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Investigation of Cutting Tool Wear in the Milling Process of the Inconel 718 Alloy

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ABSTRACT

The article presents the results of research on the wear of the cutting tool in the process of high feed milling and plunge milling of the Inconel 718 alloy. A specially designed milling head was used in the study, allowing both of the previously mentioned milling methods to be implemented with a single tool. Ceramic inserts CNGN120712 in versions CS300 and CW100 were used for the research. During the experiment, the values of cutting depth a_p [mm], cutting width a_e [mm] and feed per edge f_z [mm/edge] were changed. The study was conducted under the conditions of accelerated wear. The results show the tool life in individual tests using the parameter of the material volume predicted to be removed in the tool life cycle G_{max} [cm^3], obtained by third degree polynomial approximation. For milling with high feeds, the volume of material expected to be removed over the tool life cycle G_{max} ranged from 54 to 106 cm^3, whereas for plunge milling it ranged from 33 to 73 cm^3.

Keywords: Inconel 718, high feed milling, plunge milling, cutting edge wear.

INTRODUCTION

Inconel alloys play a key role in the space industry [1] and the aviation industry [2], among others. The primary method of processing this alloy is machining, which brings many problems resulting from the properties of the material. One of the main challenges facing scientific research in the field of Inconel 718 machining is the issue of wear of the cutting tool, as De Bartolomeis et al. [3] point out. Despite the fact that this wear is very high and machining is very difficult, according to Wang et al. [4] at the same time, efforts are being made to increase the machining efficiency of Inconel alloys. These actions are associated with even greater intensity of cutting tool wear. The strategy of milling the Inconel alloy with increased cutting speeds to determine the limiting values of process parameters is not a new issue in the literature. Previously, as indicated by Bławucki et al. [5] it was used, among others, to determine the limiting cutting force. Increased cutting parameters in the case of milling the Inconel alloy result in the occurrence of self-excited vibrations, which accelerate the wear of the cutting edge. Machining Inconel alloys under the conditions of accelerated wear can also serve to determine the life of the cutting tool. It must be objectively noted that the pursuit of using high machining parameters is economically and practically justified, as the increase in cutting speed reduces energy consumption and improves the quality of the machined surface.

The machining strategy and process parameters have a huge impact on tool wear. The literature contains many articles determining differences in the degree of this wear depending on the machining process being implemented. Differences in tool wear between cylindrical–face milling without the use of cutting fluid and trochoidal milling with the use of cutting fluid can reach up to 900%, as calculated by Potthof and Wiederkehr [6]. Depending on the research program and the machining strategy used, scientific works point to different dominant factors influencing tool wear. Maiyar et al. [7] identified the main cause in the form of cutting speed, Saleem and Mumtaz [8] pointed to the dominant influence of axial cutting depth, while Xavior et al. [9] to the type of cutting tool used. Zetek et al. [10] indicated the significant influence of the cutting edge radius of the cutting insert. Different machining strategies also affect the signals that allow for monitoring tool wear, e.g., according to Parenti et al. [11] the measurement of power drawn by the machine tool from the electrical grid, or according to Grzesik et al. [12] the measurement of the friction coefficient between the tool and the workpiece. The use of cooling liquid has a significant impact on tool wear, as pointed out by Gueli et al. [13], particularly on the wear occurring on the rake face. Niyas et al. [14] in their research have proven that tool wear in the machining process of the Inconel superalloy can be predicted using neural networks. However, due to difficulties in modeling this phenomenon, errors in the case of using typical forecasting methods can reach up to 45%, making it hard to replace empirical research with forecasting methods.

Tool wear in the cutting process of Inconel alloys can be reduced through the proper selection of the cutting tool [9-10]. The dominant role in the case of machining the Inconel alloy is currently played by the tools from oxide ceramics and nitride ceramics for semi-finishing machining and coated cemented carbide for finishing machining, as described by M'Saoubi et al. [15]. However, in the work of Bushlya et al. [16] there is information about using PCBN tools for this purpose as well. Often, such tools also have some drawbacks. An example can be the use of SiALON ceramic tools. Ma et al. [17] indicated that despite higher wear resistance, they cause poorer quality of the machined surface. Even though Finkledei et al. and Sun et al. [18-19] suggested, among others, that ceramic tools significantly increase the efficiency of machining Inconel alloys, the question whether they should dominate in this kind of machining remains, as pointed out by Grguras et al. [20], among other things due to the fact that the relative brittleness of ceramic tools can result in chipping or catastrophic damage, especially during an interrupted process, in which there are excessive thermomechanical changes, as described by Molaieikiya et al. [21] and due to almost 40% higher tool costs, as calculated by Grguras et al. [22].

The literature reports analyzed in the introduction concerning tool wear in the cutting process of the Inconel 718 alloy suggest that the stereometry of the cutting tool and the type of cutting inserts may affect the obtained results. Hence, the idea arose that there was a real possibility of using a single cutting tool equipped with different cutting inserts in the research, which would avoid disturbance of the experimental results by the aforementioned disturbing factors.

The aim of this publication was to develop a method for determining the durability of a cutting tool in the process of accelerated wear of the Inconel 718 alloy. Accelerated wear was carried out using a high-feed milling process and plunge milling using one cutting tool. For this purpose, a special milling head was designed and manufactured to enable machining with both methods. The tested method of determining tool life in accelerated wear tests may be of great practical importance, as it enables to determine the actual amount of material removed in various machining processes.

MATERIALS AND METHODS

The Inconel 718 alloy was chosen as the work material for the research. During the research, two milling methods were analyzed. The first one was high feed face milling, which is a typical processing method for this material. The second method was plunge milling, which is rarely used for the tested alloy. This is due to the fact that high cutting forces occur during this process, as described by Zhuang et al. [23]. To make a comparison of both methods possible, it was necessary to use one tool that allows machining by these two methods. Given that none of the leading tool companies has this kind of tool in its offer, a special tool meeting this requirement was designed. Taking into account a number of machining process parameters, such as: linear feed values for constant cutting speed v_c and different tool diameters D, values of the approach angles kappa κ, spindle rotational speeds for constant cutting speed v_c, and different, typical diameters of cutting tools, as well as occurring forces and the possibility of generating vibrations [27], it was decided to use a milling head with a diameter of 80mm and an approach angle of 12.5º. The special milling head was designed to serve both for face milling and plunge milling. The tool was made based on the design in the Seco Tools company. A view of the milling head and its basic dimensions are shown in Figure 1.

To compare two different machining processes, regardless of the process kinematics or tool path, the following assumptions were adopted:

- Both methods will be used only for rough machining,
- The machining processes must be carried out using tools of the same diameter and number of teeth and with the same stereometry, in accordance with the accepted tool design,
- The cutting rate must be the same in the compared processes,
- The cutting tests must take place on the same cutting machine,
- The cutting tests must be carried out on the same material heat,
- The cutting tests must take place under conditions of accelerated wear.

The last point of the presented assumptions results from the fact that during the milling process of the Inconel 718 alloy, there are 3 phases: initial wear, stable wear, and accelerated wear, as presented by Zhaopeng et al. [24]. The implementation of research and measurement of tool wear should allow for the observation of all three of these wear phases.

The input material for the research was a rod made of Inconel 718 with a diameter of 152.4mm (6 inches) and a length of 150mm. This is a nickel-based superalloy characterized by high wear resistance also at high temperatures and good weldability. Due to the difficulties in machining this alloy, the first challenge was the proper preparation of samples for testing. The decision was made to perform preliminary machining on the FANUC Robocut C600iA/5/AWF/Z400 wire-cutting EDM machine. The machining consisted of cutting a shaft of the appropriate length from a semi-finished rod. The next step was to prepare the shape of the sample in such a way as to allow machining by both high feed milling and plunge milling. The shape of the sample should provide the possibility of measuring cutting forces, so that it would be possible to monitor the process itself. Therefore, the final shape of the sample, shown in Figure 2, is the result of adapting its dimensions to the shape of the piezoelectric force sensor from Kistler model 9199AA.

For the research, CNGN120712 cutting inserts were used in the CS300 and CW100 versions. These are rhomboidal turning inserts designed for machining superalloys, such as Inconel 718. CS300 inserts are sialon ceramic inserts ensuring high wear resistance, toughness, and thermal shock resistance. CW100 inserts are also made of SiAlON ceramics, and are additionally reinforced with whiskers. This ensures high resistance to wear, breakage, notch formation, and high hardness at high temperatures. Both types of inserts had the same geometry and were mounted in the designed milling head (Fig. 3).

The tests were carried out using the measuring system shown in Figure 4. It included: a

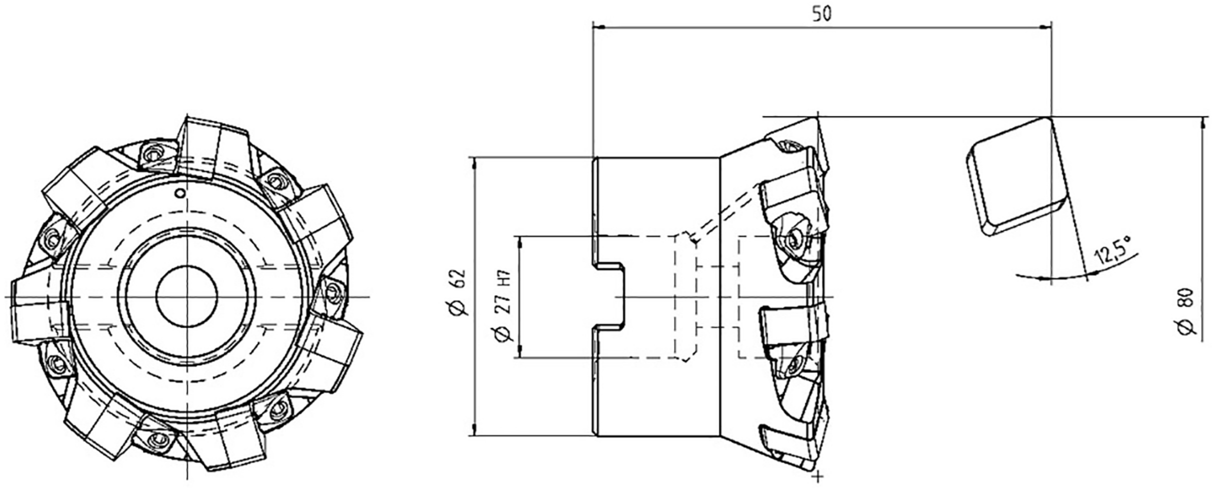

Fig. 1. Designed milling head

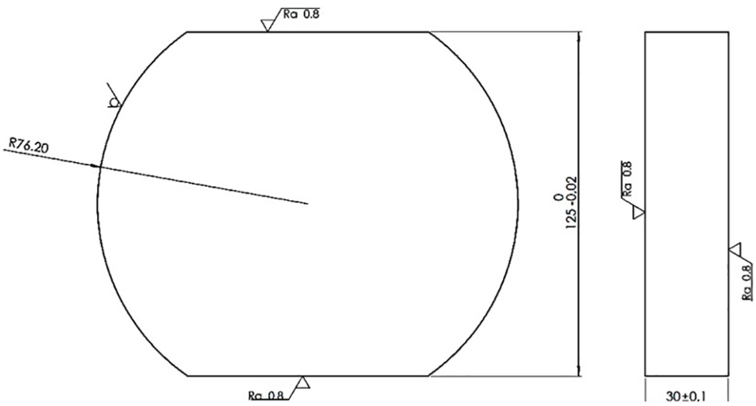

Fig. 2. A sample for testing made of Inconel 718

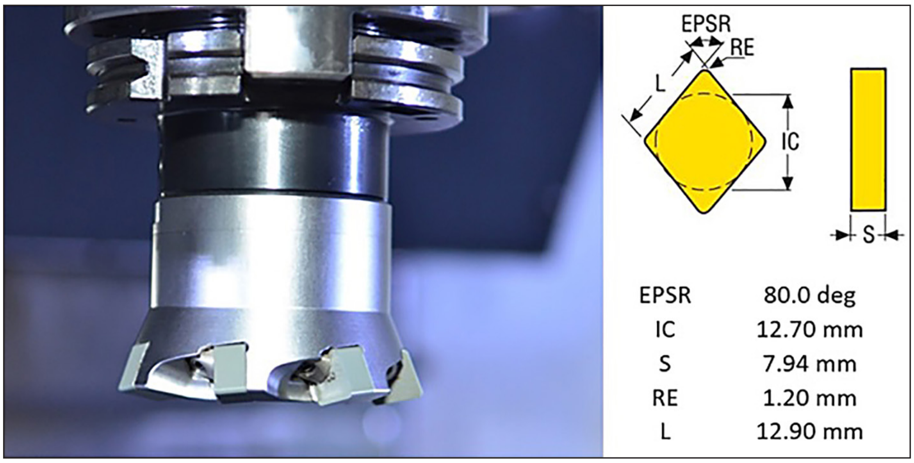

Fig. 3. Designed milling head with CNGN120712 inserts, mounted in the spindle of the milling center

Fig. 4. Cutting force measurement bench: 1- Kistler 9199AA force sensor, 2- Kistler 5070A signal amplifier, 3- Kistler 5697A data acquisition system, 4 – PC with DynoWare 2825D software

piezoelectric force sensor Kistler model 9199AA (1), an electric charge amplifier Kistler 5070A for forces F_x, F_y and F_z (2), a data acquisition system Kistler 5697A (3), and a laptop with DynoWare 2825D software for analyzing the received data (4).

On the basis of preliminary research, it was determined that the appropriate moments to measure tool wear were runs number 1, 2, 3, 6, and 9 for the assumed machining parameters. The basic parameter determining the wear of the cutting tool during milling of the Inconel alloy is usually, according to Felusiak-Czyryca et al. [25] the average width of the wear band of the flank face V_{BB} and according to Szablewski et al. [26] the radial wear *KE*, with the former being used more frequently, and this is the parameter that was analyzed as the basis for determining the wear of the cutting tool. The wear measurements of the cutting inserts were carried out in a measurement laboratory. For the analysis of insert wear, a multisensor machine ZEISS O-INSPECT 332 with a measurement range of 300x200x200mm was used. This is a numerically controlled measurement system with both a touch scanning head and a ZEISS Discovery V12 measuring lens that works on the principle of a microscope with a field of view from 1.3×1 mm^2 to 16.1×12 mm^2, depending on the applied magnification. The measurements were made in reflected light. During the experiment, V_{BB} wear was measured, directly by analyzing the microscope image, using dedicated software. The pictures showing the wear of the cutting inserts were taken both on the rake face and on the flank face, as shown in Figure 5.

On the basis of the cutting edge wear measurement, the volume of machined material predicted before V_{BBmax} wear was calculated. For this purpose, from the system of normal equations of polynomials from the third to the sixth degree, a polynomial in general form (Eq. 5) must be determined. The need to use such a system results from the assumption that the wear of the cutting edge follows the shape of a polynomial [24]. The normal equations of polynomials from the third to the sixth degree are presented below (Eq. 1-4).

$$a_0 n + a_1 \sum_{i=1}^{n} x_i + a_2 \sum_{i=1}^{n} x_i^2 + a_3 \sum_{i=1}^{n} x_i^3 = \sum_{i=1}^{n} y_i \quad (1)$$

$$a_0 \sum_{i=1}^{n} x_i + a_1 \sum_{i=1}^{n} x_i^2 + a_2 \sum_{i=1}^{n} x_i^3 + a_3 \sum_{i=1}^{n} x_i^4 = \sum_{i=1}^{n} x_i y_i \quad (2)$$

$$a_0 \sum_{i=1}^{n} x_i^2 + a_1 \sum_{i=1}^{n} x_i^3 + a_2 \sum_{i=1}^{n} x_i^4 + a_3 \sum_{i=1}^{n} x_i^5 = \sum_{i=1}^{n} x_i^2 y_i \quad (3)$$

$$a_0 \sum_{i=1}^{n} x_i^3 + a_1 \sum_{i=1}^{n} x_i^4 + a_2 \sum_{i=1}^{n} x_i^5 + a_3 \sum_{i=1}^{n} x_i^6 = \sum_{i=1}^{n} x_i^3 y_i \quad (4)$$

The general form of the polynomial should look as follows (Eq. 5):

$$ax^3 + bx^2 + cx + d = y \quad (5)$$

where: a, b, c – the coefficients of the unknowns, d – the absolute term, y – the sought boundary value, x – the variable of cutting edge wear (V_{BB}) as a function of the material volume.

As the coefficients a, b, c and d in equation (5), the appropriate coefficients $a3$, $a2$, $a1$ and $a0$ determined from the systems of equations (1-4) were assumed. Then, the sought y value from the polynomial should be compared to the boundary V_{BB} , permissible before catastrophic wear. This value can be obtained using experimental data or manufacturer's data. The formula obtained in this way should have the following form (Eq. 6):

$$ax^3 + bx^2 + cx + d = V_{bmax} \quad (6)$$

where: V_{BBmax} – the maximum allowable value of cutting edge wear.

The solution of this equation is done using the Cardano formulas. As a result of the calculations, one real solution is obtained. The value obtained is defined as the volume of material predicted to be removed in the tool life cycle and is defined as G_{max} [mm^3]. The tests were carried out on a HAAS VF3/YT milling center. This is a 4-axis machining center with a working space of dimensions 1016×660×635 mm. It was equipped with a tool clamping system on the SK50 cone, which is dedicated to rough machining. The machine was equipped with a spindle with a maximum power of 22.4 kW. The maximum spindle speed and feed rates were n = 7500 rpm and v_f = 12700 mm/min, respectively (Fig. 6). The research plan envisaged the use of two types of CNGN120712 inserts – ceramic – CS300 and whisker-reinforced ceramic

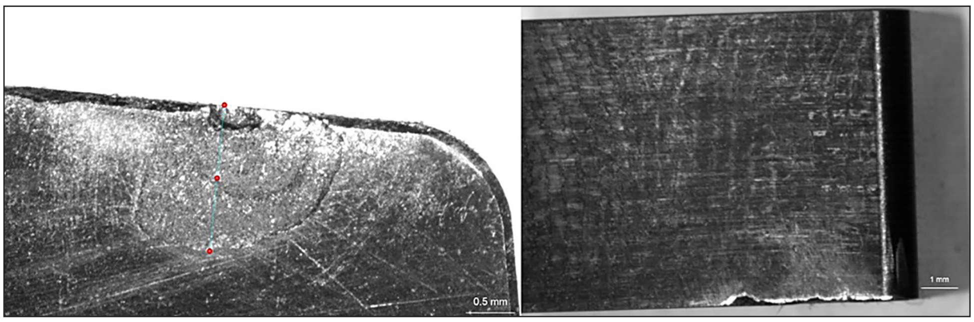

Fig. 5. Microscope image of the flank face of the CS300 insert for high feed milling (optical magnification 0.5x). Microscope image of the rake face of the CS300 insert for high feed milling (optical magnification 1.6x)

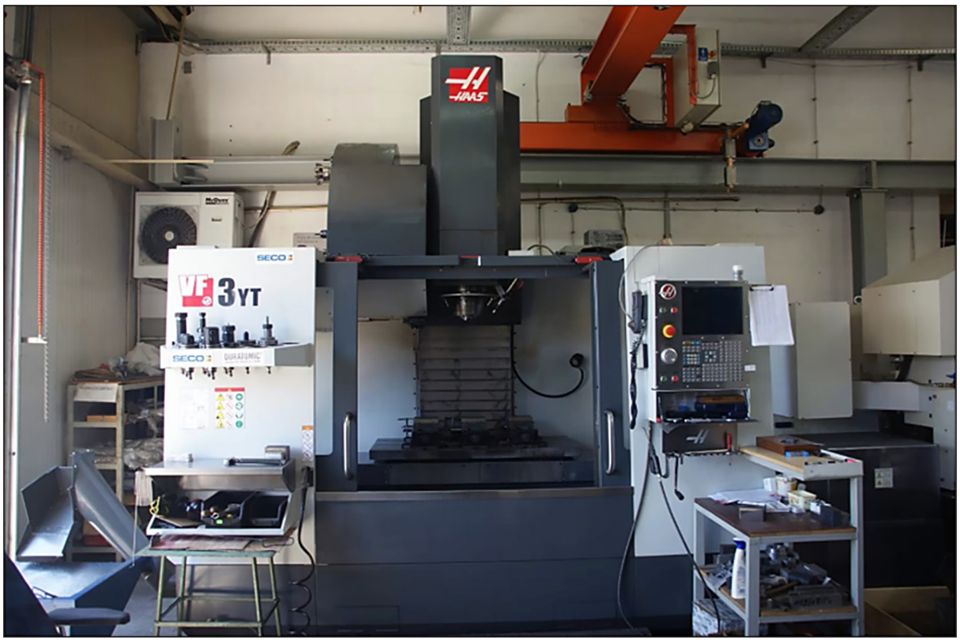

Fig. 6. HAAS VF3/YT milling center used for machining tests

– CW100. For the experiment, a constant cutting speed of v_c=800m/min was assumed. The variable parameters for high feed milling were cutting depth a_p [mm] and feed per edge f_z [mm/edge], while for plunge milling the cutting width a_e [mm]. The use of such a matrix of variable parameters in combination with the geometry of a special tool allowed achieving different values of cutting performance Q [cm^3/min]. For each set of parameters, 9 machining runs were planned. The original main research plan included 20 sets of parameters and a total of 180 machining runs, but due to machine power limitations, the final research plan was reduced to 14 sets of parameters and a total of 122 machining runs. Details of the research plan are shown in Table 1.

RESULTS AND DISCUSSION

On the basis of the measured values of the tested quantities, the extrapolated volume of material removable up to the limit of the cutting edge wear value was determined. As an example, for

Table 1. Master research plan

Set	Type of insert	Type of machining	f_z [mm/edge]	a_e [%D] or [mm]	a_p [mm]	Theoretical diameter D [mm]	Rotational speed n [rpm]	Feed rate V_f [m/min]
A	CS300	Highfeed	0.3	100%	0.5	70.54	3610	7581
B	CS300	Highfeed	0.4	100%	0.5	70.54	3610	10108
C	CS300	Highfeed	0.5	100%	0.5	70.54	3610	12635
D	CS300	Highfeed	0.3	100%	1	72.8	3498	7346
E	CW100	Highfeed	0.3	100%	0.5	70.54	3610	7581
F	CW100	Highfeed	0.4	100%	0.5	70.54	3610	10108
G	CW100	Highfeed	0.5	100%	0.5	70.54	3610	12635
H	CW100	Highfeed	0.3	100%	1	72.8	3498	7346
I	CS300	Plunging	0.08	1 mm	-	80	3183	1783
J	CS300	Plunging	0.08	1.5 mm	-	80	3183	1783
K	CS300	Plunging	0.08	3 mm	-	80	3183	1783
L	CW100	Plunging	0.08	1 mm	-	80	3183	1783
M	CW100	Plunging	0.08	1.5 mm	-	80	3183	1783
N	CW100	Plunging	0.08	3 mm	-	80	3183	1783

set *C*, the following approximated polynomial waveform, shown in Figure 7, was obtained based on the results of measuring V_{BB} values.

For the inserts used in the experiment, the maximum cutting edge wear limit (V_{BBmax}) was 3.5 mm. After substitution into the above formula, the following relation was obtained (Eq. 7):

$$0.0004x^3 - 0.0028x^2 + 0.0636x - 0.0068 = VB_{Bmax} = 3.5 \quad (7)$$

In this case, the value of the extrapolated volume of material that can be removed in the machining range until the tool reaches the limit of the cutting edge wear value equal to 66.028 cm³.

First, research was carried out on the more common milling method – high feed milling. The results shown in Table 2 indicate that the cutting parameters used affect the predicted wear of the cutting tool in different ways.

The reported results show that in high feed milling there are slight differences between the volume of material expected to be removed during the tool life cycle and the actual cutting process. The averaged values for the machining parameters used do not make it clear which of the two types of edges used in machining is better for milling the Inconel 718 alloy with high feed rates. The results obtained for the volume of material expected to be removed during the tool life cycle G_{max} of 50–110 cm³ are within the expected wear ranges declared by cutting insert manufacturers. The values obtained with the D and H parameter sets suggest that when milling with high feed rates of the Inconel 718 alloy, it is necessary to use the highest possible cutting depth values, as this increases the life of the cutting tool and is also economically justified by the volumetric cutting efficiency. The prevalence of

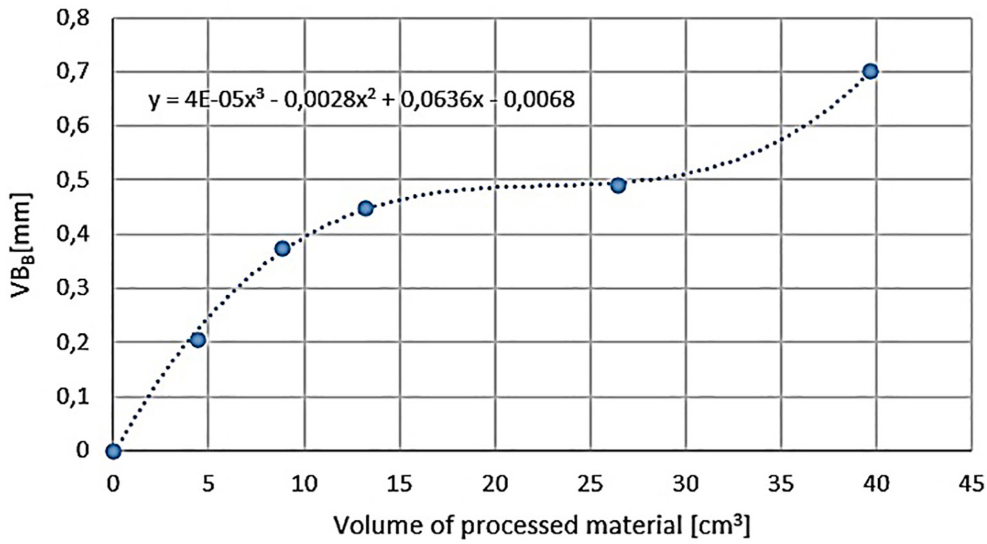

Fig. 7. Diagram of the dependence of cutting edge wear (V_{BB}) on the volume of machined material for high feed milling with CS300 insert for machining parameters: v_c = 800 m/min, f_z = 0.5 mm/edge, a_e = 70.54 mm, a_p = 0.5 mm

Table 2. Measurement results for milling with high feeds

Set of parameters	Type of insert	Volumetric efficiency of cutting *Q* [cm³/min]	Volume of material expected to be removed over the tool life cycle G_{max} [cm³]
A	CS300	267.39	61.499
B	CS300	356.52	71.935
C	CS300	445.65	66.028
D	CS300	534.78	96.248
E	CW100	267.39	57.320
F	CW100	356.52	54.042
G	CW100	445.65	57.890
H	CW100	534.78	106.39

Table 3. Measurement results for plunge milling

Set of parameters	Type of insert	Volumetric efficiency of cutting Q [cm^3/min]	Volume of material expected to be removed over the tool life cycle G_{max} [cm^3]
I	CS300	142.61	36.51
J	CS300	213.91	37.96
K	CS300	427.82	69.18
L	CW100	142.61	33.61
M	CW100	213.91	50.58
N	CW100	427.82	73.16

whisker-reinforced inserts (CW100), as described in the literature [28], consisting of increased cutting tool life, becomes apparent only when high machining parameters are used.

Further analogously, a study of a less frequently used machining method – plunge milling – was conducted. It is noteworthy that the results obtained for this milling method (Table 3) demonstrate that this method for a machine tool of a certain power has greater limitations in terms of being able to apply a sufficiently high volumetric cutting capacity. This is most likely due to the fact that higher values of power consumed during the process are recorded than in the case of milling with high feed rates.

As with the results of measurements for high feed milling, it can be observed that also in this case there are slight differences between the volume of material expected to be removed during the tool life cycle and the actual cutting process. The advantage of whisker-reinforced inserts (CW100) over inserts without such reinforcement (CS300) is that CW100 inserts enable a greater volume of material to be removed over the tool life cycle. The performance results obtained in the 30–75 cm^3 range are slightly lower than expected and indicate some problems with the possible use of this method for roughing the Inconel 718 alloy, due to the need to change cutting inserts more often than in the high feed milling method. Increasing the cutting width improves tool life. The volume of material expected to be removed during the tool life cycle is then greater than if lower cutting width values are used. When using the highest values of the cutting width parameter for plunge milling, the life of whisker-reinforced ceramic inserts (CW100) was 5.9% greater than that of ordinary ceramic inserts (CS300), while when using the highest values of the cutting depth parameter for high feed milling, the life of whisker-reinforced ceramic inserts (CW100) was 10.6% greater than that of ordinary ceramic inserts (CS300)

CONCLUSIONS

On the basis of the conducted research, it can be concluded that the machining tests carried out confirmed the usefulness of Inconel 718 plunge milling with a ceramic insert head with a small rake angle. The durability values of the cutting inserts compared to high-feed milling were slightly lower. For both maintenance conditions for plunge cutting, the compliance was approximately 32%. Currently, leading cutting tool manufacturers do not offer a tool suitable for such machining. This means that this milling method can be implemented in industry when milling heads with a small rake angle dedicated to machining this material appear on the market. A tangible benefit in favor of implementing Inconel 718 plunge milling into the industry is high machining efficiency, comparable to high-feed milling.

The research also showed the usefulness of the method for determining tool life under the conditions of accelerated wear for high-feed milling and plunge milling of the Inconel 718 alloy. The method is universal and can also be used to determine tool life when machining other superalloys. By conducting an experiment under accelerated wear conditions, it is therefore possible to determine an extrapolated value for the volume of material that is likely to be removed over the life of the tool. The usefulness of the presented method can be increased by using a vision system to determine the current state of cutting edge wear, which would significantly shorten the stage of collecting experimental data necessary for evaluation with the developed method, avoiding the need to remove cutting inserts from the milling head in order to obtain measurement results.

The cutting process with whisker-reinforced ceramic inserts (CW100) is characterized by an increase in the durability of the cutting tool compared to the use of ordinary ceramic inserts (CS300), both in high-feed milling and plunge milling of rge Inconel 718 alloy. The volume of material to be removed during the life cycle of the tested tools for high-feed milling is on average 78.7 cm^3 – CS300 and 78.9 cm^3 – CW100. However, for plunge milling, G_{max} is on average 52.5 cm^3 – CS300 and 54.3 cm^3 – CW100. The advantage of whisker-reinforced inserts increases along with depth of cut in high-feed milling and width of cut in plunge milling. The greatest achievement of the authors of this work is determining which Inconel milling strategies should result in the highest values volume of material expected to be removed over the tool life cycle G_{max}.

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