END MILLS WITH PCD INSERTS INCLUDING INTEGRAL CHIP BREAKER

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Diamond – the chemically metastable form of carbon at room temperature and standard atmospheric pressure – has become the standard material used for cutting tools. Its specific cutting properties also correspond to its difficult machinability, making it one of the most difficult-to-machine materials. With regard to this, the optimal processing technology, sharpening parameters, soldering conditions as well as tool geometry are still researching and developing. Tool geometry is a complex term, which is also affected by the integral chip breaker. In the case of polycrystalline diamond (PCD), this element is produced optimally only by the laser technology, which was used in this experiment, both for machining of an integral chip breaker and sharpening of the cutting edge. After the designing and manufacturing of the tools, measurements of the end mills were carried out. This experiment itself compared the tool geometry with and without the chip breaker from the point of view of the force loading measured by the piezoelectric dynamometer Kistler 9257B. The workpiece material was alloy EN AW 6061 and EN AW 6082.

KEYWORDS

PCD, chip breaker, force loading, EN AW 6061, EN AW 6082

1 INTRODUCTION

In addition to other materials, aluminium alloys are increasingly used in the automotive, aerospace and shipping industry, due to reducing the weight of components [Borovan 2006] [Fraga da Silva 2017] [Soares 2017] [Wang T. 2015] [Wang Y. 2013]. Machining of such materials, the polycrystalline diamond which belongs to the super-hard cutting materials, is widely applied [Fraga da Silva 2017] [Soares 2017] [Wang Y. 2013]. [Weinert 1993] found out that a PCD tool with cutting speed (v_c) 500 m/min obtained smaller wear than using cemented carbide with v_c 100 m/min when machining of metal matrix composites. [Huang 2012] focused on the machining of SiCp/Al composites using TiC-based Cermet and PCD. [Rajkumar 2018] concluded that the PCD inserts are more advised than cBN for machining of aluminium based composites.

PCD (produced by HPHT) blank includes cemented tungsten carbide substrate, which provides cobalt as a binder during sintering [Elementsix 2017] [Halpin 2015]. The presence of cobalt in PCD makes this material electrically conductive. This allows machining of PCD by electrical technology. In the past, PCD sharpening was possible either by grinding or using electrical technology. However, these technologies do not allow the optimal manufacturing of the integral chip breaker on the face of PCD segment, since the manufacturing is complicated compared to the production of the chip breaker in the insert of cemented tungsten carbide [Borovan 2006] [Fraga da Silva 2017] [Soares 2017]. This has been possible with the application of laser technology in machining [Borovan 2006] [Hofmeister 2017] [Soares 2017]. The light energy is transformed into thermal energy. Acting high-energy laser beam converts the solid state into gaseous, so-called cold ablation [Borovan 2006] [Hofmeister 2017]. A small value of pulse durations in picoseconds minimizes the heating/residual damage on the surrounding material. The high value of repetition rate of the laser corresponds to the large material removal [Borovan 2006] [Zeman 2017].

The subject of the presented experiment are two end mills with brazed PCD inserts including a different integral chip breaker and an end mill with an insert without a chip breaker. The evaluation of the experiment is based on the measuring of the cutting forces at 4 levels of feed per tooth (f_z) while machining of two aluminium alloys - EN AW 6061 and EN AW 6082.

Many studies have been focused on the tool and workpiece material. [Soares 2017] dealt with 3 inserts, where two of them had an integral chip breaker. The experiment investigated the influence of each inserts, cutting conditions on cutting forces and power, the chip shape according to standard ISO 3685, and others when turning aluminium alloy AlSi9Cu3. In case of CB2 insert, continuous chips were created at a small value of feed speed, which is not required [Hofmeister 2017]. Therefore, it is necessary to select the correctly range of cutting parameter for each insert. The obtained results are applicable only to these inserts of given shapes. [Fraga da Silva 2017] also investigated the influence of cutting parameters on the force loading and chip morphology during machining of AlSi9Cu3 using PCD tool with and without a chip breaker. Experimental and simulation results were compared. [Wang T. 2015] focused on the optimal cutting parameters and the suitable size of PCD grains while milling of SiCp/Al composite. Milling speed has a greater effect on the tool life than feed rate. [Muthukrishnan 2008] also conducted an experiment at various cutting parameters using different grades of PCD inserts while machining of Al-SiC composite.

Problems with continuous chips do not occur during milling, however in many cases it is advisable to reduce the cutting forces due to the required quality of the machined surface, dimensional accuracy, etc. - for example in thin-walled parts [Borovan 2006] [Hofmeister 2017]. Another limiting factor of the resulting machining quality is the temperature in the cutting zone. Not only these parameters can be influenced by the chip breaker, hence this study is dedicated to this entity when milling. A suitable combination of a chip breaker and cooling can increase the tool life by more than 30 % [Zeman 2017].

2 DESIGN AND CONSTRUCTION

Three right-hand and two-toothed end mills with brazed inserts were designed. The tool body material was selected CTS20D - sintered carbide, which is more rigid than steel. PCD blanks are mainly manufactured in the form of circular flat plates and therefore the production of a cutting edge with constant tool cutting edge inclination (λ_s) is not possible from this blank. The tools were designed with an average value of λ_s 5°, which provides a continuous milling – see Fig. 3. The tool side rake (γ_f) has the value of 7° on the tool minor cutting edge. Due to the flat face it is a variable. Its value is increasing with increasing distance from the minor cutting edge. Tools are designed with an internal tool cooling for efficient heat dissipation, more suitable chip formation, and cutting force reduction.

All tools have the same geometry of body and position of grinding seats. The individual cutters differ only by macrogeometry on the face of the inserts [Hofmeister 2017] – integral chip breaker. The cutting tool labelled as *RHE-0351-0*,

is designed without the chip breaker - see Fig. 1. The face of the insert is formed by a flat surface of the PCD segment and the rake angles are defined only by the position of the seat in the tool body.
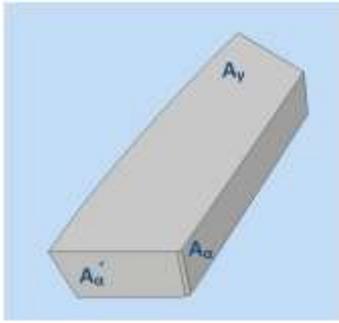
Tools *RHE-0351-1* and *RHE-0351-2* are designed with the integral chip breaker - Fig. 2, which creates a chip breaker land width of 0.04 mm on major and minor cutting edges. These chip breakers are designed for laser production. *RHE-0351-1* has a groove shape that creates a positive tool rake. The tool rake with respect to the insert has a constant value of 20°. Together with tool body geometry, the λ_s on the minor cutting edge has a value of 25° and the γ_f is increasing from 27°.
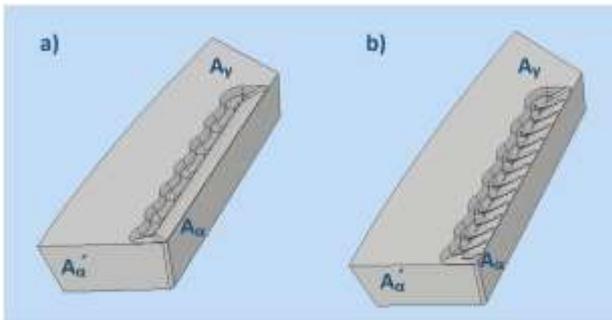
The chip breaker of the tool *RHE-0351-2* is designed with 3D shapes that create a variable tool rake. The basic shape - identical to the *RHE-0351-1* - is added by the 3D elements - drops. The tool rake of this PCD segment is in the range of 13°-20°. 3D drops are designed to reduce cutting forces in combination with cutting fluid. The aim is to create a space between the face and the leaving chip to be filled with fluid. Cutting fluid subsequently increases the volume due to the heat generated in the cutting zone to create a sliding surface, thereby reducing the chip friction on the face of the insert and the related cutting force.

In the case of end mills with a chip breaker, these are cutting tools with very positive geometry of the cutting edge. Tool side clearance (α_f) is 11° for all tools. Cutting material is PCD - sort CTM302, which is characterized by a combination of diamond grain sizes in the range of 2-30 μm. It has been developed for machining of aluminium alloys [Elementsix 2017].

3 PROTOTYPE PRODUCTION

The prototype PCD mills were produced by Rotana a.s. Tool bodies were produced on 5-axis CNC grinding machine. An important operation of the production of the milling body was manufacturing of channels for supplying of cutting fluid, which were produced by EDM sinking. Laser technology was chosen for preparation and sharpening of PCD segments, which is characterized by high precision with minimal damage on the surrounding material. Segments were cut from the circular

blank using the machine Laser Pluss. Cutting of the PCD segment was performed on individual layers with 0.08 mm increments in the **z** axis. The soldering process was carried out in a vacuum soldering furnace, which ensures a quality and strong joint through the controlled soldering process - see Fig. 3, since it has to transfer the force loading and heat between the insert and the tool body. Silver-based solder is used when soldering non-metallic materials.
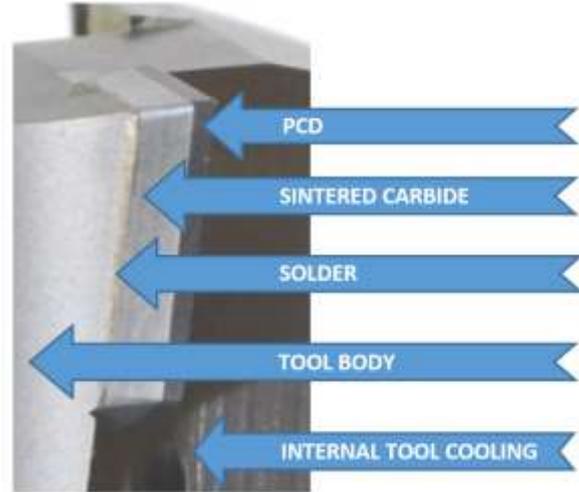
Sharpening was done using laser technology as well as cutting of the PCD segments. Machine EWAG Laser Line Ultra was used for this operation. Sharpening was also carried out on individual layers. Processing parameters for machining in the PCD layer were used for keeping high precision and minimization of damage on the surrounding material in the edge area, while parameters for higher productivity were used when machining the cemented tungsten carbide substrate. All tools were manufactured under the same process conditions. Therefore, a comparable quality of sharpening can be expected.

4 INSPECTION OF MANUFACTURED TOOLS

Inspections of the manufactured prototypes were performed by Zoller hobCheck optical measuring device and the Alicona optical microscope. Firstly, the main dimensions of the cutting tools were checked - the value of diameter of the cutting tool (**D**), the corner radius (r_ε) and the circumferential radial runout (**c**). These values are shown in Tab. 1.

	r_ε [mm]	D [mm]	c [mm]
prescribed values	0.100	12.000± 0,050	0.010
RHE-0351-0	0.096	12.004	0.002
RHE-0351-1	0.098	11,999	0.003
RHE-0351-2	0.099	12,004	0.003

The tool side rake (γ_f) was measured only for the tool labelled as *RHE-0351-0* tool, since for the other tools γ_f is created by a combination of body geometry and an integral chip breaker. As it has been mentioned, the value of the tool side rake value

is variable. For this reason, this angle is measured at two distances from the minor cutting edge - see Tab. 2.

The angle α_f was measured with a value of 10.72°.

	γ_f - 1 mm from the minor cutting edge [°]	γ_f - 5 mm from the minor cutting edge [°]
RHE-0351-0	7.12	10.74

Table 2. Tool side rake

Subsequent measurement was carried out using the Alicona InfiniteFocus measuring device. Fig. 4 shows the chip breaker of tool *RHE-0351-1* and Fig. 5 represents an image of the *RHE-0351-2* chip breaker.

Figure 4. Image of chip breaker – tool labelled as *RHE-0351-1*
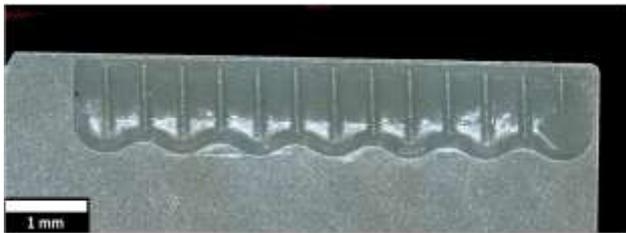
Figure 5. Image of chip breaker – tool labelled as *RHE-0351-2*

Firstly, rounded cutting edge radius r_n was measured. Values of radius are in units of μm. The specific radius values are shown in Tab. 3.

	tool major cutting edge [μm]	tool minor cutting edge [μm]
RHE-0351-0	7.6	3.8
RHE-0351-1	6.5	4.9
RHE-0351-2	6.3	5.3

Table 3. Rounded cutting edge radius

Chip breaker land width d_{Bn} (width of the facet on the face) and tool rake with respect to the insert were also measured on tools *RHE-0351-1* and *RHE-0351-2*. These are characteristic dimensions created by the production of chip breakers. For *RHE-0351-2*, the measurement was carried out in places with minimum and maximum values, as these values are variable depending on the shape of the 3D elements - drops. The measured values correspond to the model (see chapter 2) and are shown in Tab. 4.

	d_{Bn} [mm]	tool rake [°]
RHE-0351-1	0.0483	20.5

RHE-0351-2 – max value	0.0340	20.1
RHE-0351-2 – min value	0.0366	13.1

Table 4. Characteristics parameters of chip breakers

5 MEASUREMENT OF FORCE LOADING

The measurement of cutting forces acting during the milling of Al alloys destined for the aerospace industry was the aim of the experiment of prototype tools. Two Al alloys were selected, the designation system of which is shown in Tab. 5.

Number of workpieces	EN AW	DIN
1	6061-T651	AlMg1SiCu
2	6082-T651	AlMgSi1

Table 5. Designation system of AL alloys

The machining was conducted on the vertical CNC milling machine MCV 1210 - TAJMAC-ZPS. The Kistler 9257B stationary dynamometer was used to measure the force loading. Workpiece clamping via the machine vice can be seen in Fig. 6.
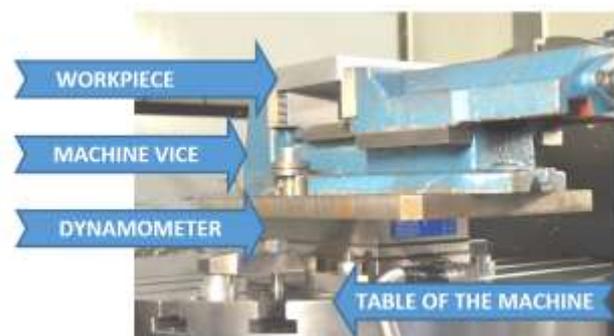
Figure 6. Setting for Measurement

Cutting conditions were based on the design of cutting tools and the application of Al alloy - see Tab. 6.

Quantity		Value	Unit
Revolutions of the spindle	n	15 000	min⁻¹
Cutting speed	v_c	*565.5*	*m·min⁻¹*
Axial depth of the cut	a_p	5	mm
Radial depth of the cut	a_e	3	mm

Table 6. Cutting conditions

A force load recording was performed on a workpiece of 130 mm length. Four f_z values have been proposed for evaluating of the effect of the chip breakers on the value of force loading, since the feed speed v_f has a significant effect on a chip formation. The measurement had a growing character, with higher f_z values being set after each pass. This measurement was repeated for each of the three tools and

both machined materials. Thus, 24 measurements were obtained from the experiment in total. The set values of feed per tooth (respectively v_f) are shown in Tab. 7.

levels	f_z [mm]	v_f [mm·min^{-1}]
1	0.08	2400
2	0.12	3600
3	0.16	4800
4	0.20	6000

Table 7. Values of feed speed

Fig. 7 shows a schematic view of the clamping of the end mill/workpiece including a partially machined workpiece.

Figure 7. Schema of machining process

6 EVALUATION OF FORCE LOADING
Measured data was evaluated using software Microsoft Excel. With this software, raw data filtering exported from software DynoWare was first performed. Maximum values from each revolution of the spindle were selected for the evaluation of the total force exerted by a cutting part (**F**). Then diagrams were created from the filtered data, which show the total cutting force depending on the tool and the machined materials. In the left part of the diagram are box plots for alloy EN AW 6061-T651, while in the right are box plots for alloy EN AW 6082-T651.

In Fig. 8 are shown the total forces for f_z of the value of 0.08 mm. The diagram shows a decrease in force of the *RHE-0351-1* tool during machining of alloy 6061-T651. The cutting force is reduced due to sharper cutting edge geometry. The *RHE-0351-2* tool (with a 3D chip breaker) shows an increase in the total force exerted by a cutting part. This is due to the increased interface between the chip and the face of the insert. On the other hand, when machining of the 6082-T651 alloy with a 3D chip breaker, the total force is reduced.
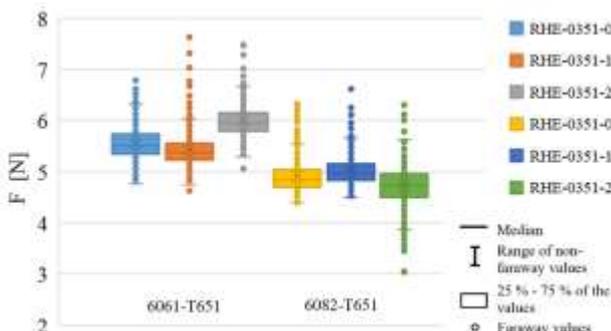
Figure 8. Graph of total force exerted by a cutting part at f_z = 0.08 mm

This force trend was found only at f_z 0.08 mm and material 6082-T651, which was most likely due to the very small chip thickness and low loading on the cutting wedge where the cutting fluid reduced the friction. The same total force trend was shown for the following values of feed per tooth from Tab. 7 – see Fig. 9, 10, 11. Geometry of the tool *RHE-0351-1* reduced the force relative to the *RHE-0351-0* with a polished face in all of the following cases. Then, the increase of the total force of the *RHE-0351-2* tool with a 3D chip breaker is noticeable.
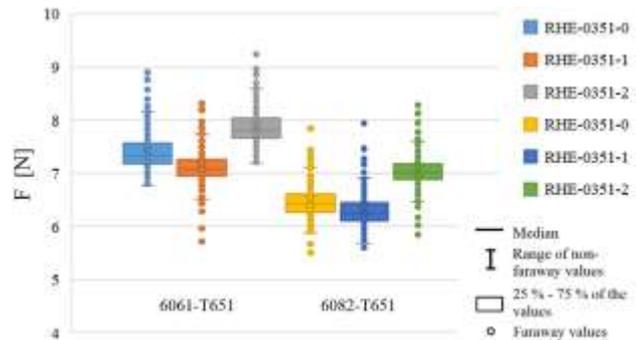
Figure 9. Graph of total force exerted by a cutting part at f_z = 0.12 mm

Values of total force depending on the increasing feed speed have a growing character, which corresponds to the increasing cross-section of the chip.

From these dependencies can be seen that higher forces were achieved when machining of the 6061-T651 alloy compared to the 6082-T651.
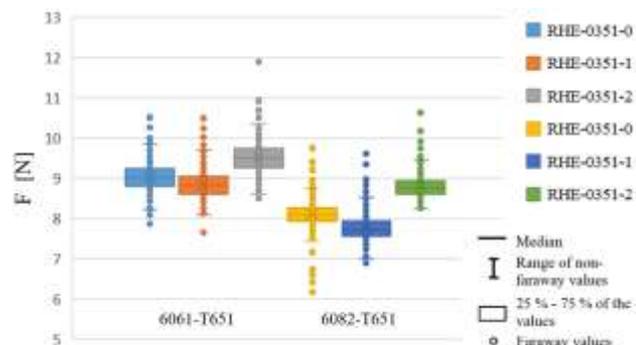
Figure 10. Graph of total force exerted by a cutting part at f_z = 0.16 mm
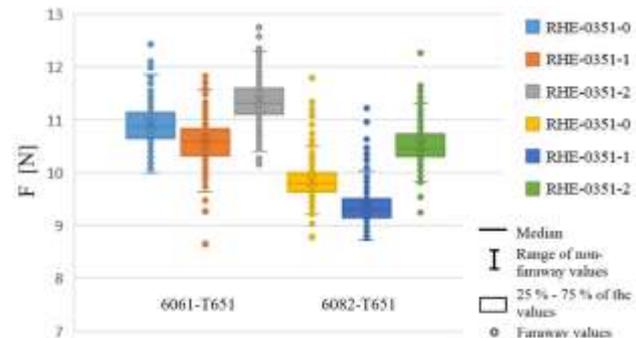
Figure 11. Graph of total force exerted by a cutting part at f_z = 0.20 mm

The total cutting forces evaluated from the equation (1) had the same trend as the F_{xy} force resultant in all cases, since the F_p force acting at the **z** axis reached very small values and did not change the trend of the achieved results. The median of F_p reaches the maximum value of 2.02 N for the *RHE-0351-2*. For this force component, the lowest value for the *RHE-0351-0*, then the *RHE-0351-1* and the highest value for the *RHE-0351-2* was measured. The *RHE-0351-0* has only a lapped face and the *RHE-0351-2* has protrusions (drops) that slowed the chip

flowing in the axial direction – in the direction of the tool cutting edge inclination (λ_s).

$$F = \sqrt{F_z^2 + F_y^2 + F_p^2} = \sqrt{F_{zy}^2 + F_p^2} \qquad (1)$$

7   CONCLUSION

Laser technology was used for sharpening and preparation of inserts, which is suitable for machining super-hard cutting materials with 3D macro-geometry of inserts.

During the short-time experiment with which the prototype tools were subjected, the influence of the geometry of the cutting edge on the value of total force was confirmed.

The same trend of the total force exerted by a cutting part for f_z higher than 0.08 mm is noticeable from the stated results. With these parameters, the decrease in total force was achieved for the tool labelled as *RHE-0351-1*, where the given chip breaker caused more positive geometry of the tool. On the contrary, the increase in the force was observed with the *RHE-0351-2* tool, where the designed 3D chip breaker proved to be an inappropriate element for decreasing cutting forces. 3D drops on the face of the chip breaker caused an increase in the interface between the chip and the tool (friction), thus increasing the cutting force during machining of the given workpiece materials, which achieve higher plasticity and lower mechanical properties compared to steel, titanium and other.

Lower cutting forces result in a decrease of the cutting edge loading at higher feed speeds, which can be used for a higher value of feed per tooth or high productivity machining. The face facet contributes to the higher strength of the cutting edge.

Higher forces were achieved when machining of the 6061-T651 alloy compared to the 6082-T651 for all levels of feed per tooth.

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