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Force Prediction Methodology for Complex Shape Broaching

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Abstract

Broaching is widely used for the manufacturing of complex geometries which requires high dimensional accuracy and surface finishing (e.g., fir tree, dovetail). A software development for force prediction in complex shape broaching is presented. The software automatically extracts the local uncut chip section along each tooth of the tool and based on the empirical specific cutting forces of the material the total force per tooth is calculated. The software was validated experimentally. For that purpose, fir trees of Inconel 718 were broached. Predicted forces showed an average relative error of 6% when compared to the experimental results.

Keywords: Broaching; Fir Tree, Modelling, Force, Inconel 718

1. Introduction

Broaching is a single-pass machining operation widely used in demanding sectors (e.g., automotive, and aeronautic) to manufacture critical components (e.g., crankshaft, fir tree, and dovetail), due to the good dimensional quality and surface integrity condition obtained [1].

Nevertheless, an increase of the Material Removal Rate (MRR) is required in order to reduce costs, without compromising the surface integrity of the piece. In broaching, there are no possibilities of modifying the cutting conditions (unless the cutting speed) after the tool is manufactured, so tool design is one of the main factors to improve MRR [2, 3]. Thus, Kokturk and Budak developed software based on an analytical model to optimize the broaching tool design and improve productivity [2]. Özelkan et al. proposed another mathematical formulation for the same aim by discretizing the initial complex optimization problem into smaller ones [3]. Özlü et al. analysed the suitability of the Broaching Operation Simulation Software (BOSS) for tool design [4]. Vogtel et al. also proposed an automatic broaching tool design methodology to reduce the tool length, based on the cutting forces [5].

Nonetheless, the rise in the MRR can lead to tool breakage or modification of the expected surface integrity. In fact, both are promoted by the high cutting forces of broaching, especially in aeronautic applications (fir tree and dovetail) due to the strength of the material being machined. Indeed, in previous research we demonstrated that force magnitude is directly related to surface topography irregularities [6].

To avoid these issues, other authors have used predictive models to obtain information about the thermomechanical loads obtained in the broaching tool and workpiece. Sutherland et al. made one of the first attempts to predict forces during the broaching of internal helical ring gear [7]. The analytical model was based on sub-models that describe the instantaneous area of contact (chip load). Kishawy et al. proposed an analytical energy-based methodology for simulating the cutting forces during the broaching operation in AISI 12L14, Al 7075 and AISI 1045 with reasonable agreement with the experimental results [8].

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Among the analytical works, Mandrile et al. developed the most complete work for nickel-based alloy broaching [9]. They created a software programmed in Matlab able to predict the forces per tooth while broaching Udimet 720. The steps followed by the program were: i) description of the roughing and finishing of the fir tree slot, ii) automatic generation of each broach tooth depending on the position of the first tooth and the rise per tooth, and iii) calculation of the forces. Nevertheless, the tool geometry was generated artificially without taking into account other geometrical changes of the tool, such as chip breakers.

Other few authors have focussed their effort in modelling the broaching process by the Finite Element Method (FEM) to predict the thermomechanical loads and reduce the number of experimental tests needed to be carried out. Some research works has focussed on fundamental outputs (forces, chip morphology and temperatures) [10, 11], while others have also attempted to predict surface integrity aspects (residual stresses and microstructural damage) [11]. Nevertheless, the calculation times and the economic costs spent characterising the input parameters are high [12]. Therefore, in an industrial environment where it is necessary to obtain fast results at the lowest possible cost, analytical modelling is often one of the best options.

To the best of our knowledge, no author has developed a software that incorporates a methodology that enables predicting the forces per tooth in a broaching operation once the tool geometry and workpiece are defined and imported in 3D Standard Triangle Language (STL) format. Undoubtedly, such a model could be used by industry to optimise their processes and tool design using data of real tools, and serve as an indicator during production of possible tool wear and even deterioration of surface integrity if set threshold values are exceeded.

Therefore, the paper presents a software development for the prediction of the forces when manufacturing any complex shape geometry (fir trees, dovetails, etc.) in Inconel 718. Starting from a 3D tool geometry, the software extracts the information of the chip load and based on an empirical database predicts the force per tooth. The information obtained in the software is presented in a user-friendly program that provides the operator with the predicted cutting force values. The program would be able to inform the machine operator of any malfunctions during the broaching process and warns of the risk of tool breakage or excessive surface topography irregularities.

2. Methodology

The methodology section is divided into two parts. First, the methodology/software to calculate the forces is presented. The software requires the design of a database of specific forces which is detailed in the second part of the section.

2.1. Force prediction methodology

The cutting forces of the broaching process are predicted in the presented methodology implemented in a software (developed in Matlab) by inputting a few machining conditions and importing the initial 3D geometry of the broaching tool and workpiece. Operation of the software is as follows:

1. Input the tool and the workpiece in STL format, which is widely used by Computer-Aided Design (CAD) software.
2. In addition to the 3D geometry some necessary input parameters must be included: cutting speed, rake angle, workpiece inclination angle, workpiece and tool materials, lubricant, tool wear, coating of the tool, pitch, number of tooth and the location of the first tooth. Most of them are used to select the specific cutting forces from the empirical database, already developed for the present research (presented in subsection 2.2), while the rest are used to facilitate the calculation of the forces (number of tooth, location of the first tooth and workpiece inclination angle).
3. The geometry of each tooth is extracted based on the algorithm triangle/triangle intersection test routine [13].
4. The uncut chip section, also named as chip load, is calculated for each tooth (ΔS_j), by adding each local uncut chip sections (dS_i) (see Fig. 1).

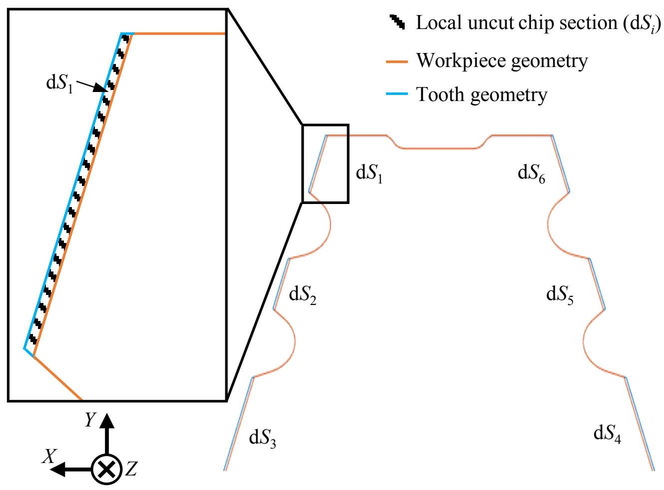

Fig. 1. Example of the uncut chip section (chip load) of a fir tree cross section.

5. The total force per tooth is calculated based on the specific cutting coefficients previously compiled in an experimental database taking also into account the information included in step 2. In the cases where an experimental test is not carried out, interpolation and extrapolation methods are used to obtain the necessary values. Eq. 1 and 2 are used to calculate the total forces at each instant, considering whether more than one tooth is machined at a time. n is the number of cutting edges in contact in each tooth (Fig. 1 shows an example with six cutting edges), l is the last tooth in contact with the workpiece at a certain moment, p_l is the number of teeth in contact simultaneously (considering the workpiece thickness and tool pitch), j is the tooth number, K_s is the specific cutting force, dS_{ij} is the chip load of all the teeth cutting simultaneously, S_j is the chip load of a j tooth, and ΔS_j is the difference of chip load between certain tooth (S_j) and the previous one (S_{j-1}).

$$F_c = \sum_{j=l-p_l}^{l} \sum_{i}^{n} K_s \, dS_{ij} \tag{1}$$

$$\sum_{i}^{n} dS_{ij} = \Delta S_j = S_j - S_{j-1} \tag{2}$$

6. The calculated forces are plotted in the user graphical interface of the software. The complete process followed by the algorithm to obtain the forces is set in Fig. 2.

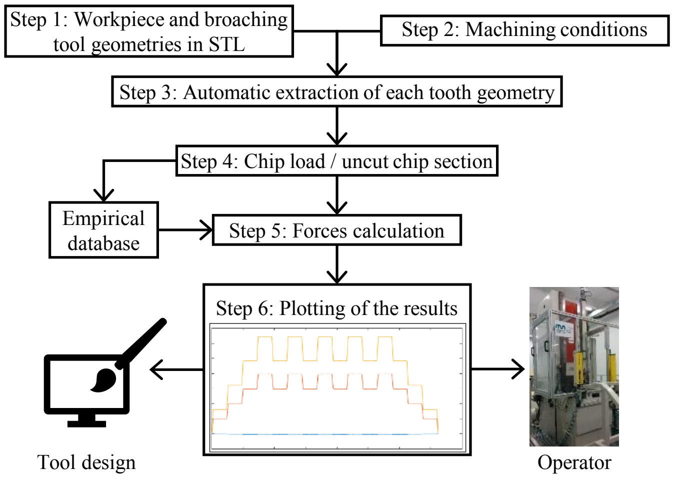

Fig. 2. Flow chart of the predictive model of forces in broaching.

The software also provides the maximum force value and the tooth number where it is reached. Therefore, the software would be able to provide the option of setting some limits to the predicted forces that represent the critical wear level of the tool, since as observed by many researchers in the literature, wear produces an increase in forces during the broaching process [14–16], which can affect the surface integrity of the component [6]. Thus, if the limits set by the operator are reached during the process, the software would be able to warn of the need to change the tool.

Hence, the software not only serves as an assistant in the technical offices for the design of new tools, but can also be implemented in the CNC of the broaching machines (or on an external device linked to the machine) and warn the operator in case of exceeding a set force threshold (see Fig. 2). The force threshold can be obtained through experimental tests [17] or using models that consider the progressive wear [18-19].

Fig. 3 shows the user graphical interface of the software. The figure shows the four main areas of interaction between the user and the software.

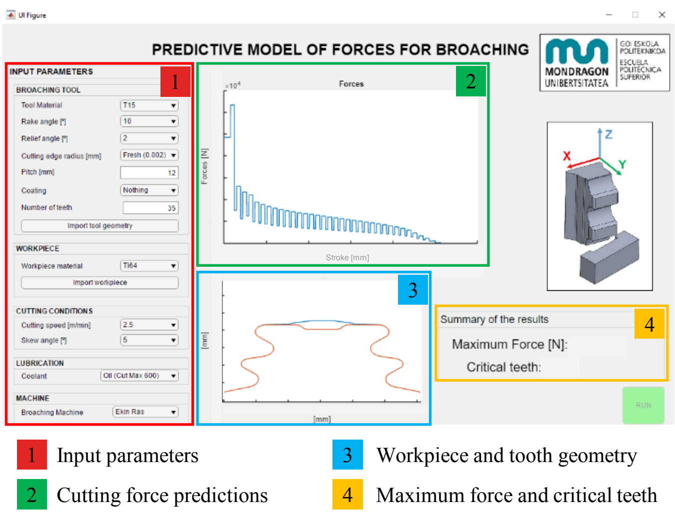

Fig. 3. User graphical interface of the software.

2.2. Experimental database design

Experimental tests were undertaken to obtain the specific cutting forces for different machining conditions. The broaching tests were carried out in an EKIN RAS 10x160x320 hydraulic broaching machine with a Kistler 9255B dynamometer to measure forces in the three directions. The complete experimental setup is presented in Fig. 4. A sample rate of 5000 Hz and a 300 Hz low-pass cut-off filter was employed. The software LabView was used to capture the forces and an algorithm in Matlab to filter them. To complete the setup, a LVDT sensor was used to measure the cutting speed of the tool.

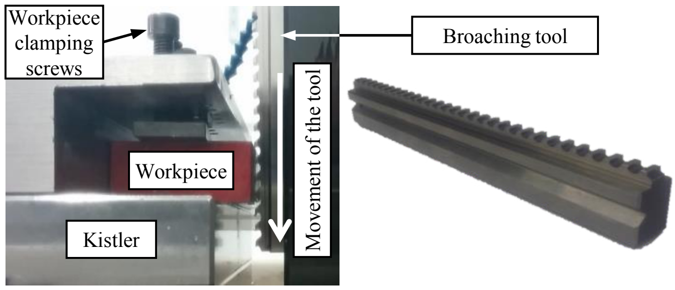

Fig. 4. Experimental setup for the experimental database development.

The workpiece material was forged Inconel 718 with aging treatment (45 HRC). The workpieces were rectangular blocks of 35 mm thickness, which means that 3-4 teeth were in contact at the same time.

Rectangular broaching tools of 10 mm width were used to obtain the cutting forces and then the specific cutting forces. A wide range of machining conditions were tested to analyse the influence of each parameter on the machining forces. It was modified the tool parameters (material, rake angle, rise per tooth, coating, cutting edge radius and flank tool wear) and the machining conditions (lubrication, cutting speed and skew angle). The summary of the experimental input parameters is shown in Table 1. Hence, 72 broaching tools were manufactured taking into account the material and geometrical variations of the tool.

Table 1. Broaching experimental plan.

Broaching tool geometry	
Broaching tool material	M35 and T15
Rake angle, γ (º)	10, 15 and 20
Relief angle, α (º)	2
Rise per tooth, f (mm)	0.015, 0.05 and 0.1
Pitch (mm)	10
Width, b (mm)	10
Cutting edge radius, r_β (µm)	6 (new) and 10 (worn)
Flank tool wear, V_b (mm)	0 (new) and 0.1 (worn)
Coating	TiN and nothing
Machining conditions	
Lubrication	Dry and wet (cutting oil Cut Max 600)
Cutting speed, v_c (m/min)	2.5, 5 and 7.5
Skew angle (º)	0 and 5

A control of the tool geometry (cutting edge, rake and relief angles) was carried out in the optical profilometer Alicona IFG4. The setup included a polarized lens of 10x with a ring light to improve the quality of the captured profiles. The vertical resolution used was of 200 nm and lateral 2 µm. The results showed an average cutting-edge radius of 6±2 µm for new tools. In addition, the flank face of some of the broaching tools was ground to simulate a 0.1 mm flank tool wear. In these cases, the cutting edge radius increased to 10±3 µm. In all cases, the rake and relief angle matched the nominal values supplied by the tool manufacturer with a deviation of less than 0.5º.

Two broaching tool materials were employed: M35 and T15. To analyse the influence of the TiN coating, half of the tools were coated, and the other half were left uncoated. Furthermore, the machining conditions were also modified by using two skew angles (0º and 5º), three cutting speeds (2.5, 5 and 7.5 m/min), and two lubrications (oiled and dry).

Three tests were carried out in each condition in order to ensure a reliable value. In total 2,592 experimental tests were done to complete the database.

The cutting force results obtained from each test were treated to obtain the specific cutting forces. Firstly, the Cross talk stablished by the Kistler Dynamometers manual was applied. It is used to determine the influence of each axis on other axes. Then, the relative angle between the workpiece and the tool was corrected (only in the tests with 5º of skew angle). The signal reconditioned was as shown in Fig. 5. The forces measured at the entrance and exit of broach were then discarded. Finally, the specific forces (K_s) were obtained by using eq. 3. F_c is the cutting force of each tooth, ΔS_j is the chip load of each tooth, f is the rise per tooth and b is the tool width.

$$K_s = \frac{F_c}{\Delta S_j} = \frac{F_c}{f \cdot b} \tag{3}$$

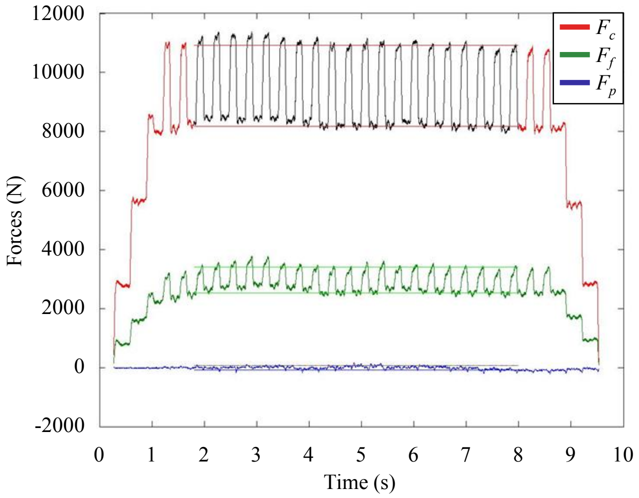

Fig. 5. Example of cutting force measurement.

A database of specific cutting forces was obtained from the experimental broaching tests, taking into account rise per tooth, tool material, rake angle, cutting edge radius, flank tool wear, coating, lubrication, cutting speed, and skew angle.

3. Experimental validation

After the software was developed, and the experimental database was compiled, experimental validation was done so as to ensure the reliability of the predicted forces. The machine used to perform the test was the same as the one used to create the database. A fir tree broaching tool was selected to carry out the validation test (see Fig. 6).

The broaching tool was part of a set of tools, so the initial geometry of the workpiece was previously machined with another tool (see Fig. 6). In order to obtain results applicable in an industrial context, the workpiece material selected was the same forged Inconel 718 with aging treatment as the one used to develop the experimental database. The test was done with fresh tools lubricated with oil, with a cutting speed of 5 m/min and a skew angle of 5º. The workpiece thickness and the tool pitch make 1 and 2 teeth to be in contact simultaneously. The acquisition system used for the validation test was the same as that used for the database generation tests.

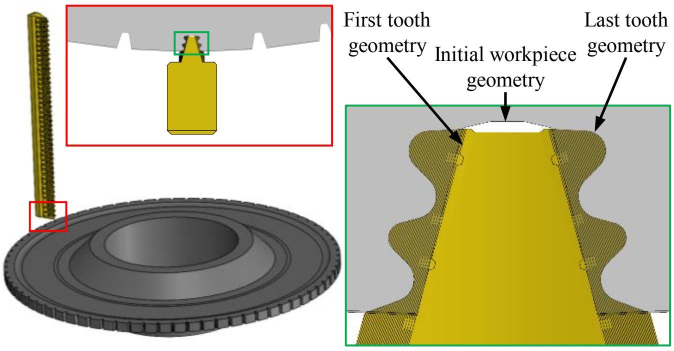

Fig. 6. Experimental setup of the experimental validation of the software.

4. Results and discussion

The software provides the geometry of the initial workpiece as well as of each individual tooth. The uncut chip section from each tooth obtained from the software were compared to the ones obtained manually from the design software AutoCad, and the differences were of less than 6% (see Fig. 7).

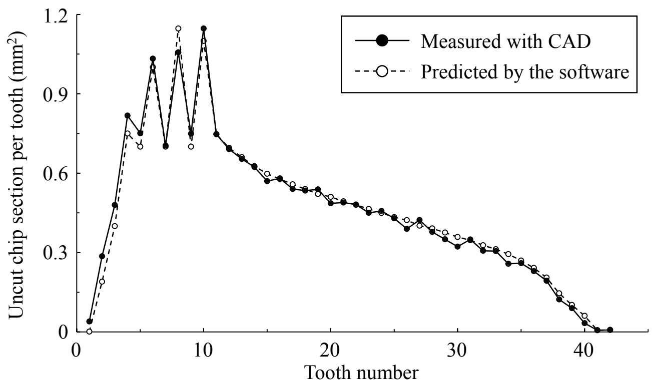

Fig. 7. Measured and predicted uncut chip section per tooth.

Fig. 8 shows the difference between the predicted forces and the measured ones. It should be noted that the value of the tooth number shown on the X-axis is the last tooth to enter in contact with the workpiece, and the force shown is the sum of the forces of all the teeth that are in contact simultaneously. That

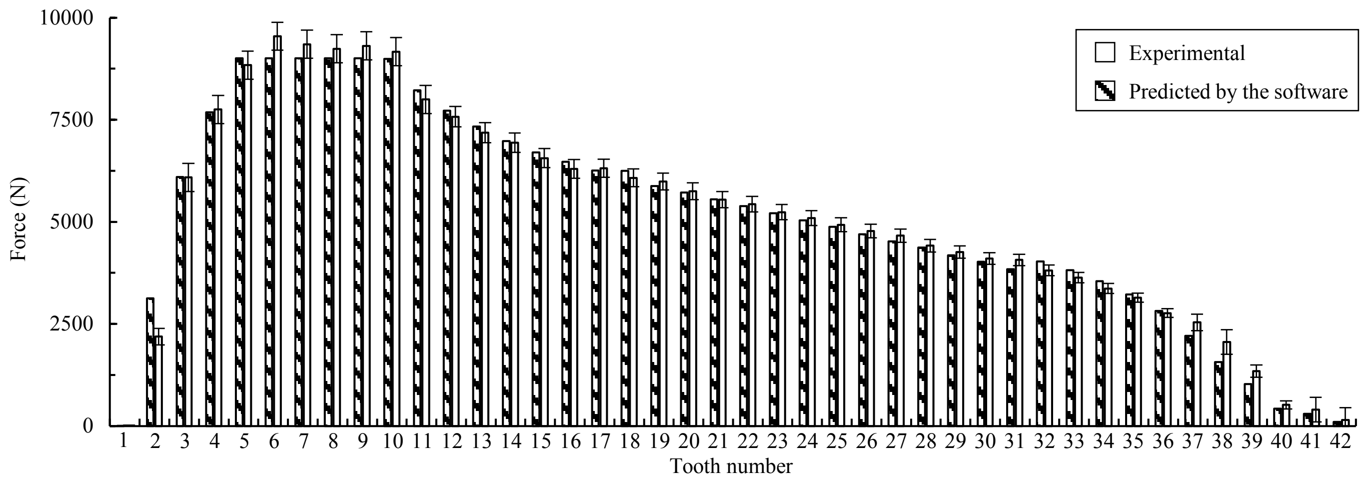

Fig. 8. Predicted and experimental cutting forces.

is, when the X axis indicates that the tooth is 10, this means that the force shown is the sum of the force of tooth 9 and 10. This is the force that would be obtained experimentally, as the thickness of the piece is taken into account in the calculation.

As can be seen in Fig. 8, the software showed a high degree of accuracy, with an average relative error of 6% considering all the teeth. Without considering the entrance and the exit of the tool, where due to the low forces a deviation of a few Newtons results in a very high relative error, the average relative error is only 5%. Additionally, the uncertainty in the most critical teeth (5-10), where the highest forces are reached, the average relative error was even lower (3%).

The reason why experimental and predicted values at the entrance are closer to zero may reside in the similarity between the initial geometry of the piece and the tool (see Fig. 6). In consequence, the first tooth does not make contact with the piece. Moreover, the last two teeth did not machine the piece as a result of the negligible uncut chip area of those teeth, which is less than 0.01 mm^2 per tooth (see Fig. 7).

The differences between the predicted and the measured forces in the last section of the tool may be explained by the selection of the specific forces from the database. The uncut chip thickness in the teeth in this section is lower than the minimum rise per tooth of the tools used for database experimental tests (0.015 mm). For this reason, an extrapolation was done to obtain the values. Although the results are not as accurate as in other regions of the tool, the average error is within acceptable value (below 20% in the last 6 teeth), which in force value is equivalent to a prediction error of less than 300 N.

5. Summary and conclusions

This paper presents a methodology implemented in a software to predict the cutting forces during the broaching process of real features for Inconel 718. The software predicts the force per tooth and would be able to warn the operator if unexpected force values are reached due to wear or other unforeseen circumstance that could put at risk the tool breakage and thus the surface integrity of the component.

In addition, the software provides in depth information of cutting forces and uncut chip area, as well as the location of the most critical tooth. This could provide helpful inputs to the design process of broaching tools.

To obtain the most reliable results, an extensive database of specific cutting forces was created with 2,592 tests.

The model was validated by the realisation of an experimental fir tree broaching test in Inconel 718. The uncut chip section results showed good agreement, with an average relative error of 6%. Concerning the predictions of the forces, the average relative error was also of only 6%. These are very low errors, which in turn indicate that the experimental database is large enough to be able to correctly predict any of the tooth geometries analysed in this validation study and can certainly be applied to many other complex tool geometries.

The same analysis could be carried out for other workpiece materials by only updating the experimental database with the necessary specific cutting forces. It could also be extended to other workpiece or tool geometry, using as workpiece material Inconel 718, but in this case no modification of the software or database would be necessary, as the program can automatically analyse any tool/workpiece geometry imported in STL format.

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