Prediction of cutting forces in broaching operation commerce essay

According to variety of workpiece profiles in broaching, the geometry of cutting edge varies from simple line to very complicated curves. Wide range of cutting edge geometry in broaching imposes complexity to the distribution of the chip load along the cutting edge. Hence, prediction of cutting forces in broaching is not as simple as other machining processes. Due to this complexity, introducing an applicable force model for all of the orthogonal and oblique broaching cutters can be problematic. In this paper, an attempt is made to present a new force model for broaching. The newly proposed force model expresses the cutting edge as a B-spline parametric curve and uses their flexibility to calculate the chip load as well as cutting forces for orthogonal and oblique broaching. Verified by experimental results, the presented model has a great capability to simulate broaching cutter geometry along with cutting forces and it can be applied for the entire broaching cutters.

1. Introduction

Broaching is a powerful process for the production of complex internal and external profiles. As a machining process, it is commonly used for the machining of a broad range of profiles such as keyways, guide ways, holes and fir-tree slots on turbine discs. Broaching has considerable advantages in comparison to other machining processes. Roughing, semi finishing and finishing of a complex profiles can be done in one stroke of the machine which would require many passes in other conventional processes such as turning, milling, slot milling, etc. It can also produce parts with high surface quality and high geometrical and dimensional tolerances in one stroke. Since the number of simultaneously engaged cutting edges with the workpiece is higher than the other cutting tools, the chip load on each of them will be smaller and tool life is distinctively longer in comparison to other machining processes such as milling and turning [1]. It can be also mentioned that broaching machines are not as complicated as CNC milling or CNC turning machines and thus considered as a simple operation that requires not a highly skilled operator. In other commonly used machining processes such as milling and turning, final geometry of workpiece is generated by combination of tool and workpiece motion and there is no similarity between final geometry of workpiece and cutting tool geometry. In broaching, the geometry of machined part is derived directly by the inversion of broaching cutter geometry. Therefore unlike other machining processes, broaching cutters have a wide range of geometries as well as parts. Consequently, chip load has a complicated non-uniform 2D or 3D geometry depending on the profile complexity of workpiece. A unique feature of broaching operation is that it is not possible to change any of the cutting parameters during process but the cutting speed. That is because all other cutting parameters such as feed, depth of cut and width of cut are built in features of broaching tool geometry which makes the tool design the most important aspect of broaching.

Although broaching is well defined in industry, just a limited number of researches have reported work in the open literatures. In 1960 Monday [2] presents the most comprehensive source on broaching. A detailed description of broaching technology can be found in his book. Kokmeyer [3] edited collection of works on broaching representing the usefulness of the process. Gilormini et al. [4] analyzed the cutting forces on a single broaching and compared them to the forces in slotting and tapping process. Terry et al. [1] presented a system for optimal design of broaching tools. They presented the factors that affect productivity in broaching and explained the design constraints, their importance and how they are selected. Finite element was used to predict the tooth deflection and experimental data in order to create the general rules for designing. Sutherland et al. [5] presented a force model for broaching based on the oblique analysis to determine the forces in the gear broaching process. Their model showed the relationship between contact area, chip load and cutting force. Sajeev et al. [6, 7] investigated the effects of broaching parameters on the tool and workpiece deflections and the final shape of the broached geometry. Budak [8] examined the performance of broaching tools used for broaching of waspaloy turbine discs with fir-tree profile based on the monitoring of force and power. It has been demonstrated that for most of the investigated tools, the load distribution among the broaching sections were non-uniform resulting in uneven wear. Recently Ozturk and Budak [9, 10] performed Finite Element Analysis to calculate the stresses in the broaching tool during the cutting process. The developed model is used to simulate the broaching process and predict the generated stresses in the tool to improve the tool design. He studied fir-tree profiles, simulated the broaching process forces and the tool stresses to improve the tool design. Later Kokturk and Budak [11, 12] performed an optimization on the geometry of the broaching tool cutting edges. In their study the cutting conditions are changed until they can satisfy the preset constraint. They also used the optimized conditions to improve the broaching process. Yussefian et al. [13] applied B-Spline parametric curves in modeling of boring process. Recently Hosseini and Kishawy [14] presented a general force model for orthogonal broaching using B-spline interpolation of cutting edge. By taking geometric flexibility of B-spline curves, their model was capable of modeling any arbitrary orthogonal broaching cutting edge geometry as well as computing the chip load for various cutting conditions. This paper proposes a 3D general force model for the broaching process. The proposed force model is capable of modelling of three force components using B-Spline interpolation of the cutting edge. Each cutting edge is first modeled by B-Spline parametric curves then the chip load is calculated by integration of area between two successive edges. The proposed force model for orthogonal and oblique broaching can calculate the chip load for any arbitrary geometry of cutting edge from the simplest to the most complicated. The proposed method is used to calculate the generated forces and the results are compared to the measured data.

2. Broaching tool geometry

Broaching tool is a straight multi tooth cutter in which several cutting edges engage with the workpiece simultaneously and each tooth removes a portion of material from workpiece surface. Broaching cutter has a tapered flat or round profile with a series of teeth on its surface [4]. Each successive tooth in a broaching tool is higher than the preceding one to perform the cutting action and remove material from workpiece surface. Broaching cutters in their general form can be geometrically divided into three categories of teeth, namely, roughing, semi-finishing and finishing teeth. Roughing teeth remove the bulk of material from workpiece, semi finishing teeth produce the basic surface finish (surface quality), and finishing teeth provide the final surface finish and set geometrical and dimensional tolerances [4]. Figure (1) shows a typical broaching cutting tool.

Figure 1: Schematic view of broaching tool

Normally the maximum rise per tooth in broaching tool belongs to the roughing teeth which perform the major part of metal removal. The rate of rising per tooth slightly decreases in semi finishing teeth as they only remove a small portion of material from workpiece surface to improve the dimensional accuracy and surface quality. In the finishing part, all of the teeth have the same height. These teeth are not cutting teeth and they provide the desired surface quality and adjust the geometrical and dimensional tolerances in the predefined range. Figure (2) illustrates the general mechanism of cutting in broaching.

Figure 2: Mechanism of cutting in broaching

When broaching cutter is accurately designed, broaching process can be faster and more accurate than many other machining processes. Although the initial cost of establishing for a broaching process is comparatively higher than that of other cutting processes, the production cost is commonly low because of the high production rates and the long tool life. Figure (3) presents some of the important geometrical parameters of broaching cutting tool.

Figure 3: Broaching tool geometry

In figure (3), and are rake angle, clearance (relief) angle, tooth height and land length respectively. The rake angle and clearance angle can be selected based on workpiece material. The rake angle is usually selected between to and clearance angle is usually selected between to [12]. The total length of the tool and number of simultaneously engaged cutting edges can be determined by the pitch length which is a linear distance between two successive cutting edges. Based on some previously conducted research [10, 12, 15], it is concluded that it is preferable to have at least two cutting edges in cut to have a dynamically stable cutting.

Another geometric feature of broaching tool is gullet space which is the empty space between two following teeth. The main advantage of gullet space is to retain the chip during cutting until the tooth leaves the workpiece. Once the broaching tool engages with the workpiece, chip is captured between tool and workpiece and it is maintained there until each tooth finishes the cut and leaves the workpiece. Small gullet space may cause tool breakage because of no space to keep the removed chip. It can also lead to poor surface finish due to rubbing of removed chip to the machined surface. If the gullet space is chosen too large it makes the tool very slender and decreases the tool strength and stability. According to the above mentioned reasons, it is very important to design the gullet space accurately to achieve acceptable space and dynamic stability simultaneously. In order to perform a reasonable design it is necessary to have a good understanding of cutting forces during machining process. If the force model can predict the cutting force truthfully the result of force simulation can be used as an input for design and optimization process.

3. Mechanics of metal cutting in broaching

Similar to almost all of the cutting processes, the cutting force in broaching can be expressed generally by three differential components which are directly related to chip load area and the contact length between cutting edge and workpiece such that [16]:

(1)

Figure (4) depicts the main features of oblique broaching and shows the force components generated during the chip removal process.

Figure 4: Mechanics of oblique broaching

In equations (1), is the differential component of tangential force, is the differential component of feed force and is the differential component of radial force. and are chip thickness and length of the cut for infinitesimal element along the cutting edge respectively. and are cutting and edge constants while the subscript refer to the tangential, feed and radial directions. Similar to the other cutting mechanics, the radial component of force appears only during oblique broaching when cutting edge has an inclination angle with the cutting direction. The total tangential, feed and radial component of cutting force for each edge can be calculated by integrating of those components along the cutting edge. Equation (2) shows the force integration along the cutting edge from the start to the end of engagement.

(2)

In equation (2), represents a differential element of chip area which is removed by the cutting edge. Equation (2) can be written in this format:

(3)

In the above equation, is chip load along the cutting edge and is length of engagement between cutting edge and workpiece. Figure (5) demonstrates the infinitesimal element of cutting edge, chip load and contact length for an arbitrary fir tree broaching tool.

Figure 5: Infinitesimal element of cutting edge

Since the chip load may vary along the broaching edge, it must be segmented into elements for which local thickness can be assumed constant. The geometry of chip along the broaching cutting edge is complicated however, since there is no relative motion between successive edges the chip load remains constant. The common approach for simulation of cutting forces is dividing the cutting edge to infinitesimal elements and calculating the area for each element separately. If total chip area can be calculated, cutting forces are obtained without the need for dividing the edge to elements. However, due to the variety and the complexity of cutting edge profiles in broaching, it is difficult to express the edge by an explicit function. Hence, calculation of the above integration in equation (3) is not a straight forward procedure. Representing the broaching cutting edge by B-Spline curves is a powerful way to express the geometry with parametric relations which makes integration and derivation along the edge much easier process.

4. Cutting edge interpolation by B-spline parametric curves

A series of data point can be obtained by collecting the coordinates for each point along the cutting edge using inspection method such as CMM, digitizing or laser scanning. The desired B-Spline of degree p defined by control points passes through all those data points and expresses the cutting edge by a parametric curve. This parametric representation of the cutting edge can be easily appllied to perform derivation and integration along the edge to find the chip load area and the total engagement length. The interpolated B-spline cutting edge of degree p can be expressed as below [17-19]:

(4)

Where is interpolating B-Spline curve of degree p, is control points which control the geometry of curve and is B-spline Basis functions which can be computed by:

(5)

In equation (5), is a B-spline knot which belongs to the knot vector of . The equation (4) has unknown control points. For this reason, it is necessary to have a parameter like to relate the control points to the data points. Since parameter corresponds to data point , plugging into the above equation yields the following [19]:

(6)

There are n+1 B-spline basis functions and parameters in equation (6). Substituting t in to , these values can be organized in a matrix N as shown as below:

(7)

Data points and control points can be expressed in similar way:

(8)

And

(9)

In equation (9) matrix D is input data points which are represents the points along the cutting edge and matrix N can be obtained by evaluating B-spline basis functions at the given parameters [19]. D and N both are known and the only unknown parameter is matrix P. Equation (9) is a system of linear equations with unknown P, solving for P yields the control points and the desired B-spline interpolation curve becomes available. Figure (6) shows control points and desired interpolated broaching cutting edge using B-spline curves.

Figure 6: B-spline interpolation of cutting edge

5. Calculation of chip load and contact length

In orthogonal broaching, all of the cutting edges are parallel together and perpendicular to the cutter axis therefore the third column of matrixes and in equation (8) are zero and only two parameters of and in equation (4) is needed to represent the cutting edge. Figures (7a) and (7b) depicts a typical Cartesian coordinates in orthogonal and oblique broaching.

(a) Orthogonal broaching

(b) Oblique broaching

Figure 7: Cartesian coordinates

In contrast with orthogonal broaching in which all teeth are perpendicular to the cutter axis, in oblique broaching cutting edges have an oblique angle with cutter axis but they are still parallel to each other. In this case , , and all of the coordinates in the third column of matrixes and are non zero. B-spline interpolation of 3D curves is possible but little bit time consuming so it is preferable to transform the 3D to 2D and use the same method for 3D after transformation. Coordinates of point in Cartesian coordinates can be expressed by in plane as follows:

(10)

The above transformation can be done for all of cutting edge data points and in the new coordinate system matrixes is as follows:

(11)

Once matrix presented in new coordinate system the interpolation process can be done the same as previous method for 2D curves. As soon as the cutting edge is presented by B-Spline curves, chip area and cutting length for each cutting edge can be calculated directly from B-Spline equations as follows [13]:

(12)

Where indicate start of the cut, end of the cut, current cutting edge and previous cutting edge respectively. Equation (12) has two coordinate parameters and it is applicable for calculation of chip load and contact length for orthogonal and oblique broaching.

6. Cutting forces simulation

In order to compare the presented geometric model with a real case, a broach cutter was selected and its cutting edges were modeled using B-Spline curves. The geometry of cutter was chosen based on previously presented research by Kokturk [12] to validate the newly proposed model capability. Figure (8) demonstrates the cutter geometry.

Figure 8: Cutter geometry

The geometrical features of cutting edge can be found in table (1) [12].

Table 1: Geometry of broaching cutter [12]

In the next step, selected cutting edges were interpolated using proposed approach. Similar to other interpolation methods, B-Spline interpolation is sensitive to the number of data points. Increasing the number of data points yields a better accuracy but it makes the running time of the algorithm longer. Decreasing the number of data points, accelerate the algorithm but it has a negative effect on the accuracy. It has been shown that smooth parts of the curve are not very sensitive to the number of data points because inaccuracy occurs in the sharp corners where the curve direction changes suddenly. As a result, it would be better to use more data points at the sharp corners and less data point at the other parts to increase the accuracy and time efficiency of the algorithm simultaneously. Figures (9a) and (9b) show the B-Spline presentation of two successive cutting edges.

(a) B-spline representation of the first cutting edge

(b) B-spline representation of the second cutting edge

Figure 9: B-spline representation of two successive cutting edges

It can be seen from the above figures that B-Spline curve follows the data point at the sharp corner with high accuracy.

7. Results and discussion

Figure (10) shows the final geometry of workpiece. Cutting conditions and force coefficients which are used in simulation can be found in table (2).

Figure 10: Final workpiece geometry

Table 2: Cutting conditions [12]

5

Since the cutting edge without oblique angle doesn't have radial component of cutting force it was assumed that for this special case. The edge coefficients of cutting force are always very small in comparison to cutting coefficients so it has been assumed that , and are negligible.

Figure 11: Simulated and experimental cutting forces for orthogonal broaching

Figure 12: Simulated and experimental resultant force for orthogonal broaching

Figure 13: Simulated and experimental cutting forces for oblique broaching

Figure 14: Simulated and experimental resultant force for oblique broaching

It can be seen from figures (11) to (14) that the results of newly proposed model are in good agreement with the previously published results [12]. Since there is no oblique angle in orthogonal broaching the cutting edge engaged with workpiece suddenly with full length so there is a jump in force diagram when each tooth engaged with workpiece. Due to presence of oblique angle in oblique broaching the tooth engaged with workpiece smoothly so the cutting forces rise gradually from zero to its final value. Also, in oblique broaching, fluctuation of cutting forces in the steady state part of the cutting is less than orthogonal one because when one of the teeth leaving the workpiece another one engages smoothly but the average force is higher because of longer contact length.

8. Conclusion

In this paper, a force model is developed to simulate the cutting forces in orthogonal and oblique broaching using B-spline representation of the cutting edge. The new model can interpolate broaching tool cutting edge without any limitations which offer the simulation of cutting forces for any desired input geometry. In order to validate the new force model, the predicted cutting forces are compared to previously measured data [12]. The comparison showed a good agreement in both measured and predicted data for orthogonal and oblique broaching. The simulated cutting forces can be used to have a better understanding of process and optimize the geometric features of broaching cutter to achieve more efficient cutting which is under investigation of authors.

Acknowledgment

The authors acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for their support to the project.