The use of HSM technology in the technological processes of milling and machining elements of aircraft structures made from (among other materials) aluminum alloys makes possible the production of elements with complex shapes, appropriate levels of precision workmanship, as well as surface roughness and waviness. The efficiency of the machining process is also a crucial factor, allowing it to compete with other manufacturing technologies. The achievement of these effects consists of many factors related to the machining process: machine tools and their rigidity, machining parameters, type of processed materials, as well as machining tools. The requirements for the tools used are related to the workpiece material and its specific properties, as well as the extreme machining conditions used (especially cutting speed $v_c$ and efficiency of the cutting process).

**KEYWORDS:** HSM, HSC, High Speed Milling, High Speed Cutting

**Introduction**

In aircraft structures, the decisive criteria for their work are appropriate strength, stiffness, lightness, and reliability. As has been demonstrated in the conducted research ensuring a particularly appropriate lightness of a structure requires the use of special technological methods allowing one to shape thin-walled structures. Some features, such as rib walls, require a thickness of 0.5 mm, or even less, to be used. According to the adopted concept of making these elements with the HSM technology, it is advisable to perform machining at cutting speeds $v_c$, which guarantee reduction of the cutting force, maintenance of the required surface roughness, as well as dimensional and shape tolerance, especially concavity of the surface, as well as high efficiency. Making thin-walled surfaces can be precarious due to the risk of their detachment from the base surface during processing, which may result in their complete destruction. The workpieces must therefore be firmly clamped. Under industrial conditions, it is necessary to achieve the appropriate efficiency of the milling process. Due to the cutting forces, the depth of cut and the feed per cutter blade should be limited. An effective way to increase the efficiency is to increase the cutting speed and the rotational speed of the spindle, with the diameter of the tool limited by design considerations [1–5].

**Research**

The research was conducted using an HES810 electromagnetic spindle by Nakanishi Inc. (the latest design solution), equipped with an ultra-precise high-speed motor. It is a chip that includes a DC brushless motor and a microprocessor-based control unit. The system
is able to reach a maximum speed of 80,000 rpm and an output power of 350 W. The solution uses bearings with ceramic material. The air taken in is used to both cool the motor and protect the spindle from incoming contaminants.

The tests were carried out on samples made of aluminum alloy 7050. The roughness of the machined surface was tested with the parameters determined in the preliminary tests, using the rotational speed of the tool \( n \) from 20,000 up to 80,000 rpm the cutting depth \( a_p \) equal to 0.2 mm and the advancing blade \( f_z \) equal to 0.03 mm (finishing) on the samples shown in Fig. 1 [5, 6]. The tool used was a carbide cutter with a ceramic coating with a diameter \( d = 6 \) mm. These parameters

![Fig. 1. Tests of the milling process of 7050 aluminum alloys with a spindle speed of 20,000–80,000 rpm](image1)

![Fig. 2. A sample made of 7050 aluminum alloy, machined at cutting speeds \( v_c \) from 753.6 m/min (over 4.5) to 1507 m/min (over 4)](image2)

![Fig. 3. The results of roughness tests of the treated surfaces: area 4.1 at a speed of \( v_c \) = 1507 m/min](image3)
allowed for a cutting speed \( v_c \) from 753.6 to 1507 m/min (Fig. 2). The tests carried out on the samples allowed the researchers to obtain walls with a minimum thickness of \( g = 0.8 \pm 0.5 \) mm. The cutting process was stable, without any local tearing of the machined surface. The parts were fastened according to a method developed by the authors, which is currently patent pending.

The results of the roughness tests of the treated surfaces are shown in Fig. 3. The tests were carried out on samples shown in Fig. 1 and Fig. 2. Fig. 2 describes the spindle rotational speeds (e.g. 80,000 rpm) and the numbers of the surfaces where the roughness was measured (Fig. 3 and Fig. 4).

Treatment of the samples’ flat surfaces with the face of the cutter allowed the authors to obtain the surface roughness as determined by the \( R_a \) parameter between \( R_a = 0.078 \) µm for \( v_c = 1507 \) m/min to \( R_a = 0.14 \) µm for \( v_c = 753.6 \) m/min. In the case of processing flat surfaces with the side surface of the cutter, the surface roughness was greater. For the treatment of such surfaces with a cutting speed of \( v_c = 1507 \) m/min, a roughness of \( R_a = 0.22 \) µm was obtained. In terms of the research and cutting speed \( v_c = 753.6 \pm 1507 \) m/min, the achieved roughness is satisfactory from a technological point of view. This is the roughness that is attained by using, for example, grinders. The use of HSM milling in the machining of aluminum alloys allows for resignation from the machining of cylindrical and flat surfaces by grinding [5–7].

**Research on the dynamics of the milling process**

Carrying out the machining process at very high spindle speeds (approx. 80,000 rpm) and cutting speeds \( v_c \) of approx. 1,500 m/min requires an assessment of the dynamics of the process and control of the state of the MHWT system, both of which can have a very strong influence on the quality of the obtained surface and process efficiency. The definition of the permissible processing areas is defined by, among other things, the so-called bag curves. In the conducted research, a high-speed HES810 spindle and a shank cutter with a diameter of \( d = 6 \) mm were used. Before starting the tests, the radial runout of the tool was checked, which at the point of its greatest protrusion showed a value of about 0.02 mm. In order to assess the dynamics of the milling process, spindle vibration tests were carried out during machining [8–10]. The Microlog CMVA 60 system developed by SKF was used to conduct the study. The set of apparatus installed on the test stand is shown in Fig. 5 and Fig. 6.

The dynamic tests of the cutting process were carried out at spindle speeds of \( n = 40,000; 60,000; \) and 80,000 rpm. The tests were carried out both in free running mode (without loading the spindle with
Fig. 5. Test apparatus for measuring spindle vibrations, type Microlog CMVA 60

Fig. 6. Test apparatus for measuring spindle vibrations of the Microlog CMVA 60 type during machining with rotational speeds of \( n = 20,000 \text{÷} 80,000 \text{ rpm} \)

Fig. 7. List of spindle vibration velocity spectra in the range of 0÷10 kHz, \( V = 0.23 \text{ mm/s} \) for the rotational speed of 80,000 rpm, no-load operation

Fig. 8. List of spindle vibration speed spectra in the range of 0÷10 kHz, \( V = 0.28 \text{ mm/s} \) for the rotational speed of 80,000 rpm, machining with a cutting depth of 0.05 mm at a feed rate of 100 mm/min
cutting forces) and under load. The machining was carried out with a minute feed $f_m = 100 \text{ mm/min}$ and cutting depths $a_p$ equal to 0.05; 0.10; and 0.15 mm [11–14]. Radial runout of the unloaded tool was 0.02 mm. The results of the tests are shown in Figures 7–9. The obtained results allowed the researchers to indicate safe areas of the spindle operation with selected machining parameters, especially the dominant vibration frequencies and the corresponding amplitude velocities. These parameters should be especially favored during machining. The highest spindle vibration amplitude velocities occurred at the spindle rotational speed of $n = 40,000 \text{ rpm}$. An increase in the spindle speed caused a decrease in the amplitude speed. An increase in the spindle load (greater cutting depth $a_p$) resulted in an increase in the amplitude of the vibration frequency. Detailed characteristics are presented and described in Figures 7–9 [15–20].

Conclusions

The tests of processing samples made of 7050 and 7075 alloys confirmed the correctness of the selection of the machining tools. The machining process performed ensured both good quality of the machined surfaces ($R_a$ up to 0.32 µm) and stable machining, which was manifested in the absence of surface waviness in the workpiece.

The selected tools worked well both with the face of the cutter as well as with the side surface, up to a height of $h = 2 \pm 3d$ (cutter diameter). No visible changes were noticed on the rake and tool flank surfaces, related to the occurrence of built-up edge and tool wear. It is advisable to use tools layered coatings especially when machining with cutting speeds $v_c$ of about 2000 m/min and higher. The dynamic tests of the cutting process were carried out under the spindle speeds of $n = 40,000$; 60,000; and 80,000 rpm both in idle run (without loading the spindle with cutting forces) and under load. The machining was carried out with a minute feed $f_m = 100 \text{ mm/min}$ and cutting depths $a_p$ equal to 0.05; 0.10; and 0.15 mm. The results of the tests are shown in Figures 7, 8, and 9. The obtained test results allowed the authors to indicate safe ranges of spindle operation within selected machining parameters, especially the dominant vibration frequencies and the corresponding amplitude velocity. These parameters should be particularly preferred during machining.

The highest spindle vibration amplitude velocities occurred at the spindle rotational speed of $n = 40,000 \text{ rpm}$. An increase in the spindle speed caused a decrease in the amplitude speed. An increase in the spindle load (greater depth of cut $a_p$) resulted in an increase in the amplitude of the vibration frequency. Detailed characteristics are presented and described in Figures 7–9.

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REFERENCES

[1] Adamski W. "Manufacturing development strategies in aviation industry". Advances in Manufacturing Science and Technology. 34, 3 (2010): 73–84.

[2] Arumugam P.U., Malshe A.P., Batzer S.A. "Dry machining of aluminum-silicon alloy using polished CVD diamond-coated cutting tools inserts". Surface and Coatings Technology. 200, 11 (2006): 3399–3403, https://doi.org/10.1016/j.surfcoat.2005.08.127.
[3] Bałon P., Rejman E., Smusz R., Kielbasa B. „Obróbka z wyso- kim prędkościami skrawania cienkościennych kon- strukcji lotniczych”. Mechanik. 8–9 (2017): 726–729, https://doi.org/10.17814/mechanik.2017.8-9.105.

[4] Bałon P., Rejman E., Smusz R., Kielbasa B., Szostak J. “Ap- plication of high speed machining technology in aviation”. AIP Conference Proceedings. 1960, 070003 (2018), https://doi.org/10.1063/1.5034899.

[5] Bałon P., Rejman E., Smusz R., Kielbasa B., Szostak J. “High speed milling in thin-walled aircraft structures”. Applied Computer Science. 14, 2 (2018): 82–95, https://doi.org/10.23743/acs-2018-15.

[6] Bałon P., Rejman E., Smusz R., Kielbasa B., Szostak J. “Im- plementation of high speed machining in thin-walled air- craft integral elements”. Open Eng. 8 (2018): 162–169, https://doi.org/10.1515/eng-2018-0021.

[7] Calatoru V.D., Balazinski M., Mayer J.R.R., Paris H., L’Espé- rance G. “Diffusion wear mechanism during high-speed machining of 7475-T7351 aluminum alloy with carbide end mills”. Wear. 265, 11–12 (2008): 1793–1800, https://doi.org/10.1016/j.wear.2008.04.052.

[8] Burek J., Płodzień M. „Wysoko wydajna obróbka częsci ze stopów aluminium o złożonych kształtach”. Mechanik. 7 (2012): 542–549.

[9] Hovsepian P.E., Luo Q., Robinson G., Pittman M., Howarth M., Doerwald D., Zeus T. “TiAlN/VN superlattice structured PVD coatings: A new alternative in machining of aluminium alloys for aerospace and automotive”. Surface and Coatings Technology. 201, 1–2 (2006): 265–272, https://doi.org/10.1016/j.surfcoat.2005.11.106.

[10] Houming Z., Chengyong W., Zhenyu Z. “Dynamic charac- teristics of conjunction of lengthened shrink-fit holder and cutting tool in high-speed milling”. Journal of Materials Processing Technology. 207, 1–3 (2008): 154–162, https://doi.org/10.1016/j.jmatprotec2007.12.083.

[11] Humieński Z., Blunt L., Jakubiec W., Osanna P.H., Tamre M., Weckemann A., Kuczmaszewski J. “Efektywność wytwarzania elementów lotniczych ze stopów aluminium i magnezu. Komputerowo zintegrowane zarządzanie”. Vol. 2. Konsola Ryszard (ed.). Opole: Oicyna Wydawnicza Polskiego To- warzystwa Zarządzania Produkcją, 2011.

[12] Kuczmaszewski J., Pieśko P. „Wpływ rodzaju powłok węglikowych na siły skrawania oraz chropowatość powierzchni przy frezowaniu stopu aluminium EN AW-6082”. Mechanik. 10 (2013): 846–854.

[13] Oe G., Kawalec A. „Kształtowanie metali lekkich”. Warszawa: Wydawnictwo Naukowe PWN, 2012.

[14] Oerlikon Balzers Coating: „Diamantschicht für die Alumi- niumbearbeitung”. 2008, http://www.maschinenmarkt. vogel.de/themenkanaele/produktion/zerspanungstechnik/articles/15726.

[15] Ratchev S., Liu S., Becker A.A. “Error compensation stra- tegy in milling flexible thinwall parts”. Journal of Mate- rials Processing Technology. 162–163 (2005): 673–681, https://doi.org/10.1016/j.jmatprotec2005.02.192.

[16] Rivero A., López de Lacalle L.N., Penalva M.L. “Tool wear detection in dry highspeed milling based upon the analysis of machine internal signals”. Mechatronics. 18, 10 (2008): 627–633, https://doi.org/10.1016/j.mechatronics.2008.06.008.