

Simulation of Broaching Operations for Tool Design Optimization

E. Ozlu¹, S. Engin², C. Cook³, T. El-Wardany⁴, E. Budak⁵

¹*Maxima Manufacturing R&D Ltd. GOSB Technopark, Gebze, Kocaeli, Turkey*

²*Pratt & Whitney Canada, Longueuil, QC, Canada*

³*Connecticut Center for Advanced Technology (CCAT), East Hartford, CT, USA*

⁴*United Technologies Research Center (UTRC), East Hartford, CT, USA*

⁵*Sabanci University, Manufacturing Research Lab, Istanbul, Turkey.*

emre@maxima.com.tr

Abstract: In this study, an approach for simulation of broaching operations is presented. The proposed approach calculates the cutting forces, power, maximum stress at the tooth root, chip thickness and rake angle distribution on all teeth, and the workpiece geometry evolution during the process. The developed algorithms are integrated in a computer software that can simulate a whole broaching process to predict various physical parameters and generate some performance measures. The model which is used to optimize the broaching process is briefly presented here together with the industrial applications.

Keywords: broaching, process simulation, process optimization

1 INTRODUCTION

Broaching is one of the ideal machining operations for a variety of applications due to its ability to produce complex features, such as non-circular internal holes, keyways, turbine disc fir-tree slots, with high surface quality in a relatively short processing time. High productivity, quality and geometric capabilities are achieved by pushing linear saw-like broach tools over the stock material. Broaching tools are typically made up of many different segments (details) and hundreds of cutting teeth, each having a different profile that creates the chip. Therefore, tool design is the most critical aspect of broaching as it determines the performance of the process exclusively and most of the cutting parameters directly. In order to make a thorough design, the process modeling of the broaching operations is critical to save time and resources compared with the try-error methods.

Although broaching has been extensively used for manufacturing of different products in the past, in some applications it has been replaced by multi-axis milling due to the development of CNC machine tools with high flexibility, speed and accuracy. This may be one of the reasons for very limited work published on broaching process. The first studies [Monday, 1960; Kokmeyer, 1984; Robert et al., 1986] mainly focused on the technology whereas process monitoring in broaching has been a topic of some

later works [Budak, 2001; Axinte et al., 2003; Axinte et al., 2005]. There are also limited number of studies which focus on process modeling [Vijayaraghavan et al., 1981; Sutherland et al, 1997; Sajeev et al., 2000; Ozturk et al., 2003; Kokturk et al., 2004]. The general modeling approach in these studies is semi-analytical, however some studies use numerical methods as well. In addition there are experimental studies which focused on the selection of proper cutting condition by means of surface quality and stable cutting [Mo et al., 2005; Axinte, 2007].

The aim of this paper is to demonstrate the application and results of modeling and simulation studies performed on different broaching operations over the last few years using a specially developed computer program, Broaching Operation Simulation Software (BOSS). The proposed approach is different than the previous ones as it uses analytical approaches for both mechanical and geometrical modeling that results in very fast solution times and accurate predictions. With the help of the developed approach, the tool design is evaluated in terms of simulated distributions of cutting forces, power and tooth stress over the tool segments and cutting teeth. It is shown that these results can be used to identify problems and opportunities in the design stage of the broaching tools. This results in reduced total tool length, faster tool travel velocities (faster cycle times), and provides a more uniform wear distribution among cutting teeth which reduces the chance of tooth breakage due to the elimination of force overload conditions. Several industrial applications are also presented.

2 SIMULATION OF BROACHING PROCESS

In this section the simulation approach of broaching process is presented. In broaching, cutting speed can be defined as a process parameter that can be varied, the feed rate and depth of cut are embedded in the broach tool. This characteristic of broaching processes differs them from other machining operations and makes the modeling complicated. Therefore, rather than developing a specific model for a single type of broaching tooth profile, a general model should be used to represent the cutting mechanics for broaching operations.

The other complexity in simulations arises due to the previously removed material which a previous tooth intersects. Therefore the updated workpiece geometry should always be considered while simulating the whole broaching process. The simulation approach developed in this study will be discussed at the following sub-sections briefly. The models developed and presented here have been implemented in a computer code called BOSS. With the help of the generated algorithms, BOSS can calculate the cutting forces, power, stresses, chip thickness and rake angle distributions on all teeth together with the evolution of the workpiece geometry during a broaching operation.

2.1 Broach Tooth Geometry

A broaching tool set consists of several details each having many teeth. Cutting angles on a broach tooth can be seen in Figure 1. The global rake angle is represented by α where the global inclination angle (or shear angle) is represented by i .

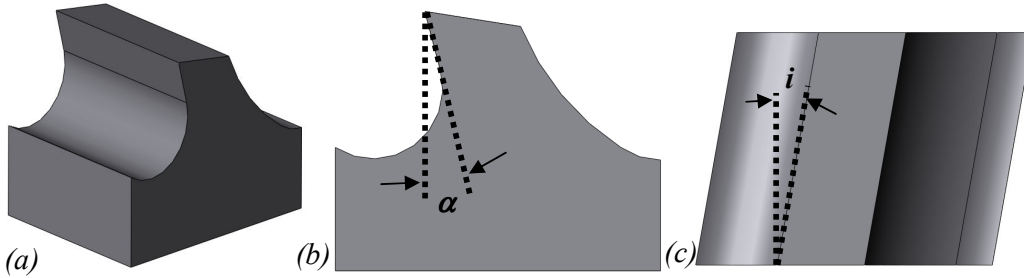


Figure 1; Cutting angles on a broach tooth : (a) 3D view, (b) side view, and (c) top view.

The global cutting angles represent the cutting mechanics for a tooth where only the top edge is in cut (Figure 1). However, for a general cutting tooth geometry which removes material on all sides, the local cutting angles should also be considered. A tooth profile which has such geometry can be seen in Figure 2, where there is no global shear angle on the tooth but a global rake angle. The profile in Figure 2 has two inclined cutting edges. Due to the global rake angle on the inclined cutting edges, the cutting speed direction is not perpendicular to the inclined cutting edges. Therefore a local shear angle, i_L exists on the inclined edges. Moreover, the angle between the chip thickness direction and the normal of the cutting edge creates a local rake angle α_L .

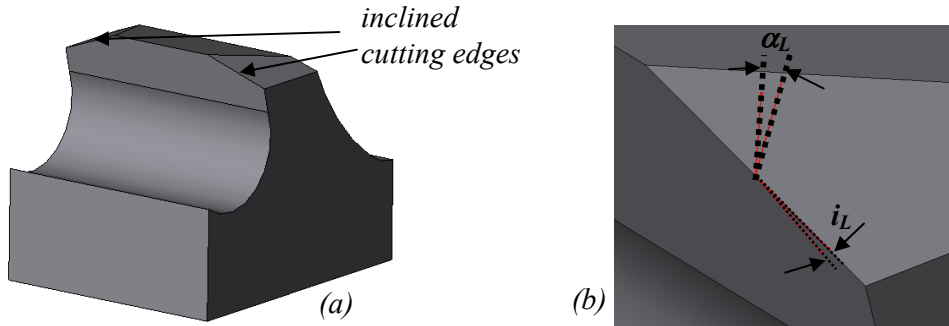


Figure 2; A tooth geometry with inclined cutting edges: (a) 3D view, (b) bigger view of the inclined cutting edge and local cutting angles.

2.2 Broaching Mechanics

Due to the variation of local cutting angles, the cutting mechanics change along a cutting edge of a broaching tooth. Once the local angles are identified, the local cutting forces in three cutting directions can be calculated with the well-known linear-oblique cutting force model as follows [Altintas, 2000]:

$$\begin{aligned}
 F_t^i &= K_{tc}^i f_i b_i + K_{te}^i b_i \\
 F_f^i &= K_{fc}^i f_i b_i + K_{fe}^i b_i \\
 F_r^i &= K_{rc}^i f_i b_i
 \end{aligned}
 \tag{1}$$

where superscript i represents the cutting point on the cutting edge, F_t^i is the local tangential, F_f^i local feed and F_r^i local radial force, K_{tc}^i , K_{fc}^i , and K_{rc}^i , are the cutting force coefficients in the tangential, feed and radial directions, respectively, K_{te}^i and K_{fe}^i , are the edge cutting force coefficients in the tangential and feed directions, respectively. These cutting force coefficients depend on the tool and workpiece material and can be obtained from calibration tests proposed by Armarego et al. (1985) and Budak et al. (1996). The calibration conditions are orthogonal, but the data is transformed to oblique cutting conditions in order to include the effect of inclination angle.

The forces in equation (1) are the local cutting forces which depend on the uncut chip thickness and local cutting angles. For each different cutting edge on the broach tooth, these local forces should be calculated separately. In order to determine the total cutting forces that are acting on the broach tooth, each local cutting force should be oriented by the rotation matrix and summed up. Once the cutting forces are obtained, the cutting power can also be calculated for a cutting speed.

As a result of the cutting forces, there exist two different types of stresses on a broach tool: local stresses along the cutting edges and the stress at the tooth root (gullet). The cutting forces acting on the cutting edge cause local stresses which depend on the edge-hone radius, clearance angle and contact mechanics on the rake face. High local stresses may cause chipping on the cutting edge. Chipping can be controlled by the limiting the maximum chip thickness and the hone radius. High cutting forces, on the other hand, result in bulk deformations yielding higher stresses at the root of the tooth. The maximum stress at the root of the tooth causes tool breakage which can be controlled by the gullet geometry and the force distribution during the broaching operations. A semi-analytical approach is developed in order to calculate the maximum stresses occurring at the root of the tooth. Several numerical simulations are conducted in FEM by changing several geometrical parameters for the tooth profiles. During the simulations, the forces acting on the tooth are transformed to the total moment acting on the root of the tooth. An analytical function that relates the maximum stress to the total moment was developed for general tooth profiles, and is used in the stress calculations of broaching teeth.

2.3 Process Simulation

In order to simulate the whole broaching process, the areas that were removed by previous teeth should be considered in order to calculate the uncut chip area. This can be achieved by updating the workpiece geometry for each cutting tooth. For accurate calculation of the updated workpiece geometry all the tooth profiles should be given appropriately. However, the number of teeth for a broach tool set can be up to several hundreds. Thus, inputting each tooth profile one by one can be very time consuming. In order to solve this problem, only the first and last tooth of each detail is entered as input. By the developed algorithms, other tooth profiles are calculated automatically. Considering the fact that there are many possible geometries between the first and the last tooth, the intermediate teeth generation algorithms must have the required flexibility and intelligence in order to construct the correct geometry accurately.

3 SIMULATION RESULTS

The outputs of the proposed models are the cutting forces, cutting power, the maximum stresses acting on each tooth, distribution of the rake angle and chip thickness acting on each tooth. These outputs are discussed in this section on a fictitious broach tool having fir-tree geometry. The applications of the simulation approach on the industrial cases are presented in the next section in detail. In order to present the outputs, the simulation results are evaluated for the outer broaching of the profile which can be seen in Figure 3.a. The last tooth of each detail of the broach can be seen in Figure 3.b.

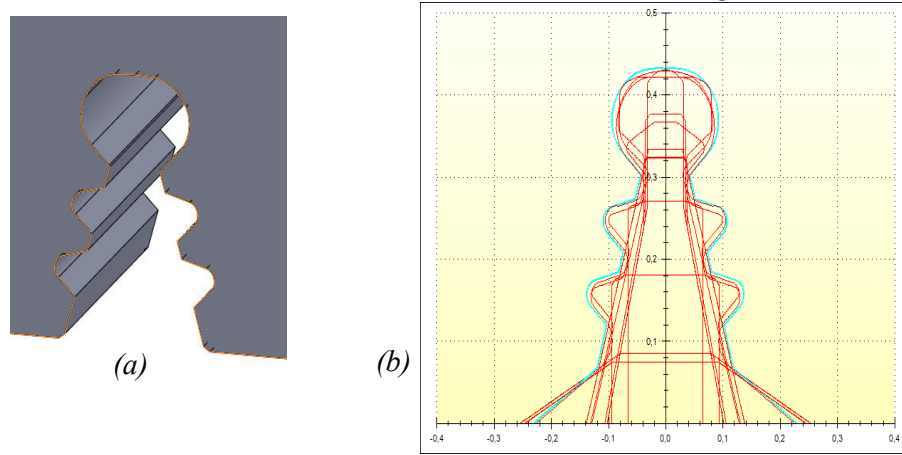


Figure 3; (a) The final shape, (b) The last tooth of each detail on broach.

The example case has 14 details with a total of 427 teeth. The global rake angle is 12° and there is no global inclination. The workpiece material is a nickel based material, and the length of cut is 20 mm. The processing time took 9 seconds with BOSS.

3.1 Chip Thickness Distribution

The maximum uncut chip thickness on each tooth can partially represent the cutting load whereas the minimum uncut chip thickness can be evaluated for the chipping. In Figure 4.a, the uncut chip thickness distribution can be seen. The integer labels on the lines parallel to the y axis represent the beginning point of each detail. As it can be observed, there is a jump at the intersection between the last tooth of the 7th detail and the first of the 8th detail (Figure 4.b). The chip thickness distribution on the first tooth of the 8th detail can be found in Figure 4.c. As another important observation, it can be seen that 7th detail does not carry any load, and can be removed totally from the broach set. At the design phase of a broach tool, the uncut chip thickness distribution plays an important role when evaluating the transitions between the details. With the proposed approach, the chip thickness distributions at each detail transition can be displayed easily.

3.2 Rake Angle Distribution

The rake angle distribution on each tooth can be evaluated in order to display the local (real) rake angle and the performance of that specific cutting edge. The max and min

rake angle distributions on each tooth for the example case (Figure 3) can be seen in Figure 5.a. As can be observed from the Figure 5.a, the local rake angle may go to negative values for some of the teeth such as the ones at the 8th detail. This is due to the effect of the inclined cutting edges. For instance observing the 6th tooth of the 8th detail (Figure 5.b), it can be seen that the cutting edges at the top has the positive rake angle values whereas the opposite edges has the negative rake angle values (Figure 5.c). This geometrical behavior shows that even if there is a positive global rake angle, due to the oppositely inclined cutting edges there may be negative rake angles which will affect the mechanics at the cutting edge.

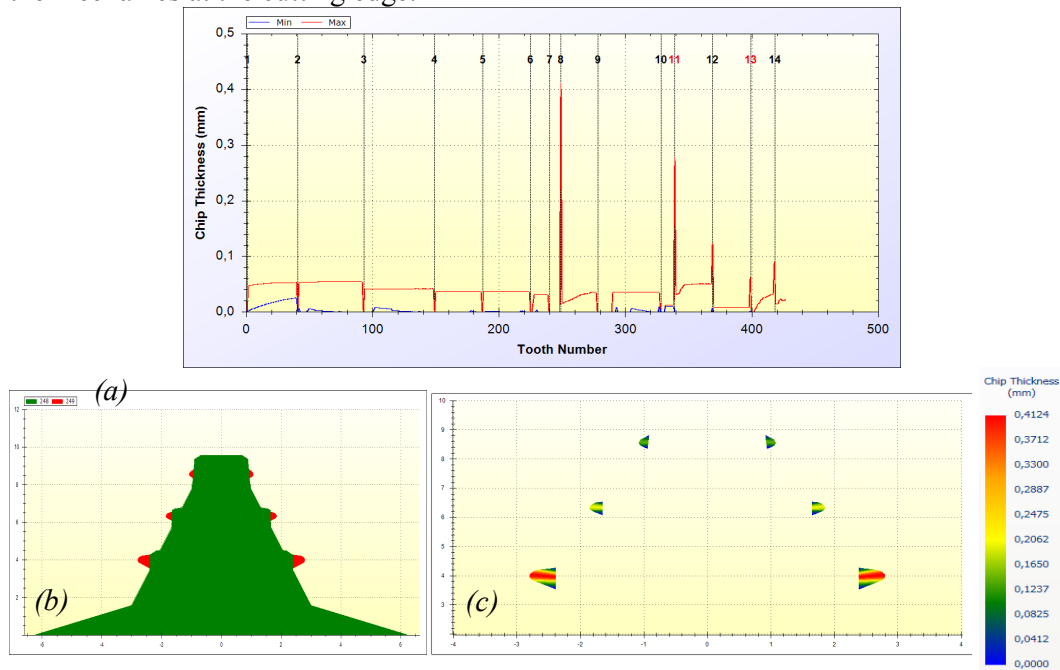


Figure 4; (a) The max and min uncut chip distribution on each cutting tooth, (b) the cut area, and (c) the uncut chip thickness distribution on the first tooth of the 8th detail.

3.3 Cutting Forces

The cutting forces can be examined in order to obtain a smooth variation which results in uniform wear distribution among the teeth. The cutting force directions in the machine coordinates can be found in Figure 6.a. Only the forces in the x direction are discussed in this section which can be seen in Figures 6.b. In Figure 6.b, the forces acting on the right hand and left hand side of the tooth are displayed together with the total cutting force. The total cutting force in the x direction vanishes for a symmetrical tooth profile since the forces from both sides of the tooth cancel each other except when the detail is staggered. In the example case, 11th and 13th details are staggered. Observing Figure 6.b, it can be seen that there exists forces acting on these details in the x direction. On all of the other details, the forces acting on the right and left hand sides of the teeth are equal to each other which generate no cutting forces in the x direction.

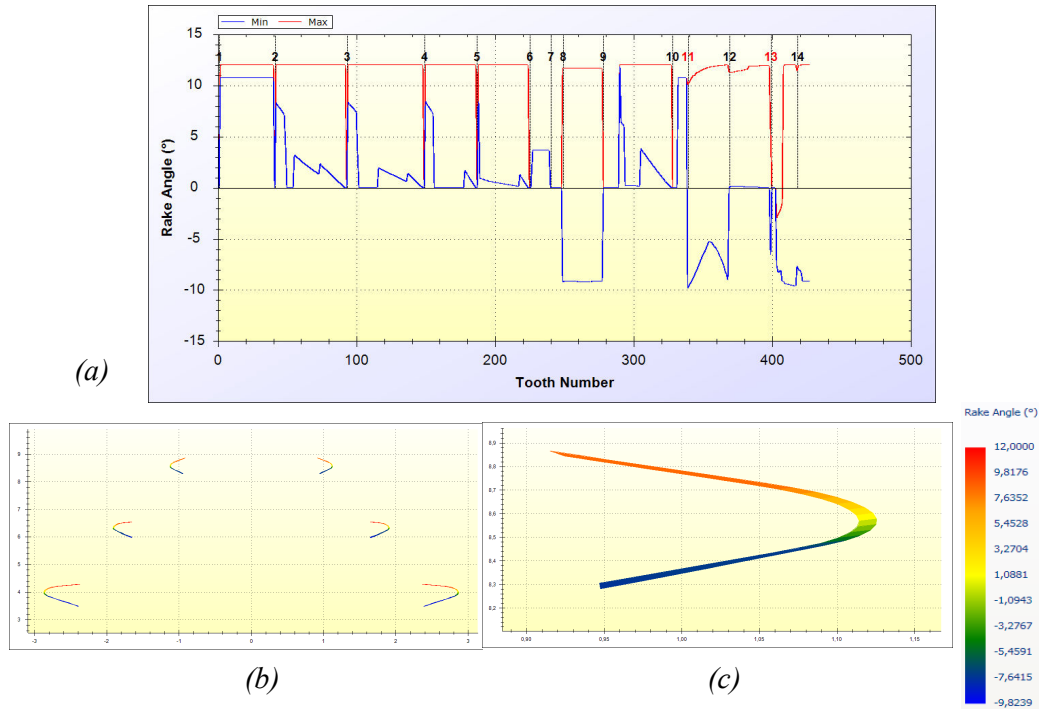


Figure 5; (a) The max and min rake angle distribution on the cutting edges of all teeth, (b) the rake angle distribution on the 6th tooth of the 8th detail, and (c) a closer look.

3.4 Other Outputs for Performance Analysis

In order to measure the performances of the details, two more outputs are proposed in this study. The first measure is the comparison of the detail length and the area that is removed by that detail. The results for the example case can be seen in Figure 7. The measure should be interpreted as the ratio of the cutting area over the detail length. This value should be high for high performance operations. However it should be noted that this performance measure is limited by the maximum load that the teeth can carry, which may eventually yield to tool breakage.

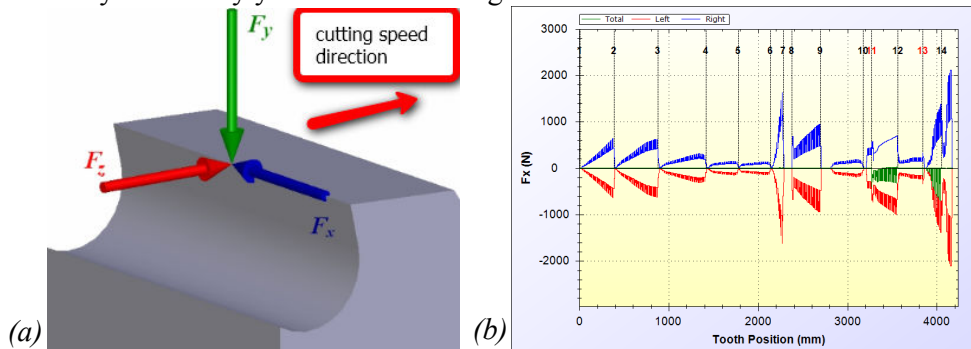


Figure 6: (a) The cutting force directions, and (b) the forces at the x direction.

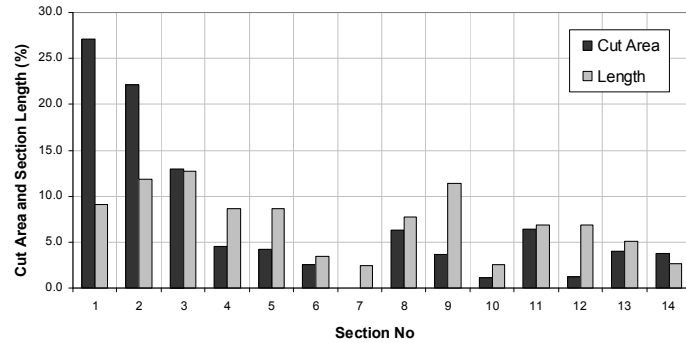


Figure 7: The comparison of the detail length and the area removed with that detail.

4 APPLICATION EXAMPLES

4.1 Optimization of compressor disk broaching process

The Connecticut Center for Advanced Technology team applied BOSS to the broaching of a compressor disk that is produced by a local company shown in Figure 8. The team first modelled the current process, generated 2D cutter profiles, applied material, tool, and process parameters, and identified areas of high force and stress. They then developed a design of experiments (DOE) process using Taguchi Method with 27 cases varying cutter parameters to attempt to achieve optimized tool geometry process parameters. The objective is to obtain acceptable surface finish and increase production rate through increasing cutting speed.

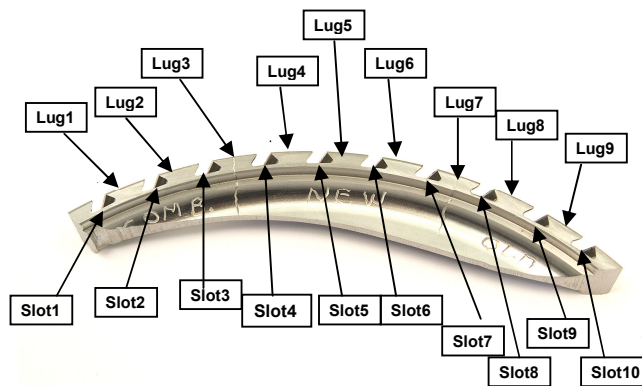


Figure 8: Disk section produced using different speeds and tool configurations.

Figure 9 presents the cutting forces for the current process used to broach the disks. BOSS identified the tool sections that are experiencing highest force and stress. High cutting force will result in deflection of the cutting edge. High radial force will

result in the opening of the slot, which will reduce chip thickness and lead to a higher chance of rubbing. The results obtained support the selections of tool configuration that can reduce the cutting forces and stresses.

The Taguchi analysis of the results obtained from the 27 test cases helped in identifying the optimum broach tool configuration and speed, which are listed in Table 1. The chosen process parameters predicted lower overall forces, stresses, and power consumption; shorter, less expensive tooling; longer tool life and better part quality. The team predicted a 15% reduction of the length of the broach set, 28% reduction in cycle time, 30% reduction in stress of the highest stressed insert, and expected increased dimensional accuracy. The new tool design also shows a reduction of stresses as illustrated in Figure 10.

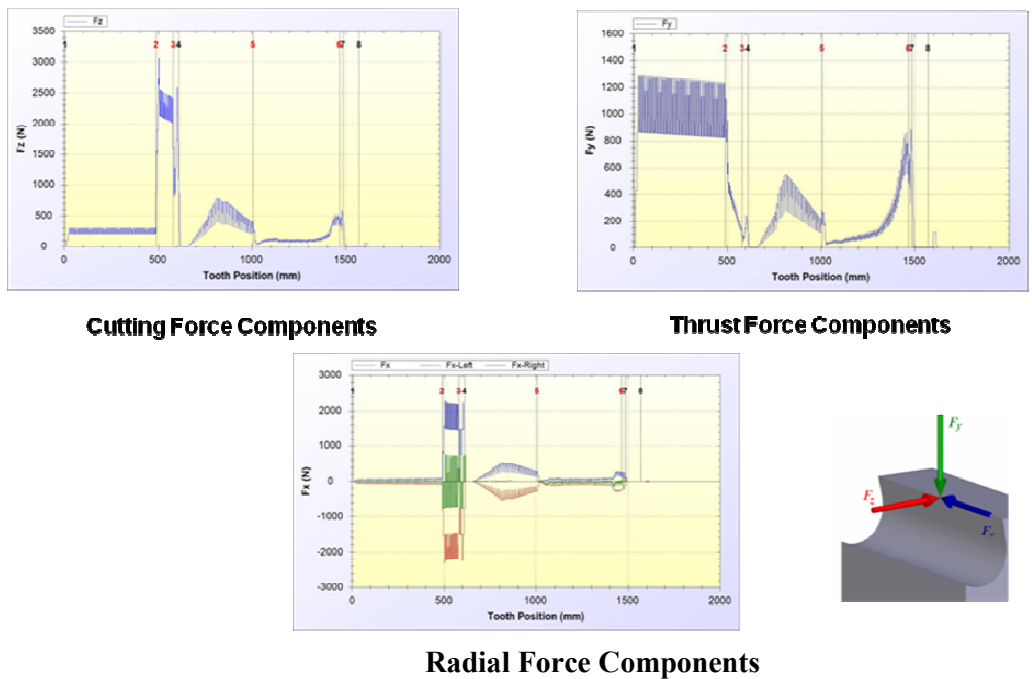


Figure 9: Sections 2 and 3 of the broach tool experience highest force values

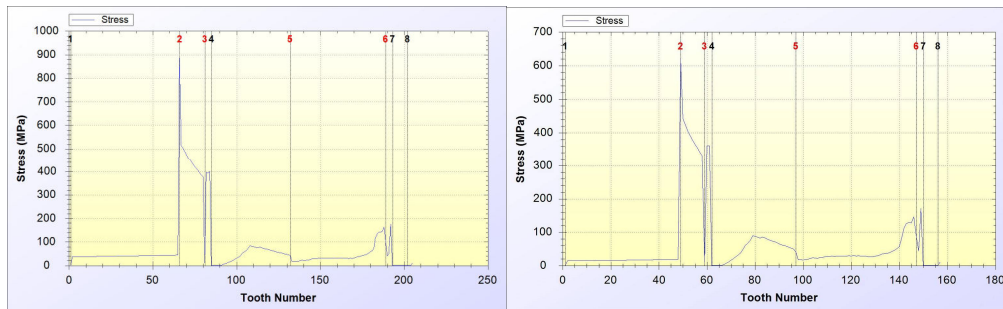


Figure 10: Stress distribution Sections 2 and 3 of the broach tool experience highest stress values, however it was 25% less than that predicted for current tool.

Current Tool (Speed 35-38 ft/min)

Section	1	2	2X	3	4	4X	5	5X
Number of teeth	65	15	4	47	57	4	9	4
Pitch	.313	.375	.375	.354	.315	.315	.375	.375
Tooth rise	0.0022	0.001	0.0005	0.0016	0.0014	0.0006	0.0008	0.0004
Tooth depth	0.094	0.065	0.065	0.125	0.102	0.102	0.13	.13
Rake Angle	15	15	15	22	22	22	22	22

New Tool (Speed 45 ft/min)

Section	1	2	2X	3	4	4X	5	5X
Number of teeth	48	10	3	35	50	3	6	2
Pitch	.3375	.375	.3375	.3375	.3375	.3375	.375	.375
Tooth rise	.003	.0016	.0008	.0022	.0016	.0008	.0012	.0008
Tooth depth	0.094	0.094	0.094	0.125	0.102	0.102	0.13	.13
Rake Angle	18	18	15	22	22	22	22	22

Table 1: List of current and modified tool sections, tooth rises, tooth depth, and pitch

After receiving approval for changes to the tool design, CCAT supported the manufacturing of a new set of broach tools to verify the results obtained by BOSS software. A series of test cuts using the current broaching process on a test piece of the compressor disk, as well as the new CCAT-BOSS analyzed process, and a combination of the current and new processes were performed. The three separate test cuts were prepared, as follows:

- “Comb” represents the new tool cutting at the maximum customer specified 38 SFM.
- “New” represents the new tool cutting at the CCAT recommended feed rate of 45 SFM.
- “Old,” or current process, represents current tool design cutting at 38 SFM.

Initial visual inspections conducted indicated that the "New" process design resulted in a superior surface finish and overall process result when compared to the current, or "Old" design.

4.2 Optimization of Firtree Shape Broach Design

As another application which is conducted at P&W Canada, a firtree shape broach tool has been optimized for an experimental purpose by using force simulation capability in the BOSS. Large force in Y direction for roughing tool causes rapid pre-mature tool wear due to large deflection. The force graph in Figure 11 shows Detail #1 as the most demanding detail, with its force exceeding the acceptable limit. Therefore, the design was changed to get a force under that limit (Figure 12).

Also, for the same tool, the overall length was reduced by 25% by modifying different parameters such as overlap and chip load. For the form finishing detail, the chip load was increased mainly to improve the cutting condition, which BOSS highlighted as an increase in forces (Figure 11, detail#12 versus Figure 12, detail#10).

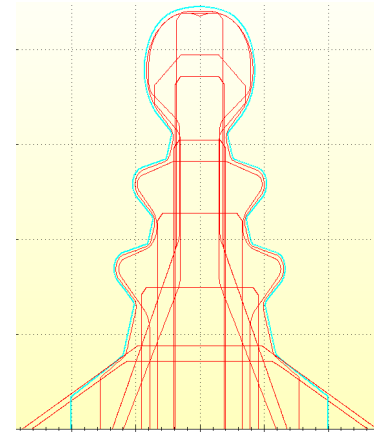
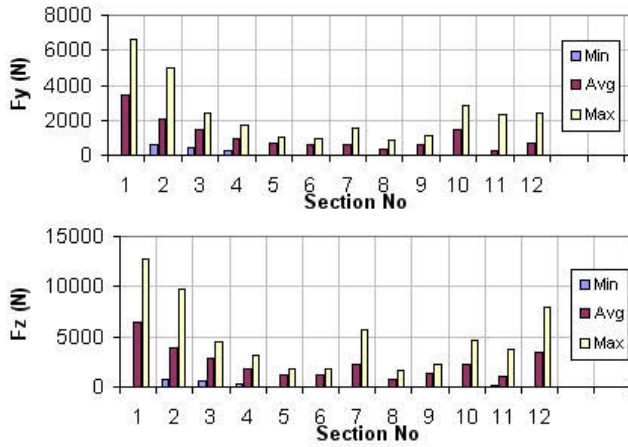


Figure 13 : Original tool.

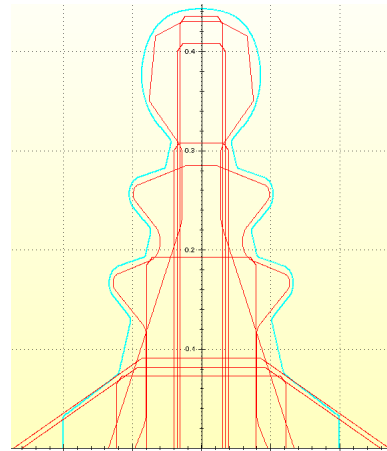
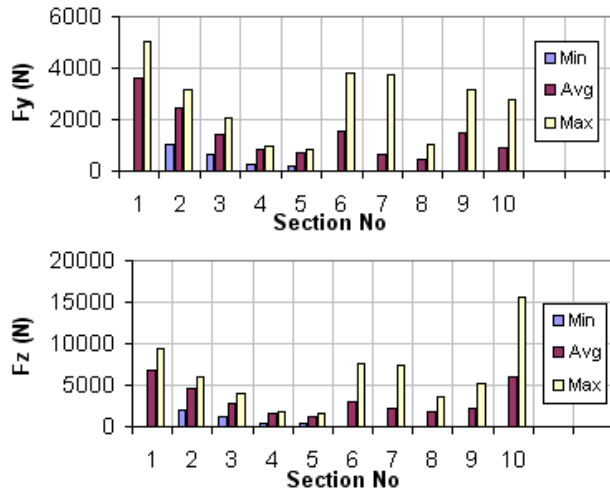


Figure 14: Optimized tool.

5 CONCLUSIONS

In this study, a simulation approach for broaching processes is presented. An analytical model is used in order to simulate the part geometry and the cutting process mechanics. Due to the analytical approach the solution times are very fast. The outputs of the model are the cutting forces and power acting on each tooth, the stress distributions among the details, the chip thickness and rake angle distributions and the workpiece evolution during the operation. This approach can be used to select the optimum cutting and detail parameters for the broaching processes. The developed model is integrated in a computer code in order to enable the applications in industry. Several industrial applications using the approach showed improvements which implies that the broaching simulations in virtual environment can be used to optimize the broaching processes.

REFERENCES

- [**Altintas, 2000**] Altintas, Y., "Manufacturing Automation", *Cambridge University Press*, 2000.
- [**Armarego et al., 1985**] Armarego, E.J.A. and Whitfield, R.C., 1985, "Computer based modeling of popular machining operations for force and power predictions". *Annals of the CIRP*, 34: 65-69)
- [**Axinte et al., 2003**] Axinte, A., Gindy, N., 2003, "Tool condition monitoring in broaching", *Wear*, 254, 370-382
- [**Axinte et al., 2005**] Axinte, A., Bound, F., Penny, J., Gindy, N., 2005, "Broaching of Ti-6-4 – Detecting of Workpiece Surface Anomalies on Dovetail Slots through Process Monitoring", *CIRP Annals - Manufacturing Technology*, 54:1, 87-90.
- [**Axinte, 2007**] Axinte, D.A., 2007, "An experimental analysis of damped coupled vibrations in broaching", *Int. J. of Mach. Tools and Manuf.*, 47:14, 2182-2188.
- [**Budak et al., 1996**] Budak, E., Altintas, Y. and Armarego, E.J.A., 1996, "Prediction of milling force coefficients from orthogonal cutting data." *Trans. ASME Journal of Manufacturing Science and Engineering*, 118, 216-224.
- [**Budak, 2001**] Budak, E., 2001, "Broaching Process Monitoring", *Proceedings of Third Int. Conf. on Metal Cutting and High Speed Machining*, Metz-France, 251-260.
- [**Kokmeyer, 1984**] Kokmeyer, E., 1984, "Better Broaching Operations", *Society of Manufacturing Engineers*.
- [**Kokturk et al., 2004**] Kokturk U., and Budak E., 2004, "Optimization of Broaching Tool Design," *CIRP ICME '04*, Sorrento, June-July 2004.
- [**Monday, 1960**] Monday, C., 1960, "Broaching", *The Machinery Publishing Co. Ltd.*
- [**Mo et al., 2005**] Mo, S.P., Axinte, D.A., Hyde, T.H., Gindy, N., 2005, "An example of selection of the cutting conditions in broaching of heat-resistant alloys based on cutting forces, surface roughness and tool wear", *J. Mat. Proc. Tech.*, 160:3, 382-389
- [**Ozturk et al., 2003**] Ozturk O., and Budak E., 2003, "Modelling of Broaching for Improved tool design," *Proc. of the IMECE'03 ASME*, Washington, D.C., November 16-21.
- [**Robert et al., 1986**] Robert, T.W., Cutright, K.W., 1986, "Computer aided design of a broaching process", *Computers & Industrial Engineering*, 11:1-4, 576-580.
- [**Sajeev et al., 2000**] Sajeev, V., Vijayaraghavan, L. and Rao, U.R.K., 2000, "Analysis of the Effects of Burnishing in Internal Broaching", *Int. J. of Mech. Eng. Edu.*, 28/2 :163-173.
- [**Sutherland et al., 1997**] Sutherland, J.W., Salisbury, E.J. and Hoge, F.W., 1997, "A Model For the Cutting Force System In the Gear Broaching Process", *Int. J. Mach. Tools Manufacture*, 37:1409-1421.
- [**Vijayaraghavan et al., 1981**] Vijayaraghavan, L., Krishnamurthy, R., Chandrasekaran, H., 1981, "Evaluation of stress and displacement of tool and workpiece on broaching", *Int. Journal of Machine Tool Design and Research*, 21:3-4, 263-270.