Journal of Manufacturing Processes 56 (2020) 1392–1396

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Structural coloration using face turning and variable tool vibration frequency[☆,☆☆]

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ARTICLE INFO

Keywords:
Face turning
Compensation
Structural coloration
Frequency control
Elliptical vibration

ABSTRACT

The technique of manufacturing surface micro-/nano- structures to colorize metal surfaces by using elliptical vibrating cutting has been continuously developed and has good industrial potential. However, the image rendering is based on a raster scan path and constant variation of cutting velocity. The process efficiency and stability are significantly restricted. In this study, a new approach is proposed to implement the elliptical vibration texturing in a face turning setup, where the image rendering is achieved by an equidistant spiral tool path and modulation of the tool vibration frequency. The basic principle is that, while moving at a constant surface velocity, the tool follows a variable frequency elliptical vibration to machine gratings with different spacings on the workpiece surface. In order to ensure the uniformity in the radial direction and the consistency of the color under the same frequency excitation, a smoothly accelerated equidistant spiral tool path is designed. In addition, since the running speed of the machine tool is not completely synchronized with the signal of the tool vibration, a compensation method through the pre-experimental calibration test is proposed. The machining test on the ultra-precision lathe is performed. It is found that on the compensated machined image, cumulative errors caused by the asynchronous operation of the lathe and vibration tool are eliminated, which validates the feasibility and effectiveness of the method.

1. Introduction

Besides coloring with pigments, structural coloration is another color-generating approach that is widely involved in nature [1], which utilizes micro-/nano-structured surfaces to manipulate visible light by diffraction, interference, and scattering [2]. One major characteristic of structural color based on diffraction and interference is that the displayed color changes with the viewing angle, or referred to as iridescent color [3]. Due to this unique feature, structural coloration has been widely used in the applications for functional decoration and anti-counterfeiting [4].

In order to engrave micro-/nano-structures on metal surfaces for structural coloration, our group has previously proposed an innovative approach to fabricate tunable diffraction gratings by ultrasonic elliptical vibration texturing. By utilizing the overlapping tool vibratory trajectories and the ultra-sharp cutting edge of a single crystal diamond tool, wavelength-scale gratings can be directly machined with a conventional shaping setup [5]. As shown in Fig. 1, the grating profile is shaped by the tool trajectory and tool geometry, while the grating pitch is determined by the ratio of tool vibration frequency and nominal cutting velocity. The grating spacing can be reduced to a sub-micron scale, close to the wavelength of visible light, so strong diffraction will occur on the processed surface. When light is incident on the gratings generated by elliptical vibration texturing, reflected light in different colors will be observed at different angles. The iridescent color, or wavelength, can be predicted by the grating equation [6]:

$$d(\sin\theta_i + \sin\theta_m) = m\lambda \tag{1}$$

where λ is the wavelength, m represents the diffraction order, d is the grating spacing and θ_i and θ_m are the light incident angle and the angle of diffracted light of order m respectively. When θ_i, θ_m and m are all set, the grating spacing determines the wavelength of diffracted light. As shown in Fig. 1, as the grating spacing changes for each pixel, the color shown on the machined surface changes accordingly. For elliptical vibration cutting process within an appropriate cutting speed range, the grating spacing is precisely determined by the ratio of cutting speed (V)

[☆] 48th SME North American Manufacturing Research Conference, NAMRC 48, Ohio, USA.
[☆☆] Peer review under the responsibility of the scientific committee of NAMRI/SME.
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https://doi.org/10.1016/j.jmapro.2020.04.035
Received 3 December 2019; Received in revised form 27 February 2020; Accepted 11 March 2020

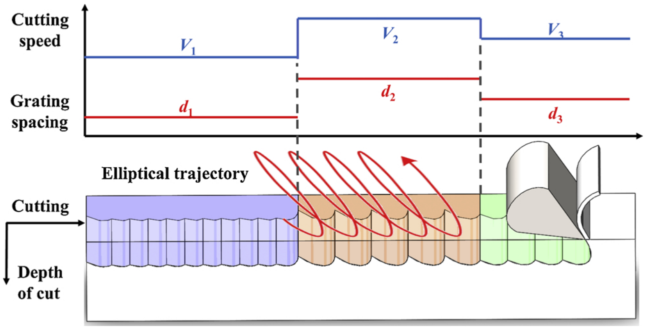

Fig. 1. Structural coloration by changing cutting velocity.

and tool vibration frequency (f) as [6]:

$$d = V/f \tag{2}$$

Therefore, by changing the cutting velocity in elliptical vibration texturing, pixelated color blocks can be rendered in the cutting direction. By following a raster scan pattern, a complicated image then can be rendered. Based on the theoretical basis above, a method using elliptical vibration texturing to realize structural coloration by continuously changing the cutting velocity has been developed [6]. The raster scan rendering is schematically shown in Fig. 2. In this tool path planning strategy, the pixel coordinates and machine coordinates are aligned, which makes itsimple to generate a sequence of velocity commands to represent the image design. The red lines, indicating the cutting motion, are interpolated by the position-velocity-time (PVT) programs to control the cutting velocity. The blue lines indicate the retraction motion in the opposite direction without cutting.

Based on this method, by skillfully planning the tool path of the cutting process, a coloring technique that displays different patterns as the viewing angle changes is realized [7]. In addition, by modulating the cutting depth in combination with the cutting velocity variation, this method is also extended to engraving relief images with structural colors [8]. Not only providing practical methods for structures coloration based on vibration machining, these works also extend the application scenarios.

2. Method

Although the results generated from the previous techniques are promising, it suffers from several shortcomings in efficiency and stability, which severely limits its efficacy in industrial applications. Firstly, since the tool follows a raster scan path, there is a retracting action for each cutting, which greatly reduces the cutting efficiency. In the actual experiments, the time wastes due to the retracting motion can reach up to 50 %. To make the case even worse, before and after each cut, a pre-acceleration and post-deceleration stage is required outside of the cutting region, which further slows down the process. Secondly, since the apparent color is controlled by the cutting velocity, the machine needs to be in constant acceleration or deceleration motion. The dynamic response of the axis limits the rendering resolution and the overall structural color effect due to the undesirable vibration of frequent jerk motion. An optimization method has been proposed to blend the tool motion to avoid jerk [9], but even at a moderate cutting velocity with ultrasonic vibration, the optimized tool path cannot truthfully render the target image.

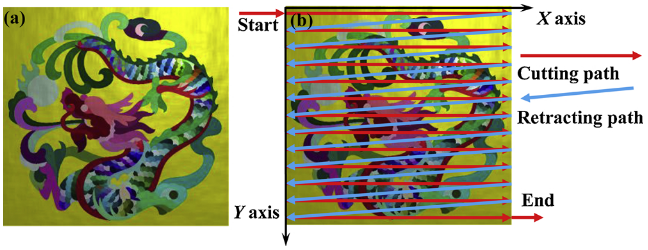

Fig. 2. Raster scan for tool path generation.

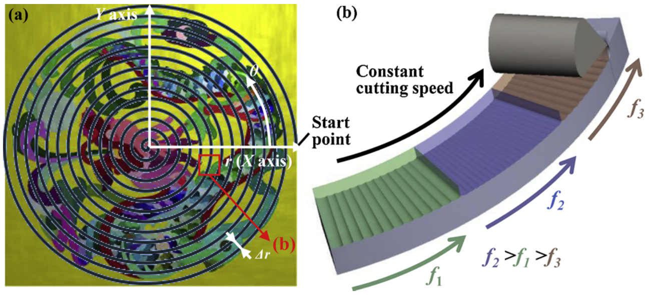

Fig. 3. Schematics of (a) tool rendering path in face turning and (b) frequency modulation of elliptical vibration texturing.

To address the two challenges discussed above, this paper proposes an alternative approach for vibration texturing of structural colors by (1) face turning and (2) tool frequency modulation. Due to the continuous tool path in a face turning operation rather than a disrupted raster scan path, not only the retraction motion is eliminated, but the spindle axis also is rotating with small acceleration change. Both will significantly help the process efficiency and stability. While the surface cutting velocity is maintained to be constant, the grating spacing is tuned by changing the tool vibration frequency. With the special design of a high-bandwidth vibration cutting tool, much higher acceleration/deceleration (or faster change of grating spacing) can be achieved without affecting the machine stability.

The conceptual illustration of the proposed method is shown in Fig. 3. According to Eq. (2), in addition to the change of cutting velocity, the grating spacing can also be controlled by the tool vibration frequency. If all the rendering information is captured by the tool frequency change, the surface cutting velocity is required to be constant. In a face turning operation, in order to achieve a constant surface velocity, the spindle speed needs to be adjusted based on the tool radial coordinates. Therefore, the proposed algorithm composes of three parts. The first part is to program the CNC lathe to complete a spiral path with a constant surface velocity. It differs from the simple constant velocity turning, such that the feed motion has to be adjusted according to the spindle velocity. A fixed feed per revolution must be maintained to achieve a constant aerial scan speed. Based on the generated tool path, the second part of the algorithm adjusts the tool vibration through a separate controller with a precise timing sequence. The tool will instantaneously switch its vibration frequency over a fixed interval on the turning surface. In addition, because a sub-millisecond synchronization is required to coordinate the tool/spindle motion and tool vibration, the third part of the algorithm is to compensate for the delay between the machine controller and the external controller through experimental calibration.

Therefore, a process system consisting of pre-processing, cutting and compensation is designed. The pre-processing module is responsible for converting the original image design to a frequency information matrix utilized by a LabView program to control the tool vibration and the spiral tool path to maintain a constant aerial scan for the CNC machine tool. At the beginning of the machining process, the CNC controller sends a trigger signal to the LabView program for a synchronized operation. The calibration piece is designed to be a special two-tone half rings. By observing the machined pattern of the calibration piece, the actual timing mismatch can be compensated for between the LabVIEW program and the CNC controller. The flowchart of the system procedures is summarized in Fig. 4.

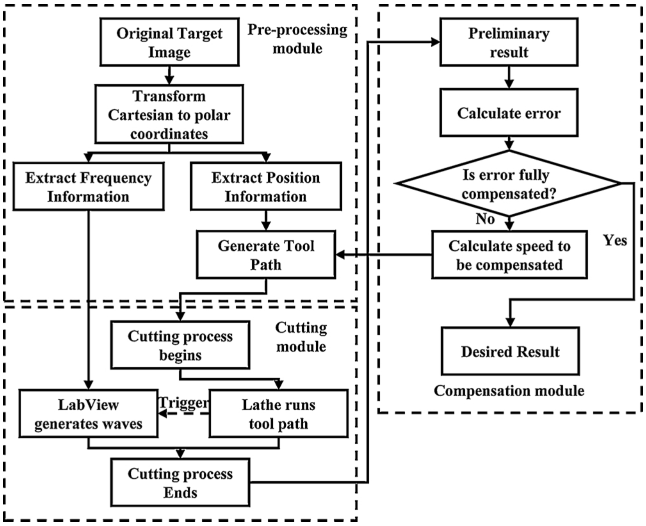

Fig. 4. Process flowchart of pre-processing, preliminary cutting, and compensation.

3. Hardware design

3.1. Non-resonant cutting tool and tool trajectory

In order to control the frequency of tool vibration to control the surface color, a specially designed non-resonant tool was used in the experiment [10]. It acts as a two-dimensional and high-bandwidth fast tool servo, which can generate a controlled elliptical trajectory up to 2 kHz limited by the amplifier current capacity. The first resonant frequency of the structure reaches 7 kHz, which ensures a flat frequency response in the operational bandwidth. A typical tool vibration trajectory is measured and demonstrated in Fig. 5, where the tool vibration frequency is at 2 kHz.

3.2. Experimental setup

The cutting experiments are conducted on Precitech Nanoform X Ultra-precision lathe where the elliptical vibration tool is mounted on the YZ stage. The vibration tool is controlled by voltage signals generated by a National Instruments PXI system and amplified by two channels of PiezoDrive PX200 voltage amplifiers. A single crystal diamond insert is mounted on the vibration cutting tool, with a 0° rake angle, 7° clearance angle, and a 400 μm nose radius. The workpiece material is 360 ultra-machinable brass. The actual machine setup with the coordinate system definitions are shown in Fig. 6. The workpiece is selected to be ultra-machinable 360 brass plate with 3 in. diameter (*Mcmaster-carr, USA*).

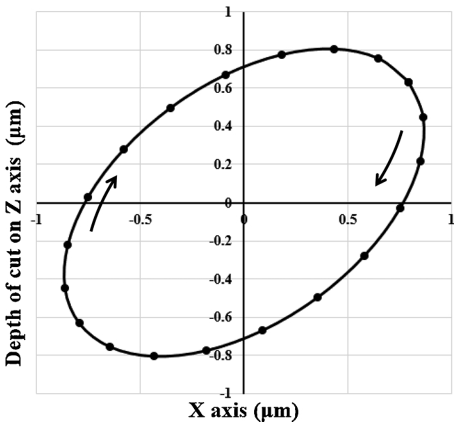

Fig. 5. Measured tool vibration trajectory @ f = 2000 Hz.

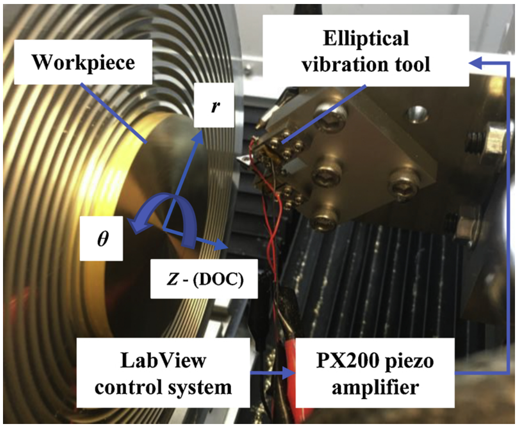

Fig. 6. Experimental setup on Precitech Nanoform X.

4. Pre-processing

4.1. Frequency output sequence

The first step of pre-processing is to transform the original image from the Cartesian coordinates to the polar coordinates at equal-spatial partitions. The method here is to use the position of the pixel in the actual cutting process to find the corresponding position in the original image and extract the color information accordingly. Here, the color information is represented by frequency calculated with Eqs. (1) and (2).

To guarantee that no distortion occurs along the radial direction of the resultant image, the tool path in the turning process is set to be equidistant spiral which is shown in Fig. 3(a):

$$r_0 - \frac{\theta}{2\pi}\Delta r = r \tag{3}$$

where r_0 is the starting radius for the process; Δr is the pitch of the spiral (feed rate per revolution); and θ is the total sweeping angle of the tool on the workpiece. Alternatively, θ is also the accumulated angle that the spindle has rotated since the start of the process. The feed rate per revolution Δr mainly affects the cutting width, which corresponding to the resolution in the feed direction. For the balance between the speed and the resolution, Δr is set within an appropriate range.

Since the size and color information of each pixel in the resulting image are all predetermined, it can be utilized in advance to calculate the polar coordinates of each point from the starting point on the spiral. Suppose that the coordinate of the Nth point on the spiral is represented by (r_N,θ_N). In the original image, its corresponding position can be expressed as:

$$\begin{cases} X_N = r_N\cos(\theta_N) + X_c \\ Y_N = r_N\sin(\theta_N) + Y_c \end{cases} \tag{4}$$

where X_C and Y_C are the coordinates of the center point in the original image. X_N and Y_N are the Cartesian coordinates corresponding to the polar coordinates (r_N,θ_N). With simple linear interpolation and rounding, the tool vibration frequency at the position (X_N,Y_N) or (r_N,θ_N) can be calculated. The output frequency sequence can be expressed as a discrete function of N. Since the pixel size and the cutting speed are all constants, the cutting duration for each pixel is also identical. The frequency is thus changed at a fixed interval. The frequency output sequence is pre-calculated and stored in a data file. When the LabView program receives the trigger signal from the CNC controller, it utilizes an edge triggering function to start the generation of vibration signals according to the predetermined frequency sequence at equal time intervals.

4.2. Tool path design

As the turning process proceeds, the radial position of the tool on the workpiece will gradually decrease as indicated in Eq. (3). The decrease of radius, in turn, results in two different adjustments in the CNC and LabView programs. The spindle speed needs to be increased accordingly to maintain a constant surface cutting velocity:

$$\omega = V/r \tag{5}$$

Since the LabView program only outputs the frequency sequence based on constant timing, in order to achieve the perfect synchronization between the machine axis motion and tool vibration sequence, an accurate description of the position-time relationship of the cutting tool in the polar coordinate system is critical. By combining Eqs. (3) and (5), the differential equation of the tool path can be derived as:

$$\frac{d\theta}{dt}\left(r_0 - \frac{\theta}{2\pi}\Delta r\right) = V \tag{6}$$

By solving the differential Eq. (6), the relationship between the sweeping angle, tool radial position, and time can be obtained:

$$\theta r_0 - \frac{\theta^2}{4\pi}\Delta r = Vt \tag{7}$$

According to Eq. (7), when θ, r_O, Δr and V are all given, the relationship between the angle of rotation and time can also be uniquely determined as illustrated in Fig. 7. The lathe will follow this curve to speed up during the cutting process. According to Fig. 7, it can be concluded that both the angular velocity of the spindle and the feed rate of the X-axis are increasing continuously and nonlinearly with the time. Since both the velocity curves are continuous, jerk motion can be prevented during the process.

If the cutting speed and the retracting speed are both set to be 300 mm/min, when cutting images in the same size, turning process using the introduced tool path is 61.2 % faster than the raster scan process. It can be concluded that using turning for structural coloration has indeed considerably improved cutting efficiency.

5. Compensation for synchronization

Due to the relatively low rate of the servo loop (2 kHz), the actual time delay between the tool contact and start of the vibration generation sequence is on the order of 10 ms and unpredictable. In addition, due to the rounding error, the actual running time of a PVT command could be off by four-thousandths of a second according to our measurement. When these errors accumulate with the spiral path, the resulting rendered image will be severely distorted even for such a small time mismatch (milliseconds).

As shown in Fig. 8, because the timing of the CNC controller and the LabView programs are not completely synchronized, the lathe completes the predetermined action ahead of LabView, causing each pixel to be stretched during the actual cutting process. Even if the pixel produces a corresponding error of only about four thousandths, the error will be accumulated as the cutting process proceeds. Since the entire cutting tool path is a continuous equidistant spiral, this error cannot be compensated in the middle of the cutting process, and the desired image will be severely twisted as shown in Fig. 9.

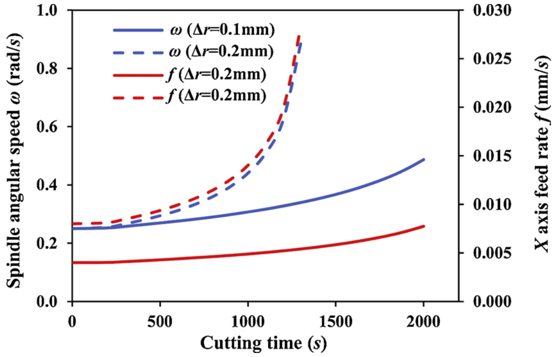

Fig. 7. Spindle angular speed and feed rate changing with time (r_O = 20 mm and V = 5 mm/s).

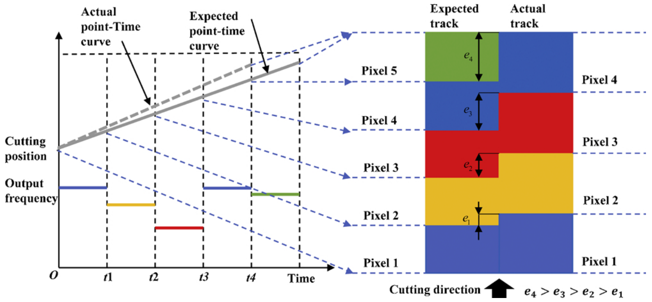

Fig. 8. Diagram of accumulative error during cutting.

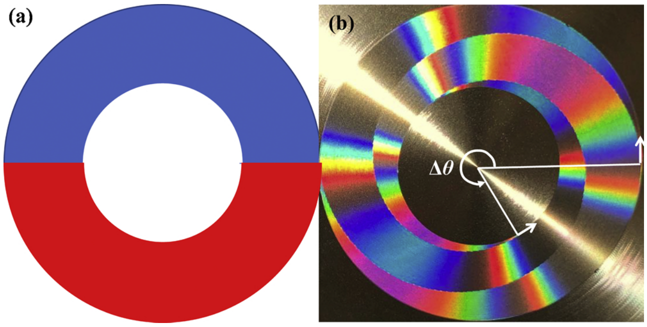

Fig. 9. (a) Calibration pattern design and (b) cutting result before compensation.

A preliminary test is conducted to investigate the actual value of the error. A two-tone calibration pattern design of two symmetrical half rings is designed as shown in Fig. 9(a). The boundary of the red and blue regions of the machine sample is expected to be a straight line, while in the actual cutting, a spiral pattern with a twist angle $\Delta\theta$ is obtained as shown in Fig. 9(b).

The values of detailed cutting parameters are summarized in Table 1.

The intuitive strategy to eliminate this distortion is to slightly slow down the spindle speed to compensate for the timing error. If ΔV is the change of surface cutting velocity, by investigating the small variation based on Eq. (7), the relationship can be stated as

$$\begin{cases} \theta r_0 - \dfrac{\theta^2 \Delta r}{4\pi} = Vt \\ (\theta + \Delta\theta) r_0 - \dfrac{(\theta + \Delta\theta)^2 \Delta r}{4\pi} = (V + \Delta V)t \end{cases} \tag{8}$$

The ratio of V and ΔV then can be obtained:

Table 1
Experimental parameters.

Parameters	Values
Nominal Depth of Cut	6 μm
r_O	20 mm
Δr	0.1 mm
V	5 mm/s
Radial pixel width	100 μm
Circumferential pixel length	250 μm

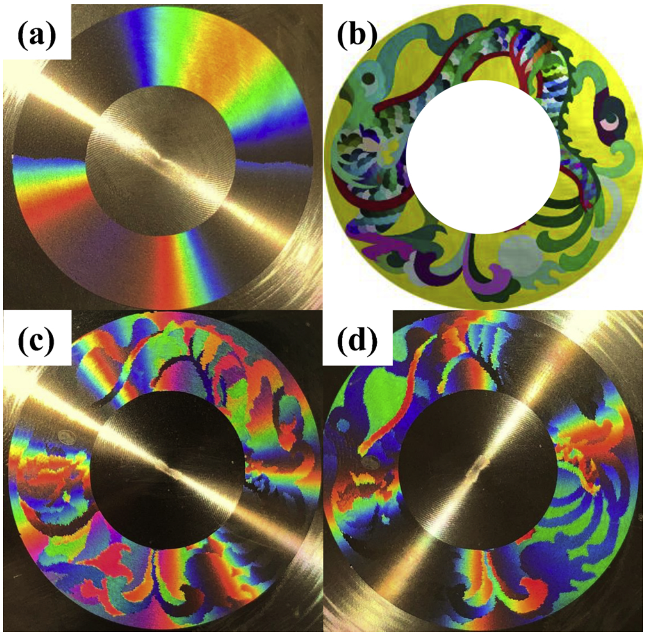

Fig. 10. (a) Compensated calibration pattern; (b) designed image for verification experiment; (c) machined sample viewed from one particular direction; and (d) machined sample viewed from another direction.

$$\frac{\Delta V}{V}=\frac{4\pi\Delta\theta r_0-(2\theta\Delta\theta+\Delta\theta^2)\Delta r}{4\pi\theta r_0-\theta^2\Delta r} \tag{9}$$

By numerically solving the equation, the difference between the actual spindle speed and predetermined surface velocity can be calculated. By using the obtained speed difference to modify the aforementioned tool path, the timing mismatch can be compensated to obtain a distortion-free rendering. The new tool path can be described by:

$$\theta r_0-\frac{\theta^2}{4\pi}\Delta r=(V+\Delta V)t \tag{10}$$

Fig. 10(a) shows the cutting result of the calibration pattern after the compensation. The twisted spirals in Fig. 9(b) are transformed to approximately two straight lines per design. However, due to the nonlinearity of the solutions and round errors, some sawtooth patterns appear on the two boundary edges. Another possible reason is that as the frequency changes during the cutting process, the cutting force also changes, which causes a slight difference in the error of the machine tool in each time period. These near-random differences will offset themselves in the long term process but produce sawtooth in the short term. A further complex image was designed to verify the rendering process as shown in Fig. 10(b). The calibration and compensation procedures were repeated as described for this new design. The corresponding machined results are demonstrated in Fig. 10(c) and (d).

Since the incident light parallel to the grating direction will not result in diffraction. For a circular distributed grating patterns, some portions of the image will not display structural colors due to the parallel light illumination. The incident light came from two orthogonal directions for the cases shown in Fig. 10(c) and (d). It was found that in a diffused illumination condition, the surface turned samples demonstrate a much wider viewing angle compared to the raster-scanned samples, where the grating directions are all parallel.

6. Conclusion

This paper presents a way to colorize metal surfaces by elliptical vibration texturing in a face turning operation. The surface cutting velocity is maintained constant, while the tool vibration frequency is adjusted to achieve tunable color at each pixel. Since the turning process featured with a continuous velocity curve, the process is more stable. The rendering resolution is also not limited by the machine axis acceleration capabilities. At the same time, since the rendering path is continuous, there is no retraction motion as in a raster scan path, which improves the cutting efficiency.

The proposed method utilizes a special equidistant spiral tool path for achieving constant surface line speed and a set of compensation methods that allow the tool vibration to be synchronized with the machine axis motion. It is demonstrated that the strategies of tool path generation, hardware design, as well as the compensation method with a calibration pattern design. The preliminary cutting results of rendered images are consistent with our design, which shows the promising aspect of the proposed process.

Based on this technology, it is possible to achieve a variety of extended applications on metallic structural coloration in the future research. For example, during the cutting process, the tool trajectory can be changed while changing the vibration frequency of the tool to achieve changes in the grating spacings and surface quality of the machined surface. Then the color and brightness can be changed in the resulted image. In addition, since the tool trajectory can be continuously changed during processing, a special tool trajectory can be designed to process the blazed grating with different grating constants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the start-up fund from McCormick School of Engineering, Northwestern University, Evanston, IL, USA.

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