Research on the influence of machining parameters in HSC technology in the automotive industry

Badania wpływu parametrów obróbki HSC w branży motoryzacyjnej

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The article presents the use of high speed cutting, which is a reliable alternative for in the automotive industry. It is a method that allows for the replacement of energy-consuming technologies used in the preparation of semi-finished products (e.g. castings) with a universal technology that is much cheaper at the part production stage including the selection of a semi-finished product. This method is widely used in many areas of the machining industry, including increasingly bold applications in the automotive industry. A wide area of utilization of HSC technology is finishing, where high cutting speeds are used. In the case of shaping machining, where the decisive factor is the cutting efficiency, one must take into account the demand for high power of the main drive, which is not always available for every machine tool. The paper presents the possibilities and benefits of using the high-performance HSC machining method.
KEYWORDS: HSM, HSC, high speed milling, high speed cutting, experimental verification, MES

W pracy przedstawiono zastosowanie frezowania z dużą prędkością (HSC), które jest niezawodną alternatywą obróbkową w branży motoryzacyjnej. Jest to metoda pozwalająca na zastąpienie energochłonnych technik stosowanych przy wytwarzaniu półfabrykatów (np. odlewów) technologią uniwersalną, znacznie tańszą na etapie produkcji części, w tym doboru półfabrykatu. Metoda ta znajduje szerokie zastosowanie w wielu dziedzinach obróbki skrawaniem, m.in. w coraz śmielszych rozwiązaniach dla branży motoryzacyjnej. Szerokim obszarem zastosowania frezowania z dużą prędkością jest obróbka wykończeniowa z dużymi prędkościami skrawania. W przypadku obróbki kształtowej, gdzie decydującym czynnikiem jest wydajność skrawania, należy uwzględnić zapotrzebowanie na dużą moc napędu głównego, która nie zawsze jest dostępna w obrabiarce. W artykule przedstawiono możliwości i korzyści wynikające z zastosowania wysoko wydajnej metody obróbki HSC.
SŁOWA KLUCZOWE: HSM, HSC, frezowanie z dużą prędkością, weryfikacja eksperymentalna, MES

Introduction

The automotive industry uses many technologies to make a wide variety of motor vehicle components. In the technologies employed to date, these elements have been manufactured by joining components using welding, fusing, or riveting, or making them as castings. Currently, in designing the structure of cars, the aim is to minimize the number of parts and produce a vehicle consisting mainly of integral parts. This group of integral parts includes such parts as reinforcements, stringers, reinforcing belts, stiffeners, engine heads or bodies of more multi-part structures e.g., fuel injection pumps. After machining, these parts are assembled into larger assemblies and prepared for final assembly. The main objective of the procedures used in the production of integral elements, in addition to meeting their functionality criterion, is to obtain the best possible strength-to-weight ratio of the structure. A very important factor is the economic and energy indicator, especially today, where the limitation of highly energy-consuming technologies is one of the important criteria for their application. In the automotive industry, this applies in particular to elements shaped by machining, especially where the semi-finished components of the final product are castings. Therefore, in what is surely related, the use of cast semi-finished products is increasingly being replaced by machined parts. The introduction of such technology allows for the maintenance of high production standards, quick production launches, as well as product cost reductions. Cutting costs is also related to the increasing use of aluminum alloys in automotive structures. In relation with the above, it is prudent to introduce high-performance machining. By introducing HSC technology, it is possible to make very complex integral parts of various shapes from a rectangular blank, including thin-walled elements [1, 2, 3, 4]. Machining complex parts and

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subassemblies from a single piece reduces the number of components in the assembly and thus reduces its weight. However, the use of HSC machining requires the use of specialized, high-speed, numerically controlled machine tools, allowing for the generation of complex shapes [5].

Technical factors influencing the development of HSM machining in the automotive industry

The use of high machining speeds enables economical production of integral parts by reducing machining time, but also improves quality of the machined surface due to the fact that cutting forces are much lower for high cutting speeds than for classic machining methods, which affects the deformation of the structure. Reduction of deformations and resulting displacements in the processing process, it improves the precision of the product. In order to reduce the displacement of the machined walls, the appropriate number of tool passes should be used and the contact time of the tool with the workpiece should be shortened by using a high cutting speed and a small ratio of the depth of cut a_p to the width of the cutting layer a_e. The stiffness of the MGFT system plays an important role in the process of high-speed machining and its stability, which is related to the stiffness of the system under consideration.

In order to assess the possibility of introducing the HSC technology in its production of motor components, ZPU Mirosław Pogoda carried out a study of the cutting process in this technology. The tests were conducted on cuboidal samples and structural elements in the form of thin-walled bodies made of aluminum alloy 7075. HSC processing allows for the production of components with a tolerance of 0.05 mm, which is sufficient for structural parts of transport aircraft, as well as working machines and cars of various types and purposes (automotive). HSC technology, when applied to numerically controlled machine tools, enables the production of elements with complex shapes and a wide range of wall thicknesses of at least 0.3 mm (own research), without limiting the maximum thickness. An important feature of this treatment is the possibility of obtaining surface roughness from $Ra = 0.6$ μm to $Ra = 0.2$ μm and low surface waviness. However, in the case of machining thin-walled elements, there is a risk of reducing the thickness of the walls beyond the permissible tolerance due to their displacements (deflections) and a change in the condition of the surface layer of the treated surface (residual stresses, plastic deformations). Such a risk occurs especially when machining high walls, where $h/g > 15$, and when machining large, thin surfaces. This phenomenon can be partially counteracted by supporting free surfaces with elements of high stiffness and using special fixing devices, submitted by the authors for a patent. Examples of models of an injection pump motor housing made as a semi-finished product in the form of a cast and a rectangular cube utilizing HSM technology are shown in fig. 1 [6, 7].

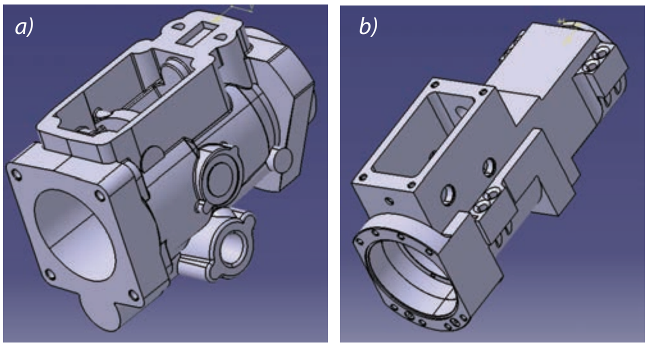

Fig. 1. Model of the injection pump motor housing: *a*) made on the basis of a cast, *b*) we will make in HSM milling technology

The use of subtractive machining with high cutting speeds (HSC) allows one to shorten machining time by up to 30%, increase machining efficiency, reduce cutting force, and obtain a better quality of the machined surface compared to conventional machining. The advantages of high-speed machining also include: reduced burr formation, improved chip evacuation, and increased process stability. Comparing HSC technology and conventional machining, it can be concluded that during HSC, smaller values of the cutting depth a_p and the milling width a_e are used, at high cutting speed v_c and feed per tooth f_z. For HSC, there are also different conditions of contact of the tool blades with the workpiece. The use of high cutting parameters is one of the reasons for the occurrence of self-excited vibrations, which significantly reduces the machining, because it causes significant surface roughness, severe wear of the blade and machine tool elements, and often unbearable noise. Hence, avoiding them is essential. This can be achieved by: selecting stable machining conditions, searching for areas of stable work, significantly lowering the cutting speed, configuring the stiffness of the MGFT system, using passive or active vibration dampers, reducing the number of teeth in the cutters. An important factor that allows one to limit self-excited vibrations is the work of the machining unit in a stable area of the tool rotational speed [8].

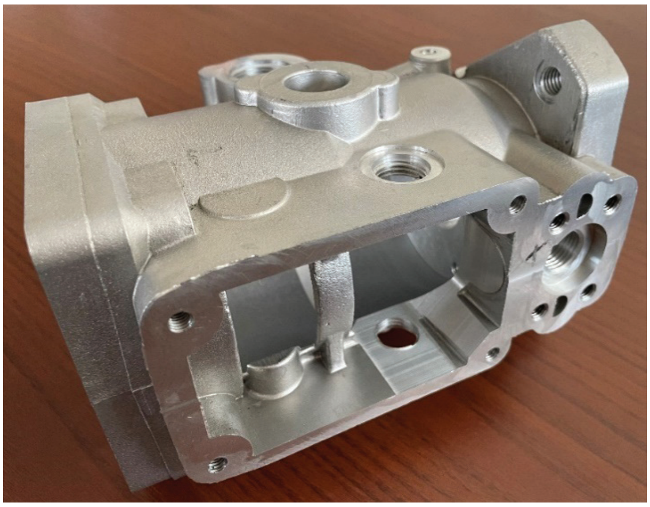

Fig. 2. The body is made of a semi-finished product in the form of a die-cast, finally made in HSM technology

TABLE. List of variables included in the dynamic analyses of the milling process

No.	Milling cutter	Tool diameter	Frame overhang	Material	Milling width
1	Head MKB113--080R06A27--SD12	80 mm	$L = 300$ mm	AW-7050	$a_e = d = 80$ mm
2	TRT-37444 20,00	20 mm	$L = 160$ mm		$a_e = d = 20$ mm
3	M9--444XA7-0160	16 mm	$L = 70$ mm		$a_e = d = 16$ mm
4					$a_e = 0.75d = 12$ mm
5					$a_e = 0.5d = 8$ mm
6					$a_e = 0.25d = 4$ mm
7	4HCEG 120 260 S12	12 mm			$a_e = d = 12$ mm
8	4HCEG 100 220 S10	10 mm			$a_e = d = 10$ mm
9	4HCEG 080 190 S08	8 mm			$a_e = d = 8$ mm

Our own research on the HSM machining process of aluminum alloys

As discussed above, performing machining at high cutting speeds (and thus high tool revolutions) may lead to unstable operation, and hence to a significant deterioration in the quality of the machined surface. The areas of stable work are described by the so-called bag curves showing the relationship between the limiting width of the cut layer and the rotational speed of the machine tool spindle. Such curves should be made for each machine tool used, the tool used, and the tool clamping conditions. These curves allow one to determine the stable operation of the machine tool in which there will be no self-excited vibrations, causing jerking of the workpiece at the moment of starting the tool feed. The tests were carried out on a stand consisting of the following elements: modal hammer, accelerometer, data acquisition module, and a computer with CutPro software (fig. 3). The machining tools used are listed in table. The aluminum alloy AW-7050 T745 (hardness HB140; Young's modulus $E = 720$ MPa) was adopted as the processed material. In all cases, the feed per tooth was assumed at $f_z = 0.1$ mm/tooth and the milling width corresponding to the diameter of the tool. Additionally, for a tool with a diameter of 16 mm, four milling widths were used to illustrate the effect of the milling width on the machining stability.

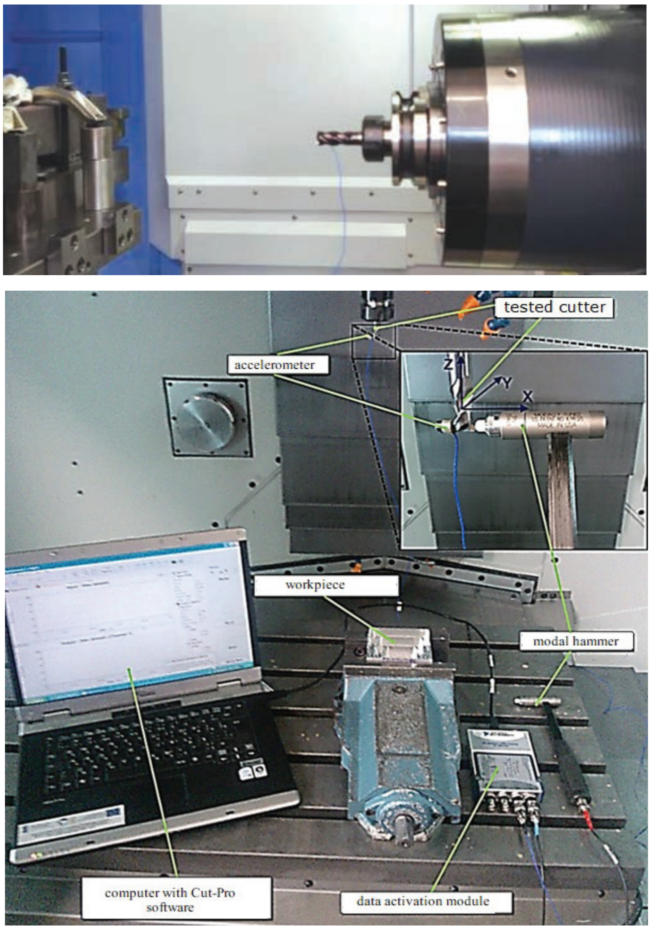

Fig. 3. Stand for determining bag curves in the HSM milling process

Examples of test results shown in figs. 4 to 6 are cutting stability charts (so-called bag curves).

By analyzing the results of the calculations performed, it can be observed that for each operating condition there is a certain constant maximum depth of cut, a_p, below which the machining process is stable. The machining stability decreases with the increase of the total length of the tool and holder and the reduction of the cutter diameter. This is related to changes in the flexural stiffness of the tool holder-tool system. The width of the milled layer has a very significant influence on the stability of machining. Reducing the milling width shifts the stability curve upwards as well as its local maxima, which increases the area under this curve corresponding to stable machining. The determined bag curves enable the selection of milling conditions on a specific machine tool and the use of appropriate machining tools [12–15].

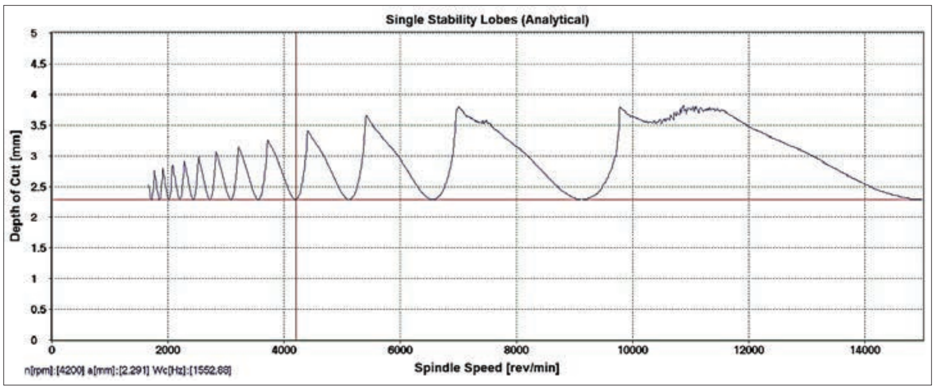

Fig. 4. Stability diagram of the milling process for the milling cutter $d = 12$ mm and the milling width for $a_e = d = 12$ mm

Machinability tests of the AW-7050 T745 aluminum alloy in the milling proces

During the research work, the focus was on two factors, i.e., cutting force and the quality of the surface obtained. The blade wear parameter was abandoned because the aluminum

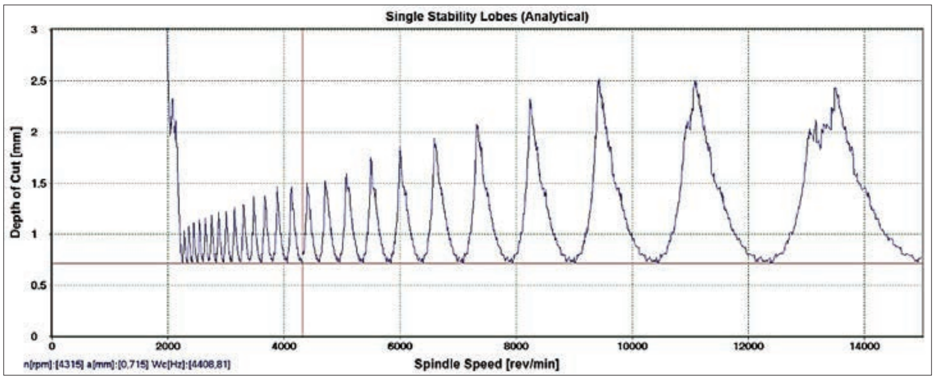

Fig. 5. Stability diagram of the milling process for the milling cutter $d = 10$ mm and the milling width for $a_e = d = 10$ mm

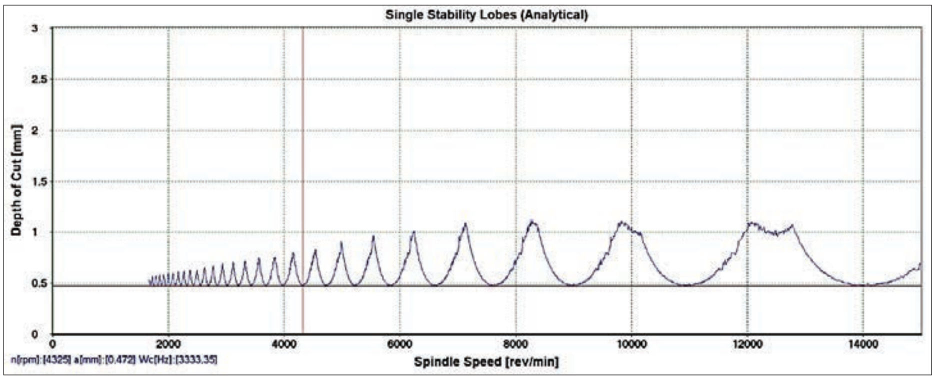

Fig. 6. Stability diagram of the milling process for the milling cutter $d = 8$ mm and the milling width for $a_e = d = 8$ mm

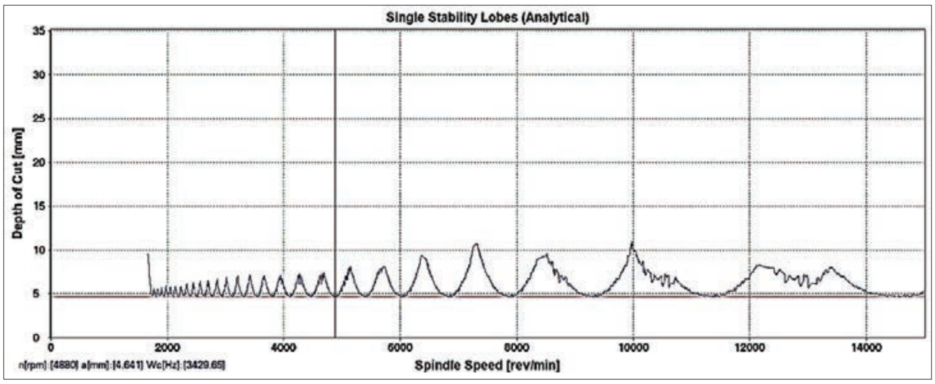

Fig. 7. Stability diagram of the milling process for the FENES M9-444XA7-0160⌀16 mm milling cutter, milling width $a_e = 0.75d = 12$ mm

alloy was processed from the 70XX group with carbide tools, with PCD blades and diamond tools, which ensured their significant durability. Conducting HSC machining of aluminum alloys requires the selection of an appropriate machine, especially the spindle speed and the power available on the drive motor. In this context, at the known cutting speeds v_c used in the above-mentioned machining, it is necessary to experimentally determine the cutting forces, which is related to the cutting power. In the course of the research, using the set shown in fig. 6, three components of the cutting force (F_x, F_y, F_z) were measured (fig. 7).

The distribution of these components is shown in fig. 7. The F_y component corresponds to the F_f feed component, and the F_x component of the component perpendicular to F_f. The components measured by the dynamometer are given in parentheses. For the tests, a D10.1210 cutter with a diameter of $d = 12$ mm, number of teeth $z = 3$ and material of the blade made of diamond and tungsten carbide. Based on the measurement results, it was found that the highest values are achieved by the F_{fN} component and therefore this component was accepted for further analysis.

The tests were performed for a cutting speed range from $v_c = 100$ m/min to $v_c = 900$ m/min. The measurement results are shown in figs. 8–10. Based on fig. 8, a reduction in the cutting force F_{fN} can be observed with the increase in cutting speed, with a clear minimum. The thesis is confirmed that the transition to HSC machining reduces the cutting force. Throughout the range of tests, a small difference in the cutting force F_{fN} is noticeable for a carbide-tipped tool and a diamond-tipped tool. Figures 9 and 10 show the change in the cutting force with increasing feed per tooth f_z. In both cases, an increase in the cutting force is visible with an increase in feed, which results from the increase in the cross-section of the cutting layer. Comparing the values of the forces for the tool with diamond and carbide blades, it can be concluded that for the speed $v_c = 300$ m/min, the cutting forces are greater for the tool with a diamond tip, and for the speed $v_c = 900$ m/min, these forces assume similar values. On this basis, it can be concluded that due to the generated forces and cutting powers, it is advisable to use a diamond blade tool when cutting at higher speeds. For lower cutting speeds used in HSC, carbide tipped tools are a better choice, where cutting forces are lower. One of the indicators of the machinability of the material is the quality of the machined surfaces, which was controlled by measuring the surface roughness measured after all machining variants. The research was carried out on specially prepared samples. The Hommel Tester T1000 contact profilometer was used to measure the 2D roughness parameters. Roughness measurements were carried out in three places of the sample, repeating 5 times, i.e., on the edges and in the middle, treating the obtained average as a result from one precise point. Two parameters of surface roughness were analyzed: the arithmetic mean deviation of the *Ra* profile and the mean interval between the elevations of the R_{Sm} profile. Exemplary test results are shown in figs. 11–13. On the basis of the obtained results, it was noticed that the highest values of the analyzed roughness parameters were recorded at the edges of the sample, therefore it was decided to focus on the comparison of the roughness parameters from the center of the sample. Figure 11 shows the roughness parameter *Ra* as a function of cutting speed v_c at a constant feed f_z for the two tested tools.

Figures 12, 13 show the dependence of the *Ra* parameter on the feed f_z at a constant cutting speed v_c. Based on the results obtained (figs. 11–13), it was found that the roughness parameter *Ra* decreases with increased cutting speed v_c and increases with increased feed f_z. In both cases, the value of the *Ra* parameter is greater for the surface treated with a carbide tipped tool. The lowest surface roughness was obtained with the cutting speed $v_c = 900$ m/min and the lowest feed $f_z = 0.05$ mm/tooth. Moreover, it was observed that lower values of the roughness parameters *Ra* were recorded for the cutter with PCD blades compared to the carbide tool.

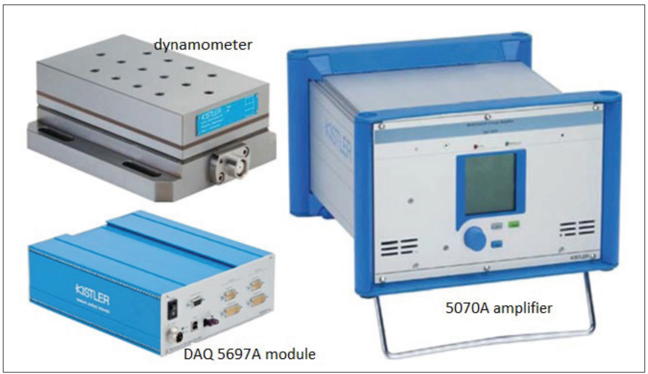

Fig. 8. Cutting force measurement kit

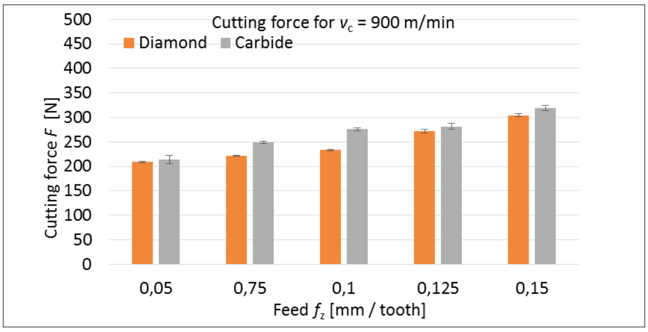

Fig. 12. The value of the F_{fN} component depending on the feed for the cutting speed $v_c = 900$ m/min and tools with PKD and carbide blades

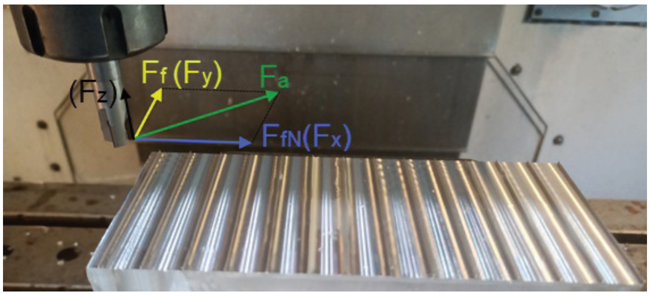

Fig. 9. View of the sample after machining and the distribution of cutting forces: F_a – active force (active), F_f – feed component, F_{fN} – component perpendicular to the feed component

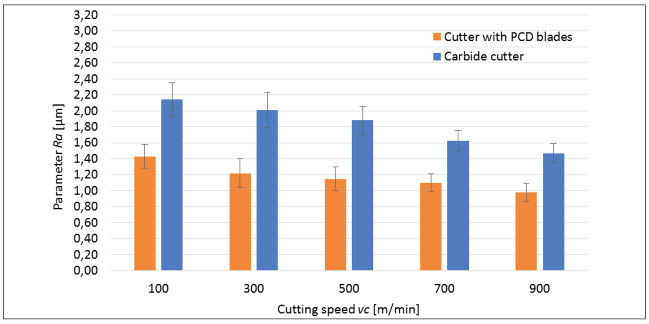

Fig. 13. Roughness parameter *Ra* as a function of cutting speed v_c at constant feed $f_z = 0.1$ mm/tooth

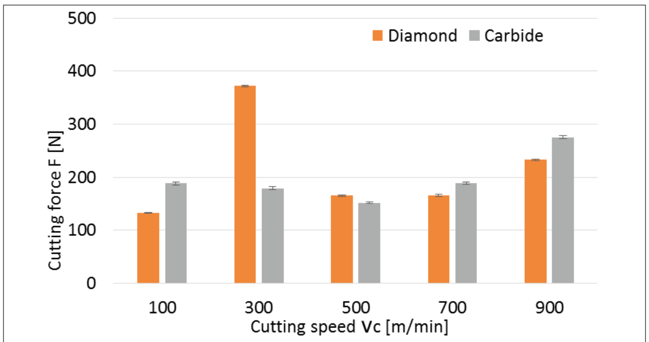

Fig. 10. The value of the F_{fN} component, depending on the cutting speed for tools with PKD and carbide blades

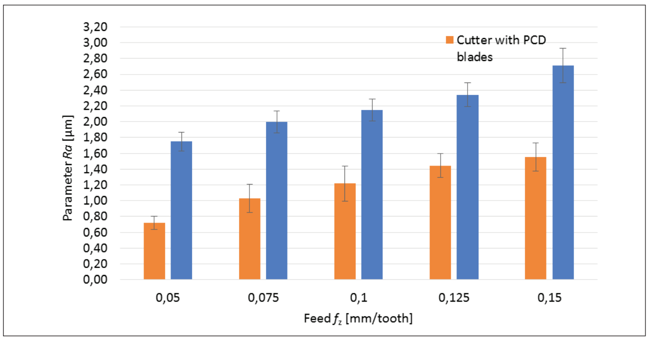

Fig. 14. Roughness parameter *Ra* as a function of feed f_z, at a constant cutting speed $v_c = 300$ m/min

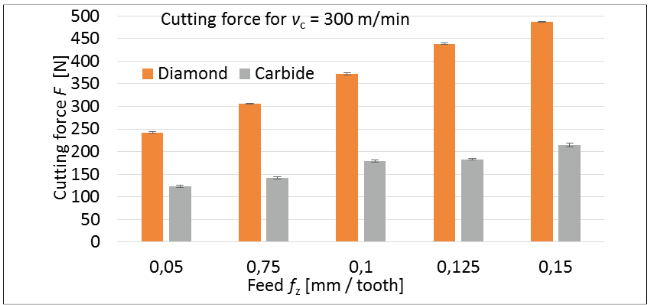

Fig. 11. The value of the F_{fN} component depending on the feed for the cutting speed $v_c = 300$ m/min and tools with PKD and carbide blades

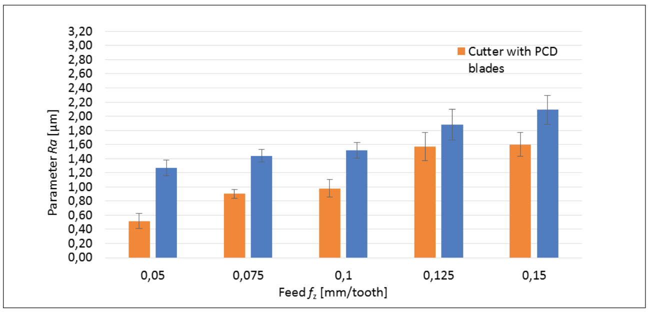

Fig. 15. Roughness parameter *Ra* as a function of feed f_z, at a constant cutting speed $v_c = 900$ m/min

For the body shown in fig. 2, attempts were made to process flat surfaces with cutting speed $v_c = 1507$ m/min – spindle speed $n = 80{,}000$ rpm, cutting depth $a_p = 0.05$ to 0.15 mm, and minute feed $f_m = 100$ mm/min, tool cutter $d = 6$ mm with a diamond blade. In the entire assumed range of cutting parameters, the surface roughness was $Ra = 0.078$ to 0.082 µm. This surface roughness is sufficient for the parts shown and is satisfactory from a technological point of view.

Conclusion

HSC machining are constantly developing, and the cutting speeds used are becoming higher and higher. This is due to the existing tendency to increase the efficiency of production and the constant shifting of technical limitations in the possibilities of HSM application. New innovative tool materials appear, in particular tool coatings and blade geometries with greater wear resistance, limiting the negative impact of increased cutting parameters on tool wear. There are also machines which employ more dynamic drives using control systems with greater potential power of the spindle and a degree of automation. Progress in these areas is conducive to shifting the recommended cutting speeds towards higher values. The use of very high spindle rotational speeds requires the utilization of special drives with which the machine tools are equipped. In the conducted research, the use of HSC machining allowed for the production of complex elements, such as the body of an injection pump, as one integral part. This technology uses very high cutting speeds and spindle speeds above 29,000 rpm (cutting speed υ approx. 950 m/min) and a small depth of cut, even revolutions $n = 80{,}000$ rpm and cutting speeds v_c up to 1500 m/min for finishing. This allows for the removal of the cut material using low cutting forces, obtaining a machined surface with low roughness (*Ra* approx. 0.08 µm) and low thermal deformation of the workpiece.

HSC machining also allows one to achieve high machining efficiency, perform integral elements, and eliminate assembly operations. The implementation work conducted by the authors on elements with complex shapes and small wall thicknesses allowed them to reduce the labor utilization from 300 man-hours per piece in the classic production design to 16 man-hours using HSC technology.

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