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Automatic Broaching Tool Design by Technological and Geometrical Optimization

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Abstract

The paper presents an approach for automatic broaching tool design for a user-defined complex-shaped slot. A systematic method was developed to generate a cutting strategy for the broach. A set of technological constraints such as maximum allowed cutting force per tooth or maximum allowed rise per tooth are considered. Thereby, an optimization based on the cutting forces is carried out.

Aim of the automatic, technological and geometrical based broaching tool design is to reduce the total length of the broaching tool. Hence, manufacturing cost of the tool itself is reduced as well as manufacturing time of each slot and thereby, production costs of the slots are optimized.

1. Introduction

Broaching is a widely used machining operation for the production of complicated profiles in the automotive or aerospace industry. The advantages of broaching are the machining of complex slot geometries within a single stroke. Thereby, high production rates, component accuracies and surface qualities can be achieved. However, because of the process principle, it is necessary to design a special broaching tool for each slot geometry. The tool design includes the cutting strategy and the determination of the rise per tooth as a part of the tool geometry. Both together have a high impact on the number of teeth and thereby the total length of the broaching tool needed to machine specific slot geometry. Furthermore, a number of constraints, such as the maximal allowable load on a single cutting edge or the total load on the tool, must be considered during the design phase. Therefore, the design process of broaching tools is very complex and time consuming and it directly affects the tooling costs and productivity. The whole procedure bears an optimization potential which is subject of this paper. This paper presents an algorithm for automatic broach tool design for any given arbitrary slot profile with the aim of optimal cutting force distribution and thereby to increase efficiency by a reduced tool length. The developed algorithms utilize the maximum rise per tooth allowed by the given constraints in each detail so that the number of teeth required in each detail is minimized.

2. Principles of Broaching

1.1. Broach tool geometry

A broach tool consists of multiple teeth each being separated by the thickness of one chip which causes the removal of material. The height difference between the teeth is called rise per tooth and represents the undeformed chip thickness h, Fig.1. Common tools use a constant rise per tooth within each detail. In contrast to other machining processes thereby the undeformed chip thickness is an integral part of the tool geometry. Depending on the work piece material, the cutting speed, the tooth width and the undeformed chip thickness...
thickness the mechanical load on each tooth can be calculated. The distance between two teeth is called pitch \( t \), Fig. 1. The height of the component and the pitch influences the number of teeth which are simultaneously cutting. This relationship results in the total load that has an effect on the tool performance.

Fig. 1. Profile of a tooth of a broach tool

Beside the rise per tooth, also the cutting direction is fixed by the tool geometry. The different cutting methods are defined in DIN 1415-1 [1] and are illustrated in Fig. 2. The different types of cutting direction are referred to as stepping (Fig. 2 a). If the teeth of a detail only cut on top it is called depth stepping. A second and third option is that the teeth cut on both sides, which is called lateral stepping (Fig. 2 b) or wedge stepping (Fig. 2 c) if the teeth are perpendicular or inclined, respectively. The methods can be applied for external and internal broaching operations. Fig. 2 d and e shows examples for depth stepping of the cutting teeth of an inner square broach and inner spline broach.

A drawing summarizing all cross sections details of a broach is called cut chart. The different broach details utilize different cutting methods. Fig. 3 represents one simple cut chart of a spline profile as it is used in turbines disc.

The roughing details utilize depth stepping in order to achieve high material removal rates (Details #1 to #5 in Fig. 3). The semi-finishing details utilize wedge stepping with different angles \( \alpha \) for each side flank of the profile (Detail #6 in Fig. 3). The teeth of the finishing detail have the shape of the final profile. They cut on the full length with a small tooth rise in order to achieve a high workpiece accuracy and surface quality. The shape of each detail depends on the slot geometry.

2. Technological Approach to Broach Tool Design

2.1. Systematic procedure for broaching tool design

The traditional procedure of broach tool design is done by a design engineer. Thereby he follows a construction methodology as shown in Fig. 4 [3]. The broach tool designer has to consider several parameters relating to the workpiece, the utilized materials and the constraints of the machine. The single steps of this design methodology and the interrelation between the process parameters and the constraints of the machine are illustrated in Fig. 4. In a first step, the material removal for the given profile shape has to be calculated, and a cutting plan is determined based on the engineering standards and on the expertise of the designer [1, 2]. In a second step, the cutting material is chosen. Depending on the cutting material, the cutting speed is determined. Beside the cutting material, the applicable cutting speed depends on the performance of the broaching machine. In the next step the tool geometry parameters pitch, rake and clearance angle are selected from standardized tables. In order to ensure the feasibility of the broaching process it must be proved that the total tool length and the process forces caused by the broach meet the constraints of the broaching machine.

![Fig. 2. Different methods of cutting for a broach tool [1]](image)

![Fig. 3. Cut chart for a spline profile](image)

![Fig. 4. Broach tool construction methodology [3]](image)
The outcome of this design process is highly dependent on the expertise of the tool designer and supportive standardized table out of norms such as DIN1416. This circumstance leads to the motivation of developing mathematical models and algorithms which can be implemented in computer software and support the optimal tool design.

Lauffer [3] developed a computer-aided methodology for the broach tool design process. For a user-given rise per tooth, the software optimizes the cutting speed according to the desired tool wear and surface quality. Hosseini [5] presented a simulation method of the broaching process utilizing an energy based force model. He also developed an optimization procedure for the tooth profile geometry by simulating the tooth as a cantilevered beam subjected to a distributed load. In the patent application publication US2009/0287458 [6], El-Wardany et al. present a broach tool design methodology which uses reverse engineering and FEM simulation for a solid model of a broach tool in order to adjust the broach tool design regarding component requirement such as accuracy or surface integrity values. Budak et al. [4] developed simulation software for broaching operations which can simulate the cutting forces, the maximum stress and other process data for a given tool design. Furthermore, the model is capable of finding the optimal process parameters which then can be used to generate a new tool design. Özelkan et al. [7] used a non-linear optimization approach for the identification of the broach parameters. The pitch and the tooth rise are subjected to the multi-start complex method in order to obtain the optimum values.

However, none of the existing models is capable to calculate a cut chart based on given constraints.

2.2. Technological constraints

As discussed above, there are several technological and geometrical constraints mainly concerning the machine which have to be considered while designing a broach tool.

The constraints provide a minimum and a maximum value for the variable parameters of each detail:

1. Minimum and Maximum rise per tooth: \( h_{\text{min}}, h_{\text{max}} \)
   The limits for the tooth rise are empirically determined by cutting tests to ensure best machinability.

2. Minimum and Maximum detail-length: \( l_{\text{min}}, l_{\text{max}} \)
   The detail length limits are set to ensure the compatibility of the broaching tool with the broaching machine and enable an acceptable handling for the worker.

3. Maximum cutting force per tooth: \( F_{c,\text{max}} \)
   This limit prevents that the maximum allowed load for single cutting teeth will be exceeded and thus possible tooth breakage is avoided.

4. Maximum cutting force of the process: \( F_{c,p,\text{max}} \)
   This limit is set in order to prevent the maximum allowed drag force of the machine to be exceeded.

The constraints are limiting the parameters tooth rise \( h \) and detail length \( l \) which are subject to optimization.

2.3. Cutting force calculation

In order to determine the cutting force, the standard force model introduced by Kienzle is used. [8] It calculates the cutting force according to equation 1 whereas the specific force \( k_{c,1,1} \) and the slope value \( m \) are empirically derived material dependent constant values:

\[
F_c = k_c h^{1-m} : k_{c,1,1}
\]  

However, the force model can be generally described as a function with two variables: the cutting width \( b \) and the undeformed chip thickness \( h \). In order to calculate the cutting width \( b \) and the chip thickness \( h \), the force function must be algebraically dissolved for each variable. In equations 4 the general description of the force model is given.

\[
F_c = K_f(b, h)
\]

\[
b = K_x(F_c, h)
\]

\[
h = K_y(F_c, b)
\]

There are several alternatives to the standard force model of Kienzle, e.g. the multivariate regression force model as described in [2] which also takes the cutting speed \( v_c \) and the rake angle \( \gamma \) into account.

To calculate the total cutting force acting in the process the maximum number of teeth \( z_{\text{max}} \) which are simultaneously cutting must be known. It depends on the pitch \( t \) and the component height \( h_k \) and can be calculated as following:

\[
z_{\text{max}} = \left\lceil \frac{h_k}{t} \right\rceil + 1
\]

The number of simultaneously cutting teeth determines the total cutting force of the process at any given time. The total cutting force \( F_{c,\text{total}} \) is then the sum of all cutting forces \( F_{c,j} \) simultaneously cutting, starting with a given tooth \( j \).

\[
F_{c,\text{total}} = \sum_{j=1}^{z_{\text{max}}} F_{c,j}
\]

2.4. Categorization of the broach details

The process of an automatic computer aided broach tool design requires a geometrical categorization of the different types of broach details which are distinguished by the different cross-section geometries of the slots. In the case of fir tree profiles, the first details of a broach have the purpose of roughly machining a basic slot, which is then enlarged with more complex shaped details until the desired profile slot is complete. Therefore, the first details contain flat tooth edges which only cut on top so they are referred to as topcut-details and they can be categorized into three basic types based on their cross-section shapes. The second section of a broach tool consists of details which machine the sides of the slot, so they
cut symmetrically in two opposite directions. The angle for the cutting direction is determined for each side flanks in order to uniformly load the cutting edges. These details are called sidecut-details. Finally, the last section of a broach tool consists of the finishing detail which has the same profile as the slot and completes the profile slot. The presented categorization is illustrated in Fig. 5.

Fig. 5. Categorization of the broach details.

2.5. Automatic Broach Tool Design Algorithm

In order to simplify computation by gaining advantage of the symmetry of the slot profile the B-Spline curve is placed in the coordinate system in such a way that the peak point of the curve lays on the y-Axis and the bottom point of the curve lays on the x-Axis (as depicted in Fig. 6). The first step of the algorithm is to compute an offset-spline with the user-defined finishing offset. After that, the characteristic points of the offset-spline are determined. These are the peak points of each neck of the curve and are illustrated in Fig 6 as $b_{10}$ and $b_{11}$. The characteristic points of the spline are crucial for the algorithm as they constrain the tooth-width of the topcut-details.

The topcut-details were determined from bottom up, that mans in the order in which they are actually cutting the workpiece. Figure 7 illustrates the overall computation process for the topcut-details in which a backtracking algorithm is embedded. First of all constraints describe in chapter 2.2 need to be define, such as values for the offset-spline, limits for the cutting force ($F_{c,max}$), minimum and maximum undeformed chip thickness ($h_{min}$ and $h_{max}$), etc..

For fir tree profiles it is common that the first topcut-details has the highest width of cut and thereby causes the highest cutting forces. Therefor the maximal allowable width of cut $b_{D1,max}$ for the first detail must be calculated by the given force equation $K_b$ (4):

$$b_{D1,max} = K_b(F_{c2,max}, h_{min})$$  (4)

In the case that the calculated rise per tooth $h_{D1,max}$ is higher than the maximum allowed rise per tooth $h_{max}, h_{D1,max}$ is set equal to $h_{max}$. Thus, always the highest possible rise per tooth is utilized in each detail without violating the cutting force constraint. Next the the maximum cross-section height $h_{A1,max}$ of the detail is calculated. Therefore, the maximum number of teeth per detail needed is given by the ratio of the maximum detail length $l_{max}$ to the pitch $t$:

$$z_{D,max} = \left\lfloor \frac{l_{max}}{t} \right\rfloor$$  (6)

Considering the identified maximum rise per tooth $h_{D1,max}$ and the maximum number of teeth $z_{D,max}$, the maximum cross-section height $h_{A1,max}$ can be calculated:

$$h_{A1,max} = h_{D1,max} \times z_{D,max}$$  (7)

Starting and ending point of the details are controlled by the peak points and the total height of the profile $h_{so}$. Fig. 8. By a distinction of cases it is decided if a rectangle, a trapezoid or a round detail should be used. If the cross-section height is limited by the next peak point $b_{10}$ or, in the case that the last peak point has been passed, by the total height $h_{so}$, the cross-section height must be adopted. This is done by decreasing the number of teeth and leads to a reduction of the detail length. If thereby the detail length falls below the

Fig. 6. Characteristic points of the offset curve.

Fig. 7. Flow chart of the algorithm for the determination of the topcut-details.

The minimum width of cut needed for the first detail is given by the by the point $b_{so}$. That allows in a second step to check if $b_{D1,max}$ is sufficient for the given profile geometry. If the width $h_{D1,max}$ is sufficient the point $b_{so}$ is set as initiating starting point $P_{start}$ for the backtracking algorithm and the algorithm starts. Sequential the maximum rise per tooth $h_{D1,max}$ of the first detail is calculated by the given force equation $K_b$ (5) using the maximum allowable cutting force per tooth $F_{c,x,max}$ and the width of cut $b_{D1,max}$:

$$h_{D1,max} = K_b(F_{c,x,max}, h_{D1,max})$$  (5)
minimal allowed detail length it becomes necessary to change the previous detail. In this case the backtracking algorithm is activated and changes the previous detail until the algorithm can proceed. This way it is ensured that maximal possible values for the rise per tooth are used for each detail and thereby the total tool length is hold as short as possible.

3. Software Implementation for Automatic Cut Chart

3.1. User Input

In order to implement the presented broach tool design algorithm the programming language Java was used. The software has a graphical user interface which is capable of displaying the automatically generated cut chart and the calculated cutting forces.

The user has to provide several inputs which can be categorized as following:

1. Component: First of all the profile geometry is needed and must be provided via a DXF-File which can be generated in any current CAD application. Furthermore, the height of the component must be defined. Finally, the workpiece material needs to be chosen.

2. Tool: The desired offset for the finishing details needs to be set. The tool grade must be chosen as well as the micro and macro geometry of cutting edge, with all its parameters as depicted in Fig. 1 must be defined. Finally, the limits for the rise per tooth, the tool length and the maximum allowable cutting force per tooth must be defined.

3. Broaching machine: In this section, the limit for the maximum total cutting force and the cutting speed are set.

4. Force model: The force model to use has to be selected. The constants that are needed for the force model must be specific cutting force parameters must be entered.

3.2. User Interface

The graphical interface of the software is divided into five different views from which three can be displayed simultaneously whereas the other two can be accessed via buttons. The general overview of the user interface is shown in Fig. 9.

In view 1, the automatically generated cut chart is displayed. This view features different measurement tools and display options like the display of the cutting edges which enable the user the further analysis of the cut chart. View 2 contains the user input which is divided into different tab folders for each input section as described above. The cutting forces are displayed in view 3. A detailed view of the cutting force display is shown in Fig. 11. View 4 contains the detail-table, which is besides the cut chart and the cutting forces the most valuable output of the model. The detail-table has the listing of the most important parameters rise per tooth, number of teeth, maximum cutting force per tooth, detail length and gullet space. An exemplary detail-table is shown in Fig. 12. View number 5 shows the solution-table which enables the management of different solutions for different input values. The user can change any input value, e.g. the force constraints, and obtain a new solution. The solutions can be saved and restored.

4. Validation

Using a broach tool which is utilized in industry, the results of the software are validated. The same slot profile has been used and the gullet geometry as well as the constraints for the rise per tooth and for the cutting forces has been adopted from the existing broaching tool. A comparison between the automatically generated and existing cut chart was conducted. The comparison shows that the automatically generated cut chart has the same number of details and the same cross section shapes. The cutting forces of the software generated tool design never exceed the user given limit and the tooth rise in each detail has always the maximum possible value. Thus the tool has the optimal material removal rate.
The cutting forces calculated for the cut chart are plotted in Fig. 11. They do not break the previous set limits and show no undesired force peaks or fluctuations.

All geometrical parameters entered into the program or calculated by the algorithms are summarized in a table and can be exported as a spread sheet which in turn can be imported by a parameterized solid model. The results of the calculated parameter are shown in Fig. 12. For each different detail type described in chapter 2.4, a parametric CAD model was designed. The geometry parameters available in the program serve as input for a parametric CAD model. For example the 3D model of detail #5 is shown in Fig. 13, which has a trapezoid shaped cross-section. This solid model can then be used for manufacturing of the broach or for further analysis utilizing FEM.

5. Conclusion and Future Work

In this paper, a computer algorithm for automatic broach tool design is presented which takes a user defined slot profile as a B-Spline and various technological constraints and produces a tool design with the maximum possible rise per tooth in each detail without exceeding the cutting force limits and thus achieves good optimization.

At its current state, the algorithm utilizes a user defined constant value for the pitch. By using the pitch as a variable, a further optimization by the algorithm became possible. Further studies will be conducted in order to include a pitch optimization procedure in the computer algorithm. The approach of non-linear optimization presented by Özelkan et al. [7] will be taken into account as well.

Another desired enhancement of the software is the connection with a material database in which all the specific cutting force constants for the different force models are stored.

References