Studies of polygons accuracy shaped by various methods on universal CNC turning center

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Abstract. In this paper modern methods of shaping polygons on universal CNC turning centers have been presented. Four different methods, depending on process kinematics, were investigated. Machining tests for different sample materials and polygons were performed. The results obtained from geometrical measurements allow to compare the accuracy of presented methods. Furthermore machining time for different methods were monitored to check their efficiency. The present paper provides comprehensive comparisons of methods used for shaping polygons on CNC turning centers. This research indicates potential fields of applications for mentioned methods and can be useful for manufacturing engineers.

1. Introduction
Last decade has brought significant development of CNC machine tools. Nowadays, CNC machine tool should be characterized by high reliability, efficiency, flexibility, as well as accuracy and repeatability of positioning. CNC lathes are the most commonly used group of machine tools in the industry. Apart from producing axisymmetric parts, modern CNC turning centers can be used for following operations:
\begin{itemize}
  \item drilling of the non coaxial holes,
  \item milling,
  \item broaching,
  \item gear hobbing,
  \item polishing,
  \item grinding,
  \item polygonal turning.
\end{itemize}
Many machines and mechanisms are characterized by very complex geometry. One example of such geometry can be flat or polygonal surfaces on axisymmetric elements. Polygons are commonly used in assembly process \cite{1}. Recently, technology process of axisymmetric components that have polygons, was requiring milling center with rotary table \cite{2,3}. Today, thanks to great improvement of machine tools, such parts can be produced comprehensively on CNC universal lathe. In this paper characterization of polygons produced by various methods on universal CNC turning center was investigated. Nowadays, four methods of shaping polygons on CNC turning center can be pointed out:
\begin{itemize}
  \item a) milling of polygon by interpolation of C-axis (spindle positioning) and linear X-axis; during this process axis of the end mill is parallel to the spindle axis (Figure 1a),
  \item b) milling of polygonal shape by interpolation of X- and Y-axis while spindle doesn't move (brake of spindle is clamped); during this process axis of the end mill is parallel to the spindle axis (Figure 1b),
\end{itemize}
c) milling of polygonal when feed motion consist of Y- and Z-axis interpolation, spindle works as an indexable axis and set a particular angular position for every flat surface of the component [4]; during described milling process, axis of the milling tool is perpendicular to shaped surface (Figure 1c).

d) polygonal turning which is led thanks to synchronization of the tool rotary motion with lathe's spindle; during machining process, polygonal cutter makes parallel movement to the spindle axis. The kinematic diagram of the process is presented in Figure 1d.

![Figure 1. Methods of shaping polygons on universal CNC lathes, a) plain milling by interpolation of C- and X-axis, b) plain milling by interpolation of X- and Y-axis, c) face milling by interpolation of Y- and Z-axis, d) polygonal turning thanks to synchronisation of spindle and tool rotary movement.](image)

The shape of polygon manufactured with polygonal turning technique is related with ratio of tool rotary speed to spindle speed and the number of cutting edges. Relationship between these factors can be expressed by the following equation [1]:

\[ p = z \cdot \frac{n_{\text{tool}}}{n_{\text{spindle}}} \]  \hspace{1cm} (1)

In above equation \( p \) stands for the number of flat/polygon’s surfaces, \( z \) is the number of cutting edges, \( n_{\text{tool}} \) and \( n_{\text{spindle}} \), are respectively rotary speed of tool and spindle. In Table 1 the configurations of \( n_{\text{tool}}/n_{\text{spindle}} \) ratio and number of cutting edges, for most commonly used polygons, are presented.

During polygonal turning process, spindle and tool rotate in the opposite direction, consequently resultant cutting speed can be described by following equation:

\[ v_c = v_{\text{tool}} + v_{\text{spindle}} \left[ \frac{m}{\min} \right] \]  \hspace{1cm} (2)

Assuming constant ratio of speed:

\[ \beta = \frac{n_{\text{tool}}}{n_{\text{spindle}}} \]  \hspace{1cm} (3)

equation (1) can be transformed to the following form:

\[ v_c = \frac{\pi \cdot n_{\text{tool}}}{1000} \left( SW + D \cdot \beta \right) \left[ \frac{m}{\min} \right] \]  \hspace{1cm} (4)
where: \( SW \) stands for polygon size (distance between two opposite and parallel faces); \( D \) is diameter of cutter. In Figure 2 the polygonal cutter used during the test, is presented. Tool has four sockets and can be set with 1, 2 or 3 inserts (depends on polygon type). The tool presented in the below picture is prepared for making hexagonal shape (3 inserts in circular pattern, 3 x 120°).

It is worth to mention, that in fact, the polygons obtained by polygonal turning hasn't got flat faces [6]. Polygons with even number of faces have convex outline which is presented in Figure 3.

### Table 1. Recommended Configurations of speed ratio and number of cutting edges for various polygons [5].

| Polygon          | Speed ratio \( \beta = \frac{n_{tool}}{n_{spindle}} \) | Number of Cutting edges |
|------------------|------------------------------------------------------|-------------------------|
| 2 parallel flat surfaces | 2:1                                                  | 1                       |
| Tetragon         | 2:1                                                  | 2                       |
| Hexagon          | 2:1                                                  | 3                       |
| Octagon          | 2:1                                                  | 4                       |

2. **Research problem**

The aim of this research was to compare the various techniques of shaping polygons on universal CNC turning center. Four different methods (described in previous point) were investigated. The efficiency of these techniques for different materials and polygons size was analyzed (for assumed cutting parameters). Geometrical accuracy of obtained polygons and roughness of the surfaces were measured. Base on the presented results potential fields of application for different methods were pointed out.
3. Methodology of research
The cutting tests were conducted on universal CNC turning centers CLX 350 V3 and CLX 450 V4 produced by FAMOT, which is a part of DMG MORI group. As a workpiece, drawn bars made of steel C45 and aluminium alloy EN AW-5083 (PA13) were used. As a sample, hexagon with various size (SW) was taken. The drawing of test sample is presented in Figure 4.

![Figure 4. The drawing of machined samples.](image)

Samples were measured with coordinate measuring machine DEA Global Image Clima 7.7.5 and PC-DMIS 2016 software equipped computer station. Maximum permissible error of applied measurement equipment is equal to:

\[ MPE_E = 1,5 + \frac{L}{333} \text{ [\( \mu \text{m} \)]} \] (5)

Machining strategy was divided into rough and finishing operation. Cutting parameters assumed for research are presented in Table 2. Cutting parameters were selected according to suppliers [5, 7] guidelines and authors experience. Down-cut strategy was used for milling process. All operations were led with coolant. Designation of tools used in this research are shown in Table 3.

| Method      | Parameter | EN AW-5083 | C45 |
|-------------|-----------|------------|-----|
|             | \( a_p \) | 15 mm      | 15 mm |
| Plain milling | \( a_e \) | \( \leq 3 \text{ mm} \) | \( \leq 0,2 \text{ mm} \) |
|             | \( f_t \) | 0,1 mm/tooth | 0,08 mm/tooth |
|             | \( z \) | 2           | 4 |
|             | \( v_c \) | 200 m/min   | 90 m/min |
| Face milling | \( a_p \) | \( \leq 3 \text{ mm} \) | \( \leq 0,2 \text{ mm} \) |
|             | \( a_e \) | 12 mm       | 12 mm |
|             | \( f_t \) | 0,15 mm/tooth | 0,08 mm/tooth |
|             | \( z \) | 2           | 2 |
|             | \( v_c \) | 200 m/min   | 200 m/min |
| Polygonal turning | \( a_p \) | \( \leq 2,5 \text{ mm} \) | \( 0,5 \text{ mm} \) |
|             | \( f_t \) | 0,08 mm/tooth | 0,05 mm/tooth |
|             | \( z \) | 3           | 3 |
|             | \( v_c \) | 500 m/min   | 280 m/min |
Table 3. Cutting tools used in the research [5, 7].

| Operation       | Tool                      | Supplier | Application range |
|-----------------|---------------------------|----------|-------------------|
| Plain mill      | R216.34-16050-CC26P 1640  | SANDVIK  | P                 |
|                 | R216.32-16025-AP20AH10F   | SANDVIK  | N                 |
| Face mill       | R390-016A16L-11L          | SANDVIK  | -                 |
|                 | R390-11 T3 04M-PM GC1030 | SANDVIK  | P N               |
| Polygonal       | L381.G090.22.04          | HORN     | -                 |
| turning         | L314.MK50.20             | HORN     | P N               |

4. Results

Nowadays, in the age of mechanization and automation of production, efficiency pays the significant role in production process strategy. In the Figure 5, machining time of hexagons in function of its size is presented for various methods. The length of analyzed polygons is 15 mm. Below charts shows that polygonal turning is distinctly the most efficient from presented methods. It is worth to note, that machining process of hexagons by polygonal turning method depends only slightly on the polygon size. Machining time is nearly constant. A gentle increase of cycle time is caused by the strategy of constant resultant cutting speed. The bigger hexagon, the higher cutting speed of spindle, consequently the cutting speed of polygonal cutter decreases (according to the equation 2) which affects insignificantly the feed rate of tool. Nevertheless, the path of tool is constant. In case of other considered methods, the length of tool path is strongly related with hexagon size, which affects significantly the cutting time.

Based on below chart, it can be stated that polygonal turning can be even a few times more efficient than milling operation of polygons. The longer polygon (analyzed sample had 15 mm), the greater would be difference in machining time between the polygonal turning and other methods.

Second important aspect that has to be taken into consideration is the geometrical accuracy of samples obtained by different methods. It can be pointed out, that the bigger hexagon, the greater geometrical error. An example of geometrical characteristics for hexagon SW=41 mm produced by various method is presented in Table 4.

![Figure 5. Machining time of hexagons in function of size t = f(SW) on universal CNC turning center for various methods.](image)
Table 4. The results of geometrical measurements for hexagon SW=41 mm made by various methods on universal CNC turning center.

| Geometrical tolerance | Polygonal turning | Plain milling | Face milling |
|-----------------------|-------------------|---------------|-------------|
|                       | Interpolation of C and X axis | Interpolation of X and Y axis |            |
| Profile error         | 0,430             | 0,048         | 0,025       | 0,026       |
| Flatness of faces     | 0,124             | 0,013         | 0,005       | 0,006       |
| Parallelism           | 0,149             | 0,025         | 0,010       | 0,015       |

Apart from the highest effectiveness of the process from considered methods, it has to be underlined, that polygonal turning is characterized by the lowest accuracy of obtained hexagons. The best quality of samples was achieved by plain milling with X - Y axis interpolation and by face milling. For selected samples, roughness of the faces was investigated. The measurements of roughness were conducted in two directions according to Figure 6.

![Figure 6. Roughness measurement of obtained samples.](image)

It is worth noting that all presented methods allow to reach very good quality of the surface with Ra < 1 µm (Table 5). The lowest roughness was observed for samples made by plain milling with X-Y axis interpolation. The parts produced by polygonal turning are characterized by directional roughness, which is higher in the direction of tool feed. It is typical for turning technology.

Table 5. Results of roughness measurement for samples made of PA13.

| Roughness | Polygonal turning | Plain milling | Face milling |
|-----------|-------------------|---------------|-------------|
|           | Interpolation of C and X axis | Interpolation of X and Y axis |            |
| Ra_z      | 0,672             | 0,220         | 0,256       |
| Ra_x      | 0,312             | 0,227         | 0,268       |

5. Conclusion
In this paper various methods of shaping polygons on universal CNC turning center were investigated. Accuracy and efficiency of presented techniques were analyzed.

Base on the obtained results, it can be stated that polygonal turning is definitely the most efficient method of shaping polygons on universal CNC turning center. This method can be even a few times more efficient than milling operation. The tool path during this operation is not strictly related with polygon size (SW), consequently the machining time of polygons which have the same length is
nearly constant. In case of milling operation, the machining time is strongly connected to polygon size. The bigger polygon, the longer tool path and machining time, as well. It was presented on an example of hexagons.

The results of conducted machining test and geometrical measurement allow to classify polygonal turning technique as a method that should be intended for machining polygons, the surfaces of which do not need to fulfill tight geometrical tolerances. It need to be underlined, that due to the kinematic of polygonal turning process, the obtained surfaces are not flat. The bigger polygon, the higher geometrical inaccuracy of its shape. The best quality of machined parts was reached by plain milling with X - Y axis interpolation and by face milling. These two methods can be used for applications which demand high geometrical accuracy.

The methods, which were introduced in this paper have some restrictions, resulting from the kinematics of the process or technology limitations. A few examples of possible application are presented in Table 6. It can be noted, that the face milling method is the most universal, despite the fact is the less efficient.

**Table 6. Application range of presented methods according to the process kinematics.**

| Application                       | Polygonal turning | Plain milling | Face milling |
|-----------------------------------|-------------------|---------------|--------------|
|                                   | Interpolation C - X axis | Interpolation X - Y axis |            |
| Hexagon on front side of machined part (L <50 mm) | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| Hexagon on front side of machined part (L >50 mm) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| Flat surface on front of the part | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| Hexagon between cylindrical surfaces | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| Long part supported by tailstock | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |
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