END MILLS WITH PCD INSERTS SHARPENED BY DIFFERENT ELECTRICAL TECHNOLOGIES

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Initially a natural diamond was used for cutting, but it was successively replaced by an man-made - synthetic diamond. Its application is limited only on non-ferrous materials, but also considering this limitation it is a very important cutting material. The most suited material based on diamond for milling operations is PCD - a synthetic polycrystalline diamond produced by HPHT (high-pressure high-temperature) process, because the high fracture toughness of the tool is required [DAVIS 1995] [Tso 2002]. Four end mills with PCD inserts sharpened by different electrical technologies were produced for the experiment as stated in this article. Two milling tools were sharpened by WEDM and the remaining two by Electrical Discharge Machining – Grinding. The aim of the experiment was to compare these technologies of sharpening. This was based on the surface roughness and topography analysis of sharpened surfaces of inserts, and in particular, on the force loading of the tools measured by the piezoelectric dynamometer 9257B over selected milling time slots.

KEYWORDS

PCD, force loading, analysis of sharpened inserts, WEDM, EDM-G

1 INTRODUCTION

Along with the development of modern super-hard cutting materials, the requirements for machine tool are also growing – high-speed spindles, feed mechanisms, tool holders, tool balancing machines, and so on. For producers of cutting tools using diamond-based materials, the requirements for sharpening and machining also increase due to their specific machinability. In the past, this material was sharpened only by conventional grinding. In this technology, diamond grains bounded in the grinding wheel act on approximately equally hard PCD grains. Because of this, the grinding coefficient (G ratio) reached only 0.01 to 0.02, which was reflected mainly in the economy and machining time [Davis 1995]. Modern machining of these materials is based on unconventional machining methods, where the machined material – diamond – is machined in a different way than by the cutting wedge. These technologies are suitable for difficult-to-machine materials, which the diamond undoubtedly belongs to. In addition to laser technology, these include especially electrical technologies – WEDM (Wire Electrical Discharge Machining) and EDM-G (Electrical Discharge Machining). For machining process, electrical energy without conversion to mechanical energy is used. These technologies are also used for manufacturing of micro milling tools, because cutting forces acting to a tool are very slight [Gao 2013]. The diamond particles themselves are electrically non-conductive, but polycrystalline diamond contains the metallic-phase as a binder – Cobalt, which fills the interstices between diamond particles and provides the electric conductivity necessary for electrical machinability [Gao 2013] [Iwai 2013] [Tso 2002] [Yan 2013] [Yanagida 2016]. There has been much research on EDM of PCD. Gao [Gao 2013] focused on the optimal roughing and finishing process parameters of wire electrical discharge machining on PCD with grains size of 2, 10 and 25 µm. Then microtool with CTB002 – PCD material was sharpened by the optimized parameters. This tool had an edge radius 6.7 µm. Using a DoE, Fonda [Fonda 2012] also found the optimal roughing and finishing conditions for fabricating a hexagonal PCD microtool by WEDM. Tso [Tso 2002] compared conventional abrasive grinding with EDM (EDM-G) of PCD. Grinding produced a finer PCD surface than EDM-G. EDM-G resulted in a best average surface roughness **Ra** of 0.27 µm. Rahim [Rahim 2016] investigated the same comparison of the technologies based mainly on surface roughness (**Ra**), cutting forces measured through a six-channel dynamometer (Kistler 9257B), wear mode of the cutting tools, value of cutting edge radius, residual stress and level of graphitization analysed with the Raman method for three types of PCD differing in a size of grains. Yan [Yan 2013] performed an experiment to study of WEDM of PCD using a novel pulse generator. A lower value of **Ra** can be achieved as well as lower damaged layer on the machined surface of PCD. On the contrary, Iwai [Iwai 2013] improved the electric conductivity of the PCD by replacing non-conductive diamond particles with boron-doped electrically conductive diamond particles. Processing speed of this boron-doped PCD was more than seven times higher in EDM. Ullah [Ullah 2015] also focused on increasing of el. conductivity of diamond by boron doping. Yanagida [Yanagida 2016] investigated the electrical discharge machinability of PCD in different types of dielectric working fluid and the corrosion suppressing method in water. Electrochemical corrosion of cobalt can be suppressed in ultrapure water with high resistivity.

2 CONSTRUCTION AND SHARPENING OF TOOLS

Four end right-hand mills with different geometry sharpened by different technology – WEDM and EDM-G were the subject of the experiment. A scheme of these tools can be seen in Figure 1. Due to the long tool life of PCD inserts, the mills were designed with one brazed insert. The dimension of the cutting edge diameter was increased compared to the straight shank to achieve the desired cutting speed for milling the

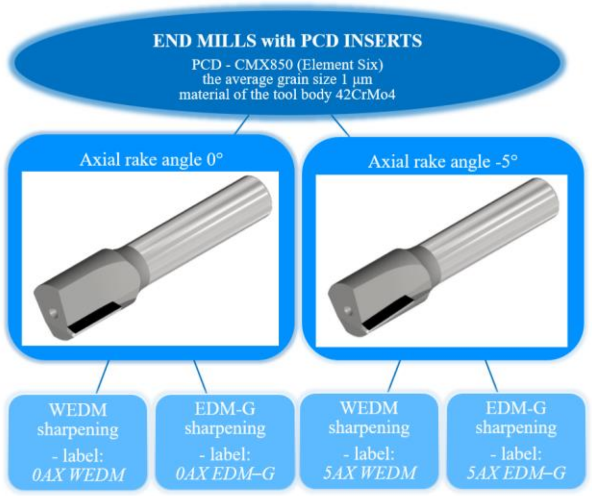

Figure 1. Types of Tool

definite workpiece. The cutter sets differ in the axial rake angle, which is defined as the angle between the plane of the face and the tool axis. One set of end mills has the angle of 0° and the other -5°. It is appropriate to define the position of the face of the inserts by the mentioned angle, because the plates were cut by laser from a circular blank, which contains a flat layer of polished PCD sintered to the base of the sintered carbides. After brazing of the inserts to the tool body, the milling cutters were coated with chemical nickel to eliminate corrosion of the tool body. All cutters have two main flank faces. The primary clearance angle α_{f1} on the PCD layer has a value of 10° and the secondary clearance angle α_{f2} has a value of 14° and starts at the sintered carbide at a distance of 0.6 mm from the cutting edge. Fanuc ROBOCUT α-600iA was used for WEDM along with an additional device for eroding rotary tools, which provides one extra machine-driven axis. Eroding was performed with three cuts. As electrode, brass wire with a diameter of 0.25 mm was used. The secondary main flank face was eroded by the first cut and the following two cuts were used for the primary main flank face. In the case of EMD-G, Vollmer QXD 250 and the copper-tungsten alloy wheel electrode were used. The primary main flank face was also eroded by two cuts as in the case of WEDM, but the secondary main flank face was machined by the abrasive wheel on the same machine. Next machining process was the check of unbalancing, eventually its re-balancing to a degree of out-of-balance G 6.3. If another function of the tool enables it, there is a possibility of re-sharpening these PCD inserts. The last process was engraving. The labels of the individual mills were marked with the laser on the straight shank.

3 ANALYSIS OF MANUFACTURED TOOLS

The cutting edge diameter of all cutters was sharpened at a tolerance of 0 to +0.04 mm from a nominal dimension of the cutting tool diameter of 18 mm. The geometrical tolerance of the circumferential radial runout to the tool axis 0.01 mm was also fulfilled. According to the result protocols from Zoller Genius 3s optical device, the inserts were measured in six positions where the maximum value of runout was 0.004 mm. These data are graphically plotted in Figure 2. The nominal values of the tool angle of the cutters in each set were the same. Small deviations were caused due to production inaccuracy. The clearance angle of all cutters was designed the same. The sets only differ in the angles of the rake. The mills with the axial rake angle of 0° have a constant radial rake angle γ_f with a value of 10°, whereas the angle γ_f of the non-zero axial rake angle differs at each given point of the cutting edge. As in the case of end mill with a zero axial rake angle, the value at the tip of the inserts is 10°, however the increasing value of a_p decreases this angle due to the negative axial rake angle. This makes the cutter more negative both in radial and axial direction. However, at any given point of the cutting edge the positive angle γ_f is ensured, which is required for the given workpiece material – PVC. These data were also obtained from the measurement protocols measured on the ZOLLER Genius 3s optical and measuring and inspection machine. Following analysis of the surface roughness of the primary main flank faces showed a smaller **Ra** value under given sharpening conditions for the WEDM. On this flank face, the roughness measurement was performed by the contact method on the Form Talysurf Intra 50 (manufactured by Taylor Hobson) with a radius of the scanning tip 2 µm and also by the optical method using the Olympus LEXT OLS4000 confocal laser microscope. A graph based on these obtained values is shown in Figure 3. In the case of the secondary main clearance angle, the value of the arithmetical mean deviation of the assessed surface roughness was lower using the EDM-G method as this angle was abrasively ground - see Figure 4. **Ra** on this surface on the end mill labelled as *0AX EDM-G* reached even 0.06 µm.

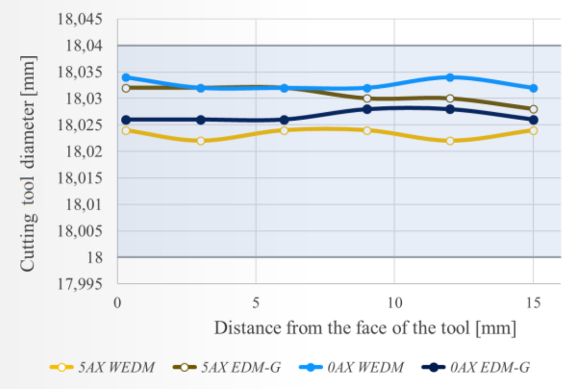

Figure 2. Measured Values of Cutting Tool Diameter

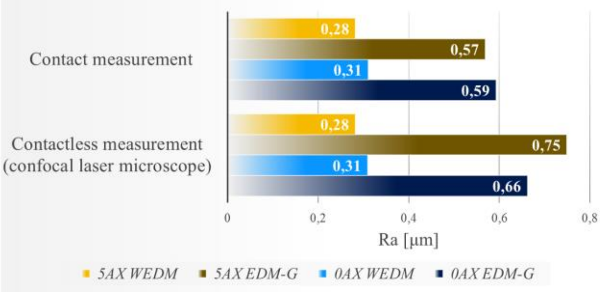

Figure 3. Graph of Ra Value of Individual Cutters Measured on PCD Layer - Primary Main Flank Face

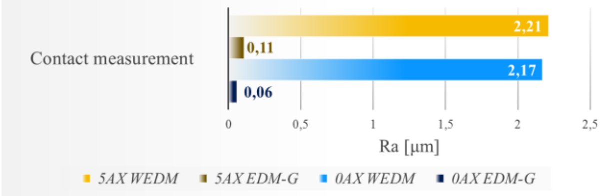

Figure 4. Graph of Ra Value of Individual Cutters Measured on Sintered Carbide Substrate - Secondary Main Flank Face

The last analysis was carried out on a non-contact optical microscope Alicona Infinite Focus 5 operating on the Focus Variation principle. Using this device, the topography images of the primary flank face on mills with the set of *0AX* were obtained. The eroded surface with EDM-G consist of regularly torn diamond grains - see Figure 5. Figure 6 shows a surface eroded by WEDM with a distinctly wavy structure. This was due to non-constant tension and feed of wire. Therefore, some bands laid above and some below. From the colour scale of each surface, considering some unusual extreme peaks, it is also possible to say that the WEDM surface exhibits lower

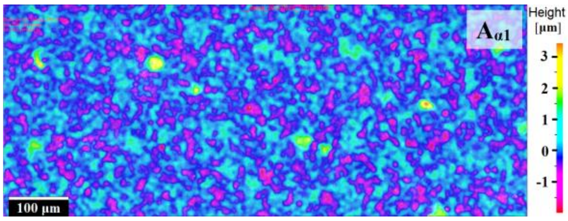

Figure 5. The Surface of The Primary Clearance Angle Sharpened by EDM-G Technology

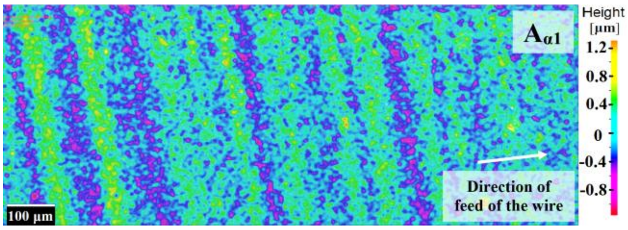

Figure 6. The Surface of The Primary Clearance Angle Sharpened by WEDM Technology

inequalities. It was also confirmed by the lower measured **Ra** value of both contact and non-contact measurements.

4 INFLUENCE OF CUTTING CONDITIONS ON Ra OF MACHINED SURFACE

The material of the workpiece used throughout the experiment was extruded thermoplastic – more precisely PVC. Its format was a board with a thickness of 20 mm. The starting cutting conditions, cutting speed and feed per tooth converted to the feed rate is shown in the following Table 1. These parameters are generally recommended for machining PVC. The revolutions were recalculated based on the recommended cutting speed [AK Plast s.r.o. 2017]. These cutting conditions were checked

	Quantity	Unit	Value
Revolutions of the spindle	n	[min^{-1}]	15 000
Feed rate	v_f	[$\mathrm{mm \cdot min}^{-1}$]	4 500
Axial depth of the cut	a_p	[mm]	3
Radial depth of the cut	a_e	[mm]	4
Air cooling with atmospheric pressure			
Climb milling			

Table 1. Cutting Parameters

for the achieved surface roughness of the machined surface by a full factorial design where 4 factors were selected at two levels [Miller 2010]. The factors were revolutions of the spindle (10,000 rpm and 15,000 rpm), feed per tooth (0,15 mm and 0,40 mm), kinematics of milling (climb and conventional) and tool geometry (A and B), which represents only replication of measurement. In both cases of levels A and B, the same tool geometry was used. This replication was intended to verify that the influence of wear and cutting conditions (temperatures) during the experiment was negligible. The response variable was arithmetical mean deviation of the assessed surface roughness measured on the vertical walls of the workpiece. The schematic drawing of the experiment, including the measuring area of **Ra**, can be seen in Figure 7. The experiment was carried out on all four end mills, which means that for each run, 4 **Ra** values were measured from which the mean value was calculated. From the Pareto chart in Figure 8, the ordered standardized effects of individual factors and their double interactions can be seen. The test performed at a significance level α=0.05 showed statistically significant **C** and **A** factors. The influence of the tool geometry (factor **D**) was completely negligible. As mentioned, this factor represented replication, which confirmed that the influence of wear, temperature and other factors was negligible during milling. According to the main effects plot, the smallest surface roughness of the machined surface can be achieved by a climb milling, a higher revolutions of spindle and a lower value of feed per tooth, which had the greatest influence on the resulting surface roughness – see Figure 9. All 16 mean response values in each run of the experiment can be seen in the cube plot in Figure 10.

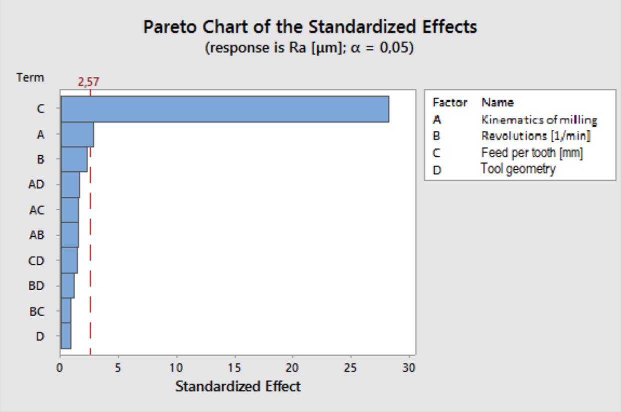

Figure 8. Pareto Chart

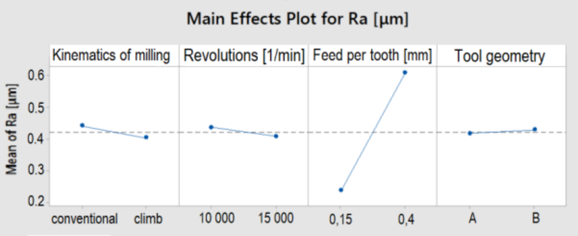

Figure 9. Graphical Representation of the Main Effects

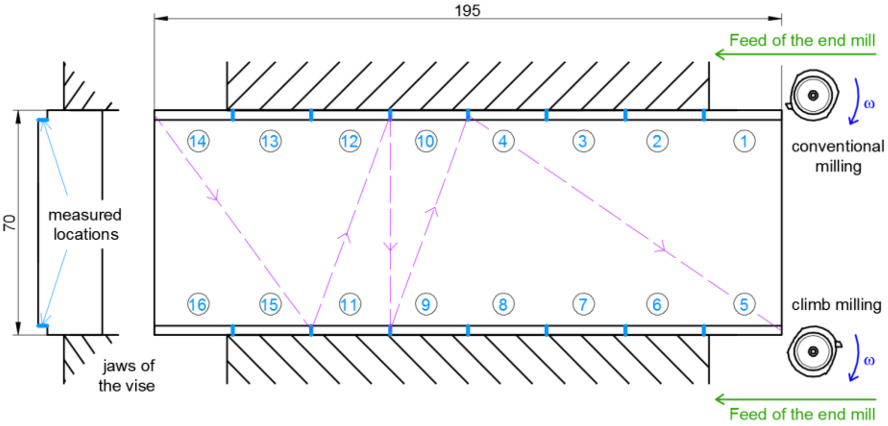

Figure 7. Milling Scheme for **Ra** Measurement - Including 16 Measuring Areas

The vertex of the cubes indicates the given factor levels, including a particular mean value of **Ra** at a given location, and each cube signifies replication of the tool geometry. This experiment verified that the surface roughness achieved for the selected starting conditions was sufficient and these machining conditions will therefore be retained for further experimentation. The lower feed rate would lead to a lower surface roughness of the machined surface but also a lower force loading of the end mills. Due to the long tool life of the PCD inserts it would be undesirable.

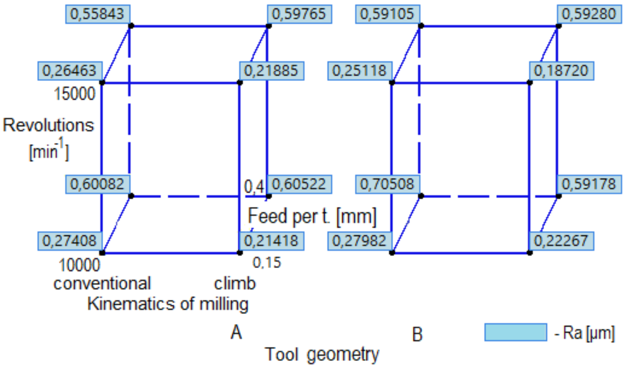

Figure 10. Cube Plot of Measured Values of Ra in 16 Runs of Experiment

5 ANALYSIS OF THE FORCE LOADING DEPENDING ON THE CUTTING TIME

The following comparison of different sharpening technologies consists of measuring load force – one of the important experimental measurements in mechanical engineering. This measurement is an indirect measurement of the wear of the milling cutters. The state of wear of the cutting edge affects the size of the deformation work as well as friction work. Each end mill machined for 112 minutes. This time did not include the overrun and startup of tool to/from the workpiece or rapid speed between the path of machining. All measurements were conducted on the 5-axis CNC milling machine Tajmac-ZPS MCV 1210 with the SINUMERIK control unit. First measurement by piezoelectric dynamometer Kistler type 9257B was performed before the first half hour milling. The schematic and realistic settings for force recording can be seen in Figures 11 and 12. Before the measurement itself, it was necessary to set up some parameters of force recording in the DynoWare software. The sampling frequency was calculated with respect to the milling conditions and the required number of measurement points while the tool was in engagement. Thereafter, the cutters machined always for a certain time slot on a Hovag Venture 20 woodworking machine – see Figure 13 – and a control measurement of force loading was performed again. This resulted in 4 force records for each end mill. The tool *5AX WEDM* has only 3 records, because the first record reached extreme values. Filtered records containing the maximum total cutting force values during the cutter in engagement are shown in the box plot of Figures 14 and 15.

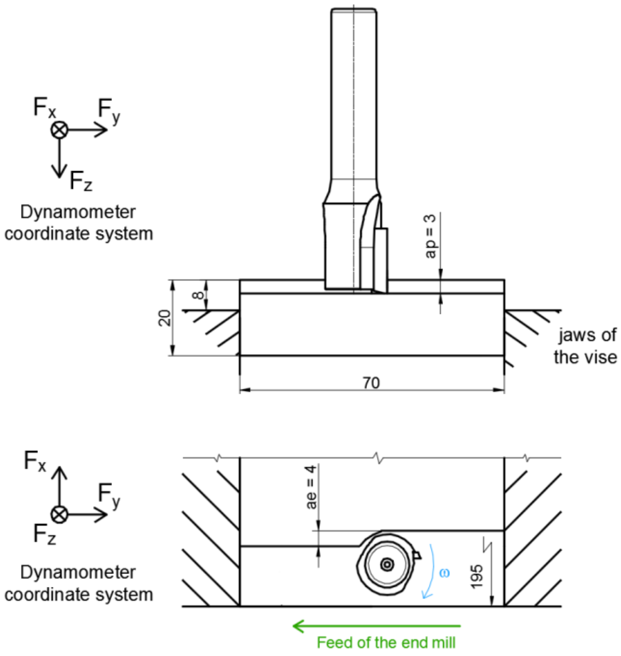

Figure 11. Milling Scheme for Force Recording

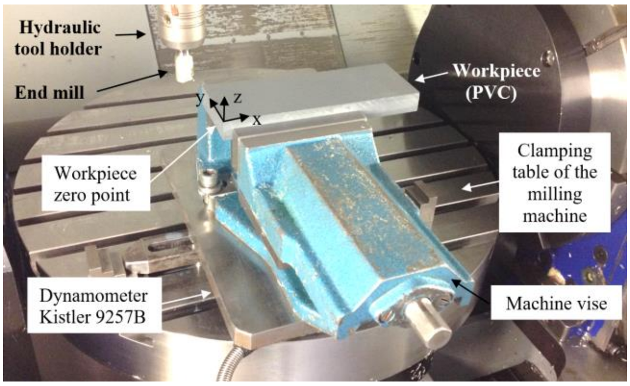

Figure 12. Setting for Force Load Measurement

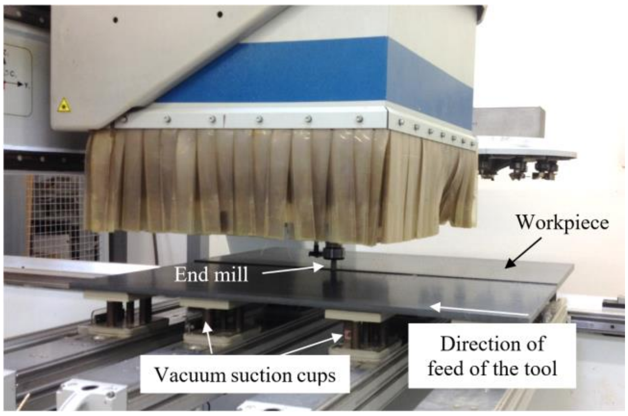

Figure 13. Experimental Milling Process with Strategy of Line Spacing

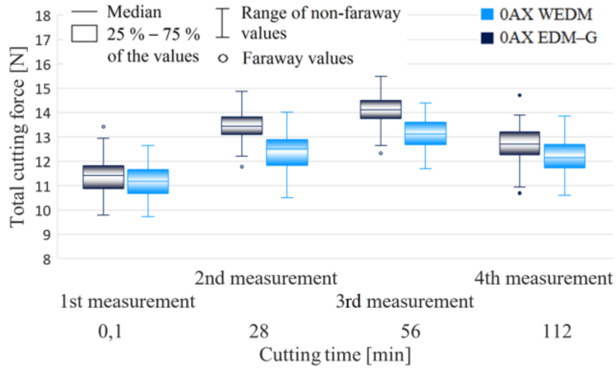

Figure 14. Total Cutting Force of Cutters with Axial Rake Angle 0°

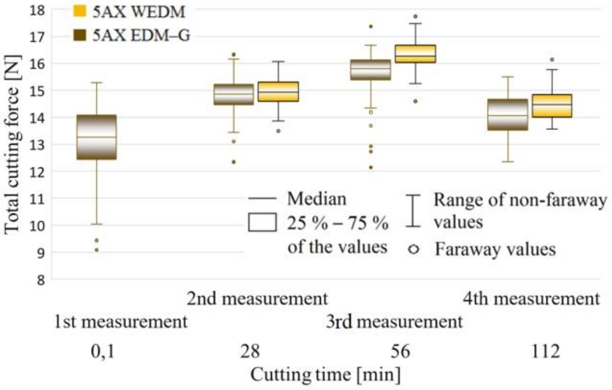

Figure 15. Total Cutting Force of Cutters with Axial Rake Angle -5°

The summary graph in Figure 16 shows that the total cutting force of all end mills increased within 1 hour of machining and then dropped. Due to the long tool life of the PCD inserts, it could be a run-in period when the contact area of cutting edge was 'grinded' and because of that, the force decreased. On the contrary, another variant could be the wear of the tool, which caused higher friction in the area of cutting process. Higher friction caused a rise in temperature, making the material more machinable, which in the end meant a drop in force loading. This can be also signalled by the low softening temperature of PVC, which is 72 °C according to Vicat.

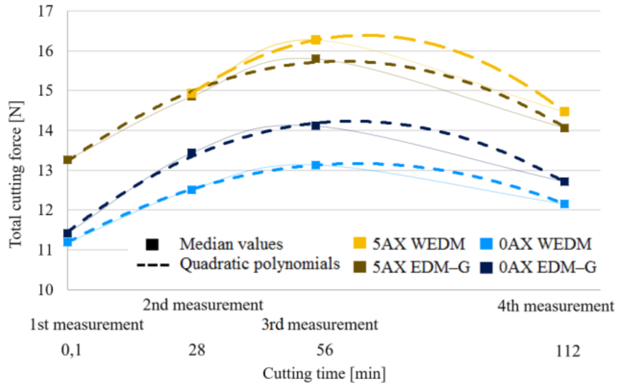

Figure 16. Summary Graph of Total Cutting Force

Total cutting force for experimental tools with an axial rake angle 0° compared to -5° was smaller, because these tools have a more positive geometry in the axial and radial directions. Cutting force of the set *0AX* began at approximately the same point. After half an hour of machining, there were different values of force that kept their difference until the final measurement record, where it is even seen that the difference between two forces were less than after half an hour of machining. The graph for *5AX* end mills set is opposite. After half an hour, very similar values of total cutting force were measured on both end mills. After that time slot, an increase in the total cutting force of a *WEDM* tool can be seen. The same difference between two measured forces occurred at the end of the experiment.

6 CONCLUSION AND DISCUSSION

Under given sharpening conditions, the arithmetical mean deviation of the assessed surface roughness on the primary main flank face was achieved using the WEDM method measured by the contact and non-contact method for individual cutters 0.28 µm and 0.31 µm. These values were 2 times lower than in the case of EDM-G under given sharpening conditions. On the contrary, a **Ra** of 0.06 µm and 0.11 µm on secondary main flank faces was achieved using this method, because this area was conventionally grinded. In the case of WEDM method the values of **Ra** were greater than 2 µm on the secondary – only eroded – flank faces. Topography of eroded primary main flank faces in the EDM-G method had a regular appearance of craters after torn grains, while in the case of the second method, it was possible to see the wavy structure caused by the feed and tension of the wire. Very similar trend of total cutting force depending on the cutting time was measured for all end mills. Smaller total cutting force of the set *0AX* was achieved by using the WEDM sharpening technology, whereas in the case of end mills with an axial rake angle of -5° smaller force was achieved by the other sharpening technology. Due to these facts, it is not possible to clearly determine which sharpening technology will achieve a higher tool life under the given experiment conditions and sharpening conditions. In this case, the geometry of the tool has the greatest influence on the total cutting force. Due to the long tool life of PCD inserts, the wear on the flank faces was minimal and almost invisible by a conventional light microscope. Therefore, the force loading was not affected by any different measured surface roughness. After 112 minutes of machining of PVC, the effect of sharpening technology on the life of PCD inserts has not been confirmed.

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