https://doi.org/10.1016/j.matlet.2021.130041

Generation of structural colors on pure magnesium surface using the vibration-assisted diamond cutting

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Abstract

The light metal magnesium has wide applications in automotive, electronics, and biomedical industries attributing to its superior properties. However, the fabrication of the micro/nanostructures on its surface, especially in the generation of structural colors, remains a challenge. Here we report the generation of structural colors on pure magnesium surface using the vibration-assisted diamond cutting (VADC) process in which the diamond cutting tool regularly vibrates on the pure magnesium surface to fabricate the microstructures using the controllable vibration frequency. The periodic saw-tooth-like microstructures with the spacing of 1.65μm and 1.45μm are successfully fabricated by the VADC process. The fabricated microstructures act as the diffraction grating that induces the generation of structural colors. Two groups of structural colors (coral color and green color; blue color and magenta color) are clearly observed at the viewing angle of 50° and 65°, respectively. Moreover, a detailed analysis is conducted to demonstrate the relationship between the spacing of grating and the cutting force.

Keywords

Magnesium; Structural color; Microstructure; Vibration-assisted diamond cutting

1. Introduction

Nowadays, the light metal magnesium and its alloy have been widely applied in various fields attributing to its superior specific stiffness, high thermal conductivity, and biocompatibility[1–3]. Structural color has drawn significant attention in academia and industries due to the potential applications in multi-color printing, micro-optic systems, and information encryption storage[4]. The structural color is generated because of the physical interaction between the visible light and the micro/nanostructured surface, in which the surface color evidently changes with the viewing angle[5].

However, to the best of the author's knowledge, up to now, it has rarely been reported about the generation of structural colors on the pure magnesium surface. It is because the commonly applied machining processes for fabricating micro/nanostructures, such as the femtosecond laser technology and lithography, are not feasible to machine the microstructures on the magnesium surface due to the ignition and flammability of magnesium. The vibration-assisted diamond cutting (VADC) process is a promising technology to fabricate the microstructures on the metallic surface[6]. The main idea of this process is that the periodic vibration is superimposed on the motion of the diamond cutting tool to generate the desired microstructures. Inspired by this, this paper utilizes the VADC process to fabricate the periodic microstructures for the structural color generation on the pure magnesium surface, which has potential applications in anti-counterfeiting devices, display devices, micro-optics, and functional decoration.

2. Experimental procedures

The fabrications were performed on an ultraprecision lathe (Moore Nanotech, 350FG). Pure magnesium with a block shape as the workpiece was mounted on the spindle through the copper block and fixture. In the VADC process, the command signals offered by the computer were converted into analog signals by the multifunction I/O device (National Instruments, USB-6341) and magnified by the piezo amplifiers (Physik Instrumente, E617.001) to drive the vibration generator, as shown in Fig. 1(a). A natural single-crystal diamond insert (Contour Fine Tooling, N0.20mLEixCV1503) was selected as the cutting tool. The cutting forces were measured through the dynamometer (Kistler 9256C1), the charge amplifier (Kistler Multichannel Charge amplifier 5080), and the software (DynoWare).

The workpiece was firstly flatted with the spindle speed of 1500 rpm, the depth-of-cut of 2μm and the feed rate of 1 mm/min. After this pre-machining stage, the sinusoidal voltage signals with the vibration frequency of 1000Hz and the amplitude of 40V were employed to drive the vibration generator to generate the vibration trajectory along Z-axis direction. Two kinds of microstructures, named as case1 and case 2, were fabricated. The cutting velocities along X-axis direction were set to be 96.7mm/min for case 1 and 86.6mm/min for case 2, respectively. Depth-of-cut along Z-axis direction and cross-feed along Y-axis direction were set to be 4μm and 60μm for both cases. The structural colors were captured under different viewing angles using a digital camera, as shown in Fig. 1(b).

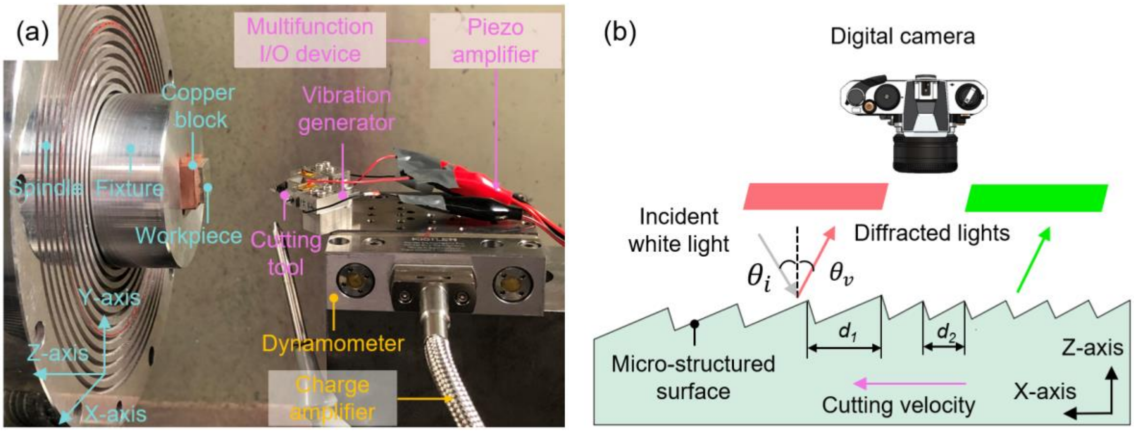

Fig. 1. (a) The photograph of the experimental setup and (b) the schematic of the structural colors generation.

3. Results and discussion

3.1. Generation mechanism of the structural colors

Firstly, an optical mirror surface with the surface roughness of 0.031μm is obtained in the pre-machining stage to guarantee surface finish, as shown in Fig. 2 (a). After the VADC process, the original color of the pure magnesium surface has been rendered into two groups of vivid colors, without any pigment and coating material. Coral color and green color can be clearly observed at the viewing angle of 50°, as shown in Fig. 2 (b). If the viewing angle is shifted to 65°, blue color and the magenta color are observed, as shown in Fig. 2 (c). In essence, these viewing-angle-dependent structural colors are attributed to the physical interaction between the visible light and the periodic microstructures, which can be described by the grating equation [7]:

$$sin\theta_i + sin\theta_v = m\lambda/d \, (m = 0, \pm1, \pm2, \pm3, \ldots) \tag{1}$$

where θ_i and θ_v are the incident angle and viewing angle, respectively; m is the diffraction order; λ is the wavelength of the diffracted light; d is the spacing.

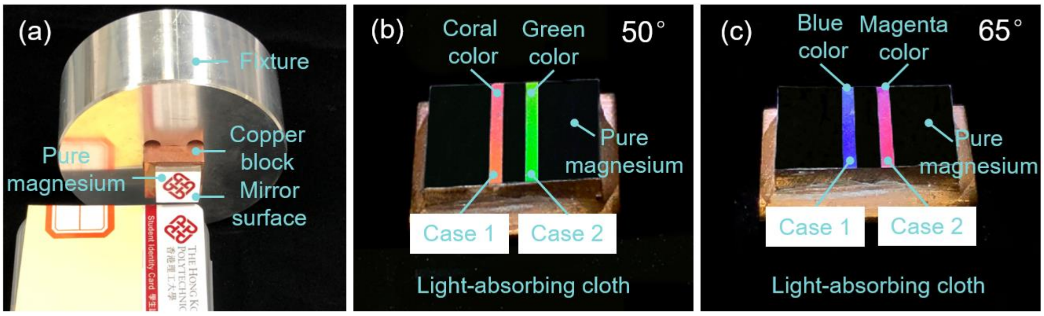

Fig. 2. Photographs of (a) optical mirror surface, (b) coral color and green color at the viewing angle of 50°, and (c) blue color and magenta color at the viewing angle of 65°.

In this study, the white light with different wavelengths is employed as the incident light, which is perpendicular to the workpiece surface (θ_i=0°), the wavelength λ of a certain color can be expressed based on Eq. (1):

$$\lambda = dsin\theta_v/m \tag{2}$$

Therefore, for the given θ_v and m, the structural color on the magnesium surface can be controlled by adjusting the spacing d. The larger wavelength λ will appear at a zone with a larger spacing d. In the VADC process, the spacing d is determined by the cutting velocity v_c and the vibration frequency f:

$$d = v_c/f \tag{3}$$

The theoretical values of spacings (d_1 and d_2) described in Fig. 1 (b) are calculated to be 1.61μm and 1.44μm. For the viewing angle θ_v=50° and a given diffraction order m=2, the wavelengths of the diffracted lights are calculated to be 617nm for case 1 and 552nm for case 2, respectively. These wavelengths correspond to the coral color and green color spectra, which agrees well with the experimental results in Fig. 2 (b). The similar generation mechanism of structural colors is also demonstrated in Fig. 2 (c).

3.2. Characterization of the microstructured surface

To investigate the morphology of the microstructures on the pure magnesium surface, the microstructured surface was measured by using a field emission scanning electron microscope (FESEM) (Tescan MAIA3) and an atomic force microscope (AFM) (Park XE-70). Fig. 3 shows the FESEM and AFM images of periodic microstructures of case 1 and case 2. The average measured values of the spacing d_1 and d_2 are 1.65μm and 1.45μm, which considerably close to the theoretical values (1.61μm and 1.44μm). It can be clearly seen that the periodic saw-tooth-like microstructures with the high-regular array and the high uniformity were successfully fabricated on the pure magnesium surface by utilizing the VADC process.

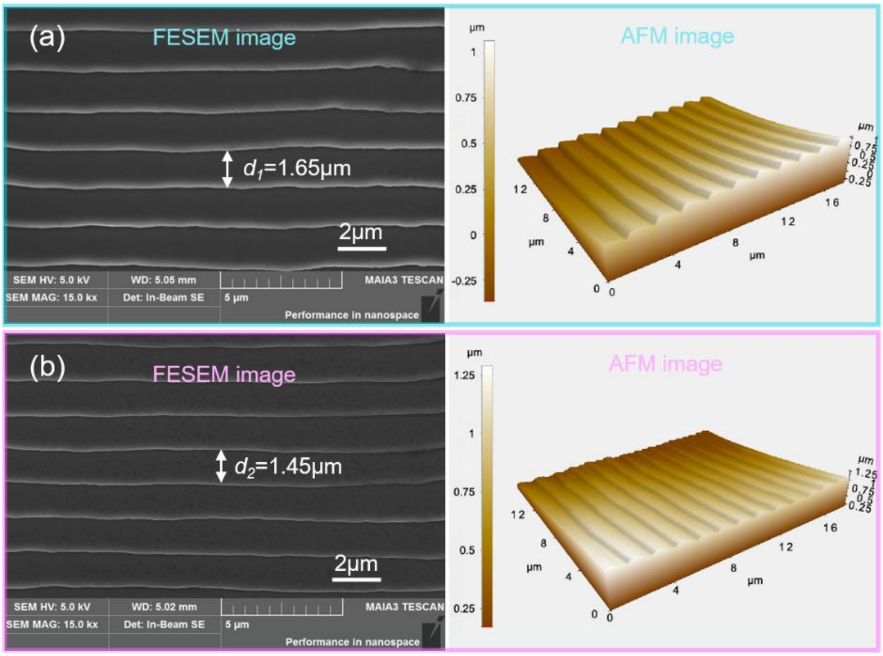

Fig. 3. The surface morphologies of (a) case 1 and (b) case 2.

3.3. Analysis of the cutting force

Fig. 4 (a) and (b) show the measured cutting forces for case 1 and case 2. F_x, F_y, and F_z represent the cutting forces along the X-axis, Y-axis, and Z-axis directions of the ultra-precision lathe. In one vibration cycle, the means of peak-to-valley values (a_1, b_1, and c_1) of F_x, F_y, and F_z of case 1 are 0.2N, 2.7N, and 1.6N, respectively. Similarly, the a_2, b_2, and c_2 of case 2 are 0.4N, 3.2N, and 2.0N, respectively. It can be clearly found that all average values of the cutting forces of case 1 are less than those of case 2. In comparison with case 2, the spacing d_1 of case 1 is larger than d_2 in one vibration cycle, which corresponds to the fewer material-removal-volumes in the same vibration cycle. For case1, this less material only needs a smaller cutting force to be removed. This means that the increase of the spacing would decrease the cutting force.

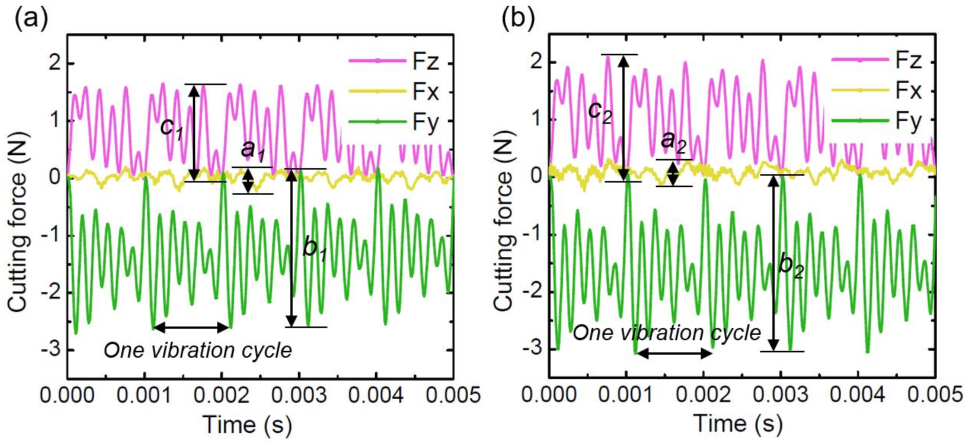

Fig. 4. The cutting forces of (a) case 1 and (b) case 2.

4. Conclusions

This study demonstrates the vibration-assisted diamond cutting (VADC) process to fabricate periodic saw-tooth-like microstructures on pure magnesium surface. The two groups of viewing-angle-dependent structural colors (coral color and green color; blue color and magenta color) are clearly observed with high saturation, which validates the successful generation of structural colors by using the VADC process. The generation mechanism of the structural colors is theoretically analyzed, and we found that surface structural colors can be controlled by adjusting the spacing of the adjacent microstructures. In addition, the increase of the spacing also leads to a decrease in cutting force. This study provides a flexible fabrication method for generating structural colors on pure magnesium surface, which are potentially applied to anti-counterfeiting devices, micro-optics, and functional decoration.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region (Grant number PolyU 152021/17E), the European Commission /

Research Grants Council Collaboration Scheme (Grant number E-PolyU502/17), and the Research Committee of The Hong Kong Polytechnic University (Project Code: G-RK2V).

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