Milling convex surfaces with toroidal cutting edge

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Abstract. The toroidal cutting edge, also called corner cutter, is a combination of the cylindrical-frontal milling cutter and the spherical head milling. The paper follows at generating the optimal trajectory for making the finished product with the toroidal cutting edge without having to use the flat end mill and the ball nose end mill. This trajectory is accomplished using a CAM (Computer Aided Manufacturing) program that is generated on a 3D model. The proposed method was experimentally verified on a 3-axis numerical control centre, making a roughness comparison according to the climb milling or conventional milling.

1. Introduction

Complex and convex surfaces are encountered in many situations, such as aerospace, cars, molds, and the field of pneumatic robots. The surfaces are 3D generated using a CAD program, helping to provide a geometric description for generating the trajectory of the milling tool.

Computer-Aided-Manufacturing (CAM) is defined as the use of software for controlling machine tools in processing processes representing computer assistance in processing processes with the primary purpose of creating a faster production process.

According to Xun Xu [1], computer-assisted manufacturing can be interpreted both from a general point of view and from a particular point of view. In a general sense, computer assisted manufacturing refers to any application used in manufacturing processes such as: machine tool control; monitoring machine tools; simulation of the manufacturing process; communication on the production platform as well as mechanical testing. In a particular sense, computer-assisted manufacturing is computer-based machining and addresses machine tools with numerical control [1].

Computer-assisted production covers a wide range of activities. At the lowest level, the automation of individual processes or a group of processes can be accomplished by microprocessors, programmable logic commands and microcontrollers [2].

Computers or microprocessors can control production equipment such as machine tools, welding machines, assembly machines, and so on. The type of control used in machine tools is called computerized numerical control (CNC). [2] The concept of numerical command was made at the Massachusetts Institute of Technology in 1951.

The term "numeric" means the inputs of command numbers that take the form of numbers. They are presented in binary code and can be processed directly by the equipment. The entered figures are intended to describe the geometry of the workpiece, the data related to tools and work speeds, in numerical form. This description by numbers is characterized by a literary prefix. These command formats are indicated in DIN 66 025 of 1983 respectively ISO 6983 in 2009 and ISO 646 since 1991 and are called blocks.
2. **Numerically controlled machine tool axis analysis**

In the numerical machine tool sector, the notion of axle has been initiated to define each fixed or circular motion direction. In order to recognize the machine axes, some internationally agreed symbolism and meanings of movement are assigned by ISO R-841-1968, and nationally by STAS 8902-1971. The axial displacement axes of the numerically controlled machine constitute, by association, a geometric coordinate system. According to STAS 8902-1971, the normal coordinate system is a straight-line clamp, which refers to a piece fixed to the machine and having the edges (s) parallel to its main guides.

3. **Effects of climb and conventional milling**

Milling is the machining of flat, cylindrical or profiled surfaces by means of a multi-pronged tool, called milling machine.

I activating in the field of machining as a CNC programmer engineer, I encounter different cases and situations where different factors have to be taken into account, which can influence the quality of the workings positively or negatively, so I have learned that when it comes to chip processing the difference makes the details, however small they are.

Machining of surfaces by climb milling is the most frequently encountered milling method, whether it is planning a surface or profiling. As the name implies, the milling teeth pull the material toward itself trying to climb through the material following the trajectory of movement. In this movement, the milling teeth first contact the outer surface of the cutting where the chip thickness is greater, continuing to taper as the milling tooth passes through a complete movement.

This feature has the advantage that the chips will be removed and stored behind the cutting without contact with the milling cutter so that a cleaner surface will be produced and will increase the life of the tool. This cutting method requires less force to achieve cutting, and the tool movement generates a force on the part that helps stabilize it, especially in surface planning and finishing. Conventional milling has a major advantage namely that the milling tooth is required as it penetrates into the material on the surface previously machined by the tooth thus increasing the friction between the material and the milling tool generating also a considerable amount of heat. As a result, when conventional milling, the tooth enters the cutting at the scissor's zero thickness and reaches the cutting edge to the maximum thickness, so there are no shocks.

4. **The experimental part**

The study of climb milling and conventional milling with classical tools has been done by many authors but a concrete part of what involves the toroidal milling is not yet what obliges me to do it in order to know the optimal principle to apply in future experiments.

4.1. **The experimental-theoretical part**

The CAM program was generated using Powermill. According to Powermill is a 3D Cam program that generates the tool trajectory for CNC milling machines from 2 to 5 axes developed by Delcam.

![Figure 1a. Climb milling](image1a)

![Figure 1b. Conventional milling](image1b)
The program generated in the first phase is shown in figure 1.a. indicates the movement of the cutter in the direction of the feed and motion against the advance, figure 1.b.

4.2. Practical experimental part
For the practical part a MCV 1016 3 axis machining centre, 2015 manufacturing year of S.C. Ramira S.A.

![Figure 2. Vertical machining centre in 3 axis MCV 1016](image)

The cutting tool used was a toroidal cutter JHP780160E2R400.0Z4-M64 with a carbide coating of Ø16 with a number of 4 teeth and a radius of R4.

![Figure 3. The toroidal milling cutter](image)

4.3. The material and the shape of the piece
The material used in the experiment is C45 (1.0503) with the following characteristics: 0.42 ... 0.50% C, 0.5 ... 0.80% Mn, 0.17 ... 0.37% Si, maximum 0.040% P [6] etc. The piece has the shape of a square being machined only one of the ends representing the active part of the piece.

![Figure 4. Form of the workpiece](image)

Figure 5 shows a visual comparison of the two types of machining and it can be seen that the climb milling has a visual advantage due to the surface gloss compared to the conventional milling where some optical scratches can be observed.
4.4. Comparing the roughness of the two pieces processed with toroidal milling

The device used to check the roughness is the TIME TR 200, this portable absolute measuring device has the sensitivity required to measure the very fine roughness of the tens and microns.

Following the two roughness determinations, a series of measurements were performed, following 6 parameters in terms of surface quality. A number of 6 measurements were made on each surface, as shown in Table 1.

| Surface roughness processed climb milling [µm] | Surface roughness processed conventional milling [µm] |
|-----------------------------------------------|------------------------------------------------------|
| Ra   Rq   Rz   Rt   Rp   Rv                  | Ra   Rq   Rz   Rt   Rp   Rv                  |
| 1. 0.289 0.472 2.900 4.539 0.759 2.14       | 1. 0.446 0.399 2.956 5.019 0.551 2.404 |
| 2. 0.621 0.897 5.032 7.619 1.888 3.144      | 2. 0.621 0.838 4.127 5.400 1.572 2.555 |
| 3. 0.431 0.905 4.780 9.140 1.383 3.396      | 3. 0.647 0.817 3.896 5.480 1.516 2.38 |
| 4. 0.681 0.962 4.932 8.819 2.023 2.907      | 4. 0.531 0.473 2.483 3.920 0.868 1.616 |
| 5. 0.603 0.905 4.288 8.039 2.036 2.251      | 5. 0.437 0.383 2.500 4.039 0.615 1.883 |
| 6. 0.447 1.028 5.119 6.199 1.896 3.223      | 6. 0.594 0.774 3.831 5.780 1.636 2.196 |
| Average 0.512 0.861 4.508 7.392 1.664 2.843 | Average 0.546 0.614 3.298 4.939 1.126 2.172 |

The probable true value and the precision indices of a measured magnitude are calculated with the formula:

\[ M_x = \frac{\sum_{i=1}^{r} m_i X_i}{\sum_{i=1}^{r} m_i} \]

in which: \( r \) is number of value ranges of measured values,
- \( m_i \) - the number of values appearing in any one \( i \), in other words, the frequency of occurrence of \( X_i \) in the \( i \) range.
The measurement accuracy of the studied sizes can be evaluated by several indices, the most used being the deviation of the square mean and the probable error. The deviation of the square mean (σ) is determined with the following relation:

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{n} m_i X_i^2}{\sum_{i=1}^{n} m_i - 1}}
\]  

(2)

Figure 7. Diagram of roughness of the two machining

To verify the accuracy of the data presented in the above diagrams, I decided to use the Table Curve 2D program following the diagram of Figure 8.

Figure 8. Diagram generated by the Table Curve 2D program

5. Experimental results

According to the experiments above, the comparison between the two types of processing, climb milling and conventional milling with the toroidal cutting edge the data centralized in Table 2 was reached.

|                  | Climb milling | Conventional milling |
|------------------|---------------|----------------------|
| Cutting edge used| Toroidal end mill Ø16 - R4 | Toroidal end mill Ø16 - R4 |
| Material used    | C45 (1.0503)  | C45 (1.0503)         |
| Cutting speed [m/min] | 55 m/min       | 55                   |
| Cutting feed [mm/min] | 328            | 328                  |
| Cooling          | emulsion       | emulsion             |
| Roughness Ra [µm]| 0.512          | 0.546                |
Large differences between the roughnesses of the treated surfaces do not exist, but small scratches can be observed visually on the surface treated conventional milling due to the shank pushed to what is exposed and to the measured values being a roughness higher by 0.034 μm, these two values being compared in Figure 9.

![Figure 9. Comparison of roughness for the two types of milling](image)

6. Conclusions
The use of the toroidal cutter in complex and coveted surfaces can be successfully applied. This can take the place of the spherical milling cutter and the cylindrical-frontal cutter in such situations.

Generating a CAM program according to these surfaces in accordance with optimal regimes and parameters leads to the best surface processing.

After comparison both visually and in terms of surface roughness, we found that when milling convex surfaces with the toroidal milling, processing in the advance direction is more efficient than processing conventional milling.

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