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Performance of Al_2O_3-cBN materials and perspective of using hyperspectral imaging during cutting tests

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Abstract. The performance of cutting tool materials (CTMs) influences the quality and lifetime of parts produced with their help. Unexpected fracturing or other failures of the tools lead to defects of parts that exaggerate materials fatigue and fracture processes. For the purpose of Industry 4 and future generations of factories it is important to enable *in-situ* monitoring of cutting processes while hyperspectral imaging can serve as a powerful tool. Cubic boron nitride (cBN) has extreme hardness and can provide improved wear resistance if mixed with other CTMs. Besides, such materials can be used without cooling liquids that helps to mitigate workplace health risks. The aim of the current work was to understand how well current hyperspectral imaging technologies can track the changes in performance of CTMs with addition of cBN. The paper presents the results of multiple in-situ (obtained during cutting with real lathe) and static (before or after cutting) tests performed with hyperspectral camera. The wear rate of CTMs and roughness of workpieces were measured with the help of scanning electron microscope and 3D optical profiler respectively. The effect of cBN content and effect of TiN or ZrO_2 additives on performance of alumina-based CTMs produced by spark plasma sintering technique is presented.

1. Introduction

Hyperspectral imaging (HSI) is known for processing the information over the electromagnetic spectrum to identify various materials by obtaining the spectrum of each pixel of the image [1][2]. In other words, HSI combines the power of spectroscopy and digital image processing to identify the materials in a scene. While HSI is a fast-growing area in the remote sensing field for earth observation; emerging mobile hyperspectral cameras made it possible to use them for material classification and object recognition in the real-world scale [3].

2. Materials and methods

2.1. Materials

Five alumina-based cutting tool materials (CTMs) reinforced by cubic boron nitride (cBN) without or with TiN or ZrO_2 additives were produced by spark plasma sintering (SPS) technique – see table 1. Their physical and mechanical properties were measured in previous work of P. Klimczyk et al. [4]. Workpiece material was hot rolled normalized unalloyed medium carbon (main constituents: 0.45 % C, 0.2 % Si, 0.7 % Mn, base - Fe) steel C45 according to EN 10083-2.

Table 1. Properties of cutting tool materials investigated [4].

Designation	Composition, %	Relative density, %	Youngs modulus, GPa	Vickers hardness HV30, GPa	Fracture toughness, K_{IC} (indentation method), $MPa \cdot m^{1/2}$
A100	Al_2O_3	>99	398 ± 7	16.3 ± 0.9	3.9 ± 0.6
A10B	Al_2O_3-10cBN	98	421 ± 9	16.4 ± 0.5	5.4 ± 0.5
A20B	Al_2O_3-20cBN	96	442 ± 8	18.7 ± 0.3	5.8 ± 0.4
A20B10T	Al_2O_3-20cBN-10TiN	96	428 ± 11	17.2 ± 0.3	5.5 ± 0.5
A20B15Z	Al_2O_3-20cBN-15ZrO_2	99	409 ± 13	18.8 ± 0.7	5.4 ± 0.5

2.2. Wear rate measurements

The cutting tests were performed on *Sumore* SP2138 CNC lathe. The test sample produced by SPS was cut into required shape and then the edges were ground (figure 1A). Total number of cuts with depth of 0.075 mm and width of 80 mm was 70; feed rate was 0.05 mm per rotation (0.88 mm s^{-1}); average cutting speed was 100 m min^{-1} (1.67 m s^{-1}); total duration of cutting was 105.66 min (6342 s); total length of removed chip was 10566 m, figure 1B. The linear and volumetric wear rates were measured according to scanning electron microscope (*Hitachi* TM1000) images. Volumetric wear was approximated by triangular pyramids, figure 1C. Roughness was measured with the help of *Bruker* ContourGT-K0+ optical 3D profiler.

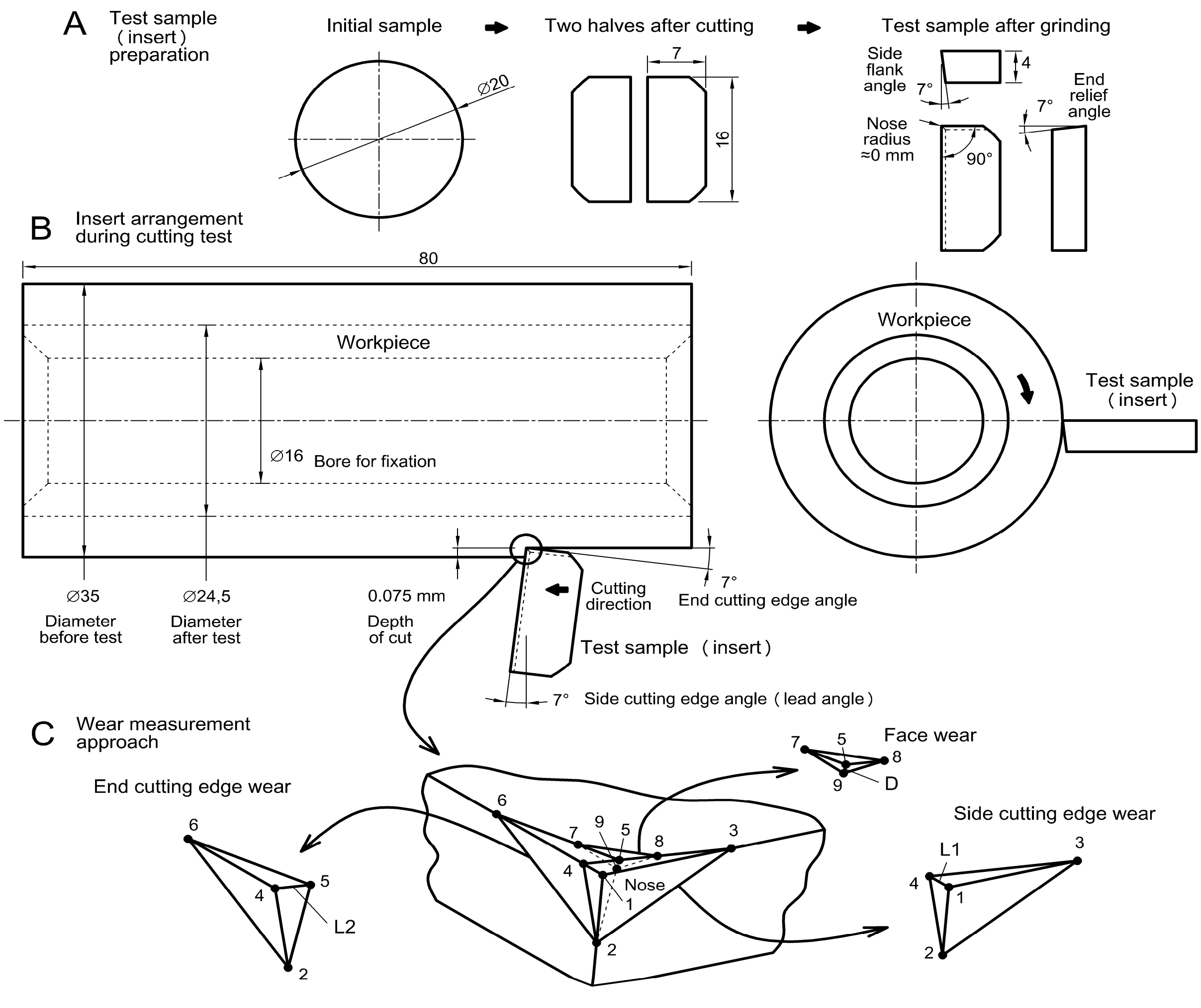

Figure 1. The sample (insert) preparation (A), it's arrangement during cutting test (B) and wear rate measurement approach (C).

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2.3. Hyperspectral investigations during and after cutting test

The system was comprised mainly of a hyperspectral camera, lighting source, the test sample fixed in the lathe, and a frame for fixation of components (figure 2). The mobile hyperspectral camera used for conducting these experiments was *SPECIM* IQ (Spectral Imaging LTD, Finland), a VNIR (Visible – Near-infrared) camera which collects the spectrum of each pixel of the image in the range of 400 – 1000 nm [5]. Recording of one image took approximately 5 minutes. Similar to other computer vision applications, the light source used during the image acquisition phase, plays a vital role in the validity of the results. Incandescent lights were applied as the best illumination source for indoor hyperspectral imaging applications [6]. A frame was assembled to install the incandescent light in an appropriate height above FOV (Field of View).

The spectrum of the insert material (before testing) and steel workpiece (after testing) was extracted in static conditions (without movement), while in addition, images of cutting zone were taken *in-situ* during machining to study the effect of feed rate (2.5, 5.0 mm/s), rotational speed of workpiece (500, 1000 rpm / 8.33, 16.66 rps) and depth of cutting (0.1, 0.2 mm).

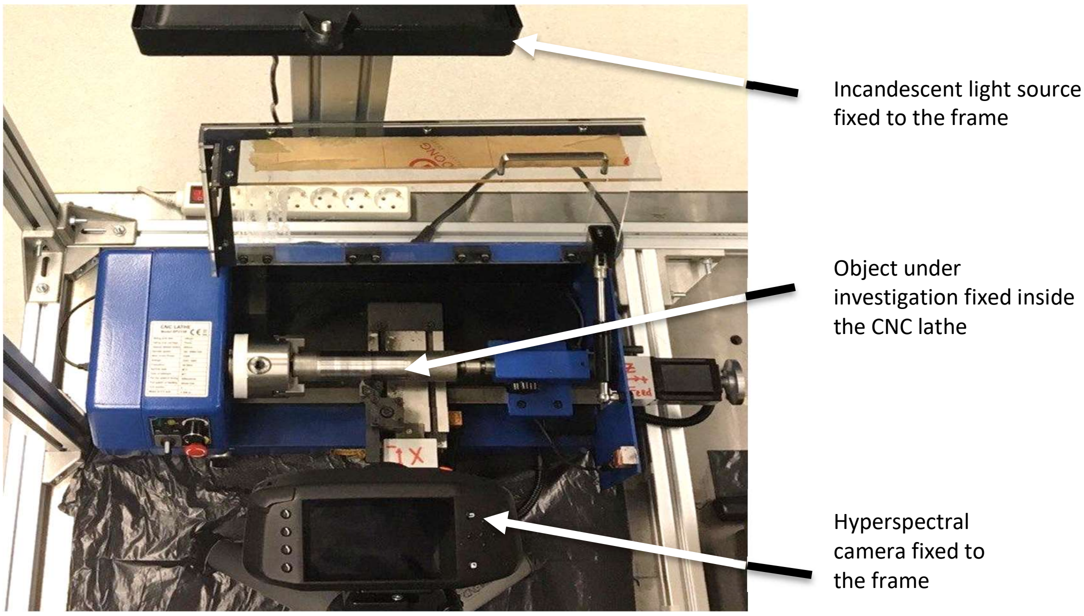

Figure 2. Test setup for hyperspectral investigation during cutting test (top view).

For acquiring the suitable images for analysis, more than 50 images from the scene from different angles with different scenarios were taken. These images were taken to find the best distance from the illumination source to the material, and material to the camera, as well as the proper angle and proper field of view. After taking these images, going through the images one by one, less than ten images have been selected. Also, the best position of the illumination source, camera and material have been found. Therefore, after these experiments, by finding the optimum values of these parameters, further experiments have been done in this optimum situation.

3. Experimental results

3.1. Wear rate measurements

The wear rates of CTMs are presented in figure 3 along with roughness of workpieces after 70 cuts.

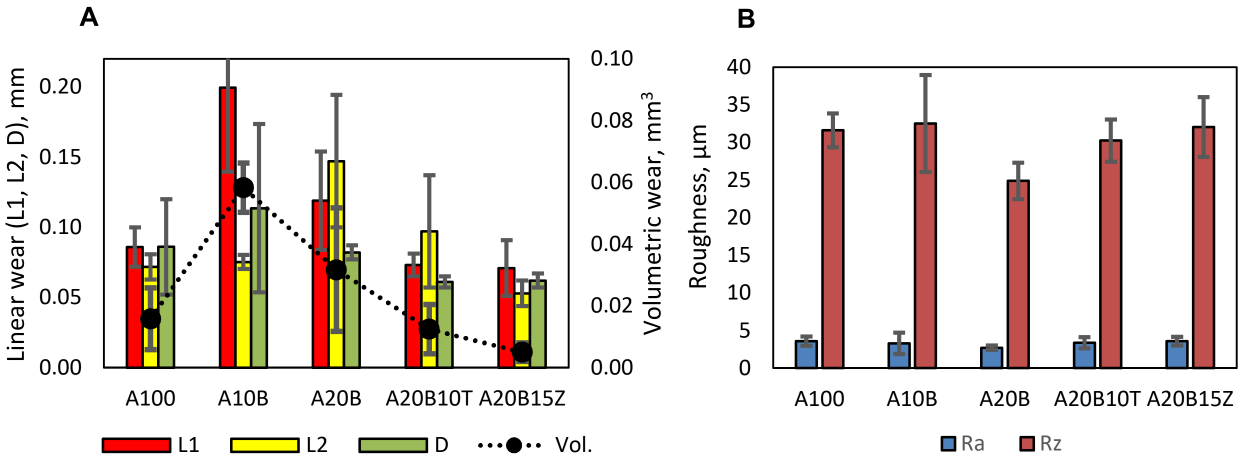

Figure 3. The wear rates of tested samples (A) and roughness of the workpiece after cutting test (B).

It is possible to see that wear resistance of alumina during dry cutting can be significantly (up to 3 times according to volumetric wear) improved by addition of 20 % of cBN and 15 % of ZrO_2 while providing the same roughness of produced parts. According to SEM images, pure alumina (A100) was suffering from chipping of the cutting edge. Reduced performance of materials with 10 and 20 % of cBN could be explained by loss of alumina between grains that facilitates adhesion of steel onto cutting insert and its overheating.

3.2. Hyperspectral investigations during and after cutting test

For minimizing the error that might happen during the image acquisition phase, each cutting tool material was under the experiment five times, and the spectral signatures of ten different pixels of the material were conducted. Then, the average of these 50 spectra (5 multiplied by 10) was calculated to have a final spectrum of the material which may better represent the object or the material. Also, since spectral signature extracted from the hyperspectral image has small fluctuation (less than one percent) over the electromagnetic, for smoothing the graph in the preprocessing stage, Savitzky-Golay filter was used similar to *SPECIM* IQ Studio software; the software for processing the hyperspectral images acquired by *SPECIM* IQ camera [7]. The graphs show the spectral of cutting tool materials (figure 4A), and the spectral signature of steel workpiece after being cut by them (figure 4B).

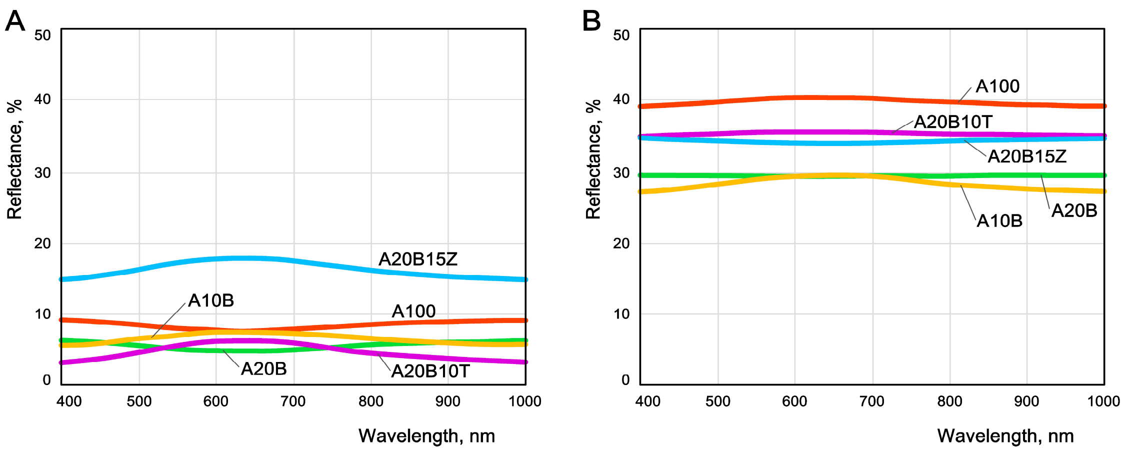

Figure 4. Spectral signature of the cutting tool materials (A) and spectral signature of steel workpiece taken after cutting test (B) in the range of 400 – 1000 nm.

It can be interpreted from figure 4A, that A20B15Z material (blue line) has a brighter colour than others, and it causes to reflect more energy to the camera. Therefore, its spectral signature has a higher percentage of reflectance in comparison with other materials over the spectrum.

However, for identifying the material using Figure 4A, there is a need to observe significant peaks or depths, while in these experiments, the spectral signatures of all materials were almost flat (less than three percent change over the range). In other words, it was not possible to see any significant peaks or depths related to these materials (the characteristic peaks) in the VNIR range. Also, in figure 4B, taken by VNIR camera, the spectrum of workpiece is almost flat over the entire range in all experiments. It shows that the characteristic peaks of steel are outside of the VNIR range.

Spectral signatures taken during *in-situ* testing have shown that doubling of the value of feed rate, rotational speed of workpiece and depth of cutting resulted in max 0.1, 1.0 and 1.0 % change of the workpiece reflectance respectively. Using of near-infrared camera (1000-1700 nm) might lead to more precise identification of materials and control of cutting process.

4. Conclusions

- It was found that wear resistance of alumina during dry cutting can be significantly (up to 3 times according to volumetric wear) improved by addition of 20 % of cBN and 15 % of ZrO_2 while providing the same roughness of produced parts. Such material can be used without cooling liquids to mitigate workplace health risks.
- It was found that unreinforced reference pure alumina exhibit chipping of cutting edge that can lead to defects of parts that exaggerate their fatigue and fracture processes.
- It was possible to establish in-situ monitoring of cutting process by hyperspectral camera.
- Spectral signatures taken during *in-situ* testing has shown that doubling of the value of feed rate, rotational speed of workpiece and depth of cutting resulted in max 0.1, 1.0 and 1.0 % change of the workpiece reflectance respectively that was not enough for tracking of the tool performance. It is advised to use near-infrared camera (1000-1700 nm) to achieve more precise identification.

Acknowledgments

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