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High-Performance Milling Techniques of Thin-Walled Elements

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ABSTRACT

The paper presents an overview of high-performance milling techniques of thin-walled elements. Currently, the tendency to simplify semi-finished products is used in aviation. In that case even 95% of semi-finished product mass is converted into chips, hence the increasing interest in such techniques as: High Performance Cutting (HPC) and High Speed Cutting (HSC). The aim of the paper was to research high-performance milling techniques of thin-walled elements in reference to conventional machining. The material was the EN AW-7075 T651 aluminium alloy. A thin-walled pocket structure was designed and manufactured. The aspects related to geometric accuracy, surface quality and cutting time were analysed. On the basis of the obtained results, it was found that in case of geometric accuracy associated with the wall deformation, the greatest deformation was obtained after HPC, while the smallest one after HSC. The difference was over 400% (comparing HPC to HSC). A similar relationship was also received for the quality of the machined surface. Analysing the cutting time, the best result was achieved after HPC in reference to HSC and conventional machining. Taking into account all analysed variables, prime solution was a combination of HPC and HSC. Thanks to the use of HSC as a finishing, it is possible to receive high geometric accuracy and quality of the machined surface, while the application of HPC for roughing allows to shorten the cutting time, translating into an increase in the efficiency of the milling process. Conventional machining is slightly less advantageous in terms of geometric accuracy and surface quality and it could possibly be used alternatively with High Speed Cutting, but its weakness is significantly lower efficiency compared to high-performance machining.

Keywords: milling, HPC, HSC, thin-walled elements, aluminium alloy.

INTRODUCTION

The dynamic progress in the field of manufacturing cutting tools, CNC machine tools and computer aided manufacturing (CAM) software contributes to the continuous improvement of machining processes. The main directions of milling development include [1]:

- High Speed Cutting,
- High Performance Cutting.

It is significant that there are no unequivocal technological parameters defining the boundaries between the above-mentioned techniques and conventional machining. This results from the close correlation of the process conditions and the type of machined material [1]. Figure 1 presents a comparison of HSC and HPC. HSC and HPC can be used for such machining as: "hard cutting" (machining materials in a hardened state), "dry cutting" (machining without cutting fluid) as well as "quasi-dry cutting" (machining with minimal lubrication) [1]. A difference between High Speed Cutting and conventional machining is a 5–10-fold increase in the cutting speed v_c, depending on the type of machined material [2, 3]. During HSC, increased values of the feed per tooth f_z are also used and the cross-sections of the cut layer are much smaller than in the traditional approach. However, the actual cutting speed v_c does not depend only on the type of machined material, but also on, for example: machine tool capabilities, tool geometry and its material. In the literature, there is also the concept of "limit cutting speed" v_{cl}, beyond which the cutting force begins to

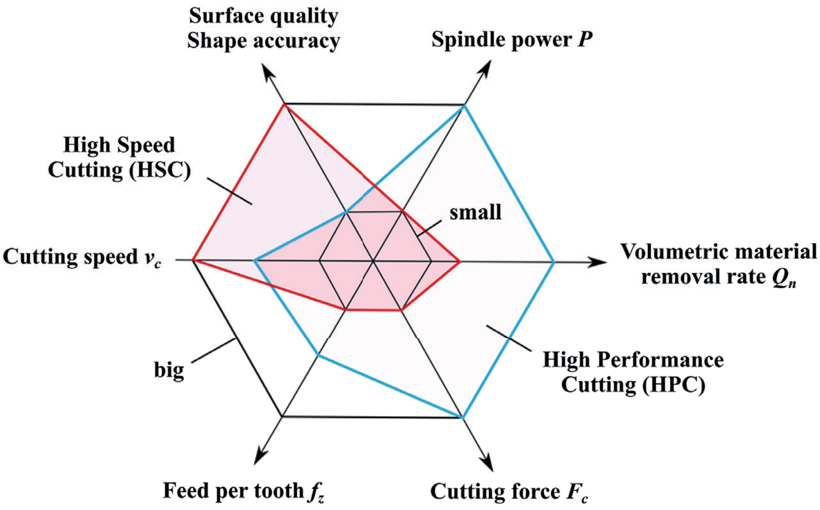

Fig. 1. Comparison of High Speed Cutting and High Performance Cutting [1]

decrease. It can be concluded that high-speed machining starts when the cutting force decreases noticeably with an increase of the cutting speed v_c [4–7]. Figure 2 presents an illustrative image of the cutting force as a function of cutting speed for conventional and HSC machining. Using HSC it is possible to shorten the main cutting time (even by more than 30%), increase the volumetric material removal rate, reduce the cutting force and achieve a better quality of the machined surface. The advantages of high-speed machining also include: limited burr formation, better chip disposal and increased process stability [8–12]. Fig. 3 presents the impact of increasing the cutting speed on selected characteristics of the cutting process. High Speed Cutting finds application primarily in the machining of light metal alloys as well as plastics and polymer composites (e.g. reinforced with glass and carbon fibres). Additionally, it is also possible to cut high-alloy steels and cast iron [14]. Figure 4 presents the cutting speed v_c ranges for conventional machining as well as HSC, depending on the type of machined material and the cutting method.

High Speed Cutting is widely used in the aerospace, automotive and precision industries. It finds application in the production of both thin-walled elements with a thickness of up to 0.1 mm as well as of very complex shapes. It is also increasingly more often used in the machining of moulds and dies [15–19]. Cutting tools used for HSC are subject to much higher requirements than in terms of conventional milling. One of the basic limitations is their low durability resulting from the increased cutting speed. The tool materials used during HSC are mainly sintered carbides,

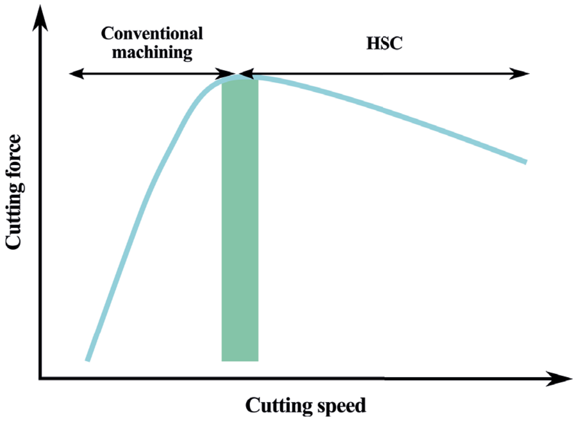

Fig. 2. Illustrative image of the cutting force as a function of cutting speed for conventional and HSC machining [4]

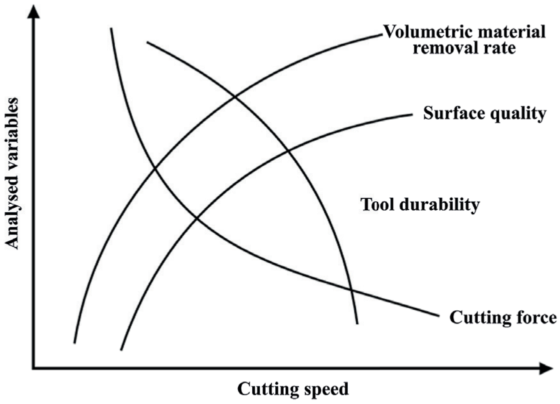

Fig. 3. Impact of increasing the cutting speed on selected characteristics of the cutting process [13]

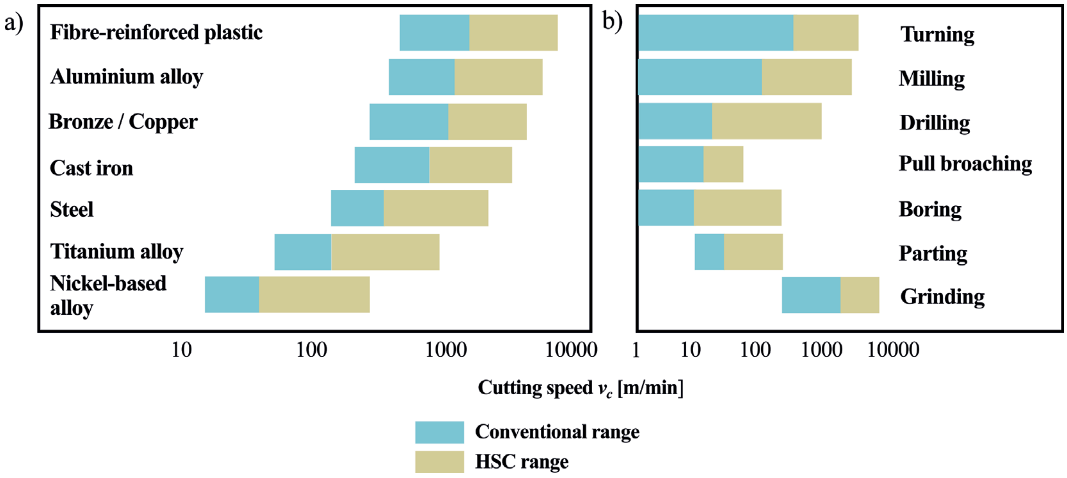

Fig. 4. Cutting speed v_c ranges for conventional and HSC machining depending on: a) type of machined material, b) cutting method [14]

tool ceramics, polycrystalline diamond (PCD) and cubic boron nitride (CBN). Sintered carbides from the K group (coated and uncoated) and polycrystalline diamond are used mainly for cutting light metal alloys. Cutting tools intended for High Speed Cutting should be characterised by, among others: better wear resistance (additional anti-wear coatings are applied) [20], greater accuracy (radial and axial runout should be as limited as possible), high static as well as dynamic stiffness, resistance to centrifugal forces occurring at increased rotational speeds. In high-speed cutting, monolithic cutters are mainly used. Additionally, the tool geometry should ensure proper formation of chips and facilitate their removal from the cutting zone [1, 21].

Modern CNC machine tools designed for HSC are equipped with high-speed electro-spindles, usually with hybrid bearings and linear drives of the feed axes with accelerations of 1–2 g. Characteristic features of such machines are, for example: high stiffness, high power (up to 60kW) and rotational spindle speed (even 60,000 rpm), increased values of working and setting feed rates, great accuracy of movements as well as CNC control allowing to calculate displacements in advance (the look-ahead function - loads and analyses the NC code in advance of 150–200 blocks) as well as enabling designing a correct tool path [22–25]. A characteristic feature of High Performance Cutting is an increased volume of removed material per time unit during the cutting. This is possible thanks to using technological parameters higher than in conventional machining, i.e.: cutting speed v_c, feed per tooth f_z and depth of cut a_p, depending mainly on the type of machined material. The high-performance cutting assumes the maximum use of the machine spindle power in order to rise the volumetric material removal rate and reduce auxiliary times, resulting from the increased positioning speed as well as shortening the tool exchange time [26, 27].

Cutting tools used in HPC are also subjected to special requirements. First of all, they must be adapted to transfer significantly greater cutting forces and heat loads. It is possible thanks to the progress in developing new and modifying existing tool materials as well as adapting tool geometry and design. Tool coatings are increasingly often applied to the working parts, which affect a tool's cutting and operational properties. They increase the machining efficiency and the durability of the blades [20, 28–30]. Machines designed for HPC are also equipped with high-speed electro-spindles with a power of at least 60 kW (sometimes even exceeding 100 kW) and rotational speeds in the range of 10,000–16,000 rpm. Machine tools should be characterised by a compact structure, modern (usually hybrid) bearings, CNC control and an integrated supervision system [31]. Comparing both technologies (Fig. 5) it can be concluded that HPC is characterised by higher values of the depth of cut a_p (axial infeed), the milling width a_e (radial infeed) and feed per tooth f_z, while cutting speed v_c is lower. However, higher cutting speed v_c and smaller cross-sections of the cut layer are used during HSC. For HSC and HPC, there are also different conditions of contact between the cutting edges of the tools and the machined object. In the case of High Performance Cutting,

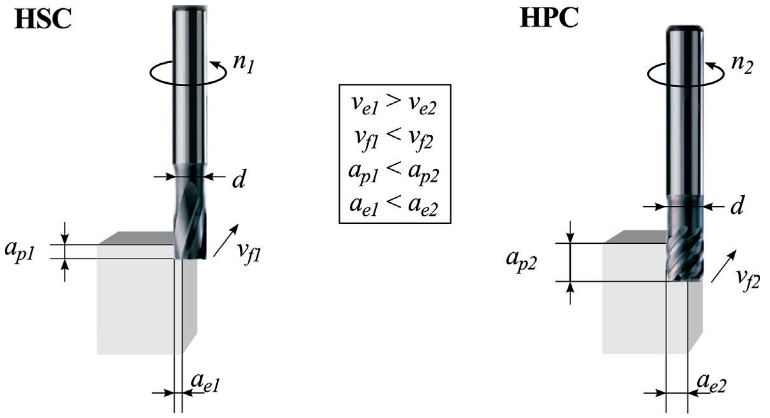

Fig. 5. Comparison of the basic cutting parameters of HSC and HPC [14]

the contact angle is up to 180° and causes strong heating of the blades. Therefore it is justified to use a lower cutting speed v_c in comparison to High Speed Cutting, for which the contact angle is much smaller (about 30°). Furthermore, a significantly worse surface quality is obtained after cutting with HPC [1]. The effect of the presented differences consists in the different purpose of both technologies. High Speed Cutting is used for finishing, while High Performance Cutting is used for roughing [32, 33]. The author of the paper [1] formulated the following important conditions for effectively application of HSC and HPC:

- using precise tool holders, ensuring a stable course of machining,
- using balanced tools made of high-quality tool materials,
- using cutting tools with proper geometry equipped with chip breakers, retractors, or crushers with a properly shaped rake surface, facilitating the removal of chips from the working space,
- ensuring the correct movement path of cutting tool,
- using a properly selected machining strategy,
- ensuring correct mounting and fixing of workpiece,
- using the correct cutting fluid and adjusting its application.

The interest in HSC and HPC, especially from of aviation industry, implies their dynamic development, which is possible thanks to the use of newer tool materials, modifying tool geometry and design as well as the construction of machine tools and improving CNC control [34]. Summarising, milling is one of the fastest developing methods of machining. Limiting the number of elements produced in a single production series and the related simplification of semi-finished products imply the need to increase the volumetric material removal rate, hence the great interest in High Performance Cutting and High Speed Cutting techniques.

Machining of thin-walled elements, especially large-size ones, causes a number of problems related to their dimensional and shape accuracy as well as the quality of the machined surfaces. The performance is also an important aspect. Currently, companies, especially from the aviation and automotive sectors, are looking for the possibility of faster production of parts. Therefore such technologies as High Speed Cutting and High Performance Cutting are widely used. For the production of thin-walled elements, monolithic rolled plates made largely of aluminium alloys are increasingly applied. It is worth noting that the mass of the produced chips is over 90% of the mass of the semi-finished product and it is economically justified. The mentioned dimensional and shape accuracy is a problem in the case of thin-walled elements. It is especially visible after unfastening the element from the clamping device [35–39]. The papers [40–42] presented the various possibilities of deformation reduction by: heat treatment, seasoning, or even special solutions used during the technological process, e.g. double-sided machining of a thin wall. The authors [33, 34] also showed the possibility of using high-performance techniques to minimise post-machining deformations as well as how to increase the surface quality. High-performance techniques are widely used in aviation to machine aluminium alloys that differ in terms of machinability from other materials. This is mainly due to their properties such as: high linear expansion coefficient, low Young's modulus and high thermal conductivity (in relation to steel) [1]. The most general division of aluminium alloys, in respect of machinability, includes the following groups [1]:

- group I: pure aluminium and wrought alloys with a low content of alloying elements,
- group II: cast alloys with the content of Si < 12% and wrought alloys (work hardened or precipitation hardened),
- group III: cast alloys with a content of Si > 12%.

Materials from the first group are characterised by low hardness and high ductility, which means that they possess adhesion tendencies in terms of the blade material and often for work hardening. At low cutting speeds, this leads to the formation of a built-up on the surface of the tool's blade. The second group of alloys is characterised by increased strength. During machining, there is usually no built-up on the tool's blade. In comparison to the other two groups of aluminium alloys, these are the materials that are the best machinability. The third group of alloys, due to the primary precipitation of silicon, is characterised by high abrasiveness, which causes faster tool wear. For materials from the first group, tools with sharp geometry should be used, for the second group carbide cutters without a protective coating, while for the third group, less sharp geometry is recommended and the most preferred are blades made of PCD or with PCD coatings. The machinability of aluminium alloys depends mainly on the chemical composition (mainly silicon content) and the structure of the material closely related to heat treatment [1].

MATERIALS AND METHODS

The aim of the paper was to research high-performance milling techniques of thin-walled elements in reference to conventional machining. The geometric accuracy, the quality of the machined surfaces, and the cutting times were analysed. The tests were performed on the EN AW-7075 T651 aluminium alloy, widely used in aviation, which in terms of machinability is classified in group II (group II: cast alloys with the content of Si < 12% and wrought alloys, work hardened or precipitation hardened). It is a material characterised by increased tensile strength and yield strength, but limited both corrosion resistance and weldability. The EN AW-7075 T651 alloy is used in the production of heavily loaded elements of aircraft structures, including thin-walled structures. Table 1 presents its chemical composition and selected mechanical properties.

As part of the research, a thin-walled pocket structure was designed (Fig. 6) with overall dimensions of 300×200×50 mm, consisting of a bottom and vertical walls with a thickness of 1 mm. As a semi-finished product, a rolled plate with a thickness of 50.8 mm (2 inches) was used, the surfaces of which were initially machined on both sides with the following technological parameters: a_p = 0.4 mm, v_c = 200 m/min, f_z = 0.02 mm/tooth. High Performance Cutting was used for roughing, while conventional machining and High Speed Cutting were applied for finishing. In the case of High Performance Cutting, for comparison purposes, the parameters corresponding to the high-performance machining for the last pass were also used.

The machining tests were performed on an Avia VMC 800HS machining centre allowing

Fig. 6. Tested thin-walled structure

Table 1. Chemical composition and mechanical properties of the EN AW-7075 T651 alloy [43, 44]

<table>
<tr><th colspan="10">Chemical composition [%]</th></tr>
<tr><td>Si</td><td>Fe</td><td>Mg</td><td>Cu</td><td>Mn</td><td>Zn</td><td>Ti</td><td>Cr</td><td>Other</td><td>Al</td></tr>
<tr><td>≤0.4</td><td>≤0.5</td><td>2.5</td><td>1.6</td><td>≤0.3</td><td>5.6</td><td>≤0.2</td><td>0.23</td><td>Zr+Ti
≤0.25</td><td>Rest</td></tr>
<tr><th colspan="10">Mechanical properties</th></tr>
<tr><td colspan="2">Yield point $R_{p0.2}$ [MPa]</td><td colspan="3">Tensile strength R_m [MPa]</td><td colspan="2">Elongation A [%]</td><td colspan="3">Brinell hardness [HB]</td></tr>
<tr><td colspan="2">440</td><td colspan="3">525</td><td colspan="2">11</td><td colspan="3">155</td></tr>
</table>

high-speed and high-performance machining. Selecting of cutting tools resulted from researching cutters used in industry of high-performance machining of aluminium alloys. The following tools were used:

- SGS Tools 44303 – High Performance Cutting (Fig. 7a),
- SGS Tools 44631 – bottom and vertical wall machining – conventional machining and High Speed Cutting (Fig. 7b),
- SEGER AL103-120 – used to "remove" the pocket structure from the frame (Fig. 7c).

Table 2 presents the technical data of the tools. The tools were mounted in heat-shrinkable toolholder HSK and were balanced in class G2.5 up to 25,000 rpm. Table 3 presents the applied values of technological parameters for each variant. Their selection was based on many years of research conducted at the Department of Production Engineering at the Lublin University of Technology. Wet machining was performed with the use of the MobilCut 230 coolant – solution with a concentration of 8%. The coolant capacity was approx. 25 l/min. The workpiece was

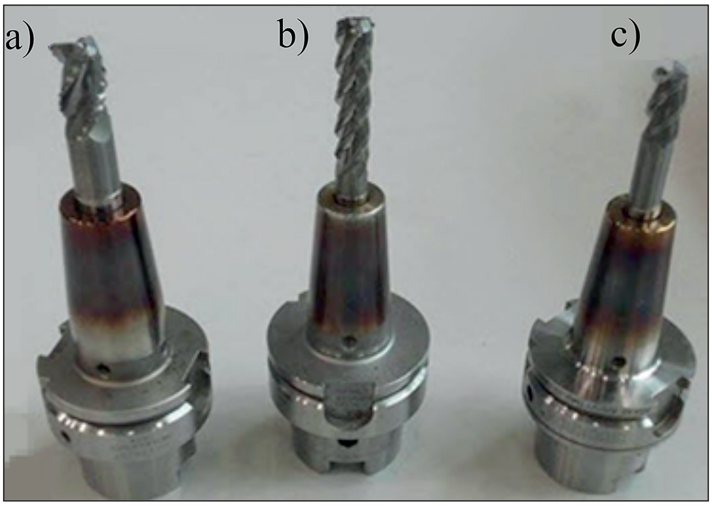

Fig. 7. Cutting tools used during tests: a) SGS Tools 44303, b) SGS Tools 44631, c) SEGER AL103-120

Table 2. Technical data of the used cutters

Symbol	SGS Tools 44303	SGS Tools 44631	SEGER AL103-120
Number of blades z	3	4	3
Working part diameter d [mm]	16	12	12
Total length L [mm]	92	100	24
Maximum depth of cut a_{pmax} [mm]	32	48	24
Grip part diameter D [mm]	16	12	12

Table 3. Values of applied technological parameters

Technological parameters	Strategy		
	HPC	HSC	CM
Cutting depth a_p [mm]	5; 4*	0.5	0.5
Milling width a_e [mm]	12	9	9
Cutting speed v_c [m/min]	800	900	200
Feed per tooth f_z [mm/tooth]	0.1	0.02	0.02
Rotational speed n [rpm]	15,915	23,873	5305
Number of passes i [-]	10	1 (10**)	1 (10**)

* last pass

** 9 passes of HPC: a_p = 5 mm; 1 pass of HPC: a_p= 3.5 mm mounted using properly shaped geometry of the semi-finished product and additional allowance, which was cut off during the final stage of machining as waste in the form of a "frame". This type of fastening method is widely used in the production of thin-walled elements in the aviation industry. It enables 5-axis machining of parts with the use of High Performance Cutting and High Speed Cutting. A mounting system with the use of a "frame" also allows for significantly reducing the cost of tooling and reducing the set-up time. Its advantages also include the possibility of minimising the deformation of the part manufactured during machining and facilitating the removal of chips. Whereas, its disadvantages are mainly the occurrence of vibrations, which contribute to the instability of the machine tool-clamping device-workpiece-tool system. The machining program was generated in the NX 10 software of Siemens.

The geometric accuracy was assessed on the basis of wall thickness measurements performed in two sections A-A and B-B, as shown in Fig. 8, with the use of a Vista coordinate-measuring machine of Zeiss. The Renishaw PH10 probe head with a TP-20 probe with low measuring force was used as well as a special straight stylus adapted to measuring thin-walled elements. This allowed to avoid, primarily, the deformation of walls under the pressure of the measuring force. The quality of the machined surfaces was assessed in accordance with results of roughness parameters measurements and isometric maps, made with the Hommel Tester T1000 contact profilometer as well as the Hommel Etamic T8000RC device, respectively. The measurements were performed at the bottom of the thin-walled structure, for which the circuit was purposefully not closed at the design stage so that the device head could be placed. The analysis was carried out for the following parameters: *Rz* – the maximum height of roughness profile and *Rsk* – skewness [45, 46]. The analysis for *Rz* parameter was performed, because it is a typical vertical roughness parameter, widely used also in industry, while *Rsk* parameter is a coefficient characterising the symmetry of the ordinate distribution in regard to the mean line, on the basis of which it is possible to conclude about the shape of the roughness profile. As part of the research, 5 elements were made for each configuration. Moreover, the measurements were repeated 10-times on one element. Each time the measuring head was placed in the centre of the cutting tool passage. The mean value was adopted as the estimator of the real value. In the next step, the standard deviation, i.e. the standard uncertainty, was determined. Due to the finding of significant differences between the results, statistical analysis was not performed.

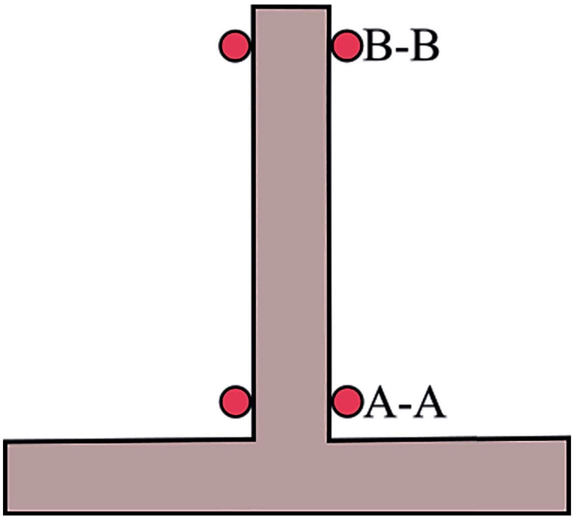

Fig. 8. Wall thickness measurement scheme

The machining time was determined on the basis of measurements of the cutting time performed with the clock of the CNC machine.

RESULTS AND DISCUSSION

The obtained results of own research were analysed in the context of comparing high-performance machining techniques, i.e.: High Performance Cutting and High Speed Cutting in reference to conventional machining (CM). The analysis began with geometric accuracy and the results of wall thickness measurements. Fig. 9 presents the results of measurements of the thickness of the vertical walls, in two sections A-A and B-B in accordance with Fig. 8, for HPC, HSC and conventional machining. On the basis of the results, a difference between the wall thickness in individual sections was observed. Furthermore, it was found that higher values were recorded at the top of the wall, meaning in the B-B cross-section. The greatest values of wall thickness were obtained after HPC machining and the smallest ones after using the HSC in the last pass. Comparing HPC with HSC, the wall thickness values in the B-B cross-section were higher by almost 30% in case of HPC, while comparing HPC with conventional machining by 15%. The differences between results obtained at the B-B and A-A cross-sections were, respectively,

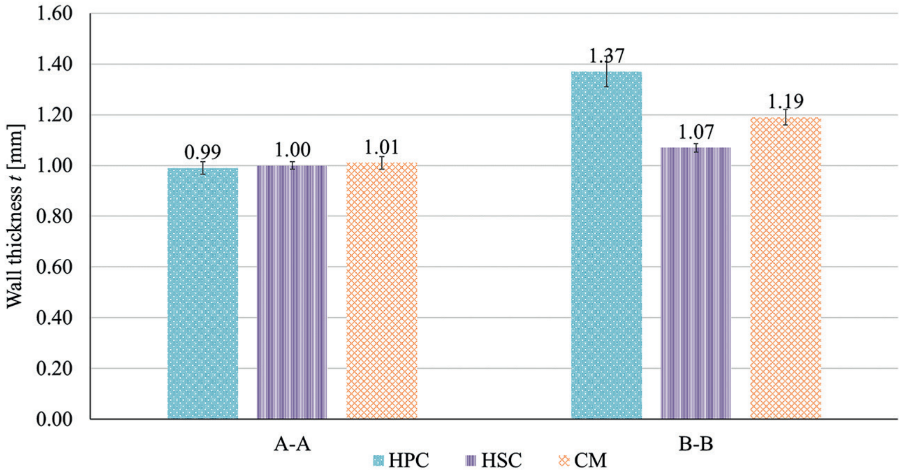

Fig. 9. Wall thickness measurements obtained in A-A and B-B sections for HPC, HSC and conventional machining

HPC – 40%, HSC – 7% and conventional machining – 20% (compared to the A-A cross-section). Fig. 10 presents the calculated difference between the wall thickness in B-B and A-A cross-sections, which was defined as wall deformation. The results are presented for HPC, HSC and conventional machining, while the standard deviation was assumed as the sum of the deviation of the wall thickness measurement in cross-sections A-A and B-B. On the basis of the obtained results, it was found that the greatest wall deformation was obtained after HPC, while the smallest one after HSC. The difference was over 400% (comparing HPC to HSC).

Analysing the geometric accuracy, which was assessed on the basis of the deformation of the thin-walled wall, it was found that the cross-section of the machined vertical wall was similar to a trapezoidal shape with a shorter base in the lower part of the wall (A-A) and a longer base in the upper part of the wall (B-B). It was the effect of elastic deformation of the wall during machining and the influence of the cutting force. The obtained lower wall deformation after High Speed Cutting resulted from lower value of cutting force in comparison to HPC and conventional machining. Such considerations were presented in [47].

During the following stage of analysing the obtained results, the focus was placed on surface roughness measurements. Parameters such as *Rz* and *Rsk* were selected for the analysis. Fig. 11 presents *Rz* parameter received respectively after HPC, HSC and conventional machining. On the basis of the results, it was determined that the greatest value of *Rz* parameter was recorded after High Performance Cutting, while the smallest one after High Speed Cutting. Comparing HPC with HSC, the value of the *Rz* parameter was greater

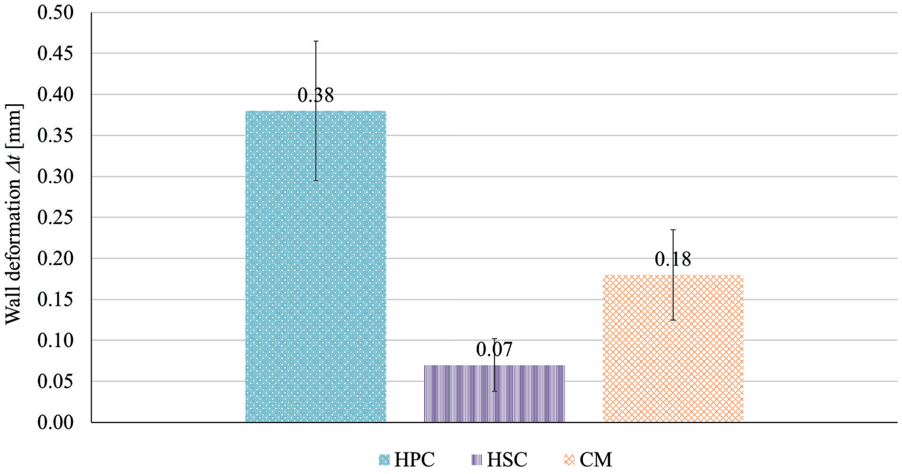

Fig. 10. Wall deformation for HPC, HSC and conventional machining

by more than 130% for HPC whereas comparing HPC with conventional machining by 50%.

Then, an analysis was performed for *Rsk* parameter, i.e. skewness. On the basis of this parameter, the symmetry of the ordinate profile distribution with respect to the mean line can be concluded. For all cases, positive values of *Rsk* parameter were observed, which proves "sharp" peaks (Fig. 12). Figs. 13–15 present isometric maps of the surface obtained after HPC, HSC and conventional machining. 3D maps of the surface topography confirmed the measurement results of 2D roughness parameters. It was noticeable that the greatest roughness was obtained after High Performance Cutting, while the lowest one after High Speed Cutting. Additionally, characteristic marks formed after the cutting tool had passed through was noticed. The surface topography was characterised by a uniformly periodical structure that is typical for milling. In the case of HSC, there were also visible micro-inequalities, being probably the result of vibrations generated during high-speed cutting. A classical roughness profile was observed, but an additional wave with a smaller frequency was noticed. Material dents and other defects were not found.

The quality of machined surfaces is also directly related to the cutting force value. In the case of HSC, a decrease in the cutting force is noticeable, which translates into lower roughness parameters. For HPC, the cutting force value was the highest, so the surface quality was also significantly worse.

During the final stage, the cutting times were compared. Figure 16 presents the machining time for HPC, a combination of HPC and HSC as well as a combination of HPC with conventional machining. On the basis of results it was determined that the most advantageous solution was to machine the pocket element solely with the use of HPC. However, a combination of

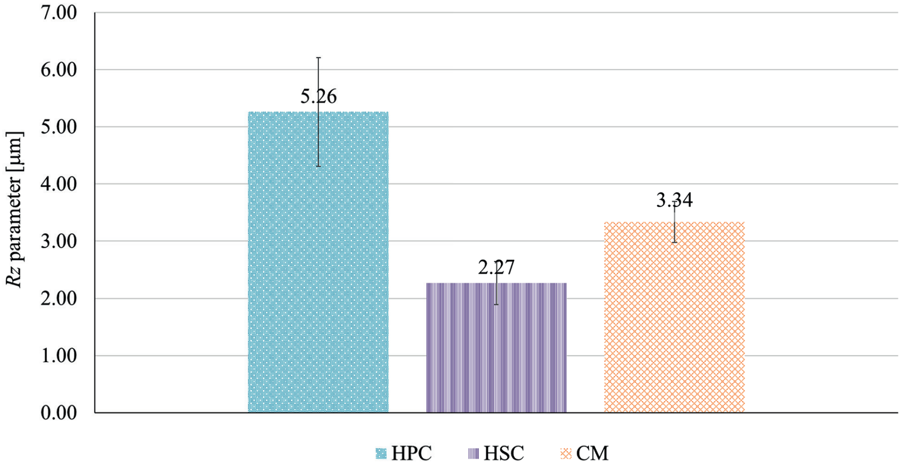

Fig. 11. *Rz* parameter values obtained for HPC, HSC and conventional machining

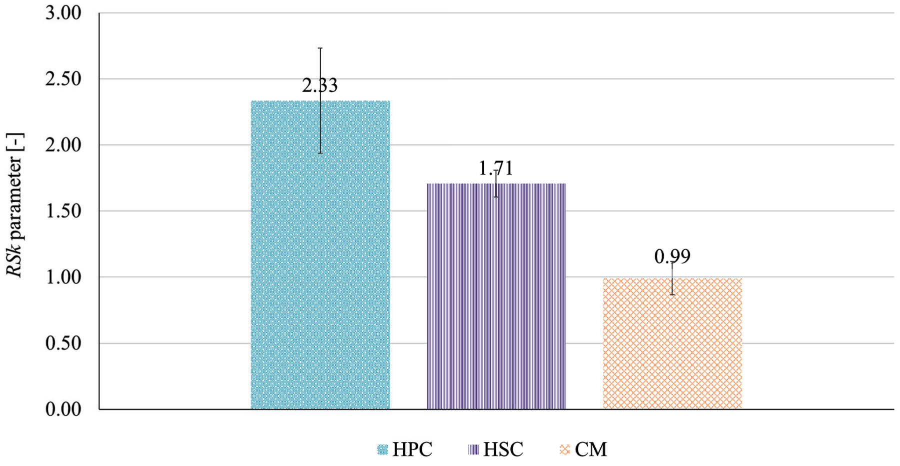

Fig. 12. *Rsk* parameter values obtained for HPC, HSC and conventional machining

HPC and conventional machining was the longest. When combining HPC with conventional machining, the total cutting time was longer by almost 200% in comparison to HPC, while for the combination of HPC and HSC, this difference was approx. 25%.

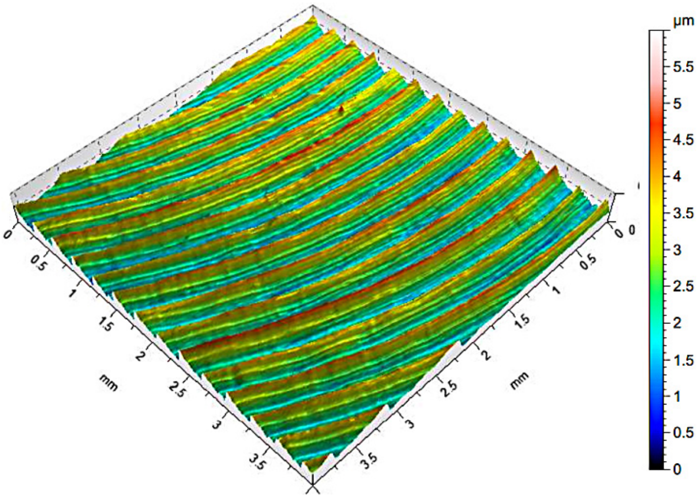

Fig. 13. 3D isometric map obtained for High Performance Cutting

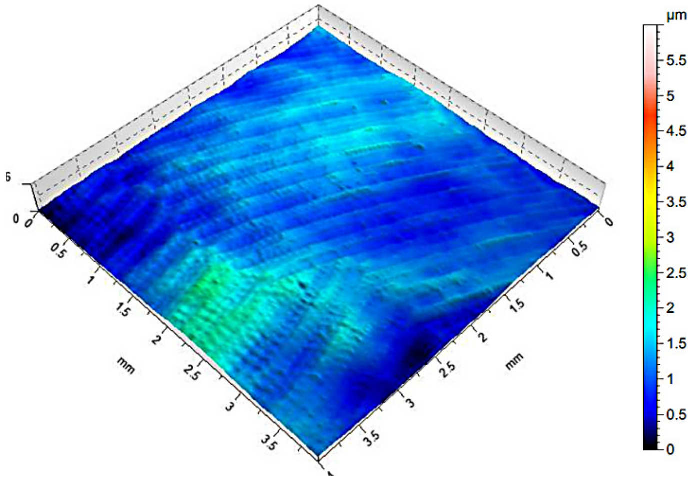

Fig. 14. 3D isometric map obtained for High Speed Cutting

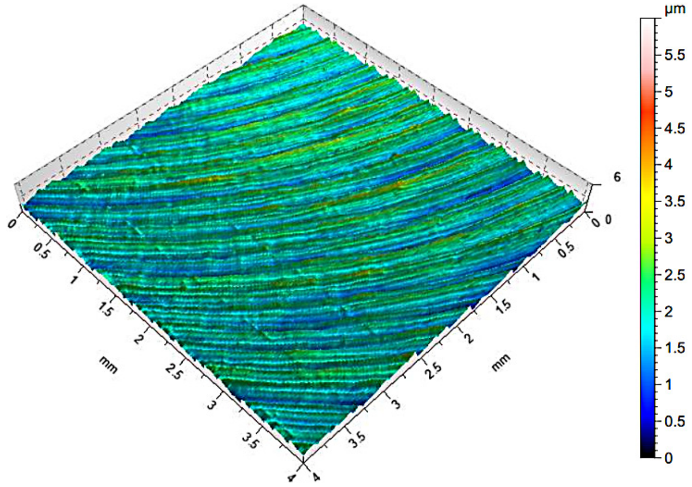

Fig. 15. 3D isometric map obtained for conventional machining

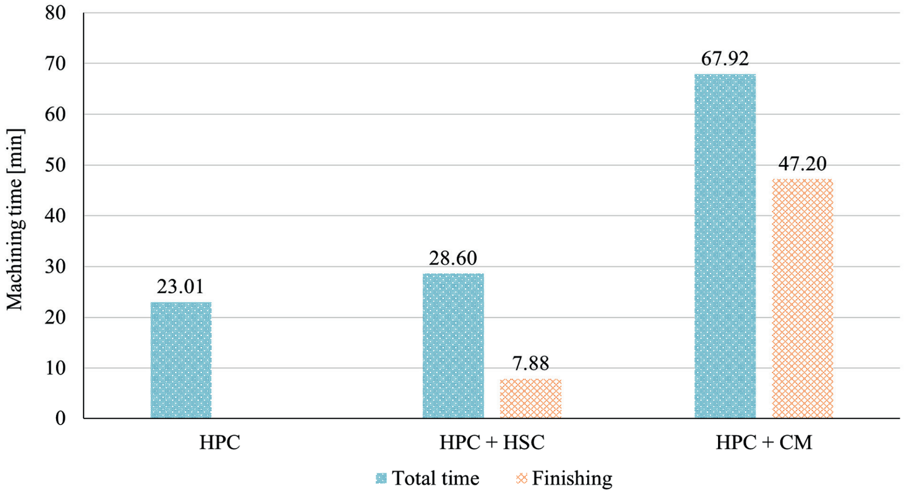

Fig. 16. Machining time obtained for HPC, combination of HPC with HSC as well as combination of HPC with conventional machining

Referring to the cutting time, it should be noted that it was primarily the effect of increased cutting parameters, as well as a significantly greater cross-section of the cut layer in the case of HPC and in reference to HSC as well as conventional machining.

Based on the analysis of all examined aspects, i.e.: geometric accuracy, surface quality, and cutting time, it was found that it is recommended to use a combination of HPC with HSC, which, despite the reduced performance, shows relevantly better results in terms of geometric accuracy and surface quality.

The issue of machining thin-walled elements is very complex and depends on many factors. The paper analysed only a certain scope that requires expansion.

CONCLUSIONS

The machining of thin-walled elements is demanding in many aspects. It requires taking into account the dimensional and shape accuracy of the manufactured parts as well as the efficiency of the process. The greatest wall deformation was obtained after HPC, while the smallest one after HSC. The difference was over 400% (comparing HPC to HSC). Comparing HPC with HSC, the value of the *Rz* parameter was greater by more than 130% for HPC, while comparing HPC with conventional machining by 50%. According to 3D topographic maps, a characteristic marks formed after the cutting tool had passed through was noticed. The surface topography was characterised by a uniformly periodical structure that is typical for milling. During combining HPC with conventional machining, the total cutting time was longer by almost 200% in comparison to HPC, while for the combination of HPC and HSC, this difference was approx. 25%. Taking into consideration the geometric accuracy and quality of the machined surface, it is the most advantageous to machine thin-walled elements with the use of High Speed Cutting for finishing, and High Performance Cutting for roughing, that give very good results also in terms of cutting time. Conventional machining is slightly less advantageous in terms of geometric accuracy and surface quality and it could possibly be used interchangeably with High Speed Cutting. However, its low efficiency related to the volumetric material removal rate in time unit causes in that its use is limited.

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