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Investigation of the machinability by milling of the laser sintered Inconel 625/NiTi-TiB_2 composite

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ABSTRACT

Introduction. The processing capability of milling a metal-matrix composite based on Inconel 625 with the addition of NiTi-TiB_2, obtained by laser sintering, is investigated. The composite is intended for turbine blades manufacture and has strength characteristics close to Inconel 625, however, due to the addition of TiB_2, its' heat- and wear resistance is higher. This material is new; its machinability has not been studied yet. **The aim of the work** is to determine the technological capabilities of milling with end mills of this composite. **Investigations.** The new composite is milled with end mills, and recommendations on the selection of cutting speed, milling depth and width are obtained. **Experimental Methods.** Measuring end mill wear and cutting force. Wear is assessed by the flank chamfer using a microscope, and cutting forces are measured with a Kistler 9257B dynamometer. Milling is carried out at three speeds: 25, 35 and 50 m/min. To determine the optimal parameters of the depth and width of milling, the following ratios are used: 1 : 1, 1 : 4; 1 : 16, while the volume of chips removed per unit of time remained constant for all ratios. **Results and Discussion.** The back surface of the cutter teeth wears out more intensively. After reaching the wear chamfer along the flank surface of a value equal to 0.11...0.15 mm, there is a sharp increase in forces and brittle destruction of the tooth. Milling at a speed of 25 m/min guaranteed 28 minutes of stable operation, after which the amount of wear quickly approached the critical value of 0.11 mm, at a cutting speed of 50 m/min, critical wear occurred already after 14 minutes. The dependences of the cutting force on time for all selected cutting speeds, throughout the test time, have an increasing character, which indicates the effect of wear of cutters on cutting forces. It is found that the durability of cutters increases with increasing width and decreasing the depth of milling.

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Introduction

Currently, metal alloys and composites obtained using additive technologies are becoming increasingly common. Such materials may have higher parameters of strength, hardness, and wear resistance in comparison with materials obtained by classical fusion. At the moment, about 29 metals and alloys are produced in the form of powders, including stainless and tool steels, aluminum alloys, as well as heat-resistant steels [1]. The creation of powder materials allows for obtaining new properties of alloys by changing the structure of the material in a certain way.

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This paper considers a laser sintered composite based on Inconel 625 with the addition of NiTi-TiB_2 ceramic particles to its matrix [2]. This composite was obtained at High-Energy and Special Materials Research Laboratory, Tomsk State University for the manufacture of turbine blades [1]. The blades of gas turbines operate at high temperatures and loads. The alloys used for the manufacture of turbo engine parts must have high strength, toughness, heat resistance, and corrosion resistance [3]. In Russia, nickel-based alloys are used for the manufacture of turbine blades, for example, such brands as KhN35VTYu, KhN55VMTKYu, KhN62MVKYuL, KhN67MVTYuL, KhN70MVTYuB, KhN75VMYu, KhN80TBYu, ZhS6UD [4]. The properties of these alloys today do not always meet the requirements. Importantly, the products or workpieces obtained using additive technologies may have a higher tensile strength and flow stress as well as low elongation values compared to samples obtained by casting and rolling [5]. The disadvantage of composites obtained by additive technologies is the uneven distribution of the added particles inside the metal matrix, which significantly reduces their physical and mechanical properties. The method of obtaining a composite proposed by the authors [1] reduces this disadvantage to a minimum. For this study, samples were taken in the form of bars; their chemical composition, some physical and mechanical properties are presented in Table 1.

The composite obtained in the study [1] is characterized by increased wear resistance and heat resistance. Since the material is new, its machinability by cutting has not yet been studied. This paper presents a study of this composite machinability by milling.

The term machinability is seen as the property of metals to be processed by cutting. According to [6], the main indicators for assessing machinability are such parameters as cutting forces, the quality of the surface layer, tool wear, the heat released during deformation of the cut layer material, the presence or absence of a tendency to build up, as well as the type, shape, and size of the cut chips. Depending on these characteristics, all materials are divided into 8 groups [4].

According to the recommendations from the reference manual [4], the chemical composition of the Inconel 625 composite with NiTi-TiB_2 corresponds to the V-VI group of machinability. These groups include heat-resistant, refractory, acid-resistant steels as well as nickel-and iron-nickel-based alloys. These groups have very low machinability with a coefficient of 0.16...0.08 in comparison with steel 45, whose coefficient is 1. Low machinability is associated with high tensile strength and hardness, which have a significant impact on the cutting forces during processing. The cutting forces during the processing of sintered alloys may be greater than the forces arising when cutting similar alloys obtained by classical

Table 1

Physical and mechanical properties of the Inconel 625 and NiTi-TiB_2 composite

Physical and mechanical properties	Value
Density, g / cm^3	8.3
Compressive strength, MPa	1830
Tensile strength, MPa	860
Bend strength, MPa	1320
Compression flow stress, MPa	990…1090
Tensile flow stress, MPa	110…160
Modulus of elasticity, GPa	290…330
Poisson's ratio	0.29
Coefficient of thermal conductivity, W/m K	12.5…13.6
Coefficient of linear thermal expansion, K^{-1}	11.3…12.4 · 10^{-6}
Hardness (H_V), HRC	44….46

methods [7], which is most likely caused by the higher strength characteristics of the alloy obtained by laser sintering.

Another feature of the studied composite is that it includes titanium diboride TiB_2, which has a high hardness and negatively affects the durability of the cutting tool. There are no recommendations on the choice of cutting modes for metal matrix composites obtained from powders with the addition of ceramics.

Due to the low thermal conductivity coefficient of such alloys, the heat produced during processing is transferred more to the tool than to the workpiece, thus causing excessive heating of the cutting edge and, as a result, tool wear [3].

In the process of milling hard-to-machine materials, the processing speed and the feed rate have the greatest impact on the tool life, surface roughness, and cutting forces [8]. According to the reference manual [9], milling heat-resistant nickel alloys is recommended to perform by a hard alloy tool at low cutting speeds of about 15...20 m/min with a feed of 0.02 mm/tooth. However, in the literature [10, 11], heat-resistant alloys milling is recommended to perform at more aggressive cutting modes by a hard-alloy tool with a wear-resistant coating, i.e., processing should be carried by cutdown milling technique at a cutting speed of 20 to 50 m/min at feeds of 0.10...0.15 mm/tooth. In addition, the paper [12] argues that ceramic tools show greater resistance when processing some heat-resistant alloys (such as Inconel 718), but such tools are much more expensive.

To improve the machinability of heat-resistant materials, ultrasonic vibrations are applied to the tool or workpiece, which reduces cutting forces, temperature, and tool wear. The paper [13] describes the possibility of processing nickel-based materials on DMG MORI ULTRASONIC machines. However, literature analysis showed that this technology is mainly used for processing brittle materials, glass, and carbon fiber plastics [14, 15]. At the same time, the work [16] describes the positive effect of ultrasonic vibrations during the milling of a hard-to-machine Ti-6Al-4V alloy.

Importantly, the literature on the choice of cutting modes provides information for choosing cutting speeds and feed, while there are almost no recommendations for choosing the depth and width of milling. The authors [17–21] described the method of High-Efficiency Milling (HEM). This method is intended for roughing metals using a small milling depth t and a large milling width B. Milling, which usually uses a large *t value* and a small width B, causes a concentration of heat in a small part of the cutting tool, accelerating the wear process. The use of the entire available length of the mill allows distributing wear over a larger area, thus prolonging the service life of the tool, as well as dissipating heat and reducing the probability of the mills' failure. The HEM method assumes the use of 7...30 % of the milling cutter diameter in the radial direction and twice the milling cutter diameter in the axial direction in combination with an increased feed rate [17].

Therefore, the machinability study of this nickel-based composite with the addition of ceramics has not been studied, so the work is relevant.

The main tasks of this work are:

1. to determine the technology options of end mills processing of a composite based on Inconel 625 with the addition of NiTi-TiB_2.

2. to determine the cutting speed based on the conditions of minimal tool wear and minimal cutting forces that occur during processing.

3. to determine the optimal ratio of the milling depth to width based on the conditions of minimal tool wear and minimal cutting forces.

Research Methodology

All work was carried out on a Haas VF1 vertical milling machining center with a CNC, (USA). The processing was carried out by the cutdown milling technique. As a tool, we used solid-carbide end mills Ø10 mm of the model ZhT641 manufactured by the company "PC MION" (Russia), designed for processing heat-resistant titanium alloys. The main geometric parameters of this mill have the following values: the front angle $\gamma = 4°$, the rear angle $\alpha = 10°$, the helix angle of the tooth $\omega = 38°$, the number of teeth $z = 4$. Based on the recommendations on the processing modes of heat-resistant alloys for the ZhT641 mill and the analysis of the literature [4, 9, 11, 22], the feed per tooth $S_z = 0.04$ mm/tooth was selected for the experiments. The mills were fixed in a collet chuck with the same overhang, its value being 24 ± 0.5 mm. The wear of the mills and the cutting forces were measured to assess the quality and quantity of the experimental results.

Tool wear was assessed by the flank chamfer. The wear chamfer was measured on a UIM 21 microscope on each tooth of the mill. The cutting forces were determined using *a Kistler* 9257B dynamometer (Switzerland). The measurements were carried out in three mutually perpendicular directions (Fig. 1). To evaluate the results, the total force $F = \sqrt{F_x^2 + F_y^2}$ was used; it acted in a plane perpendicular to the axis of the mill. The dynamometer, mounted on a special plate, was fixed in a machine vise. Prior to the experiments, mounting holes were drilled in the workpiece to fix it to the dynamometer with four screws (Fig. 1).

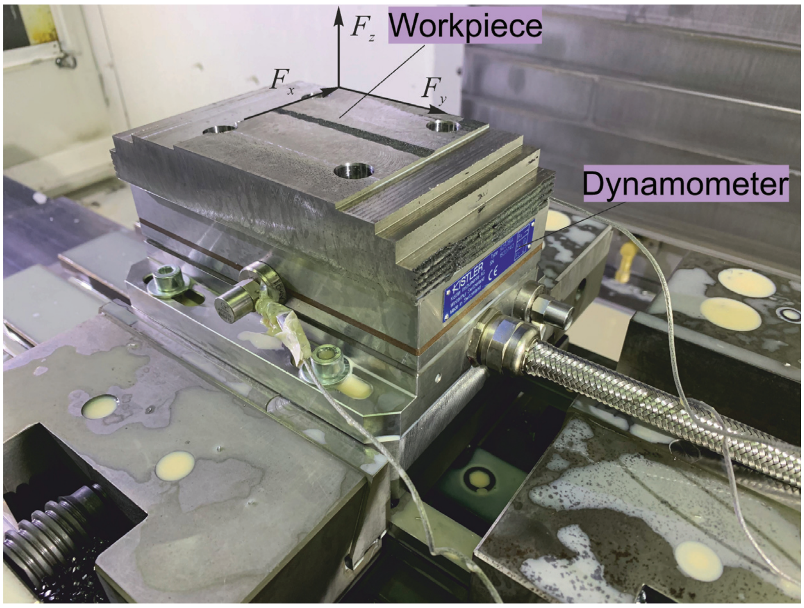


Fig. 1. Workpiece clamped in the dynamometer

To solve the problem of choosing the cutting speed, processing was performed at three cutting speeds: $V_1 = 25$ m/min; $V_2 = 35$ m/min, and $V_3 = 50$ m/min. The feed per tooth, the depth and width of milling remained constant: $S_z = 0.04$; $B = 4$; $t = 1$. The wear of the mills was measured at the same intervals.

To determine the optimal depth and width of the cut for the mill resistance to be the highest, three variants of t and B ratio were selected: $t = B$; $t = B/4$; $t = B/16$. This provided the same amount of the cut layer per unit of time, i.e. the product of $t_1B_1 = t_2B_2 = t_3B_3$ for all three variants of the selected modes remained the same and maintained the same processing performance. The cutting speed was 25 m/min, the feed speed was $S_z = 0.04$ mm/tooth. The cutting techniques are shown in Fig. 2.

So, for mill No. 1, the depth and width of milling were $t = 2$ mm and $B = 2$ mm, respectively. For mill No. 2, the depth was $t = 1$ mm, therefore, the width increased to $B = 4$ mm. For mill No. 3, $t = 0.5$ mm, the width was $B = 8$ mm (fig. 2).

The DynoWare software (Kistler, Switzerland) was used for data collection and analysis. Processing of all the received data was performed in the Microsoft Excel program.

Results and discussion

Fig. 3 shows the dependence of the amount of chamfer wear on the tooth flank surface on the machining time for cutting speeds of 50, 35, and 25 m/min (curves *1*, *2,* and *3*, respectively). The graph shows that the

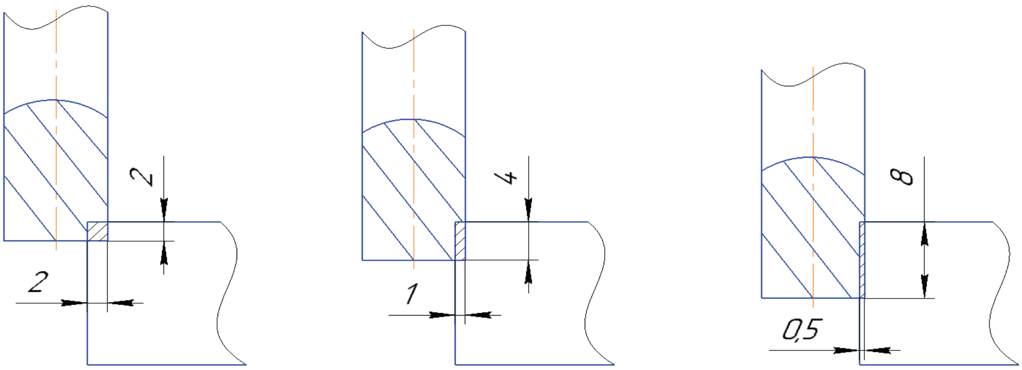


Fig. 2. Milling technique

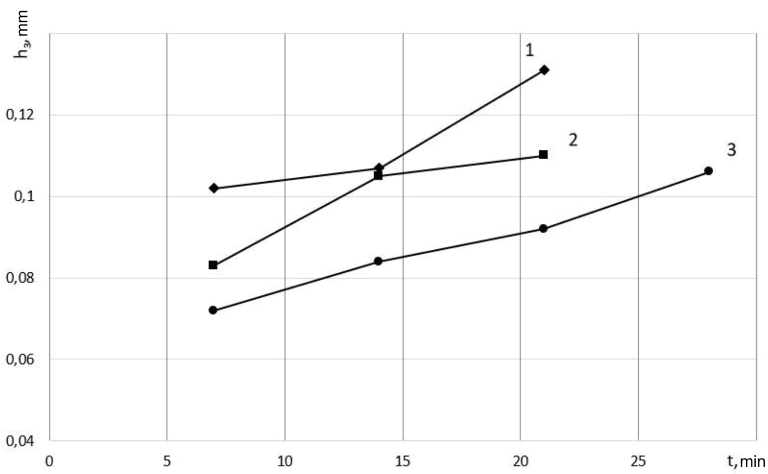


Fig. 3. Dependence of flank wear on the machining time:
1 – V = 50 m/min; *2* – V = 35 m/min; *3* – V = 25 m/min

mill operating at a cutting speed of 25 m/min experienced the least wear during the experiment time. Thus, at the 28th minute of operation, the wear chamfer on the flank surface reached 0.11 mm. The mill operating at V = 50 m/min has the greatest wear since the chamfer value reaches 0.11 mm in 14 minutes.

Obviously, the growth of forces in the experiment time is caused by the wear of the mills (Fig. 4). The mill operating at V=50 m/min (curve *1*) demonstrates the most intensive growth of cutting forces in the entire studied range. For mills operating at speeds of 35 and 25 m/min, the increase in cutting forces over time also correlates with the amount of wear but is less intense than for the mill cutting at the speed of 50 m/min.

Figure 5 shows the wear dependences, and Figure 6 shows the dependences of the cutting forces on the operating time for different ratios of the milling depth and width. After 40 minutes of milling, there occurs critical wear of mills No. 1 and 2 with the cutting edge being painted out. The mill No. 3 working at a ratio of 1:16, worked significantly longer than the others (117 minutes) and was not subjected to catastrophic wear with the destruction of the edge. A sharp increase in the wear intensity of mill No. 3 occurred only at the 92nd minute, after the wear chamfer value exceeded 0.15 mm, while the mills No. 1 and 2 reached this wear value at the 32nd and 43rd minutes, respectively. The maximum value of the wear chamfer of mill No. 3 after 117 minutes of operation was 0.28 mm. The graph of forces (Fig. 6) demonstrates that the forces had very similar values for the mills working time from 0 to 40 minutes for different ratios of the milling depth and width. This is explained by the same volume of the cut layer per unit of time. However, as soon as the

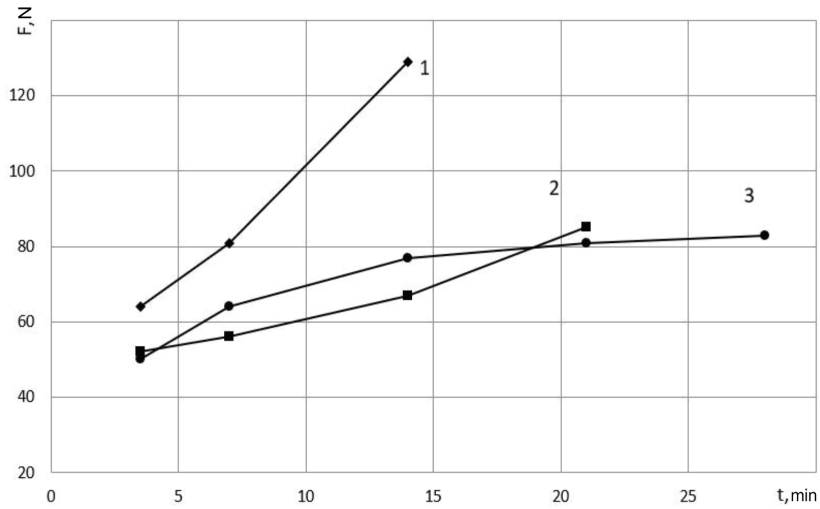


Fig. 4. Dependence of the cutting forces on the machining time:
1 – V = 50 m/min; *2* – V = 35 m/min; *3* – V = 25 m/min

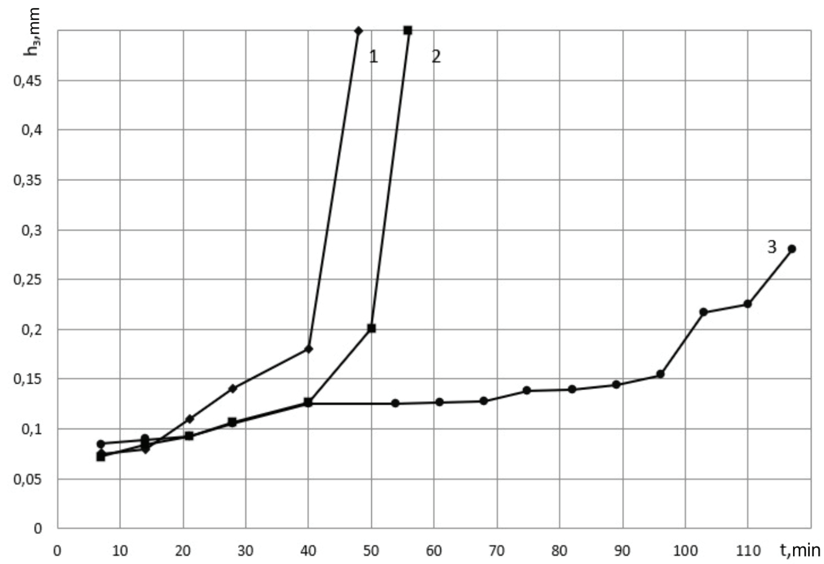


Fig. 5. Dependence of flank wear on the milling configuration:
1 – mill No. 1; *2* – mill No. 2; *3* – mill No. 3

wear becomes critical, which varies in the range from 0.11 to 0.15 mm, there is an instantaneous increase in forces. It follows that before the onset of critical wear, there is no influence of the milling width to depth ratio on the cutting forces. The change in the forces for different ratios t to B (with the same volume of the cut layer per unit of time, i.e. tB = constant, at S = constant) is explained only by the different wear of the mills, which is fully confirmed by Fig. 5 and 6. The research revealed that wear prevails on the flank surface of the mill tooth. Notably, the uneven wear is mainly caused by mechanical abrasion (Fig. 7–9).

The analysis of the established dependencies graphs and photos of the mills' wear reveals that the most effective is the processing technique of mill No. 3 with a depth to width ratio of 1:16. This is assumed to be due to the lower bending moment acting on the mill during operation and to a more uniform distribution of the cutting temperature along the cutting edge.

The force graphs demonstrate that for different t to B ratios with the same volume of the cut layer, the values of the cutting forces before the onset of critical wear are approximately the same, but if the distributed load along the cutting edge is replaced by a concentrated force, the point of this force application will be different, as shown in Fig. 10.

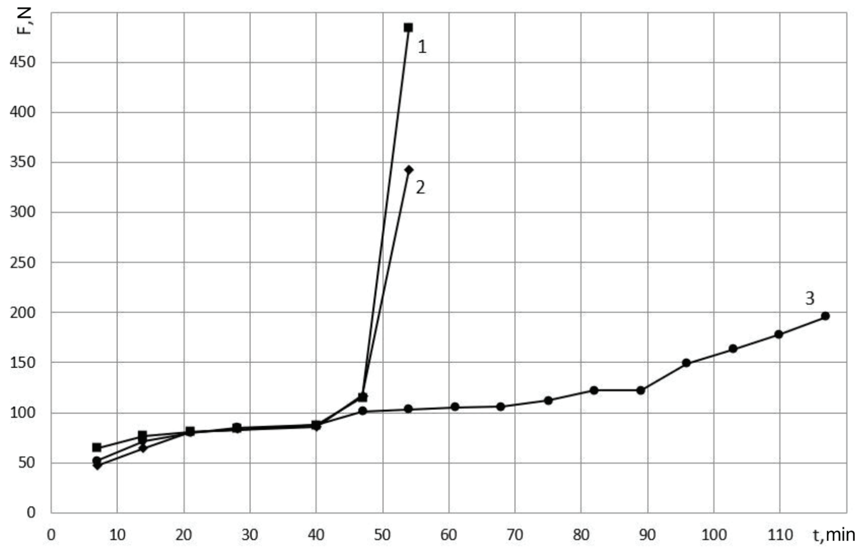
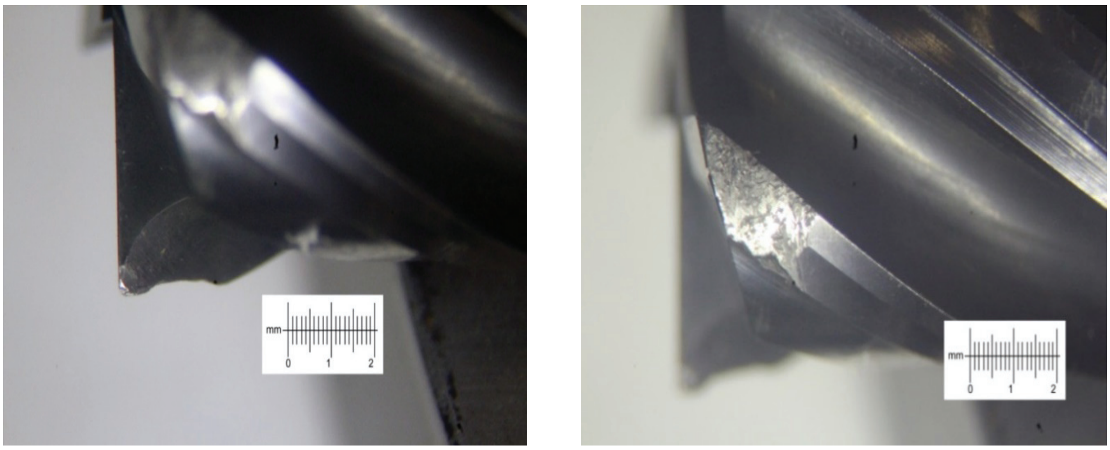
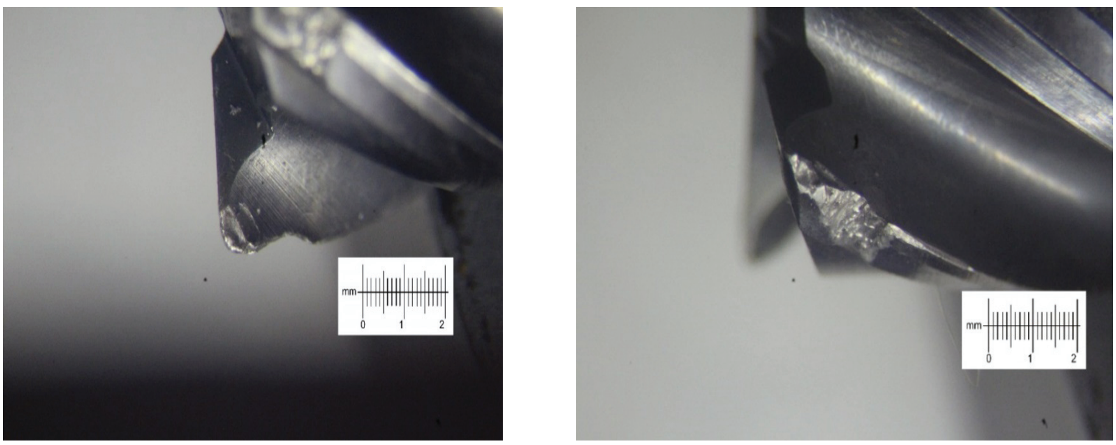


Fig. 6. Dependence of cutting forces on the milling technique:
1 – mill No. 1; *2* – mill No. 2; *3* – mill No. 3



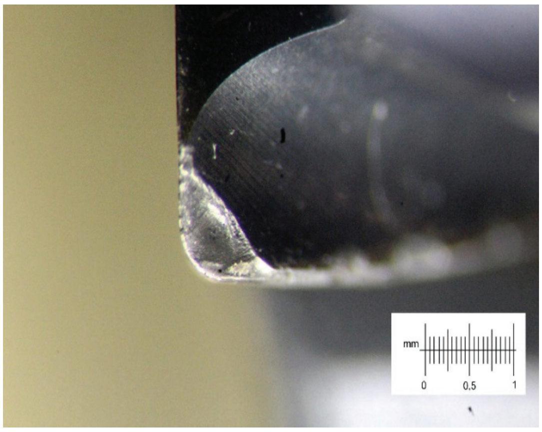
a *b*

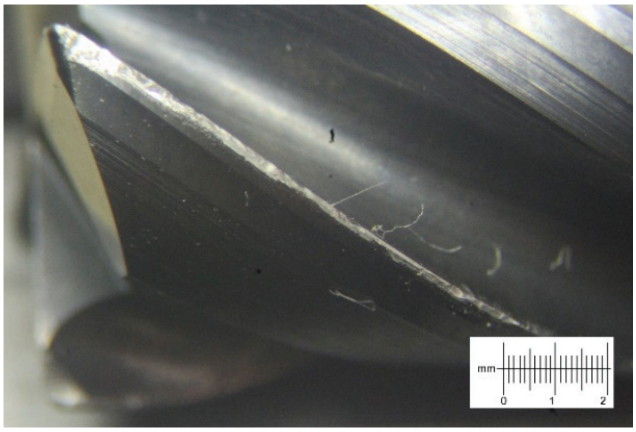
Fig. 7. Photo of the wear of the mill No.1 on the rake (*a*) and flank (*b*) surface



a *b*

Fig. 8. Photo of the wear of the mill No. 2 on the rake (*a*) and flank (*b*) surface





a *b*

Fig. 9. Photo of the wear of the mill No. 3 on the rake (*a*) and flank (*b*) surface

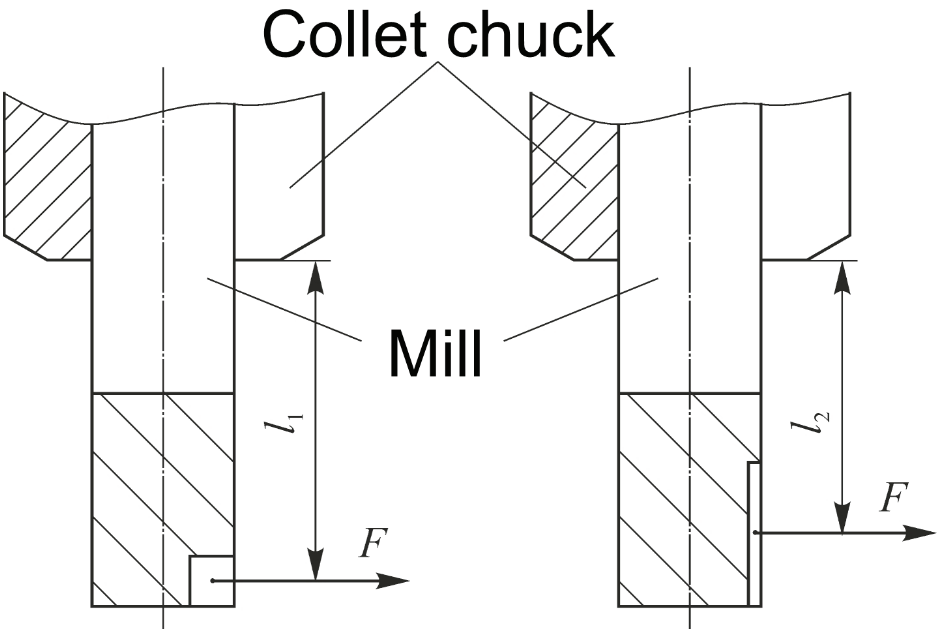


Fig. 10. Application of point force for different depth to width ratios

The diagram shows that with the depth to width ratio of 1:1, the lever of the concentrated force l_1 = 23 mm is greater than the lever l_2 = 20 mm, with a ratio of 1:16. Therefore, the bending moment acting on the first mill is greater. For mill No. 1, the bending moment is M_1 = 2.75×Nm, and for mill No. 3, M_3 = 2.26 N×m. To calculate the bending moment, the force value is obtained from the experiment, and the lever of the acting force is determined according to the scheme shown in Fig. 10. The bending moment of the first mill is almost 20% greater than that of the third. This leads to a greater vibrations amplitude as well as to the mill vibrations and increases its wear. After reaching the critical value of wear, the force increases sharply, while the difference in bending moments becomes even greater.

Another reason for excessive wear may be the temperature distribution in the cutting area. For example, with a small width and a large milling depth, the temperature during the cutting process is localized on a small area of the tool [17], which causes an acceleration of the wear process. As the milling width increases, the temperature is distributed over the longer length of the mill cutting part thus reducing the wear rate.

Conclusions

The conducted research showed:

1. The composite material under study can be effectively processed with end mills designed for processing heat-resistant steels and titanium alloys with geometries $\gamma = 4°$, $\alpha = 10°$, $\omega = 38°$, $z = 4$, with a cutting speed of 20 to 30 m/min and a feed per tooth of 0.02 to 0.04 mm/tooth.

2. The optimal milling technique is the one with the value of the milling width being many times greater than the depth. The durability of the mill operating at milling depth to width ratio of 1:16, with other conditions being equal, is almost 3 times higher than at a ratio of 1:1, and 2 times higher than at a ratio of 1:4.

3. The main wear is concentrated on the flank surface of the mill tooth. With the selected processing modes, the critical wear value is in the range of 0.11 to 0.15 mm. After reaching this value, the wear and destruction of the mill tooth are more intensive.

4. Before the onset of critical wear of 0.11...0.15 mm, the cutting forces at different ratios of depth to width and the same volume of the cut layer per unit of time have similar values of about 70 ... 86 N.

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Conflicts of Interest

The authors declare no conflict of interest.