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SELECTED EXAMPLES OF RESEARCH AND KNOWLEDGE TRANSFER IN THE AREA OF MACHINE BUILDING AND EXPLOITATION

Key words: machinery, construction, mechanical technology, precision machining, laser machining, unconventional machining (EDM, ECM), residual stresses.

Abstract: The variety of possible construction solutions of machinery and technological equipment and research related to these solutions require knowledge of materials engineering, mechanics, strength of materials, electronics and mechatronics, the basics of machine construction and machine technology. It is impossible to cover such an extensive range of required information in just one publication. Therefore, the authors of this article concentrated only on selected examples of research, construction solutions, and technological recommendations that have found application in industrial environments. Topics presented in the article include the following:

– A research and design solution of a specialized drill for making holes in the diameter range of 4 to mm to a depth of 1600 mm;
– Shaping elements by precision machining;
– A research workstation for precision machining of microelements with the use of unconventional technologies – laser machining and Electrical Discharge Machining (EDM); and,

The influence of machining conditions on the state of residual stresses in the surface layer of the workpiece.
The choice of the above examples shows how wide is the area of problems which can be presented in the journal "Journal of Machine Construction and Maintenance."

Wybrane przykłady badań i transferu wiedzy w zakresie budowy i eksploatacji maszyn

Słowa kluczowe: maszyny, konstrukcja, technologia mechaniczna, obróbka precyzyjna, obróbka laserowa, metody niekonwencjonalne (EDM, ECM), naprężenia własne.

Streszczenie: Różnorodność rozwiązań konstrukcyjnych urządzeń i wyposażenia technicznego oraz prowadzonych badań w zakresie tych rozwiązań wymaga wiedzy z obszaru inżynierii materiałowej, mechaniki, wytrzymałości materiałów, elektroniki i mechatroniki, podstaw budowy maszyn oraz technologii maszyn. Nie jest możliwe, aby w jednej publikacji objąć tak szeroki zakres merytoryczny, dlatego też, autorzy artykułu skoncentrowali się na wybranych przykładach badań, rozwiązań konstrukcyjnych oraz zaleceniach technologicznych, które realizowano w warunkach przemysłowych. Zaprezentowana w artykule tematyka obejmuje: Badania oraz rozwiązania projektowe specjalizowanego wiertła do wiercenia otworów o średnicy od f4 do ϕ32 mm do głębokości 160 mm; Kształtowanie elementów w procesie obróbki precyzyjnej; Stanowisko badawcze do obróbki precyzyjnej mikroelementów z wykorzystaniem niekonwencjonalnych technologii – obróbki laserowej i obróbki elektroerozyjnej (EDM); Wpływ warunków obróbki skrawaniem na naprężenia własne w warstwie wierzchniej próbki.
Wybór powyższych przykładów pokazuje obszerność problematyki, która może być zaprezentowana w czasopiśmie "Journal of Machine Construction and Maintenance".

1. Machine and technology for deep hole drilling

Drilling long holes (which are most commonly described as deep holes), where the length is at least ten times greater than the diameter of the hole, is associated with a number of technical and technological problems. These problems are related with the difficulty of coolant supply to the machining area and the difficulty of chip removal from the holes. During the hole drilling process, a risk of significant execution errors may occur caused by tools of low stiffness. Such tools can lead to the imbalance of forces acting on the cutting edge of the drill tip caused by the wear of the cutting edge and changes in the structure of the workpiece. This has a significant impact on the straightness of the hole [1, 2, 3].

Numerous industrial queries on the possibility of deep hole drilling led to the cooperation with PROREST company in Brzeszcz. A specialized CNC machine tool WCZ140 was produced for hole drilling with the ration of the diameter of the hole equal to L/d 140. The task was achieved within the target project[1] that was 50% co-financed by NOT. In the first step of the task, a virtual model of the designed machine was developed (Fig. 1).

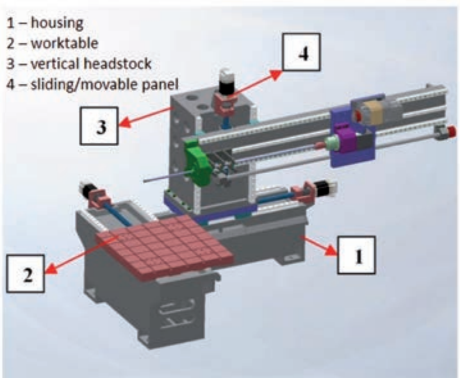

Fig. 1. Virtual model of the designed machine WCZ 140

Due to the high mass of intended elements (500kg), the housing (1) was designed in form of cast iron reinforced by suitable ribs. Appropriate calculations were done in order to assess whether the construction is accurate. Deformation of the housing were assessed under the load applied mainly by the weight of the workpiece and cutting forces with the assumed length of the drill holes up to 150 mm. Calculations were made in Solid Works. Examples of the analysis of the movement of the housing are presented in Figs. 2 and 3.

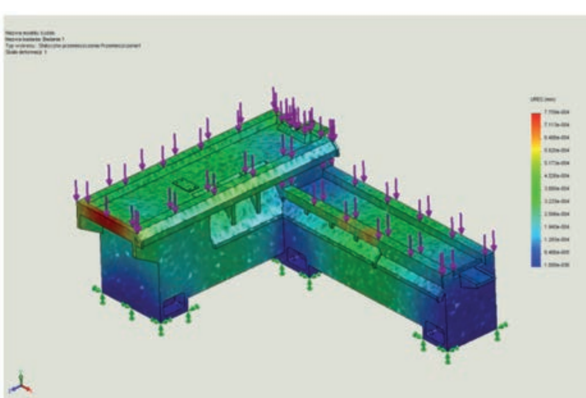

Fig. 2. The analysis of the movement distribution of the housing under the load of cutting forces and weight

The housing construction was enhanced based on the obtained results from analysis. The rib system was modified to eliminate, the excessive, unfavourable deformations.The workpiece was mounted on the movable table (2). Gundrills (ISCAR Company) were

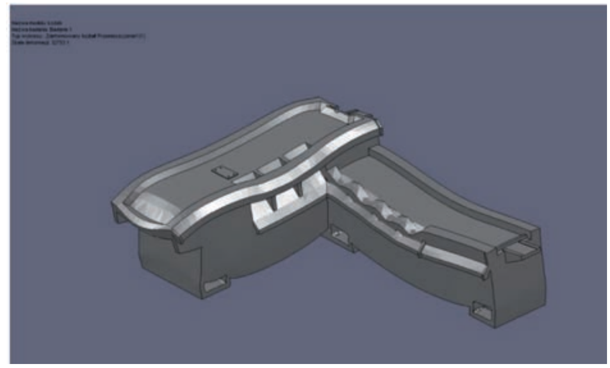

Fig. 3. A view of the substrate with calculated displacement

applied for deep holes [4]. The course and effects of the drilling process with gundrills can be determined by number of factors associated with the workpiece, tools, and conditions of the drilling process. For the proper functioning of the tools, an appropriate lead is required, which was solved by the use of three movable guides with guide rings.

A housing of vertical headstock (3) was added to the base construction of the drill, which significantly expanded the possibilities of machining. The box-like structure enables the mounting of the sliding/movable panel (3) for the machining of complex elements such as holes in housings. The machine tool consists of ball circulation guides. The machine is provided with a control system SINUMERIK 840D with independent drives of fast headstocks and drives of feed motion [5]. Torque moment of the main drive is equal to 12Nm and the maximum ration speed is 500 rpm.

During drilling of blind deep holes, the main problem is associated with the chip evacuation and maintaining safe working conditions of the tool (wear resistance of the tool needs to be avoided). Chip evacuation from the machining area enables supplying (by a spindle) of the machining fluids under the pressure of 10MPa.

To determine working conditions of the drill, the machine tool is equipped with a measuring system (Fig. 4). The use of an axial force sensor is reasonable for the monitoring of the deep hole drilling process. The sensor indicates interferences related with chip evacuation from the machining area. Periodic discontinuity of the drilling process is also justified, because it facilities chip removal and prevents damages (fractures) of the drill. It is also possible to use fluid flow sensors, which provide information to the surveillance system to reduce the liquid flow. When holes that supply machining fluids to the fluks of the drill are blocked or when channels that carry chips away from machining area are locked, fluid flow sensors can be used [6]. A machine tool that was created as a part of the project is shown in Fig. 5.

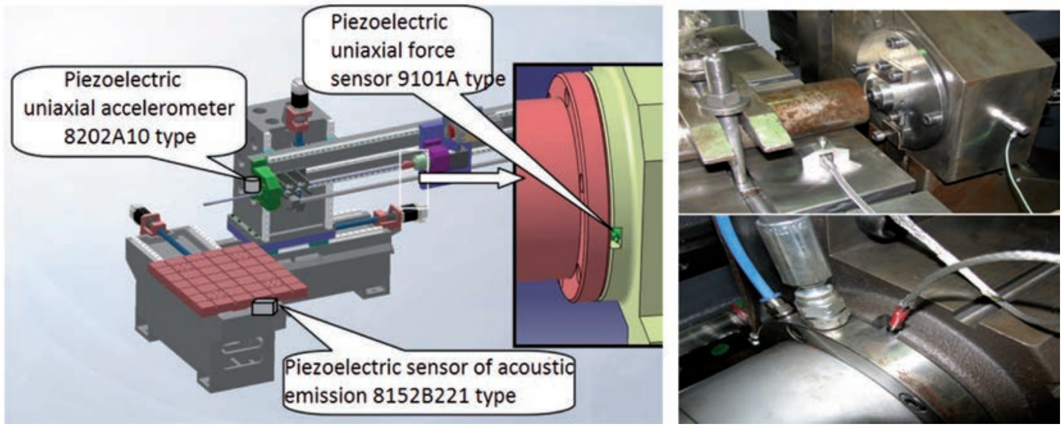

Fig. 4. The locations of sensors on the WCZ 140 drill during research

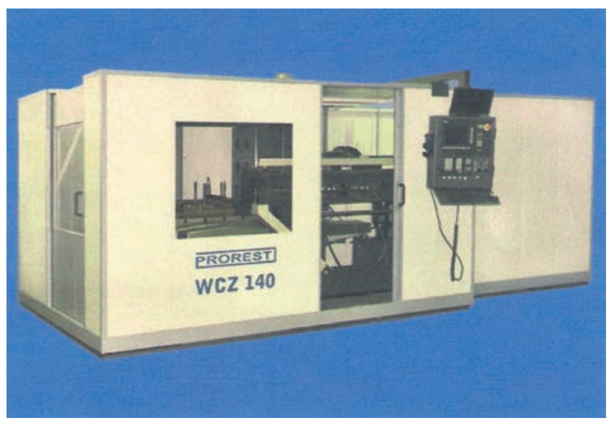

Fig. 5. Multitasking WCZ 140 drill for deep hole drilling in the diameter range of 4 to mm to a depth of 1600 mm

2. Shaping elements during precision machining

Compared to the machining of large size elements, the machining of microelements is almost a separate field. Examples of the machining of small-size elements and thin-walled elements are presented in Fig. 6. This kind of machining causes a number of problems associated with elastic and plastic deformation of the workpiece [7].

The difference between conventional manufacturing in microscale and micromachining includes several factors that influence the technical quality of the product, including the following:

– The microstructure of the workpiece (shape and size of the grains, type of a phase, inclusions);
– The material and properties of the cutting tool (micro hardness, fine-grained, type of a coating);
– The geometry of the tool (rake angle, cutting edge radius); and,
– Cutting parameters (mainly cutting speed).

Elastic deformations of the machining layer may cause vibrations and other problems. On the other hand, plastic deformations may be the cause of residual stresses and shape errors in the workpiece, which are very difficult to eliminate when they appear in the surface layer [9, 10]. Residual stresses and deformations of fragments of machining parts of machines generate significant costs in many machining operations, which

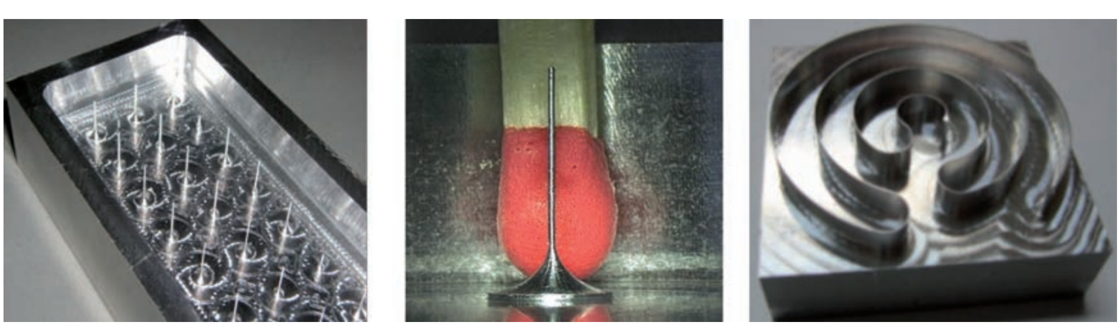

Fig. 6. Examples of performed small-sizes and thin-walled elements [8]

is associated with the formation of spoilages and with increased manufacturing time (fabrication of products in aircraft industry can be an example). Residual stresses can be caused by plastic deformations and thermal gradients generated in the workpiece during manufacturing operations.

The small sizes of machining traces require taking into account size effect [2, 11] and the impact of dislocations [12] at particular stages of the modelling of precision machining. In some cases, the thickness of the cutting layer is compared with the size of the cutting edge radius. Then the impact of the retention zone and "microflashes" on the value of the components of cutting forces can be significant. Machining errors need to be eliminated in order to obtained the required quality of the microelement and thin-walled elements. This can be done by the following:

– The optimization of machining strategies;
– The use of higher cutting speeds (HSC); and,
– The optimization of cutting parameters (f_z and a_e), taking into account the minimization of the perpendicular cutting speed to the machined surface of the workpiece.

The selection of an appropriate machining strategy is the basic method for the proper machining of thin-walled elements, where the value of the height to thickness ratio of the (milled) wall needs to be taken into account. Three different values of this ratio can be distinguished as follows and they are illustrated in Fig. 7 [6]:

1. A small value of the height to thickness ratio of the wall (<15:1),
2, A moderate value of the height to thickness ratio of the wall (<30:1), and
3. A high value of the height to thickness ratio of the wall (>30:1).

The number of toolpaths is determined by the size of the wall and by the axial depth of cut. To reduce the bending of the wall during machining, contact time between the cutting tool and the workpiece must be shortened. It can be done by applying higher values of the cutting speed and with a small value of the ratio (a_p/a_e). The crucial role is played by the stability of the machining system. When the support of milled thin-walled elements is not rigid enough, then "up-cut milling" must be applied.

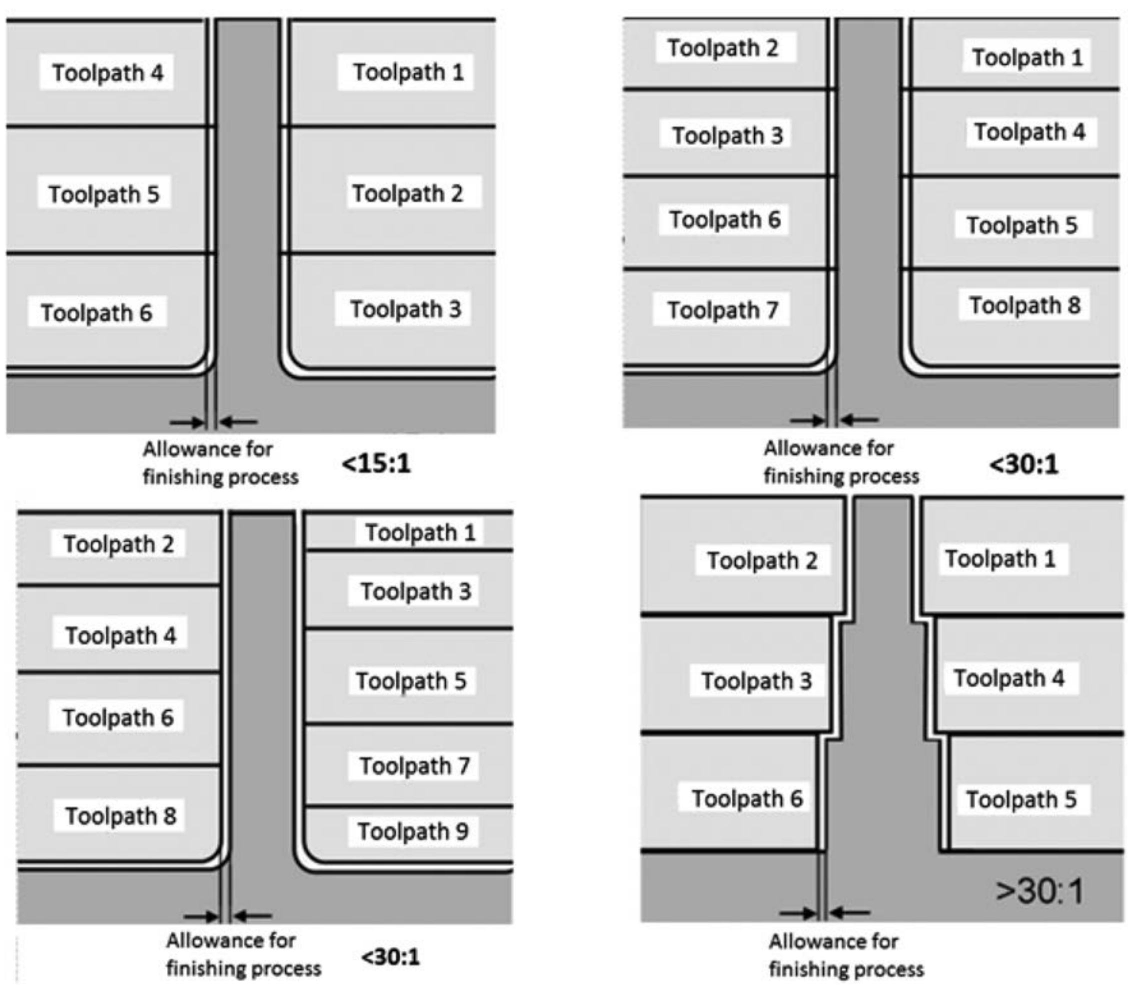

Fig. 7. Machining strategies of thin-walled elements depending on the height to thickness ratio of the milled wall

When the value of the height to thickness ratio of the wall is below 15:1, only one side of the wall should be machined in non-overlapping toolpaths. The same must be done for the opposite side of the wall. Allowance should be left on the both sides of the wall for further finishing machining processes.

The sides of the wall should be changed when the value of the height to thickness ratio of the wall is below 30:1. The milling process should be performed in non-overlapping toolpaths (milling at the same level) with the determined depth of cut. Better support of machined element is guaranteed when milling at different levels is used (when overlap occurs between the toolpaths on the opposite sides of the wall). A reduced depth of cut equal to $a_p/2$ should be used during first toolpath/pass. Allowance should always be left on both sides of the wall for further finishing machining processes.

The desired wall thickness should be achieved (with the use of “hemlock fir” method) along with the changing of the sides of the wall during machining at a high value of the height to thickness ratio of the wall (>30:1). During the machining process, a thinner layer of the workpiece is always supported by thicker layers.

The participation of materials with special properties (high fatigue strength, corrosion resistance, high strength-to-weight ratio and others) dedicated to specific application constantly grows. These materials belong to the group of difficult-to-cut materials; therefore, they require special shaping methods that fulfill the required quality standards [13, 14, 15].

Electrochemical machining (ECM), electrical discharge machining (EDM), and laser machining belong to the group of unconventional machining techniques that are used for the manufacturing of machine components (including microelements). These machining methods play a significant role in the phase of production planning of casts or tools manufacturing for planning, modelling or testing of new solutions.

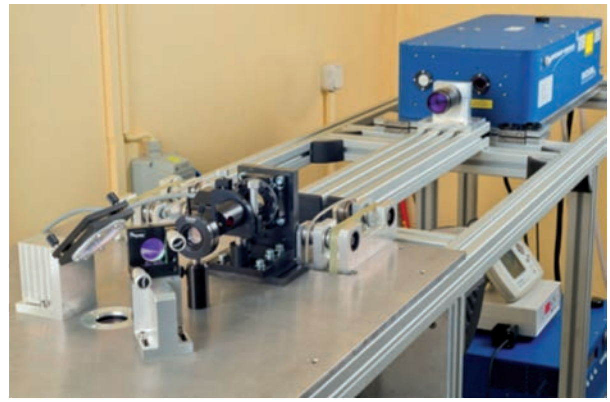

Fig. 8. Prototype workstation for laser machining[1]

They are also used for the manufacturing of special microstructures which can be used in MEMS systems or in the medical or pharmaceutical industries.

To conduct theresearch work, three prototypes of workstations were developed at Cracow University of Technology in Production Engineering Institute. These include workstations for abrasive, laser, electrochemical, and electrical discharge machining operations and are mainly intended for the machining of small-size elements.

The prototype workstation for laser machining is presented in Fig. 8. It consists of the following units: support frame, worktable XYZ, mounting plate for lens and mirrors with a lens handle, mounting plate for the laser with a power system, a positioning system, and a control system [16].

The prototype workstation for electro-discharge micromachining (Fig. 10) consists of the following functional units: the mechanical part, the process control system, the current power supply, and systems for preparation and circulation of fluids.

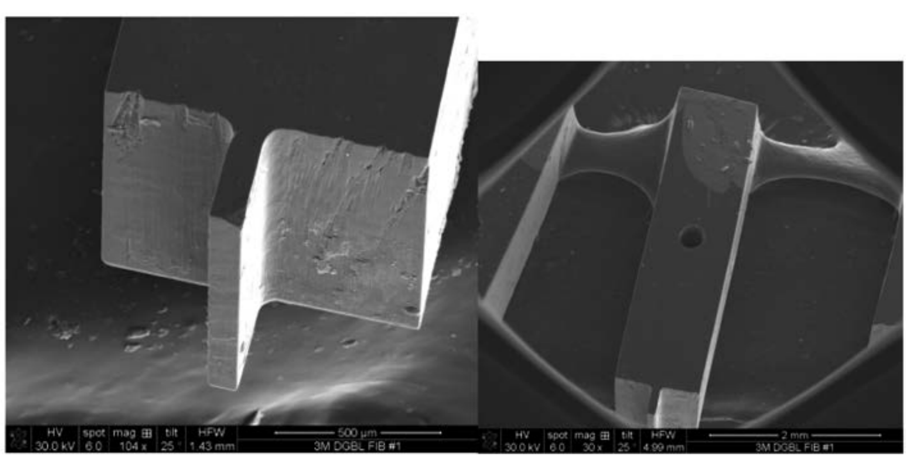

Fig. 9. Examples of diamond microelements made on the workstation for laser machining [13]

[1] Workstation designed by: D. Wyszyński.

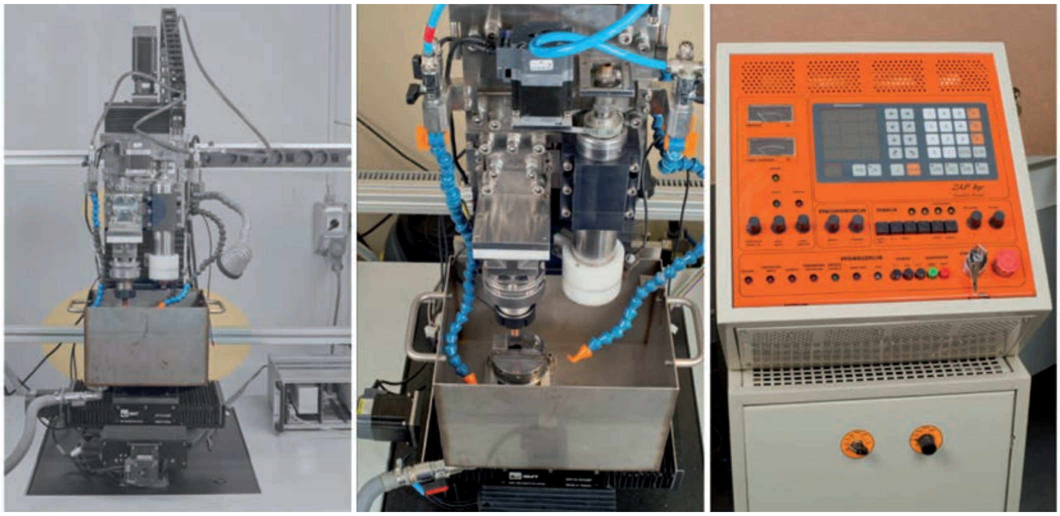

Fig. 10. Figures shows prototype workstation for electro-discharge micromachining with the mounting system of the workpiece, a bath for dielectric liquid, a power generator and a generator for programming the machining conditions[2]

Examples of the through-holes drilled in a SiSiC ceramic material on the prototype workstation with the use of a tube electrode of a 1mm diameter are presented in Fig. 11. Dielectric (Exxsol D80) is a mixture of hydrocarbons, and it flows through electrode at a pressure of 40bar. The technological quality of the drilled holes is determined by the machining conditions which can be seen in Fig. 11. The change of the thickness of the side gap also has an impact on the technological quality (Fig. 12).

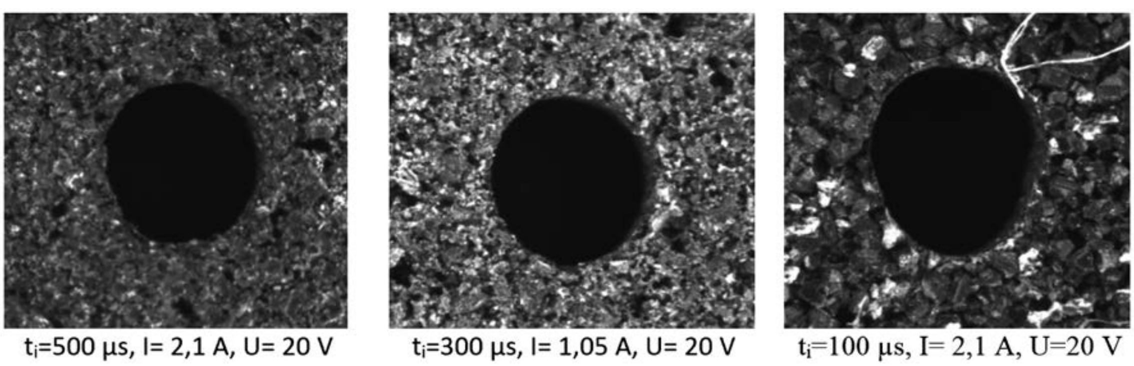

Fig. 11. Examples of the holes drilled in B_4C carbide for different input machining parameters: pulse time, I – current intensity, U – interelectrode voltage

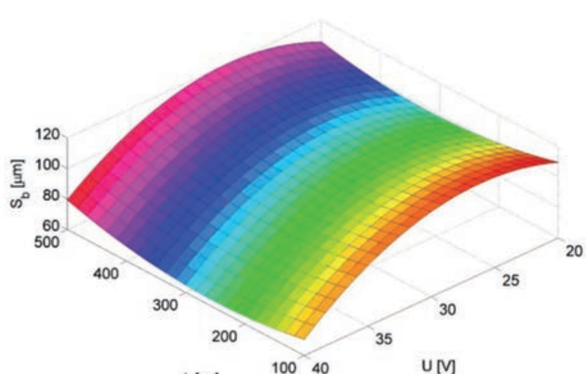

Fig. 12. The relationship between the thickness of the side gap, pulse time, of the duration impulse and interelectrode voltage U

[2] Workstation designed by: Lipiec P., Ruszaj A., Skoczypiec S.

Fig. 13. The prototype workstation for machining of spherical ceramic elements, a) the workstation with the control system, b) a module for preliminary machining

The prototype workstation for machining of spherical ceramic elements was developed based on the housing of the milling machine FNX-30P[3], and it is presented in Fig. 13.

The advantage of this workstation is the spindle machining system with no-speed control. Moreover, the milling machine FNX-30P can work in horizontal and vertical milling systems. Special abrasive tools with diamond grains were used for preliminary machining (Fig. 14a) of the workpiece (Fig. 14.c) and lapping iron was used in the finishing process (Fig. 14b) [17]. The research was performed in order to achieve a finished product (Fig. 14.d) in form of a head of the endoprothesis.

As a result of the technological process, a geometrical structure of the surface is created, that determines the correct functioning of the kinematic pair – the head of the prosthesis and acetabulum. An example of the spatial structure of the surface in the prosthetic's head sample (size 1 mm x 1 mm) is shown in Fig. 15.

4. Residual stresses in the surface layer after machining process

The operational quality of the products is mainly determined by the state of the surface layer formed during the machining process. The state influences the tribological wear in normal conditions, and it has a significant impact on the fatigue wear during variable loads (mechanical or thermal loads).

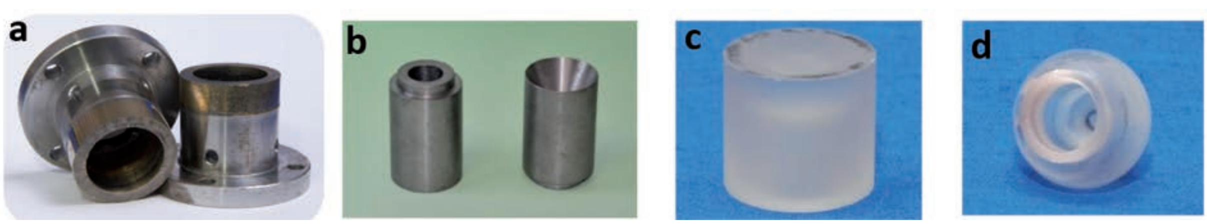

Fig. 14. Special tools: a) for preliminary machining of spherical elements, b) lapping iron for finishing machining, c) semi-finished product made out of single crystal sapphire, d) finished product

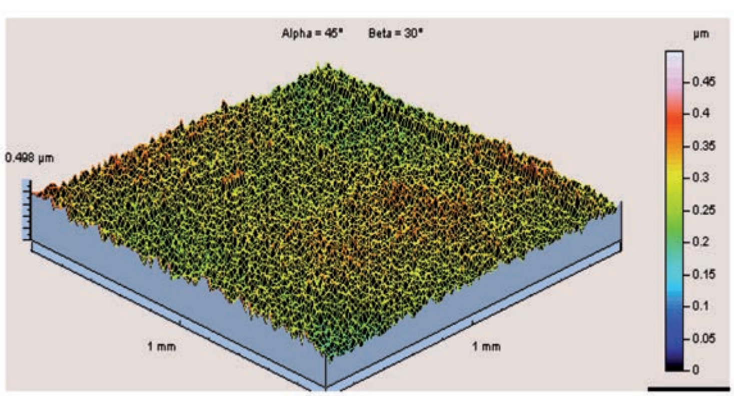

Fig. 15. The roughness of a spherical element after the finishing machining process performed by lapping iron and with a diamond micropowder abrasive paste

[3] Workstation designed by: Gawlik J., Cieciak S.

The components that are used in the aircraft industry have to work in extreme conditions, e.g., at elevated temperatures, and they are mainly made out of titanium and nickel based alloys. Therefore, samples made out of Ti6Al4V and Inconel 718 were used. They were subjected to the "up-cut" peripheral milling process performed by 4 cuts of sintered carbides cutters, and residual stresses were measured [18]. During the machining process, variable cutting parameters were used (Table. 1) in accordance with the rules of experiment planning.

Residual stresses were measured by XRD- $\sin^2\Psi$ on a diffractometer produced by Brukers. Deformations of the crystal lattice were measured for a selected family of lattice planes (hkl). The X-ray tests were performed on a diffractometer equipped with a lamp of a cobalt anode ((λ = 1,79026 [Å]) of 1400 W voltage. The research was carried out in the Institute for Sustainable Technologies – National Research Institute in Radom.

Residual stresses were measured in perpendicular and parallel directions toward the machined surface. Distributions of measured residual stresses were determined in Matlab and are presented in Figs. 16 and 17.

It should be noted that there is a great influence of the cutting conditions on the values and character of residual stresses. After the milling process, compressive residual stresses exist in the samples made out of Ti6Al4V, and tensile residual stresses are present in the surface layer of Inconel 718 samples. This information is very important for technologists and machine designers (while operating conditions planning), because the character and values of generated residual stresses influence the wear of cooperating parts.

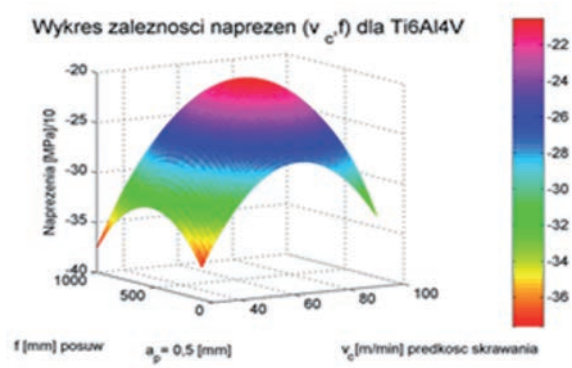

Fig. 16. The relationship between values of residual stresses measured in the perpendicular direction to the machined surface and cutting parameters (variable values of v_c, f) at constant depth of cut a_p = 0.5 [mm] for samples made out of Ti6Al4V

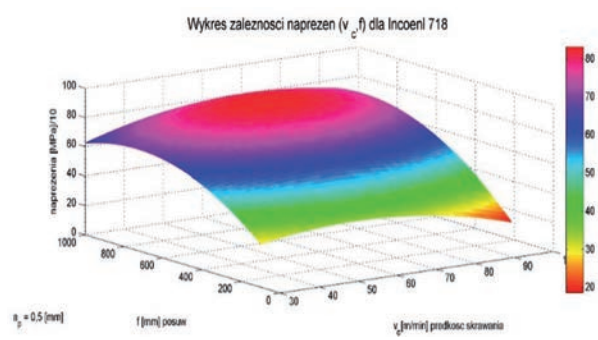

Fig. 17. The relationship between values of residual stresses measured in the perpendicular direction to the machined surface and cutting parameters (variable values of v_c, f) at constant depth of cut a_p= 0.5 [mm] for samples made out of Inconel 718

Table 1. Cutting parameters used during milling process

Material of the workpiece	Ti6Al4V – titanium based alloy			Inconel 718 – nickel based alloy		
α=1.215	x_1	x_2	x_3	x_1	x_2	x_3
	n [rpm]	f [mm/min]	a_p [mm]	n [rpm]	f [mm/min]	a_p [mm]
-α	955	500	0.2	955	100	0.2
-1	1485	677	0.35	1485	280	0.35
0	1978	750	0.5	1978	550	0.5
+1	2470	823	0.65	2470	820	0.65
+α	3000	1000	0.8	3000	1000	0.8

Conclusions

The complexity and multifaceted field of machine building and exploitation requires the application of knowledge from different disciplines and fields. Usable features of the machines are formed during technological processes. Technological quality and operational quality are formed in the life cycle of the machine. Therefore, knowledge about manufacturing processes and machine exploitation processes should be collected and used to improve the construction, performance and product quality. Due to the wide range of the area of machine building and exploitation, only selected examples were presented in the article.

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