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Surface Roughness of Poly-Crystalline Cubic Boron Nitride after Rotary Ultrasonic Machining

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Abstract

Rotary ultrasonic machining (RUM) is suitable particularly for machining hard and brittle materials, such as glass and ceramics. This contribution investigates the machining of poly-crystalline cubic boron nitride (PCBN) by using this advanced machining method. In the experiment, a tool for friction stir welding (FSW) was manufactured. Such tool is 1pprox.1 for welding the materials with enhanced mechanical properties. The research was focused on machined surface roughness, because roughness has a significant influence on the welding process, especially on sticking ability. If roughness of the tool is too high, the welded material will stick on the tool and the weld cannot be fabricated. According to the performed experiment, RUM seems to be a proper method to manufacture a FSW tool, owing to the low roughness achieved (Ra 0.24 µm).

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Keywords: Rotary ultrasonic machining; Poly-crystalline cubic boron nitride; Surface roughness; Advanced machining method.

1. Introduction

Poly-crystalline cubic boron nitride (PCBN) is a very hard material (the hardest material, similarly to diamond) which is manufactured by powder metallurgy at 1500 °C and 5 Gpa. Its superior hardness (1pprox.. 7000 HV – depending on grain size) usually guarantees that no additional treatment is necessary – it is often manufactured directly to final shape. However, there are some applications, where machining of PCBN is demanded. Materials of

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such hardness cannot be machined by conventional machining technologies. Therefore, advanced machining methods have been designed. Many authors deal with PCBN as a cutting material, but only a very few of them deal with PCBN as a material of workpiece. Therefore, machining process of PCBN is not sufficiently described in the literature. Advanced machining technologies which are able to machine such hard material are as follows: laser beam machining (LBM), diamond grinding and rotary ultrasonic machining. This article belongs to the very first ones dealing with ultrasonic machining of PCBN [1], [2], [3], [4], [5] and [6].

The tools for friction stir welding (FSW) could be an example of PCBN application. FSW process is based on the application of a tool with a specially designed shoulder and pin (Fig. 1) which is rotating and impressed into the interface of the welded materials. During the welding process, majority of mechanical power is transferred to heat. FSW process is typical for: low heat input, low residual stress, increased mechanical properties, safety, environment-friendliness, welding without filler metal, etc. [7], [8], [9], [10], [11] and [12].

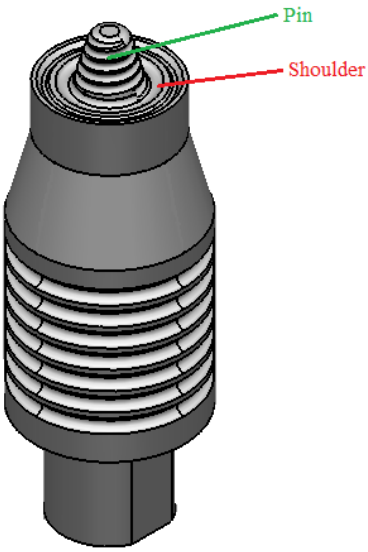

Fig. 1. Tool for friction stir welding with a special design.

Welding tool which is utilised in FSW process has to be sufficiently tough, robust and wear resistant, even at the welding temperature (approx. 90 % of welded material´s melting point). They should also have good oxidation resistance and low coefficient of thermal conductivity. Shoulder profile is usually concave. These tools are characterised by different sizes and geometry. Size of tool depends on thickness of the welded sheets. Geometry of tool depends on the welded material. Material of welding tools also depends on the welded material. Materials, such as magnesium alloys and aluminum alloys could be welded by the welding tool made of high speed steel (HSS). However, materials with higher strength, such as stainless steels and titanium alloys, cannot be welded by such tools, otherwise tempering of tool steel can lead to the damage of pin or destruction of the whole tool. These kinds of welded materials require advanced materials for the welding tool. PCBN is one of the best materials for welding tools for welding the materials with higher mechanical properties. In experiments, PCBN tool for FSW of steel plates with 2 mm thickness was manufactured by RUM. This tool has a diameter of 12 mm. We will investigate, if RUM is suitable for making a tool for FSW with sufficiently low surface roughness.

Nomenclature

Rc	mean height of the roughness profile elements	(μm)
Ra	arithmetic average height	(μm)
Rq	root mean square roughness	(μm)
Rsk	skewness	(–)
Rku	kurtosis	(–)
Rp	maximum height of peaks	(μm)
Rv	maximum depth of valleys	(μm)
Rt	total height of the profile	(μm)
Rz	maximum height of the roughness profile	(μm)
RSc (Sc)	mean height of the profile in space	(μm)
RSa (Sa)	arithmetic mean height in space	(μm)
RSq (Sq)	root mean squared height in space	(μm)
RSsk (Ssk)	skewness in space	(–)
RSku (Sku)	kurtosis in space	(–)
RSp (Sp)	maximum peak height in space	(μm)
RSv (Sv)	maximum valley depth in space	(μm)
RSt (St)	total height of the profile in space	(μm)
RSz (Sz)	maximum height in space	(μm)

2. Machining method

In experiments, rotary ultrasonic machining (RUM) was applied. RUM utilises a diamond tool which rotates around the vertical axis and oscillates by ultrasonic frequency in vertical direction. Some machining systems utilises vibrations with lower frequency than ultrasonic, but these systems are not as effective as ultrasonic ones. The rotating motion and vibration interaction cause micro-cracks on the surface. These cracks are broken and lead away as microchips by coolant. Coolant also enhances this effect by cavitation effect. Therefore, proper properties of coolant are necessary. Coolant is fed on the tool-workpiece interface. Accordingly, very hard and brittle materials (such as ceramics) can be machined. Advantages of this process are: decreased cutting force, reduction of heat generation, no chemical affection of workpiece, increased tool life, improved machined surface, etc. In the experiment, rotary ultrasonic milling machine ULTRASONIC 20 linear was used. The machine tool is able to operate continuously in five axes. It could be also used for the ultrasonic assisted machining [13], [14], [15], [16], [17] and [18].

As a tool, ultrasonic milling cutter (Fig. 2) with a diameter 24 mm was used. A 3D model of workpiece was designed by CAD software PowerShape, and NC program for machining was generated by CAM software PowerMill [19] and [20].

Fig. 2. Ultrasonic milling cutter with diamond abrasive.

3. Description of the experiment

As a machined material, poly-crystalline cubic boron nitride (PCBN) was used. The material was provided by the Welding Research Institute – Industrial Institute of the Slovak Republic (VÚZ – PI SR). They also requested to manufacture the tool for FSW.

PCBN consists of two parts: grains of cubic boron nitride (cBN) and alumina (Al_2O_3) matrix alloyed with cobalt (Co). On this specimen, EDX microanalysis was used. The analysis was performed in the Laboratory of structural analysis at the Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava (STU MTF). EDX analysis served to identify chemical composition. Composition of the above-mentioned specimen is shown in Tab. 1. PCBN is characterised by very high hardness. Its value is usually over 8000 HV (over 80 GPa). The diamond hardness reaches the value up to 10,000 HV [21], [22] and [23].

Table 1. Chemical composition of PCBN.

B [at. %]	**N** [at. %]	**Al** [at. %]	**O** [at. %]	**Co** [at. %]
55.77	*37.18*	*2.98*	*3.75*	*0.32*

For experiments, PCBN cylinder was used with the following dimensions: diameter 12 mm and length 20 mm. Specimen was machined to the shape of the welding tool for FSW process. Dimensioned longitudinal section of the tool is shown in Fig. 3.

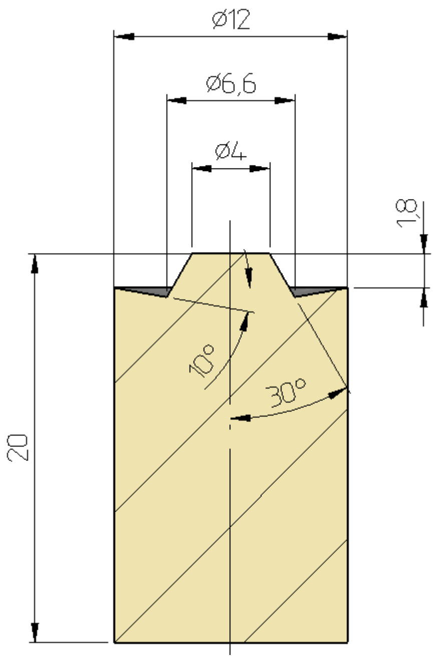

Fig. 3. Drawing of a demanded tool for friction stir welding.

In the experiments, we used: spindle speed 8000 rpm, feed rate 300 mm.min^{-1}, depth of cut 0.003 mm, frequency of vibration 21.6 kHz, amplitude of vibration 6 μm. The surface quality of machined area was evaluated according to the roughness obtained by confocal microscope in the STU MTF Laboratory of structural analysis. Roughness was evaluated on a machined inverted cone which had an angle 10°.

4. Results of the experiment

Surface topography was obtained by confocal microscope on the machined surface. Resultant topography of the surface is shown in Fig. 4. The left image shows a 3D representation of the evaluated machined surface. There is a red line in the middle, which represents the section for the 2D roughness evaluation. This kind of evaluation is shown in the Figure on the right [24].

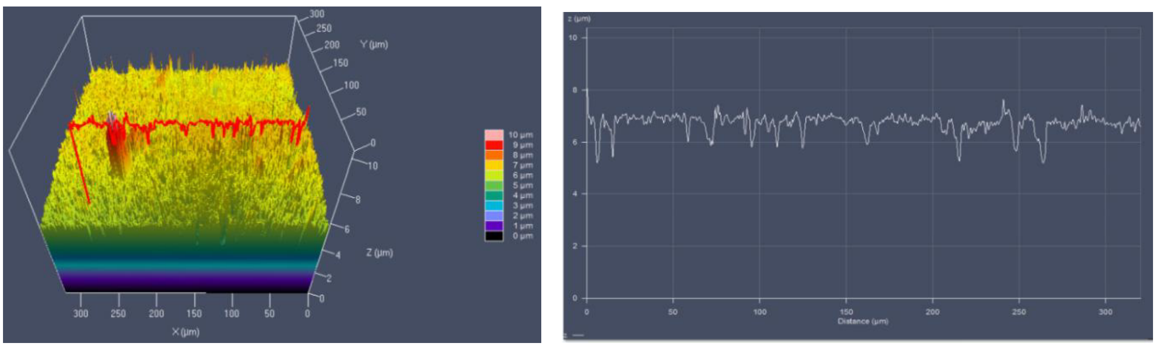

Fig. 4. Topography of the machined surface after RUM.

Nine 2D surface parameters and nine 3D surface parameters were measured, as recorded in Tab. 2 [25], [26] and [27].

Table 2. Surface roughness of PCBN.

2D roughness		3D roughness	
Rc	1.582 µm	**RSc**	4.911 µm
Ra	0.240 µm	**RSa**	0.422 µm
Rq	0.351 µm	**RSq**	0.604 µm
Rsk	-1.681	**RSsk**	-1.684
Rku	7.232	**RSku**	13.412
Rp	1.324 µm	**RSp**	4.009 µm
Rv	1.525 µm	**RSv**	6.392 µm
Rt	2.849 µm	**RSt**	10.400 µm
Rz	2.834 µm	**RSz**	7.917 µm

In further experiments, we plan to evaluate residual stresses and hardness changes, and to compare the reached results with other machining methods suitable for this purpose, such as laser beam machining (LBM).

Conclusion

Rotary ultrasonic machining can be used to achieve sufficient low roughness (Ra 0.24 µm) during machining of PCBN for the welding tool for FSW. Owing to the negative inverted cone of the resultant machined object, five axis machining is required. There could be a problem to achieve the proper shape in some cases, because the diameter of the used tool is limited by the angle of the cone. The machined surface after RUM shows the absence of ledges. It is caused by the fact, that the depth of the cut was not higher than the amplitude of the tool vibration. Generally, tool for RUM is characterised by long tool life. However, during machining a hard material, such as PCBN, the tool wear is more significant in comparison with machining the materials more typical for RUM. Therefore, RUM should be suitable especially for surface-finishing. Then the machined area maintains the advantages of machined surface fabricated by RUM (such as low roughness, etc.). Influence of surface roughness on FSW process will be an objective of further research. The research could be performed in the Welding Research Institute – Industrial Institute in Bratislava. The STU MTF workplace of Centre of Excellence of 5-axis Machining could also investigate the possibility of fabrication the tool for FSW process by laser beam machining (LBM) on Lasertec 80 Shape.

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