 3. It is seen
that the prediction results correlates with the monitoring data reasonably well. It should be noted that the measured data is not the cutting power only, but the total power on the ram motor. This is one of the discrepancy sources between the experimental and prediction results. The frictional effects, tool wear etc. are also responsible for the differences. The maximum surface form error for this case was calculated as 29µm. The tooth stress predictions are shown in Fig.12. The stress variations within a section are due to the change of the tooth height as a result of the tooth rise.

**Figure 9:** The Algorithm of the simulation program.

**Figure 10:** Cutting force predictions for a broach tool with 12 sections as shown in Fig. 2.

**Figure 11:** Power data comparison.
4.2 Improvement on Broach Tool Design

The simulation results demonstrated that some sections do not conform to the constraints proposed in Section 2. The tool design can be improved by applying the methodology presented in this paper. Two main parameters are varied for optimization: rise per tooth and pitch. The main objective is to reduce the tool length by respecting all the constraints. The simulation is always started by varying the rise as it is a much simpler parameter to modify on the tools. After this is completed, the pitch is varied in each section in order to reduce the length further, by again respecting the constraints.

As a first step, the rise in all sections were increased or decreased until a constraint is encountered. The maximum or minimum chip thicknesses are usual limitations. Next, the pitch was decreased in order to reduce the length, increase the force, and thus reduce the force fluctuation. The force fluctuation with the original tool design is as high 430% which was reduced significantly. Chip space may become an important limitation for small pitches which reduce the chip space substantially. Considering the recommended 2-4 range in Monday [1], a minimum of 3 has been used in the simulations.

After the modifications listed in Table 3, the cutting force and tooth stress predictions are shown for the new geometry in Fig. 13 and Fig. 14, respectively. The main constraints were chipping and manufacturability. Therefore, stress limit was never encountered for this application. The yield strength of the tool material (HSS-T) is specified to be about 2400 MPa by the manufacturer. Then, the factor of safety for this case is about 3.

As it can be seen from the figure, the fluctuation amount and the peak forces have been reduced. The total broach length has also been reduced by about 24%. Further improvements are possible, but would require modifications on the tooth profiles in each section which will be a topic of another study.

<table>
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<th>After</th>
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<tr>
<td>Form error (µm)</td>
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<tr>
<td>Max. Tooth Stress (MPa)</td>
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<td>Chip Space Percentage (%)</td>
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<td>Force Fluctuations from section to section ( F_p (%) )</td>
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<tr>
<td>Force Fluctuations from section to section ( F_f (%) )</td>
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</table>
5 CONCLUSION

Broaching is used in a variety of applications and can provide high productivity and part quality. Tool design is the most critical aspect of broaching as the cutting conditions are set by the broach geometry which cannot be modified during the process. Monitoring results indicate extremely uneven force distribution among tool segments in broaching of fir-tree slots on turbine discs. There are number of constraints which have to be respected in optimization of the tool design. Cutting loads must be limited according to the available machine power and tooth breakage limit. The force fluctuations must be minimized to eliminate quality problems and accelerated tool wear. Deflections must be also limited for tolerance integrity of the part. These and similar other constraints considered in optimization of the rise and the pitch of broaching tools. A simulation system has been developed for prediction of cutting forces, power, tooth stress and part deflections. The program provides predictions for a given work material and tool geometry. Tool design can be improved based on the predictions which is demonstrated by an example.

Table 3: Improvement after modification.

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Table 4: Modifications done on broach tool.

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ACKNOWLEDGMENTS

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REFERENCES
