Development of a New CNC Grinding Machine for 3+2-Axis Grinding of the Profile Rotary Milling Cutter

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Due to the great expansion of woodworking, profile tools manufacturing has become current and in demand. In wood industry there are two large groups of tools: rotary and spindle milling cutters that can be profile or flat. The technology of making profile rotary milling cutters requires, apart from cutting, turning, milling, 5-axis grinding operation that is performed on a 5-axis CNC grinding machine with the $A'OXYZC$ configuration. It is a machine of a very complex kinematics and high cost-price. The paper presents a new machine that has been built for 3+2-axis grinding - Profilator 100,used for industrial manufacturing of rotary and spindle profile milling cutters. The accuracy of measures and shapes of the profile cutters built on Profilator 100 is of a high level and in industrial exploitation the difference is not observed between the profile cutters built on 5-axis CNC grinding machines. Regarding technoeconomic cost-effectiveness, production costs of Profilator 100 are lower even by ten times compared to the cost-price of 5-axis CNC grinding machines of renowned world manufacturers such as Schneeberger and Volmer.

Key words: **CNC grinding machine, Grinding, Rotary milling cutter, Hard metal.**

Introduction

DUE to the great expansion of woodworking [1], the production of profile tools has become very current and in demand. In wood industry, there are two large groups of tools: rotary and end milling cutters that can be profile or flat. Geometry of both types of cutters is complex [2, 3] therefore cutter design and production procedures are very complicated. Profile cutters highlighted in this paper are used for making complex surfaces on the workpiece (bar and plate shaped semifinished wood products) in a single pass on appropriate machines, which raises productivity and does not require a highly skilled workforce. Profile cutters have a complex-shape cutting edge that consists of basic geometric features (straight line and segments of a circular arc) [4]. The major requirement for tool construction is creating a shape of the cutting edge that can produce a desired shape of the workpiece [5], where the shape of the cutting edge is obtained by applying some of the CAD software package [6] or by developing a mathematical model [7, 8].

Although the grinding method falls into the category of conventional machining methods, it often happens, from one case to another, that geometric surfaces made on the workpiece differ greatly from each other. For that reason, not infrequently, CNC grinders are built as special-purpose machines and used for making complex standard geometric surfaces on a random workpiece. One of such machines is featured in the research

paper [9]. The CNC grinder is used for sharpening industrial cutting blades with a straight cutting edge. Forming blade geometry is a complex task so that 5-axis CNC grinder is used for the purpose. Five-axis CNC grinder intended for grinding of gears is described in research paper [10] and five-axis CNC grinder for grinding turbine blades is shown in the paper [11]. For making cutting edge of the rotary milling cutters, CNC grinders are also used such as those presented in [12, 13].

Five-axis CNC grinders, as well as other CNC machines, require an appropriate program that controls machine drive axes to realize the formation of a desired shape. CNC grinders are special-purpose machines of complex kinematics and are not that much common as other CNC machines such as CNC lathes and CNC milling cutters. This is the major reason why broadly used CAM software packages do not have appropriate modules for defining tool motion during machining based on which APT file is created nor do they have appropriate postprocessors for generating G-code programs [14]. A specialized software package Quinto [15,16] is used for CNC grinders [12, 13] to obtain the program in G-code format. To avoid the use of the specialized software packages, the authors in [17, 18] demonstrate the methods of programming a five-axis CNC grinder when making a milling cutter with the complex cutting edge geometry.

As mentioned above, the kinematics of CNC grinders is very complex like the manner of programming itself. The

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objective of research presented in this scientific paper is to develop a CNC grinder of a simpler kinematics, which does not require specialized software packages for programming or complex mathematical calculations. Consequently, within its framework, the paper presents the development of a 3-axis grinder with which by using two indexing apparatuses the rotary cutters with a complex cutting edge shape can be made. Profile making on a cutting plate is performed by programmed grinding wheel motion in the three axes direction but after taking a desired workpiece orientation, using indexing apparatuses. For that reason, the entire concept is referred to as the concept of 3+2-axis grinding for making profile rotary milling cutters.

The concept of a new CNC grinder – PROFILATOR 100

The idea for developing a new CNC grinder stems from the five-axis grinder *Schneeberger-Sirius,* whose schematic representation is given in Fig.1. The *Schneeberger-Sirius* grinder has three translational and two rotary drive axes. The workpiece performs rotary motion around axis *X* (axis *A*), while all other motions are performed by the tool (grinding plate). Composition of motion of all five drive axes yields the desired cutting edge profile and geometry of the entire cutting plate that includes rake, clearance and axial angles [2, 3].
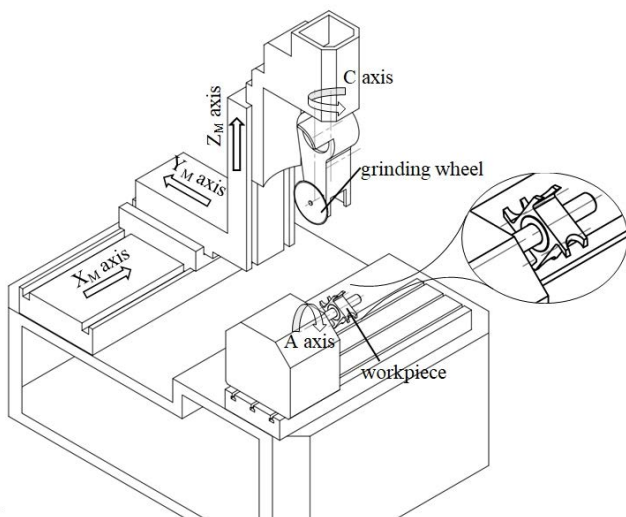
Figure 2. Schematic representation of 3+2-axis machining operation: 1) Indexing apparatus, 2) Machine rotating worktable, 3) Main spindle, 4) Machine vertical column, 5) Support structure.

Figure 1. Schematic representation of a 5-axis grinding machine *Schneeberger-Sirius*

Schematic representation of a new developed grinder is given in Fig.2. As shown, the workpiece desired orientation is done using a horizontal indexing apparatus (*C'*) and vertical indexing apparatus (*B'*) also referred to as rotating worktable.

During machining the workpiece performs translational motion along axis *X* and the tool (grinding plate) is moving along axes *Y* and *Z*. The composition of these three motions with occupied angles B' and C' yields the desired profile of the cutting edge. Configuration of the new CNC grinder is identical with the configuration of the horizontal machining center LOLA-HBG50 (Fig.3.). Therefore, the machine tool itself was used for experiments carried out prior to the design itself and prototype making of a new CNC grinder. The text below shows experimental results on HMC, which confirm that the concept of the 3+2-axis machining on HMC can be applied for making profile rotary milling cutters, thereby justifying the building of CNC grinder prototype that can be used to accomplish this concept.
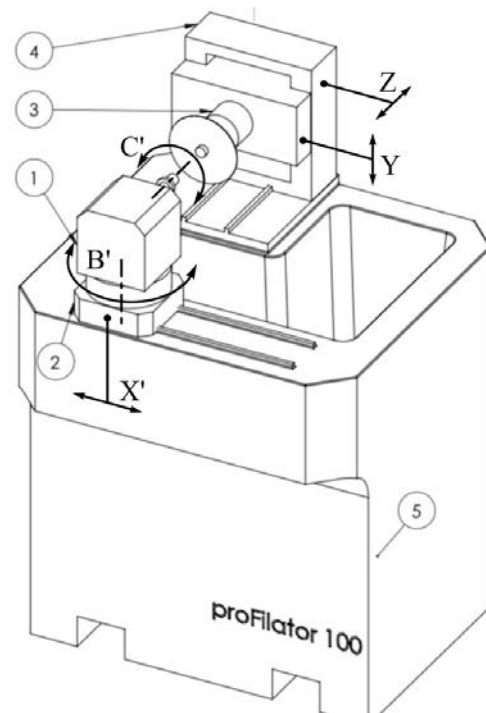
Figure 3. 3+2-axis grinding operation on a horizontal machining center

Method of forming the machined surface when machining with a profile rotary milling cutter

Method of forming the machined surface is realized by the cutter rotating around its axis, whereby the final profile is obtained in the so-called plane of the profile, which represents the basic plane for the cutter, Fig.4. In each point of the cutter profile K_{si}, a constant clearance angle must be realized. Each cutter point K_{si} by rotating around its axis passes through a corresponding point in the plane of the profile K_{pi}.
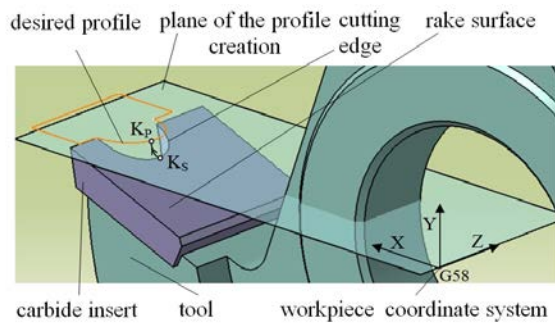
Figure 4. Creating profile on tool rake surface based on desired profile

Basically, the approach to producing profile milling cutters on a 5-axis CNC grinder is that the cutting kinematics (method of forming the machined surface) with a profile rotary cutter is the basis for the grinding kinematics.

3+2-axis grinding operation on a horizontal machining center

Machining centers are basic modules of flexible technological systems and their construction is based on the system of modular design and manufacturing [19]. Machining centers have tool magazines and can perform relative multi-axis tool motion relative to the workpiece and are successufully used for turning, boring, milling, grinding. Based on a broad spectrum of the machining center applications, a new concept of 3+2-axis grinding has been developed as described in scientific paper [20].

Using the concept of the 3+2-axis machining [20] for the grinding method, and establishing a new concept for the 3+2 axis grinding, it is possible to make a profile milling tool on a horizontal machining center LOLA HBG-50 (configuration B' $X'OYZ$) with adequately positioned indexing apparatus on the worktable, as shown in Fig. 3. When developing the program for making a profile milling cutter, standard G-code functions are used [14], with exclusively linear spatial interpolation figuring in the program, which means that each complex profile is discretized by rectilinear segments.

The horizontal machining center (HMC) is intended for machining parts of larger overall dimensions and represents a robust machine with large axes travel. The majority of HMC have sliding guides and the entire machine is designed in such way that rough (and fine) milling operations can be performed on it with extremely high cutting resistances.

Since measures of the rotary milling cutters range from the final diameter of ϕ100 to ϕ300, it is concluded that production of these cutters would be justified in a smaller amount. The reasons why rotary milling cutters would not be manufactured in small serial production on a horizontal 3-axis maching center are:
- Special type of emulsion adequate for hard metal (carbide) machining with a diamond grinding plate is needed. In its chemical composition this type of emulsion is completely different from the emulsion used on HMC for classical machining. The emulsion for grinding operation has a high flash point.
- higher pressure and emulsion flow on the nozzle is required,
- a closed cabin is needed due to large emulsion spraying and evaporation. The cabin increases the machine operator safety,
- chip – powder occurring during grinding is very aggressive when combined with emulsion, and adheres easily to all surfaces on the machine, especially on sliding tracks that are not protected on HMC and can be easily damaged,

- due to smaller sizes of rotary milling cutters during machining a slider relative to the HMC guide takes almost identical positions, which causes concentrated wear of the guides only on one part and their damage,
- the x-axis travel is not sufficient in case of machining large-diameter tools, given that the final grinding pass of a complex cutting edge is performed with a rotating swivel worktable (together with an indexing apparatus) by angle B.

Design and development of a prototype of CNC grinding machine for 3+2-axis grinding operation

Some of the mentioned disadvantages on the HMC for serial production of profile rotary or spindle cutters can be eliminated, however due to the problems with emulsion and workspace, i.e. the x-axis travel, as well as frequent use of HMC for classical machining of the large overall-dimensions parts, it would not be suitable.

Considering that:
- a new concept of 3+2-axis grinding on a horizontal machining center is verified and a profile rotary milling cutter has been built [16],
- disadvantages mentioned throughout using the machining center for 3+2 axis grinding operation, as well as
- small values of the cutting resistance that occur during grinding

The concept of a new CNC grinding machine – PROFILATOR 100 has been developed after the machining center model. It is a grinding machine that has 3 CNC translatory axes $X'YZ$ and two additional positioning axes that are manually driven. The X' axis is positioned asymmetrically relative to the spindle axis. It is positioned more to the right side, viewed from the workpiece, towards the machine column so that large-diameter tools, even by 300 mm, can be machined. Machine travel along axis Y is modified – reduced relative to HMC and amounts only to 100 mm because the grinding plate motion along axis Y is used exclusively to ensure constant flank angle on the rotary milling cutter along the overall complex cutting edge. Machine travel along axis Z is reduced relative to HMC and amounts to 150 mm. It is common for rotary milling cutters to have widths maximum to approx. 100 mm, so travel range along axis Z is sufficient to make most variants of the profile milling tool.
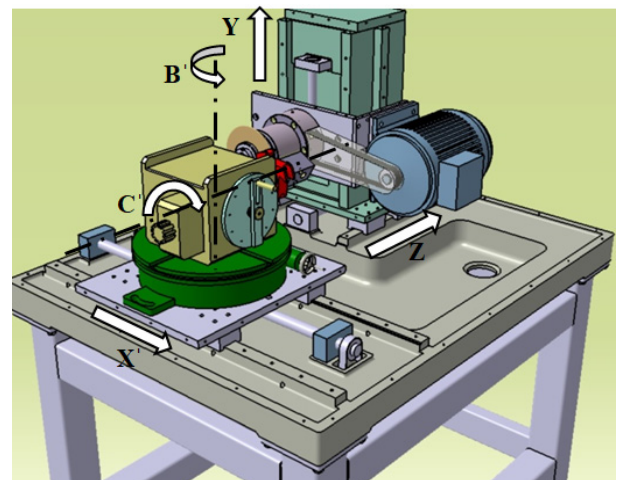

Figure 5. 3D model of a grinding machine for 3+2-axis machining operation

Configuration of a new grinding machine Profilator 100 is $B'C'X'OYZ$. Positioning axes $B'C'$ are used to position the workpiece (rotary milling cutter) prior to the initiation of grinding. Axis B' ensures workpiece rotation around axis Y because of very common complex configurations of the rotary

cutter profile that requires to ensure radial or axial relief angles, therefore it is necessary to rotate it by angle ±B'. Axis C' as a positioning axis ensures that after fine grinding, i.e. making one tooth by rotation around axis Z, the next tooth is brought to the machining position. Positioning axes B'C' represent respectively one round apparatus (rotating worktable) on which a classical indexing apparatus with differential division is mounted. Indexing apparatus that ensures axis C' has on itself a ground and nitrided pin on which the workpiece, in this case rotary cutter, is based and clamped. The 3D model of a new CNC grinder Profilator 100 is shown in Figures 5 and 6.
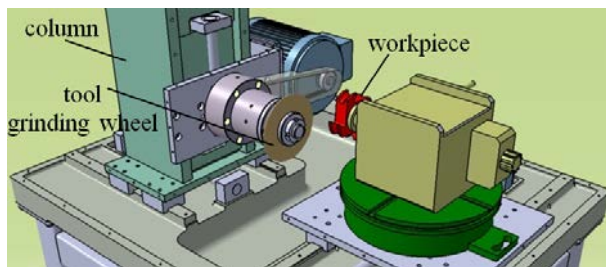

Figure 6. Positions of grinding plate and workpiece on a 3+2-axis machine

In this wqay, it is possible to produce any profile on a rotary cutter, as reported in paper [16]. Based on 3D model from Figures 5 and 6, the building of the machine itself has been started. Some steps of the machine building are displayed in Fig.7.

Figure 7. Steps of building 3+2-axis CNC machine – Profilator 100

Figures 7a and 7c show a cast part of the support structure where all other elements of the machine mechanism are positioned. The cast part of the structure is set on a welded support structure (Fig.7b). The unit which consists of two pairs of guides and sliders, two helical spindles, two nuts, and two servo motors, which allows for tool motion in the directions of axes Y and Z is set on the cast structure as shown in Figures 7d and 7e. All positioned machine elements used to realize motions in the direction of axes X,Y and Z are given in Fig.7f. Machine support structure is combined: welded box-like profiles 100x100 with wall thickness 5 mm, cast part of the support structure, where all machine elements are located. Guides are linear roller guides, the power of driving motors of axes XYZ is 400W, the main spindle engine power is 2.2 kW. Translational motion of the sliders is realized by transmission of the helical spindle and nut. Machine overall dimensions are 1500x1800x1500mm (BxHxV). Machine manufacturing costs approx. 17,000 euros. The final appearance of the built CNC grinder is shown in Figures 8 and 9.
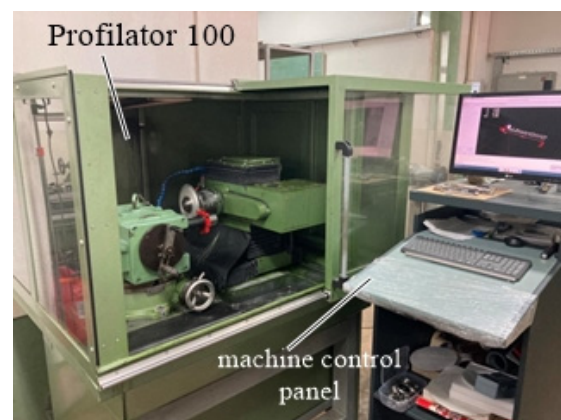

Figure 8. Representation of a built 3+2-axis CNC machine – Profilator 100

Figure 9. Representation of a built 3+2-axis grinder – Profilator 100 (back side view)

Control system of CNC grinding machine - Profilator 100

Based on the earlier works of the authors [21, 22], CNC control system of a grinding machine has been developed based on an open architecture software system, initially developed by NIST (**N**ational **I**nstitute of **S**tandards and **T**echnology) with the idea to be the basis for development of intelligent manufacturing control systems. Control unit of the new CNC grinder Profilator 100 is shown in Fig.10.

Figure 10. Control unit of the CNC machine - Profilator 100

Orginally promoted RCS (**R**eal-Time **C**ontrol **S**ystem) software library has evolved over the years and resulted in the development of numerous control applications, including LinuxCNC, *real-time* control open architecture software that can be used for control of a large variety of machine tools and robots. Extensive work and experience invested in RCS and LinuxCNC for years, produced a good technological basis for implementing own control system and programming of the Profilator 100 grinder. Configuring the control system based on LinuxCNC for the grinder Profilator 100 control involved creating the configuration directory with files that contain parameters such as feedrates, speeds and accelerations. Additionally, initialization sequence as a hardware/software interface is defined in the corresponding files.

Testing and trial operation of the Profilator 100

The built machine Profilator 100 has been tested and verified by making tools whose body is made of structural steel and profile edge of hard metal (carbide-widia) from series H and is used for working of wood, plastics and aluminum. A tool with a complex cutting edge profile has been chosen for testing the machine. The profile of the cutting edge is shown in Fig.11.
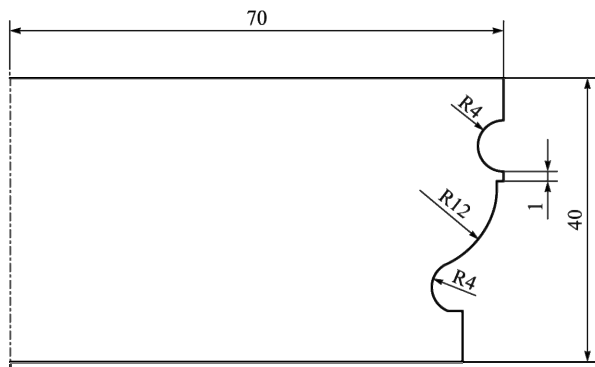

Figure 11. A complex profile for testing the Profilator 100 CNC machine

The complexity of the profile is reflected in the parts of the profile of small dimensions and in the existence of both convex

and concave radii that need to be made. The final dimensions (diameter and width of the made profile milling tool) will show the precision of the machine. The made radii and their corresponding geometry (obtained rake and clearance angles) will show the possibility of applying 3+2 axis grinding method for making a milling tool of complex geometry. Steps of bulding a profile cutter are presented in Fig.12.
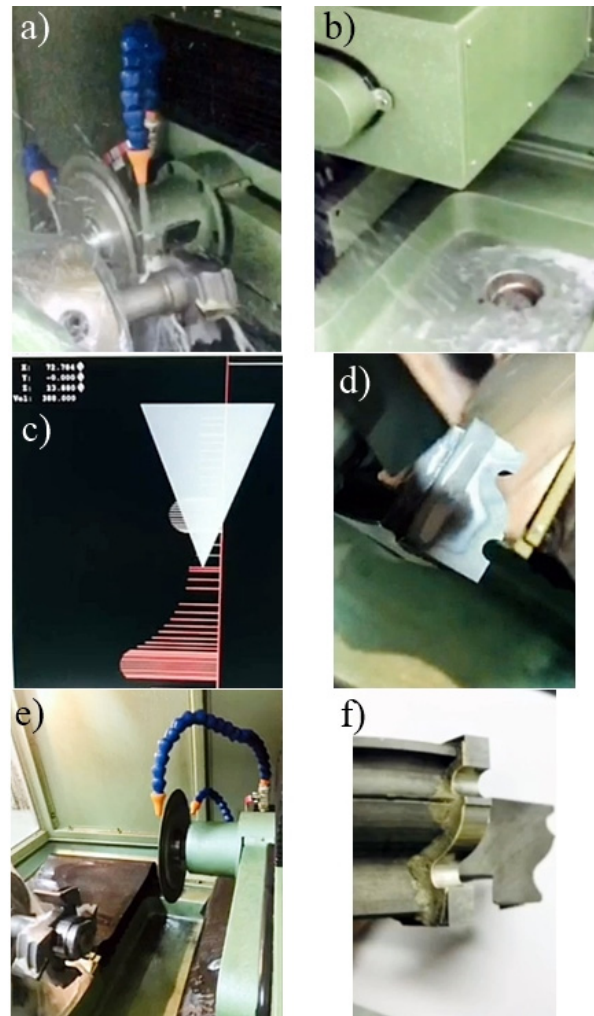

Figure 12. Making a profile cutter on a CNC machine Profilator 100

As it can be seen from Figures 12a and 12b, machining by grinding is performed with mandatory application of coolants and lubricants, which is intended exclusively for hard metal machining with a diamond grinding plate with a metal joint. Verification of the toolpath (grinding plate) in LinuxCNC environment is shown in Fig.12c. Final appearance of the rotary cutter profile, which has a constant clearance angle along the entire edge profile is displayed in Figuress 12d, 12e and 12f. The profile realized is of a high shape and measures accuracy and proved to be excellent in exploitation.

Conclusion

The paper presents a new machine and its build for 3+2-axis grinding Profilator 100 that is used for industrial manufacturing of rotary and spindle profile cutters.

The idea of developing such specific grinder of $B'C'X'YZ$ configuration has been inspired by the verified technology of building profile rotary cutters on a horizontal machining center using the strategy of 3+2-axis grinding, as explained in detail in [16].

Considering mentioned disadvantages of a horizontal machining center when it is used for 3+2-axis grinding, a new

machine for 3+2-axis grinding Profilator 100 has been built, suitable in its technical characteristics for industrial manufacturing of profile rotary cutters. Irrespective of the fact that horizontal machining center is several times larger in its overall dimensions than Profilator 100, a rotary cutter of 200 mm diameter could not be built on it due to a small X' axis travel, whereas due to asymmetrically positioned X' axis relative to the main spindle axis on Profilator 100, rotary cutters of the diameter as high as 300 mm can be made. The accuracy of measures and shapes of profile cutters produced on Profilator 100 is on a high level and in industrial exploitation no difference is observed between profile cutters made on 5-axis CNC grinders. Regarding technoeconomic cost-effectiveness, manufacturing costs of Profilator 100 are by ten times lower compared to the cost-price of 5-axis CNC grinders of renowned world manufacturers such as Schneeberger and Volmer with the average price of approx.180,000 euros.

Future research will be directed towards the development of a five-axis machine. The research will include the development of the hardware part of the machine, the analysis of the kinematics of the machine, the solution of the kinematic problems of the machine and the development of the control system. The research will include the definition and analysis of processing strategies on the basis of which it will be possible to generate G-code programs using computers. This involves developing a dedicated user-friendly application that will generate the G-code programs from which the five-axis CNC grinding machine will perform the machining.

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Razvoj nove CNC brusilice za 3+2 osno brušenje profilnih koturatih glodala

Zbog velike ekspanzije obrade drveta izrada profilnih alata je postala vrlo aktuelna i tražena. U drvnoj industriji postoje dve velike grupe alata: koturasta i vretenasta glodala koja mogu biti profilna ili ravna. Tehnologija izrade profilnih koturastih glodala zahteva, pored sečenja, struganja, glodanja, I petoosno brušenje koje se izvodi na petoosnoj CNC busilici sa konfiguracijom *A'OXYZC*. U pitanju je mašina sa vrlo složenom kinematikom i visokom cenom koštanja. U ovom radu prikazana je I napravljena nova mašine za 3+2 osno brušenje Profilator 100 koja se koristi za industrijsku izradu koturastih i vretenastih profilnih glodala. Tačnost mera i oblika napravljenih profilnih glodala na Profilatoru 100 je na visokom nivou i u industrijskoj eksploataciji ne uočava se razlika između napravljenih profilnih glodala na industrijskim petoosnim CNC brusilicama. Sa aspekta tehnoekonomske isplativosti prozvodni troškovi izrade Profilatora 100 su i do deset puta manji u odnosu na cenu koštanja petoosnih CNC brusilica renomiranih svetskih proizvođača kao što su Schneeberger i Volmer.

Key words: **CNC brusilica, Brušenje, Koturasta glodala, Tvrdi metal.**