Performance Analysis of Diamond Coated End Mill during Machining of Metal Matrix Composite

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Abstract. In this paper, a performance analysis of a diamond coated end mill during the milling of a hard-to-cut Duralcan™ metal matrix composite was presented. The conducted tests involved the measurements of cutting force components during milling with one variable parameter, evaluation of the flank wear VB_B and corner wear VB_C. Cutting speed v_c in range 300, 500 and 900 m/min was the changeable parameter. Finally, the analysis of cutting forces in time domain, as well as the correlation of the obtained measures with the tool wear values were conducted.

Introduction

One of the most popular Metal Matrix Composites (MMCs) is Duralcan™, which is a material based on aluminum cast alloys reinforced with ceramic particles SiC that is suited for high pressure die castings [1]. Its strength and abrasive wear resistance is increased due to reinforcement. In view of high mechanical properties, MMCs are difficult-to-cut materials [2-4]. Machining of MMCs is difficult because of hard ceramic particles content, which simultaneously contributes to the rapid tool wear like in other hard-to-cut materials [5-7]. Nowadays, there are a lot of ideas to improve machinability of difficult-to-cut materials, which improve surface roughness after machining and reduce tool wear. One of such methods is laser assisted machining (LAM), which improves the machining efficiency of hard-to-cut materials [8-10]. One of the example is paper [11], where the laser modification steel specimens with the boronickelized layer (B-Ni complex layer) contribute to the reduction of the microhardness of material and wear resistance. These parameters are reduced in the heating zone by means of a laser beam, which in the case of laser-assisted machining of hard materials improves machining efficiency and tool life. The other method of improving the efficiency of machining of hard-to-cut materials is various kind of prediction models of tool wear. During the monitoring of machining process, the information about tool wear is useful for the tool condition prediction process [12]. There are a lot of methods of edge wear indicator prediction, where the following are the most interesting: genetic algorithm, artificial neural networks or fuzzy logic. The most important stage is the validation of the created model and assessment of its effectiveness in predicting tool wear. Appropriate tool condition assessment will allow for its catastrophic failure detection before cutting edge chipping or surface deterioration occurrences [13, 14].

One of the problems of hard-to-cut materials machining is to simultaneously obtain a satisfactory surface with reduced tool wear and carry out the process in the shortest possible time. Materials such as Duralcan, Inconel or Waspaloy are increasingly used in the automotive or the aviation industry, so it is important to obtain the required accuracy of components. The following are examples of elements that often work at elevated temperatures or difficult conditions: brake rotors, clutch plates, brackets, belt pulley and many others [15-17].

There are still problems with the mechanical processing of these materials. The rationale for this article is the increasing use of materials such as MMC in industry.

The results of this study may be interesting for related technological processes, such as the production of protective coatings [18], including the ESD method [19], later processed with a laser [20], which is of interest to the hydraulics of heavy-duty machines with high operating precision [21]. Further work will include an in-depth analysis of the factors influencing the process [22, 23].

Materials and method

The objective of the research involved the performance analysis of metal matrix composite milling, based on the measurement of tool wear in different cutting conditions. The workpiece was a type of MMC with the trade name of Duralcan™. This material exhibits high yield strength, ultimate strength and elastic modulus due to the reinforcement of aluminum matrix with approx. 10% silicon carbide (SiC) particles. This reinforcement allowed for the improvement of mechanical properties and improved abrasion resistance. Table 1 depicts the chemical composition of the Duralcan™ matrix alloy.

Table 1 The chemical composition of Duralcan™

Duralcan™ F3S.10S	Si	Fe	Cu	Mg	Ti	Al
content (%)	8.50…9.50	0.20 max	0.20 max	0.45…0.65	0.20 max	rest

Three-edged diamond coated end mills ⌀ 10 mm were selected for machining the composite material. The diamond coating retains its properties up to the maximum of 600˚C. The base tool material is a fine-grained carbide grade with a cobalt content of 8%, which significantly improves durability and abrasion resistance.

The cutting tests were conducted on a DECKEL-MAHO DMC 70V machining center, with cutting conditions presented in Table 2. The cutting speed v_c was a variable parameter in the tests. Three repetitions were carried out for each cutting speed.

Table 2. Cutting parameters

Cutting variant	1	2	3
Cutting speed v_c (m/min)	300	500	900
Feed per tooth f_z (mm/tooth)	0.035	0.035	0.035
Cutting path L (mm)	122	122	122
Cutting depth a_p (mm)	8	8	8
Cutting width a_e (mm)	0.2	0.2	0.2

After each milling pass, the tool flank wear VB_B and corner wear VB_C were measured with the use of a microscope. The tool wear was measured for three cutting edges of each tool. The value of tool wear was averaged. The critical tool wear criterion for the milling tool was equaled to 0,3 mm. Additionally, measurements of cutting force components were carried out with the application of piezoelectric force sensor clamped to the machine’s worktable. The measurements were conducted in the following directions: X – feed direction F_f , Y – feed normal direction F_{fN} and Z – thrust direction F_z. Figure 1 presents a simplified diagram of the measurement set-up.

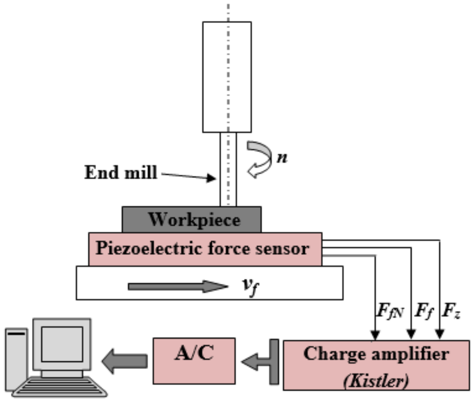

Figure 1 The scheme of experimental apparatus

Analysis of tool wear

The research results show the measured tool wear VB_C and VB_B generated during the end milling of MMC. Fig.2 depicts the relationship between the flank wear VB_C and the cutting time t_s for all repetitions. To determine the relation, the exponential function $VB_C = a{\cdot}e^{b{\cdot}t_s}$ was selected.

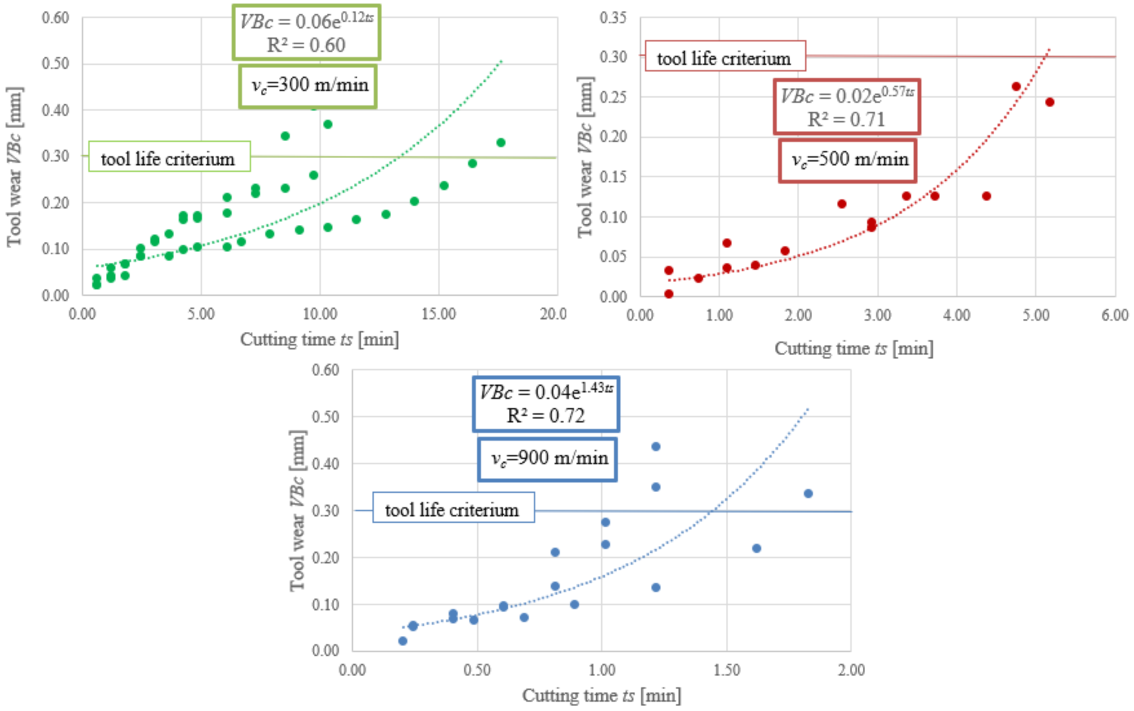

Figure 2. Tool wear VB_C in function of time for:
a) v_c = 300 m/min, b) v_c = 500 m/min, c) v_c = 900 m/min

On the basis of the selected equations, the average time needed for the excessing the critical tool wear value was calculated and shown in Table 3.

Fig.3 presents the tool flank wear VB_B values in function of time t_s for all repetitions. The exponential function VB_B = a·e$^{b \cdot ts}$ was determined similar to the corner wear analysis. The tool life T based on selected equations was calculated and depicted in Table 4. The tool life T based on selected measurement of VB_B was calculated and depicted in Table 4.

Table 3 Value of tool life T based on measurement of VB_c

Cutting speed v_c [m/min]	Equation	Tool life T [min]
300	$VB_C = 0.06 \cdot e^{0.12ts}$	13.36
500	$VB_C = 0.02 \cdot e^{0.57ts}$	5.11
900	$VB_C = 0.04 \cdot e^{1.43ts}$	1.44

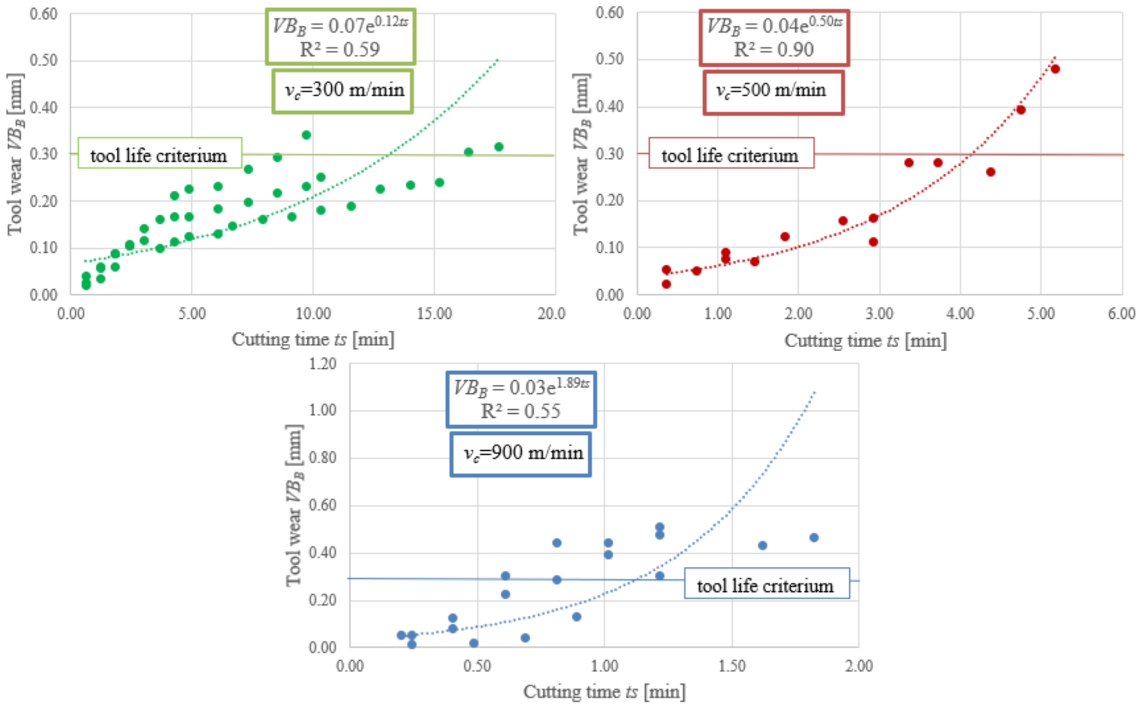

Figure 3. Tool flank wear VB_B *in function of time for:*
a) v_c *= 300 m/min, b)* v_c *= 500 m/min and c)* v_c *= 900 m/min*

Table 4. Value of tool life T based on measurement of VB_B

Cutting speed v_c [m/min]	Equation	Tool life T [min]
300	$VB_B = 0.07 \cdot e^{0.12ts}$	13.12
500	$VB_B = 0.04 \cdot e^{0.50ts}$	4.41
900	$VB_B = 0.03 \cdot e^{1.89ts}$	1.15

In the next step, the material removal rate (MMR) Q [cm^3/min] was calculated to compare these values with tool life T for each cutting tests. The MMR was calculated on the basis of the following equation (Eq.1):

$$Q = \frac{a_p \cdot a_e \cdot v_f}{1000}\ [cm^3/min] \tag{1}$$

where a_p – cutting depth [mm], a_e – cutting width [mm], v_f – fee rate [mm/min].
The summary of tool life and efficiency of metal matrix composite milling is shown in Table 5.

Table 5. Value of tool life T compared with efficiency Q

Cutting speed v_c [m/min]	Material removal rate Q [cm^3/min]	Tool life T [min]
300	1.61	**13.12**
500	2.68	4.41
900	**4.82**	1.15

Analysis of cutting force in time domain

After the tests, the each milling pass was correlated with measured cutting force components in the three directions.

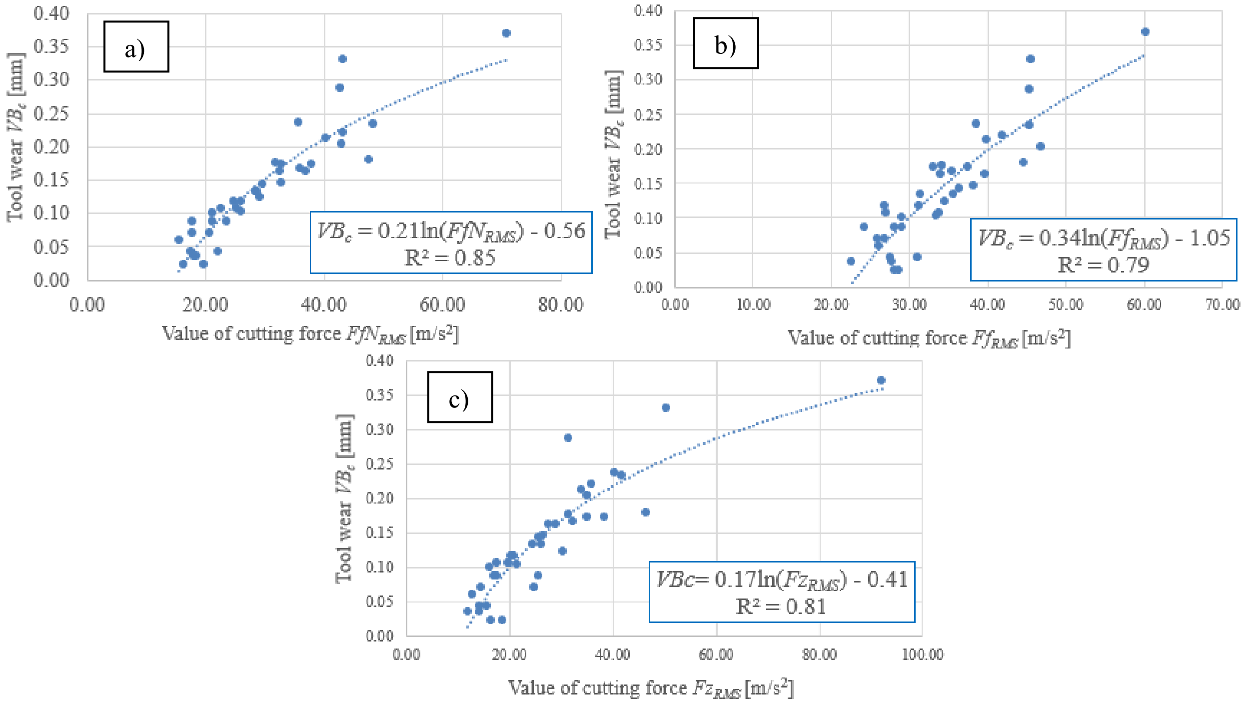

Fig. 4, Relation between VBc and cutting force components: a) Ff, b) Ff, c) Fz

The names of the selected statistical measures are as follows:

- Ff_{RMS} – root mean square value of cutting force measured in the feed direction (along the X axis),
- FfN_{RMS} - root mean square value of cutting force measured in the feed normal direction (along the Y axis),

- Fz_{RMS} - root mean square and peak value of accelerations of vibrations measured in the thrust direction (along the Z axis),

Figure 4 shows the chart containing the logarithmic equation between the tool wear and cutting forces: VB_c = A·ln(x) + b for the tests with v_c=300 m/min. The conformity of the experimental results with the logarithmic function can be described by the R^2 coefficient.

This function reflects the results obtained in the best way, and the coefficient R^2 = 0.85 for root mean square value of cutting force measured in the feed normal direction, which indicates high adjustment to the selected function.

Summary

On the basis of the conducted research, the following conclusions were formulated:

- The analysis of corner tool wear VB_C and flank wear VB_B showed that the milling of Duralcan™ metal matrix composite is difficult due to hard silicon carbide particles in aluminum. The longest tool life T was noted for the smaller cutting speed 300 m/min (approx. 13 min), but the worst results were received for 900 m/min (about 10 times lower than with 300 m/min). The highest parameter of cutting speed did not bring good results.
- The best efficiency of metal matrix composites was achieved for 900 m/min (approx. 5 cm^3/min), but compared with tool life there were no satisfying effects. For cutting speed 500 m/min tool life was 4 times bigger than for 900 m/min, but had only two times lower removal rate Q than the highest parameter.
- The analysis of cutting force in time domain allowed for selecting the measure which indicated the highest matching with tool wear during the machining of Duralcan™. The best coefficient R^2 was obtained for FfN_{RMS} - root mean square value of cutting force measured in the feed normal direction (R^2=0.85).

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