Miloš D. Pjević
Teaching Assistant
University of Belgrade
Faculty of Mechanical Engineering
Department of Production Engineering

Goran M. Mladenović
Assistant Professor
University of Belgrade
Faculty of Mechanical Engineering
Department of Production Engineering

Ljubodrag M. Tanović
Full Time Professor
University of Belgrade
Faculty of Mechanical Engineering
Department of Production Engineering

Radovan M. Puzović
Full Time Professor
University of Belgrade
Faculty of Mechanical Engineering
Department of Production Engineering

Contemporary Approach to the Design of Circular Form Tools for Complex-Geometry Part Manufacture

Form tools have been used in industry for a number of decades. Their use is booming and such growing popularity can be attributed to minimized manufacturing costs and shorter manufacturing time. On the other side, one of the major drawbacks is the method of their design. It reflects in the constraints present in the machining of straight-line and circular arc segments of a workpiece. For each segment the rake angle has a different value, which imposes an additional constraint. In case it is necessary to use form tools to manufacture complex-geometry parts, the value of the rake angle would require to be zero. The paper presents contemporary design method of circular form tools by implementing CAD system. This way, it is not only provided a constant value of the rake angle across the entire cutting edge, which can be different from zero too, but also optimum tool geometry for machining a desired material. Additionally, the geometry of a form tool designed using a new method was experimentally tested.

Keywords: *Circular form tools, lathe machining, methodology, CAD/CAM systems, computer graphis.*

1. INTRODUCTION

In order to ensure the survival of products in the market under conditions of rapid growing competition, manufacturers are competing with each other to implement novel, more efficient and innovative production methods as early as possible. The inherent feature of each new production method is the reduction of the final product's cost. It can be achieved by minimizing the machining time, reducing use of resources and substituting for cheaper ones, automation of manufacturing process, etc.

When manufacturing the rotating parts, such as shafts, axles and other, the total price of the product is strongly affected by the length of the part's manufacturing time as well as by the energy usage. If more than one tool is used for machining a single part, the total machining time for that part will be considerably longer compared to the situation when one complex-geometry tool is used. A complex-geometry tool, on one hand, can replace several tools but, at the same time, it reduces the total machining time, the most significant reduction being that of idle times. Reduction of idle times means predominant reduction of tool change time, when machining of a product requires several different tools. It is not only that usage of several tools significantly extends machining time, but it is less cost-effective, taking into account the fact that manufacturing of a single part requires far more resources. Thanks to above mentioned characteristics of form tools, they are increasingly implemented in industry, whether it is prismatic or circular form tools [1-3].

The conventional design method of form tools [4-6] has placed constraints on their implementation. On one hand, constraints occur in the form of the workpiece geometry that can be built, whereas another constraint characteristic is a varying rake angle as a function of the workpiece segment diameter, on the other hand. A new, contemporary approach to the design of form tolls, presented in this paper, eliminates all above mentioned constraints.

The paper shows a new method for designing circular form tools by implementing commercial CAD system, whereby the tool form obtained has a constant rake angle across the entire cutting edge. Another adva–ntage of this design method is the possibility of building a complex-geometry part, with the tool rake angle value different from zero or constant across the entire cutting edge. In the paper, the analysis of machining was carried out by FEM for such designed circular form tool. The objective was to establish how much the proposed design method is justifiable. By applying the conventional machining method a form tool was made and thereafter the part was machined. Scanning of the workpiece was the final check that implied inspection of the workpiece shape and dimensions.

2. THE CONVENTIONAL DESIGN METHOD OF CIRCULAR FORM TOOLS

The conventional design method of form tools, whether circular or prismatic, is based on an iterative algorithm, whose input parameters are the part dimensions (segment diameter and length) and values of the initial rake and relief angles, Fig. 1.

Initial values of the rake and relief angles apply to the values corresponding to the maximum depth of cut, namely, the tool will have those values at the location where the workpiece diameter is minimum. An iterative

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Correspondence to: Miloš Pjević
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: mpjevic@mas.bg.ac.rs

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algorithm is well-known and has been present in practice since early 1980s [7], Fig. 2.

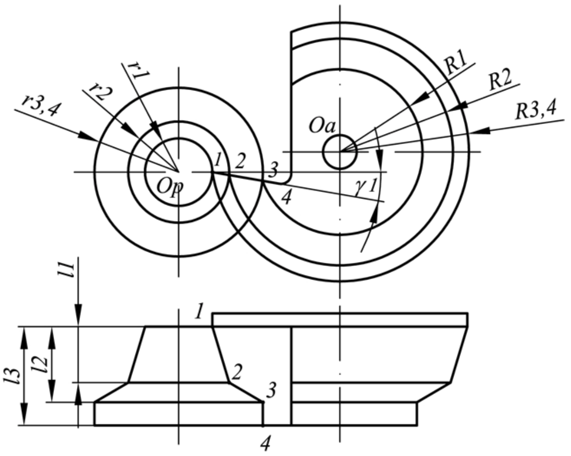


Figure 1. Scheme of machining with circular form tool for external machining

Constraints in implementing the iterative algorithm are related to obtaining tools that can be used only to build straight-line or, in some cases, circular arc segments. Although this design method is considered simple and convenient for tools used to build straight-line segments, there are additional constraints too. One of them is a varying value of rake angle across the entire cutting edge if part consists of several segments of different diameter. Since it changes across the cutting edge, different temperature distribution may occur across the edge, which could result in machining error. Additionally, a consequence of change in rake angle value is non-uniformity of the cutting force components occurring across the cutting edge and leading to non-uniform tool wear.

If a straight-line cutter is used to make a conical surface, tool cutting into the material would occur, i.e. a concave surface is obtained, which is another drawback of the conventional design method of form tools. To overcome the above mentioned drawbacks, the cutting edge should be a complex curve. Error compensation algorithms are well-known and available [7] however their implementation implies high complexity.

In case that a circular form tool is needed for complex-geometry part machining, a necessary condition is segmentation of the part form curve by straight-line segments (Fig. 3). The value of the straight-line segment length as a function of the value of allowable deviation and curve radius $L=L(\Delta h,\ \rho)$ is reached by observing a right-angled triangle ABO, and based on it, by applying the Pythagorean theorem, the following relation can be established:

$$\rho^2 = \overline{AB}^2 + \overline{BO}^2 \tag{1}$$

Taking into account that:

$$\overline{AB} = L/2 \tag{2}$$

$$\overline{BO} = \rho - \Delta h \tag{3}$$

one obtains the expression for the value of the straight-line segment length as a function of the allowable deviation and curve radius:

$$L = 2\sqrt{2\rho\Delta h - \Delta h^2} \tag{4}$$

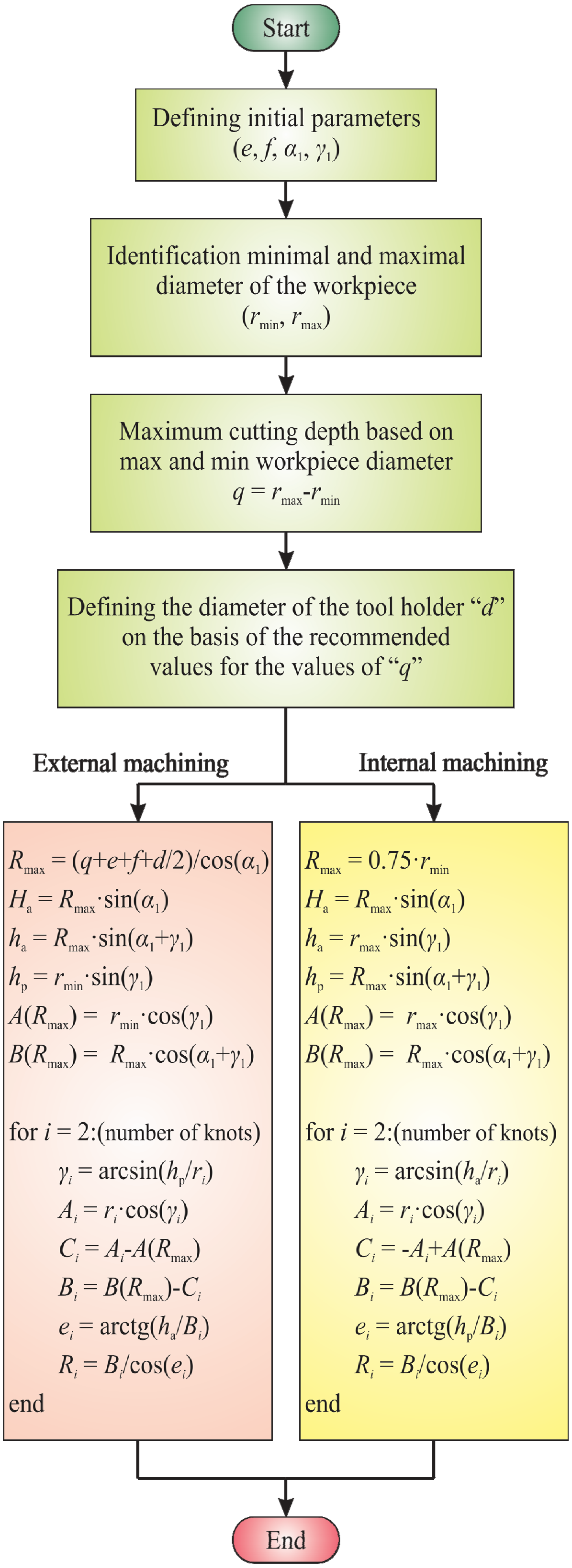


Figure 2. Representation of the algorithm for calculations of circular form tools for external machining [8]

Such method of form tools design would be achievable only for the case when the value of rake angle is equal to zero. Otherwise, one would obtain a varying value of the rake angle across the cutting edge, which could cause the above mentioned problems.

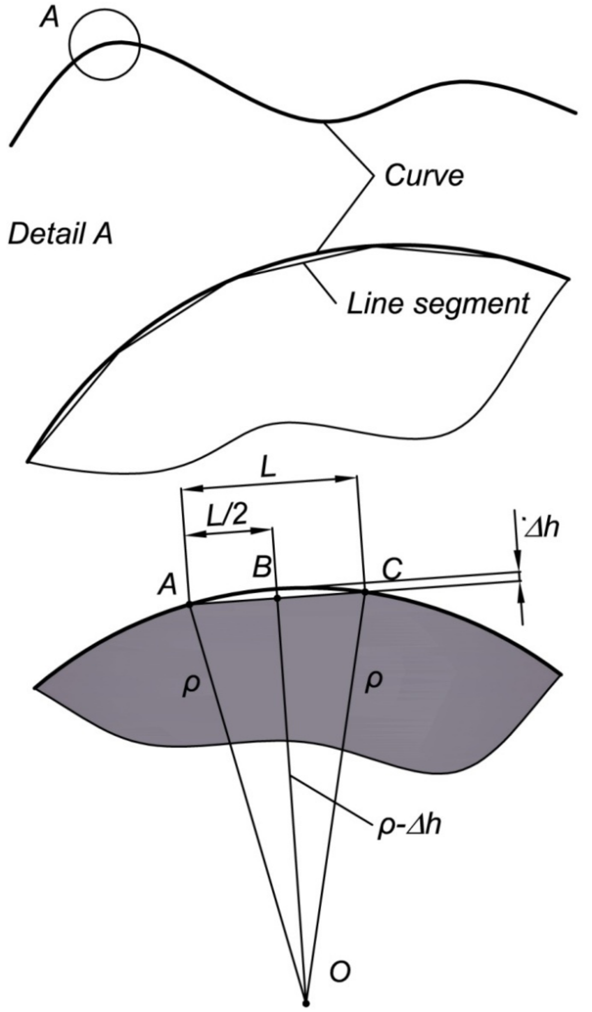


Figure 3. Segmentation of the workpiece curve form

3. DESIGN AND MAKING OF CIRCULAR FORM TOOLS BY USING CONTEMPORARY CAD SOFTWARE PACKAGES

The development of CAD software packages has opened up avenues for a new approach to the tool and product design that was earlier unthinkable of. Design and machining of complex-surface parts is no longer impossible. On the contrary, nowadays it is available and highly represented.

Implementation of CAD software packages for the design and making of circular form tools brings a series of advantages. One of the major ones is the possibility of machining complex-geometry parts.

To enable their implementation to obtain parts with complex surfaces, the initial condition is that the cutting edge is in the workpiece horizontal plane of symmetry across its entire length (Fig. 4).

In a general case, the cutting edge can be part of curve *C*=*C*(t) described by parametric equations. In commercial CAD packages the description of curves is performed by *B* spline, where the point location on curve *C*=*C*(t) is described by radius vector *r*=*r*(*t*), depending on scalar parameter *t*, i.e.:

$$r(t)=\sum_{i=0}^{n} b_i B_i^k(t), \qquad t_k \le t \le t_{n+1} \tag{5}$$

where introduced notation $B_i^k(t)$ represents the *i*-th *B* spline basis of *k* order defined by [9]:

$$B_i^k(t)=\frac{t-t_i}{t_{i+k}-t_i}B_i^{k-1}(t)+\frac{t_{i+k+1}-t}{t_{i+k+1}-t_{i+1}}B_{i+1}^{k-1}(t) \tag{6}$$

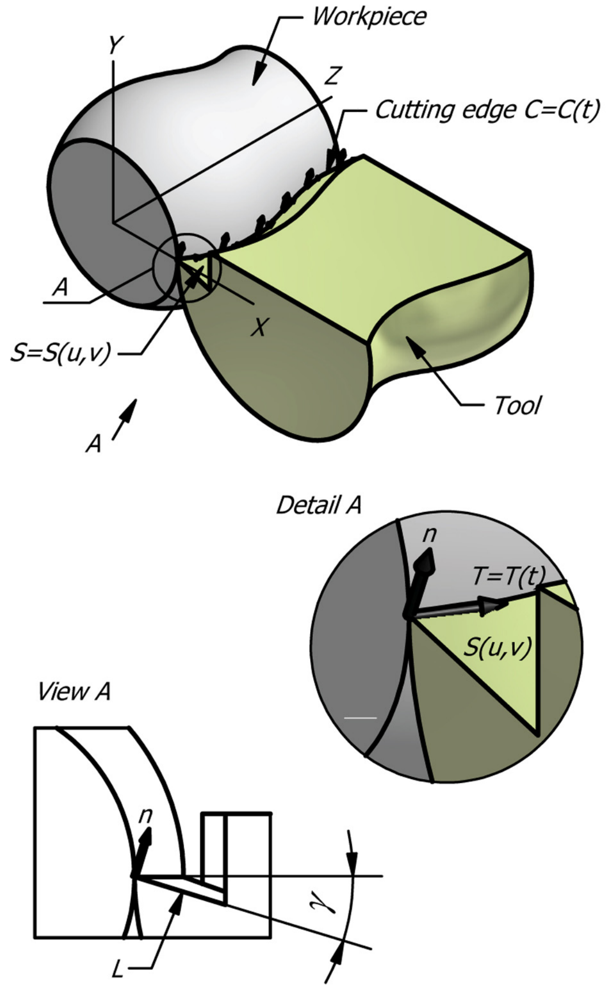


Figure 4. Tool/workpiece interaction

Each point on *B* spline is a combination of local control points b_i which form a control polygon. It is evident that the number of *B* spline basis functions is equal to the number of control points and that number represents the dimension of the function space. According to above, the number of points required to define the *B* spline function is equal to the dimension of the space plus one [10].

For the case of uniform curves, equation (5) can be written in the matrix form, i.e.:

$$r(t)=\begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}\cdot\frac{1}{6}\begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix}\cdot\begin{bmatrix} b_{i-1} \\ b_i \\ b_{i+1} \\ b_{i+2} \end{bmatrix} \tag{7}$$

This way, using CAD system makes possible to obtain the form tool cutting edge contour corresponded by the workpiece contour. The increment of parameter *t* is determined based on defined machining allowance.

One of the parameters used in constructing a form tool is rake angle (γ) defined by a designer according to recommended values for the given material. Implementing commercial CAD package allows one to define in plane z=0 (Fig.4) the intersection of the rake surface representing edge (L). Through this intersection it is arrived at the value of normal vector (n) to the edge (L) lying in plane XY, which is a function of the rake angle (γ). Parametrically described curves by means of differential calculus enabled determination of the tan–gent vector to the curve $T=T(t)$, which is obtained by means of the first derivative of the function (5), i.e. [10]:

$$\left.\frac{dr(t)}{dt}\right|_{t=x} = \sum_{i=j-k+1}^{j} k\frac{b_i - b_{i-1}}{t_{i+k} - t_i} B_i^{k-i}(x),\ t_j \le x \le t_{j+1} \quad (8)$$

the unit tahngent vector (T_0) to the curve $r=r(s)$, where s is the arc length of the curve, is obtained by differentiating (5) with respect to s. Taking into account that it is differentiation of a complex function, it is obtained:

$$T_0 = \frac{dr}{ds} = \frac{dr}{dt}\frac{dt}{ds} \quad (9)$$

from where it follows that the derivative with respect to parameter t equals:

$$\frac{dr}{dt} = T\frac{ds}{dt} \quad (10)$$

which means that the derivative with respect to parameter t is also the vector of tangent, not of the unit, but of the module one:

$$\left|\frac{dr}{dt}\right| = \frac{ds}{dt} \quad (11)$$

In other words, it is then possible to generate a complex surface grid $S=S(u,\ v)$, whose normal vector will be equal to the initially specified (n) and which will contain previously generated cutter $C=C(t)$. Namely, a complex (rake) surface is obtained by rolling of the initially specified edge L across the cutter $C=C(t)$, maintaining constant orientation of the normal vector (n).

4. ANALYSIS OF FORM TOOL GEOMETRY IMPACT ON THE CUTTING PROCESS BY THE FINITE ELEMENT METHOD

The CAD model of a form tool generated using the method described in section 3 was tested for functionality of the generated form tool by applying FEM. Geometry of the obtained tool was designed to ensure constant value of rake angle across the entire cutting edge. The FEM computations were used to analyze the impact of the rake surface geometry on load distribution across the cutting edge as well as tool wear.

For the purposes of FME computations it was necessary to define the machining conditions. They implied the geometry and material of the tool and workpiece. Johnson-Cook parameters for the workpiece material (aluminum alloy AA5083-H116) were taken over from [11, 12], whereas for the tool material (AISI H11/1.2343/X37CrMoV5-1) from [13]. Further procedure for the chosen combination of the tool and workpiece included definition of the machining process parameters. For an arbitrarily chosen depth of cut 3mm and its corresponding recommended value of cutting speed 100m/min, all conditions were fulfilled to start the machining process simulation.

The initial state of simulation corresponds to real machining conditions, where the tool cutting edge is positioned adjacent to the workpiece, Fig. 5.

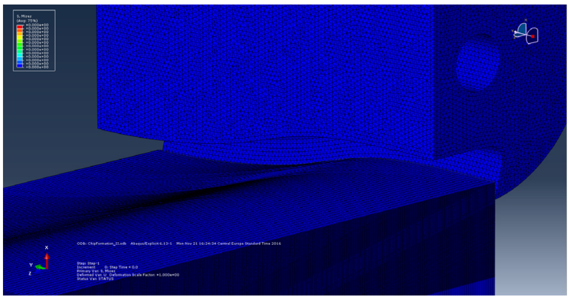


Figure 5. Initial state of the simulation

The simulation confirmed that the stress distribution within the material, along the blade is approximately constant, Fig. 6.

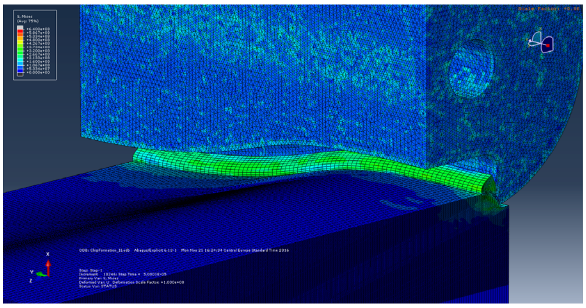


Figure 6. Simulation results

In real conditions this would affect uniform tool wear across the entire rake surface, which would result in minimized vibrations during the machining process. The aforementioned contributes directly to optimizing the tool life and uniform distribution of roughness across the workpiece machined surface.

The analysis of FEM results was employed to confirm the validity of such method of design and use of complex-geometry form tools. Taking into account the above mentioned, conditions were created to take the final step in the analysis of tool design methodology, and it was to inspect the workpiece obtained with such form tool.

5. EXPERIMENTAL VERIFICATION

Experimental verification is used to test the machining accuracy of the workpiece obtained by turning. Machining was performed with a form tool built according to the CAD model, which satisfied the FEM analysis testing, as given in section 4. The form tool made and a part of its machining process are shown in Fig. 7. The material used to make a form tool was H11/1.2343/X37CrMoV5-1.

For the needs of experimental verification, the workpiece material DOCAMID (PA-polyamide) was used. Machining was performed on Computer Numerical Control (CNC) lathe according to recommended cutting modes for given machining conditions, Fig. 8. For a more complete analysis, 20 workpieces were machined.

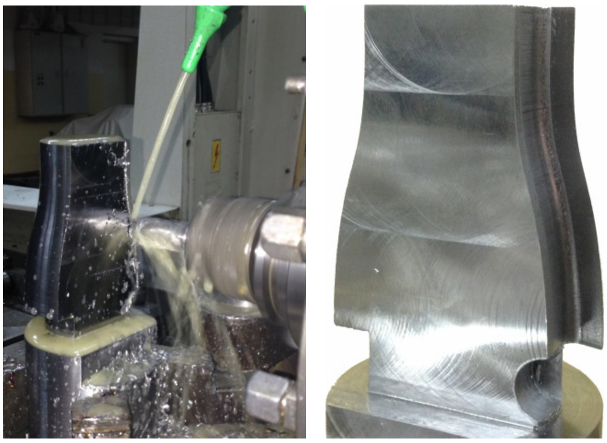


Figure 7. Complex-geometry form tool

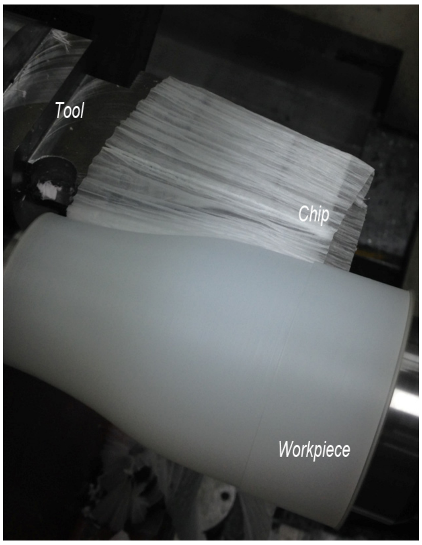


Figure 8. The machining process with a built form tool

The form tool was tested for accuracy on a random sample of the part. A point cloud was obtained by scanning with a laser scanner ZScanner®700 according to the procedure [14], Fig.9.

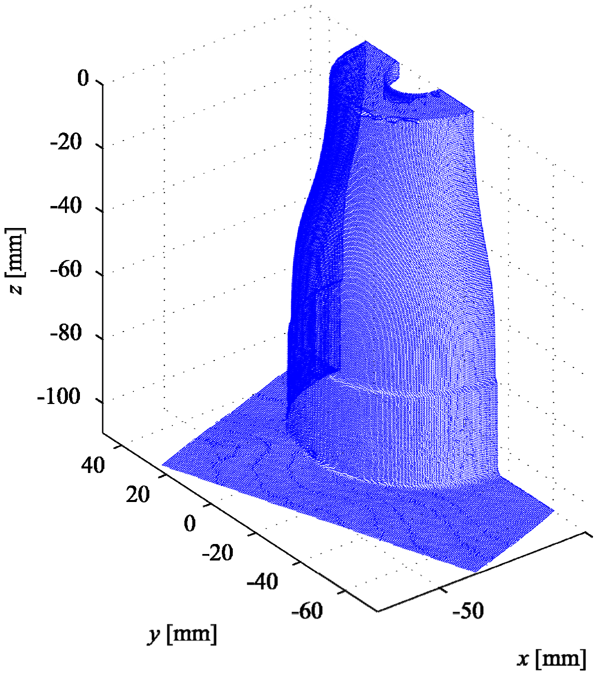
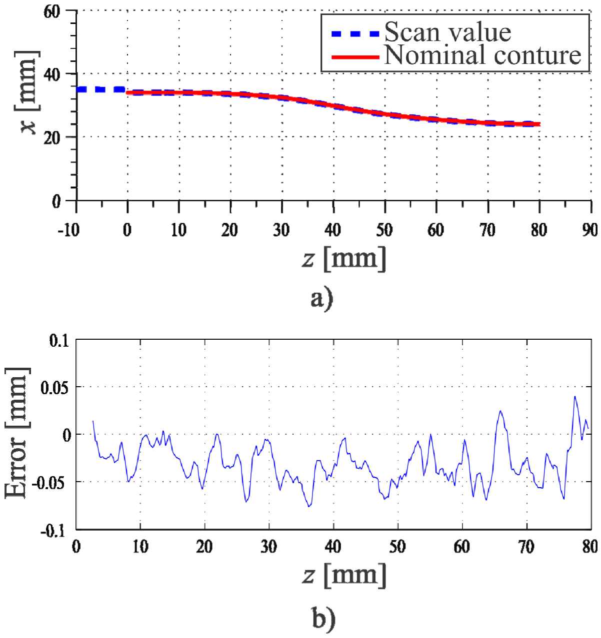


Figure 9. Point cloud of the workpiece

For the needs of experimental verification, the workpiece material DOCAMID (PA-polyamide) was used. Machining was performed on a Computer Numerical Control (CNC) lathe according to recommended cutting modes for given machining conditions, Fig. 8. For a more complete analysis, 20 workpieces were machined.

It is noticeable in Fig. 10b that the value of deviation ranges from -0.076 mm to 0.039 mm. Since the form tool was built for making parts that are within tolerance limits of free dimensions, the obtained deviation can be considered acceptable. It is also noticeable in the diagram that as coordinate *z* raises the value of deviation increases, which may be attributed to the increasing intensity of vibrations of workpiece segment located farther from the place of clamping.



a)

b)

Figure 10. Comparative representation of the workpiece contours: with nominal contour (a), deviation from the form (b)

6. CONCLUSION

The paper presents the design method of form tools by implementing contemporary CAD systems. The design methodology is based on the application of differential calculus for parametrically described curves and complex surfaces. Apart from detailed description of developed methodology, computations were done and described by FEM. The FEM was used to check the CAD model of a form tool, prior to creating its physical model. The possibility of machining with a form tool was experimentally confirmed, by designed contemporary methods. Scanning of the workpiece for inspection of the workpiece shape and dimensions, and further processing of data from the point cloud confirmed that accuracy of the part made with such type of tool completely meets the expectations. It was verified that machining was carried out within allowable deviation values. All above mentioned confirms that it is justifiable to use such approach in the design of form tools that would have a constant rake angle across the entire cutting edge, which would ensure longer tool life and better quality of workpiece machined surface. The major goal is to minimize machining cost, and thereby the final product cost.

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САВРЕМЕНИ ПРИСТУП ПРОЈЕКТОВАЊА КРУЖНИХ ПРОФИЛНИХ СТРУГАРСКИХ НОЖЕВА ЗА ИЗРАДУ ДЕЛОВА СЛОЖЕНЕ ГЕОМЕТРИЈЕ

М. Пјевић, Г. Младеновић, Љ. Тановић, Р. Пузовић

Примена профилних стругарских ножева у индустрији присутна је уназад неколико деценија. Употреба профилних ножева у индустрији је у експанзији, а ову све већу популарност могу приписати смањењу трошкова производње и уштеде времена обраде. Са друге стране, један од главних недостатака представља сам метод њиховог пројектовања. Овај недостатак се огледа кроз ограниченост обраде праволинијских и лучних сегмената изратка. Грудни угао за сваки сегмент има различиту вредност, што представља додатно ограничење.

У случају да је неопходна примена профилних ножева за израду делова сложене геометрије, вредност грудног угла захтевала би да буде нула. У овом раду представљен је савремен начин пројектовања кружних профилних ножева применом CAD система. На овај начин, не само да се обезбеђује константна вредност грудног угла дуж целог сечива која може бити и различита од нуле, већ се обезбеђује и оптимална геометрија алата за обраду жељеног материјала. Додатно је извршена и експериментална провера геометрије профилног ножа пројектованог уз помоћ нове методе.