Comparison of machining of poly-crystalline cubic boron nitride by rotary ultrasonic machining and laser beam machining in terms of shape geometry

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Poly-crystalline cubic boron nitride (PCBN) is the hardest material beside diamonds. Generally, so hard materials could not be machined by conventional machining technologies. For this purpose, advanced machining methods have been designed. Rotary ultrasonic machining (RUM) and laser beam machining (LBM) are included among them. This contribution investigate and compare these advanced methods during machining of PCBN. In experiments, a tool for friction stir welding (FSW) was manufactured. The main evaluated attributes was shape accuracy and dimension precision. When shape accuracy is not sufficient, welding process is negatively affected (lower tool life, improper weld parameters). And when dimensions of welding tool are different, it cannot be used for demanded sheet thickness. According to the performed experiments, RUM achieved good enough shape accuracy, but inadequate dimension properties. For LBM it was vice versa.

Keywords: rotary ultrasonic machining, laser beam machining, cubic boron nitride, 3D scanning, friction stir welding

1 Introduction

PCBN is very hard material manufactured by powder sintering at high pressure and high temperature, which is usually utilized as cutting material. Additional treatment after sintering usually is not necessary [1, 2, 3, 4]. However, there are some applications, where machining of PCBN is required. One of these application could be tools for friction stir welding (FSW). The principle of this technology consists in application of a rotating tool with specially designed shoulder pin which is inserted to the common line of welded materials. The tool proceeds in weld line direction. Heating occurs owing to friction and plastic strain of welded metals. Mechanical power is transferred to heat during the welding process. Temperature generated in welding zone usually attains 80 to 90 % of melting point temperature of the welded metal. Advantages of FSW process include: low heat input, low residual stress allowing fabrication of precise weldments without any additional operation, then formation of fine-grained microstructure in the welded zone leading to increased mechanical properties of fabricated welds. Welding operation takes place without spatter, harmful radiation and without filler metal. Welding by FSW process guarantees a high measure of safety and is also environmentally friendly [5, 6, 7, 8, 9].

Welding tool used in FSW process must be sufficiently tough, robust and wear resistant at welding temperature. Other requirements include: good oxidation resistance and low coefficient of thermal conductivity to minimize the thermal losses. Shoulder profile of majority of tools is usually concave, which acts as an escape volume for the material displaced by the pin. The tool prevents material expulsion from the side of pin shoulder and maintains the desired effect and thus the desirable material forging below the tool.

These tools are characterized by different sizes depending on thickness of welded plates, and by different geometry depending on welded material. Therefore, two equal tools for FWS of 2 mm thick steel plates were produced in experiments – one by RUM, second by LBM.

2 Machined material and machining technologies

As machined material was used PCBN. This material provide Welding Research Institute – Industrial Institute of Slovak Republic in Bratislava (VÚZ – PI SR), which also demand creation tool for FSW. They bought this material from its manufacturer – Changsha 3 Better Ultra-hard Materials Co., Ltd. (3b diamonds). This company is based in China.

PCBN consists of grains of cubic boron nitride in alumina matrix with alloying of cobalt. This analysis was performed at Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava (STU MTF), in Laboratory of structural analysis. Its poly-crystalline structure provide higher strength and ductility in comparison with mono-crystalline structure. PCBN is characterized by very high hardness. Its value is usually in range 4500 to 7000 HV, or above (over 50 GPa). It has high thermal stability. It is usually utilized as cutting material for machining of ferrous materials, such as hardened steels, etc. [10, 11].

As machining technologies, RUM and LBM were used. Both methods are suitable for machining of hard-machinable materials, however, they are based on markedly different principle. Machine tools, which utilize both principles are available in Centre of Excellence of Five Axis Machining (CE5AM) in MTF STU.

RUM utilize rotary tool, which oscillate by ultrasonic frequency (above 20 kHz). Interaction of rotating motion and vibration causes microcracks on surface, which are broken and lead away as microchips. This effect is also enhanced by cavitation effect of coolant. Due to this principle, very hard and brittle materials can be machined. Advantages of this process are decreasing of cutting force, reduction of generation of heat, increasing of tool life, improving of machined surface (roughness, accuracy) and also possibility to machine hard and brittle materials, such as glass or ceramics. Main purpose of coolant is not decreasing of process heat, but leading away of chips. Coolant are feed on tool-workpiece interface and therefore proper properties of coolant are necessary (such as viscosity, absorption effect, lubrication effect, cooling effect, protection against corrosion, etc.). Abrasive – diamond particles, are directly bonded on active part of tool. Tool is usually hollow and contain concentrator, too. In this experiment, rotary ultrasonic milling machine tool ULTRASONIC 20 linear, made by company DMG Mori Seiki, was used. This machine tool is shown in Fig. 1 left. It can work continuously in five axis and its spindle can reach value 42,000 rpm. There was used ultrasonic milling cutter with diameter 24 mm with following machining parameters: spindle speed 8000 rpm, feed rate 300 mm/min, depth of cut 0.003 mm, frequency of vibration 21.6 kHz, amplitude 6 μm. Cutting width spacing was adjusted on full mill engagement due to size of milling cutter. NC program was generated by CAM software PowerMill designed by company Delcam. This software was supported by CAD software PowerShape, designed by the same company. In this CAD software was created CAD model of object, which serve as input data for CAM software [12, 13, 14, 15, 16, 17, 18].

LBM utilize ablation effect of concentrated and focused monochromatic and coherent light. There is no tool to wearing and there is no cutting force. Energy of light is so focused, that there is very low heat affected zone (HAZ). No cooling of workplace is needed. Due to no cutting force, clamping of workpiece could be performed by adhesive tape. In this experiment, fiber laser machine LASERTEC 80 Shape, made by company DMG Mori Seiki, was used. This machine tool is shown in Fig. 1 right. It can continuously control five axis during machining. Its fiber is made of ytterbium and can provide laser beam with wave length 1.065 μm. It work only in pulse regime and frequency of pulses could be controlled in range 10 to 100 kHz. Feed rate of laser beam could be adjusted in range 100 to 4000 mm/min. Maximum power of laser generator is 100 W. Diameter of laser beam is approx. 1 μm. During experiment, following parameters were used: frequency 30 kHz, feed rate 1000 mm/min, depth of cut 2 μm, laser power 12.3 %. Adjusted parameters required power approx. 4 W. NC program was generated according CAD model by software Lasersoft 3D, designed by company DMG, which is part of machine tool [19, 20].

Fig. 1 Machine tools utilised in experiments [12, 21]
Obr. 1 Obrábacie stroje použité v experimentech [12,21]

3 Description of the experiment

For experiments were used two cylinders with diameter 12 mm and length 20 mm made of PCBN. One specimen was machined on ULTRASONIC 20 linear, second specimen was machined on LASERTEC 80 Shape. Both specimens were machined to same shape – to tool for FSW. Dimensioned longitudinal section of this tool is shown in Fig. 2.

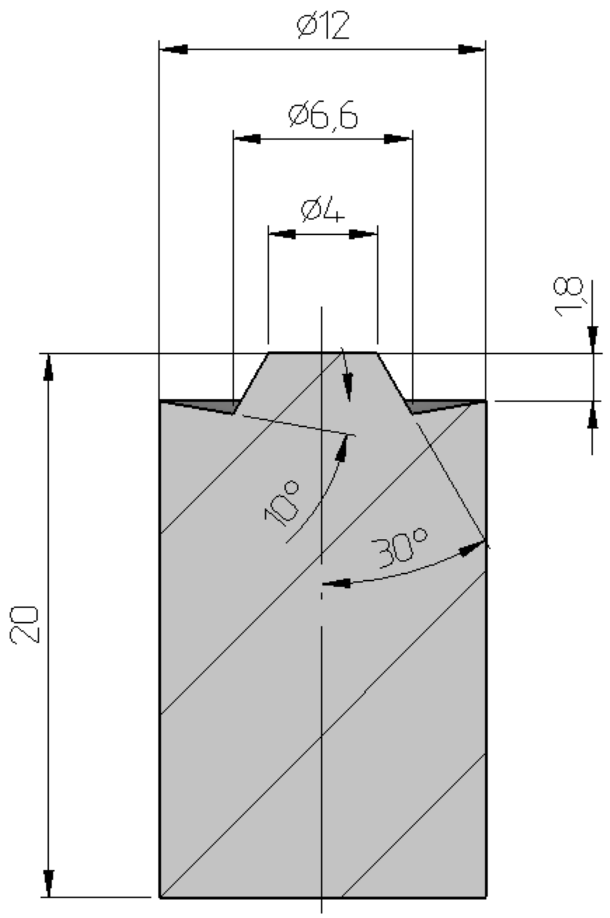

Fig. 2 Friction stir welding tool
Obr. 2 Nástroj na trecie premiešavacie zváranie

These tools were manufactured by different method, therefore different quality of machined surface is expected. Surface quality was evaluated by precision of performance based on mechanical drawing obtained by optical 3D scanner GOM ATOS II TripleScan SO (measuring volume MV 38 – L x W x H: 38 x 29 x 15 mm) (see Fig. 3). Machining parameters was adjusted by recommended values based on catalogue and experience. Depth of cut for LBM could by higher, but it should cause worse surface roughness. Therefore, depth of cut was suggested accordingly to reach approx. the same machining time. It should increase correctness of comparison.

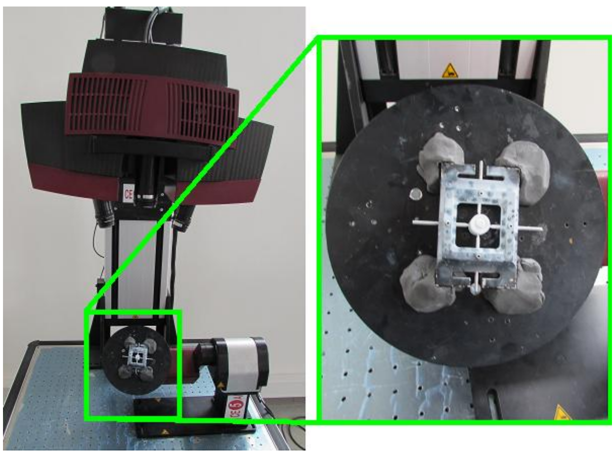

Fig. 3 3D scanner GOM ATOS II TripleScan So MV 38 during digitization of PCBN specimen
Obr. 3 3D skener GOM ATOS II TripleScan So MV 38 počas digitalizovania vzoriek z PCBN

4 Results of experiment

Machining of FSW tool spent approx. 4 hours at both, RUM and LBM methods. After machining, specimens were evaluated on 3D scanner. The surface color of specimen was black, therefore thin coating of surface by fine white powder based on TiO_2 was used. To obtain 3D scan, scanning of specimen from many sides was necessary. For clamping the measured specimens, a frame-fixture was used. The uncoded reference points (Ø 0.4 mm) were sticked on frame-fixture to ensure the correct position of individual scans into the one digital model. Precision of measuring was approx. ± 0.02 mm. To recording and editing of scanning results, software GOM ATOS Profecional v7.5 was used [22, 23]. Process of scanning is recorded in Fig. 4. Virtual model can move independently on position of real specimen.

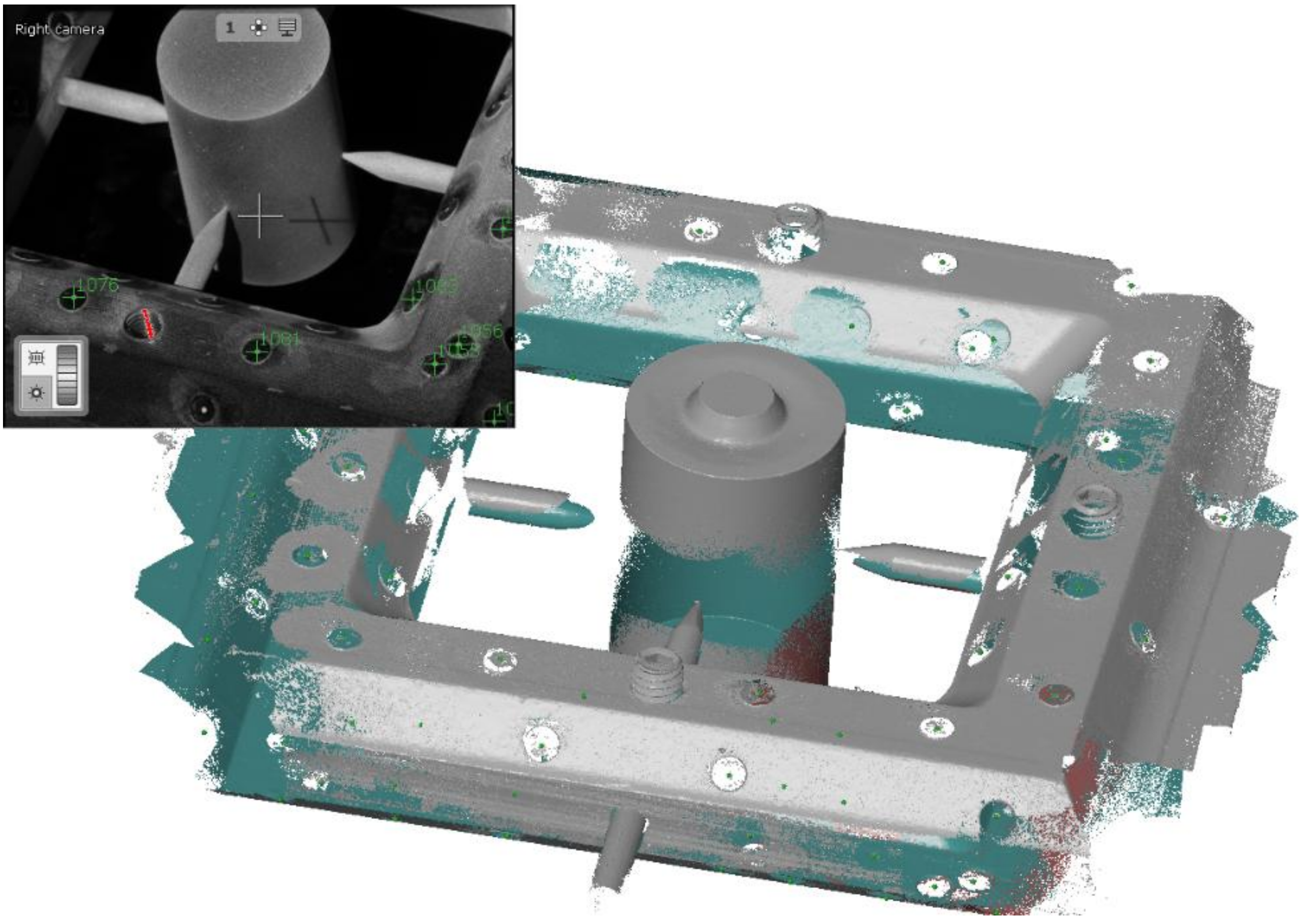

Fig. 4 3D scanning process and part of digitized specimen with frame-fixture
Obr. 4 Proces 3D skenovania a časť digitalizovanej vzorky s rámovým prípravkom

When scanning of specimen was done, the shape of the scanned digital model of the specimen was compared with CAD model of this specimen. Color deviation maps are the results of the comparisons. These results for specimen manufactured by RUM can be seen in Fig. 5. In the left figure can be seen the application of function "best fit" – CAD model was placed on inert cone and utilized scale of deviation was ± 1 mm. However, circular top of pin was not machined and therefore it is proper base to fit. It is shown in middle and right figure. Middle figure has a same scale of deviation as left one (± 1 mm), while right figure has scale of deviation ± 0.2 mm for better comparison with specimen machined by LBM. Such huge deviation were caused by rapid tool wear. Dimensional precision of manufactured specimen should be better, when tool length will be re-measured after machining and machining process repeated.

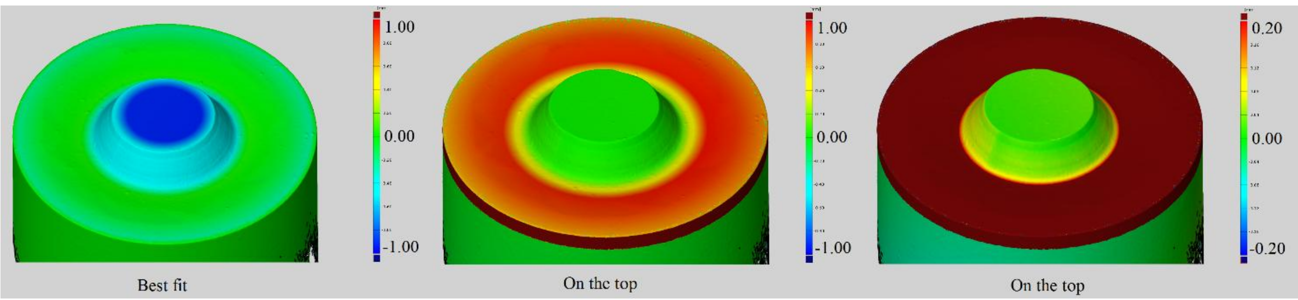

Fig. 5 Color deviation maps of specimen made by RUM (3D scanned model – reference CAD model)
Obr. 5 Farebné mapy odchýlok vzorky vyrobenej metódou RUM (3D skenovaný model – referenčný CAD model)

Results for specimen manufactured by LBM can be seen in Fig. 6. CAD model was placed directly on circular top of pin by function "best fit". On the left figure is used scale of deviation ± 1 mm. However, for clearer depict of deviations, on right figure was used scale of deviation ± 0.2 mm.

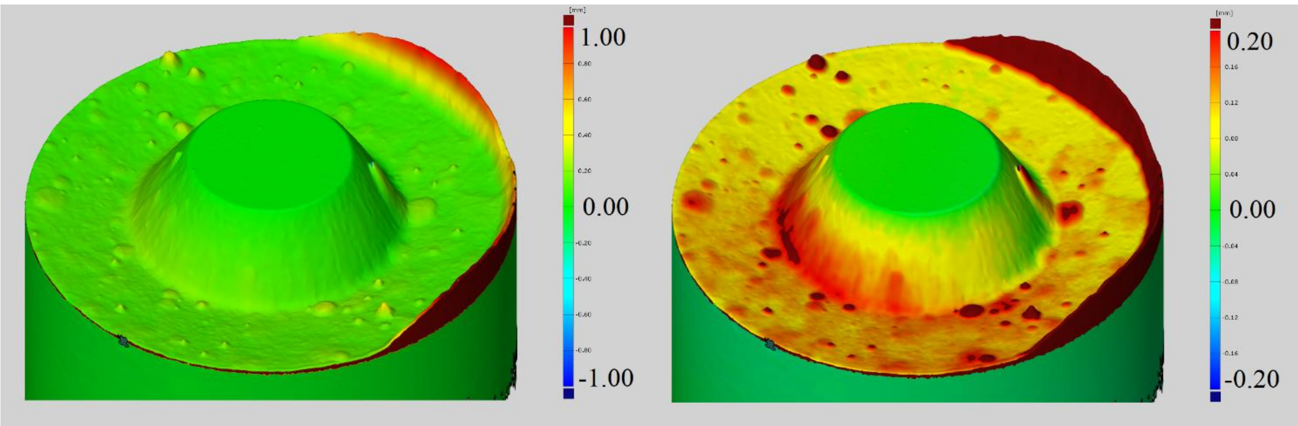

Fig. 6 Color deviation maps of specimen made by LBM (3D scanned model – reference CAD model)
Obr. 6 Farebné mapy odchýlok vzorky vyrobenej metódou LBM (3D skenovaný model – referenčný CAD model)

5 Conclusion

For machining of PCBN, RUM can achieve better geometrical shape than LBM, however, LBM achieve better dimensions than RUM, because LBM do not utilize tool, which could be worn. Due negative down cone, five axis machining is required for RUM. There could be problem to achieve proper shape, because diameter of tool is higher than diameter of specimen. That mean, angle value of cone is limited by used tool. On the other hand, LBM is able to produce recommended shape by utilizing of only three axis due focusing of beam to surface 1 μm^2. Moreover, LBM has potential to rapidly reduce machining time. It would cause also rapidly rise of surface deviations. In that cause, deviations would be even more unacceptable. However, if LBM will be used only for roughing, and RUM only for finishing, resultant surface will be manufactured at relatively short time (even less than one hour), and surface keeps high geometrical shape precision of RUM. Generally, tool for RUM is characterized by long tool life, however, during machining so hard material, such as PCBN, tool wear is more significant in comparison with machining of materials more typical for RUM, such as glass and ceramics. Therefore, when RUM will be used only for finishing, one ultrasonic tool will be able to machine more specimens in contrast with whole ultrasonic machining. Influence of surface roughness on FSW process will be objective of further research.

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Abstrakt

Článok: **Porovnanie obrábania polykrystalického kubického nitridu bóru metódami rotačného ultrazvukového obrábania a laserového lúčového obrábania z hľadiska tvarovej geometrie**

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Kľúčové slová: rotačné ultrazvukové obrábanie, laserové lúčové orábanie, kubický nitrid bóru, 3D skenovanie, trecie premiešavacie zváranie

Tento príspevok sa zaoberá výskumom a porovnávaním dvoch progresívnych metód obrábania – rotačného ultrazvukového obrábania (RUM) a laserového lúčového obrábania (LBM). Ako obrábaný material bol použitý polykryštalický kubický nitrid bóru, ktorý je považovaný za najtvrdší známy material hneď po diamante. Väčšinou je takýto material formovaný na požadovaný tvar ešte pred sintrovaním. Avšak, keďže takýmto spôsobom sa nedá vytvoriť akýkoľvek tvar a dochádza tu aj k úbytku objemu, je potrebné aj takýto material pre určité aplikácie obrobiť. Takouto aplikáciou je napríklad výroba nástroja na trecie premiešavacie zváranie (FSW) pre zváranie pevnejších materiálov, ako sú zliatiny titánu, niklu, alebo nehrdzavejúce ocele. Avšak kvôli svojej vysokej tvrdosti, nie je možné PCBN efektívne obrábať konvenčnými spôsobmi obrábania. Na tento účel sa najčastejšie používajú práve zmienené progresívne metódy obrábania. Pri FSW určuje zváraný material tvar zváracieho nástroja, a hrúbka zváraného materiálu zasa rozmery nástroja. Častým problémom pri tomto spôsobe zvárania je lepenie zváraného materiálu na zvárací nástroj. Tento nepriaznivý efekt je spôsobený najmä nevhodnými parametrami zvárania a nevhodným tvarom nástroja, prípadne jeho vysokou drsnosťou. Preto kritéria tvarovej a rozmerovej presnosti sú dôležitými faktormi pri výrobe takéhoto nástroja. Preto sú v tomto príspevku porovnávané dva odlišné spôsoby obrábania práve z hľadiska tvarovej geometrie. Na vyhodnotenie spomínaných kritérií bol použitý veľmi presný 3D skener. Výsledkom bola mapa odchýlok, na základe ktorej bolo možné určiť vhodnosť spomínaných metód na danú aplikáciu. Na základe vyhodnotenia experimentov je možné povedať, že RUM dosahuje vysokú tvarovú presnosť, avšak kvôli nadmernému opotrebovaniu nástroja počas obrábania je rozmerová presnosť nedostatočná. To znamená, že daný nástroj by mal byť schopný efektívne zvárať požadované materiály, ale nebude môsť byť použitý na požadovanú hrúbku plechov 2 mm, ale iba na približne 1 mm. Nástroj vyrobený metódou LBM vykazuje presne opačný problem – rozmerová presnosť je vyhovujúca (takto vyrobený nástroj je možné použiť na plechy hrubé 2 mm), avšak tvarová presnosť je značne horšia (to môže spôsobiť skrátenie životnosti nástroja, prípadne obmedziť jeho použitie). Preto bude najvhodnejšie použiť LBM na hrubovanie a RUM na dokončovanie.