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Study of micro/nanostructures formed by a nanosecond laser in gaseous environments for stainless steel surface coloring

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ABSTRACT

Micro/nanostructures are fabricated on the stainless steel surfaces by a nanosecond laser in different gaseous environments, including air, O_2, N_2 and Ar. Our results indicate that the dimensional feature of the micro/nanostructures is greatly affected by laser scanning speed as well as gaseous environment. The chemical composition of the structures can be flexibly adjusted by laser processing parameters. Oxygen-rich environment is found to boost the growth of the nanostructures. The coloring by the laser processing can be achieved on the laser treated stainless steel surfaces. The multicolor effect on the surfaces is found to be attributed to both feature dimension and chemical composition of the structures. The coloring of the metal surfaces has promising applications in surface marking and code identifying.

1. Introduction

Pulsed laser is proven to be a powerful tool in the fabrication of surface micro/nanostructures on the substrates of various materials. When a focused laser beam irradiates on a sample surface, it induces intense energy dynamic processes, including photo-electron energy transfer, electronic excitation, electron-phonon collision and photo-ionization [1]. These processes lead to complicated dynamics, melting, evaporation, phase explosion, and thermal plasma generation on the irradiated areas [2–5]. As a result, various micro/nanostructures, such as microcraters, micro/nano-spikes and nanogratings, can be fabricated on the substrate surfaces [6–8].

The presence of micro/nanostructures can induce great changes to the optical properties of the decorated surfaces through light scattering, absorption, surface plasmon resonance, grating diffraction and combination of these processes [9–15]. These special optical effects result in an interesting optical phenomenon: surface coloring. Li et al. [12] reported that the oxide layer of the island microstructures induced by a nanosecond laser changed with laser processing parameters, leading to different colors on the treated surfaces due to plasmon resonance effect. Dusser et al. [15] fabricated precise nanostructures with a femtosecond laser, and generated specific color patterns due to the grating diffraction effect. However, these previous studies mainly focused on the fabrication in air. The study of the surface coloring in other gaseous environments needs further investigation.

In this paper, we apply a nanosecond laser direct scanning technique to make color marking on stainless steel surfaces. The micro/nanostructures are fabricated on the laser irradiated areas in different gaseous environments, including air, O_2, N_2 and Ar. The surface analysis indicates that the size, morphology and chemical composition of the structures depend greatly on laser scanning speed and gaseous environment. The gradual change in the size, morphology and chemical composition of the structures results in an evolution of the coloring on the metal surfaces.

2. Experimental

A stainless steel substrate with a composition of Fe (73.9%), C (11.9%), Cr (13.3%) and Si (0.9%) was used in this study. The sample was polished and then cut into a dimension of 40 mm × 30 mm × 1 mm. After cleaning in acetone and deionized (DI) water, the sample was placed into a chamber with a quartz

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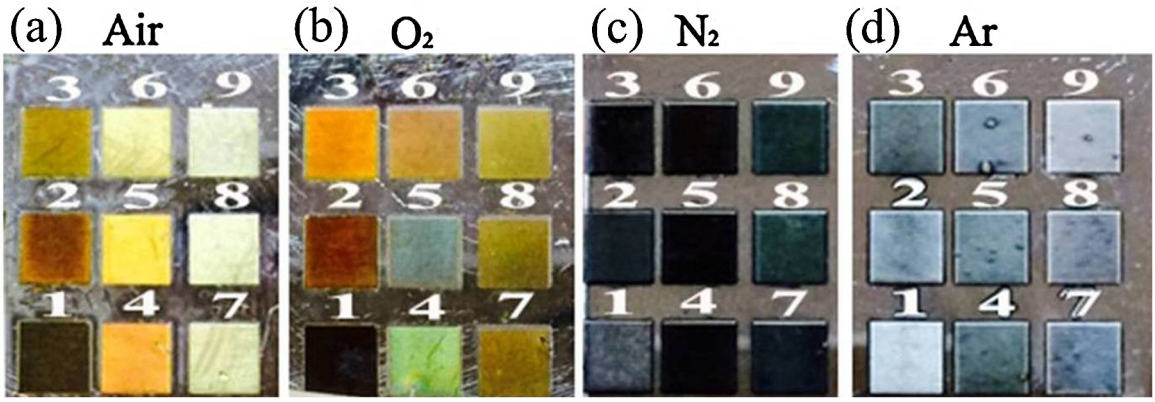

Fig. 1. Photographic images of the stainless steel surfaces processed by the nanosecond laser in various gases. The laser scanning speed was varied from 10, 20, 30, 40, 50, 60, 70, 80 to 90 mm/s. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

window. The window had an optical transmission of 90% at a laser wavelength of 1064 nm, and was designed to guide the laser beam into the chamber. The chamber was equipped with inlet and outlet ports of gas. Different gases of O_2, N_2 and Ar at a purity of 99.99% were used as ambient gases for the laser processing. A 1064 nm pulsed fiber laser, emitting a pulse train at a pulse width of 10 ns and a repetition rate of 35 kHz, was employed for the experiment. The laser pulse energy of 1 mJ was focused via an F-theta lens at a working distance of 200 mm onto the sample surfaces. The laser scanning speed can be controlled in the range from 1 to 1000 mm/s by a SCANLAB galvanometer scanner.

After the laser processing, the reflection spectra of the treated samples were measured under normal incidence by an Ocean Optics DT-mini-2 system. A deuterium halogen and HR 4000 high-resolution spectrometer were applied to measure the reflection spectra. The micro/nanostructures' feature was characterized by a scanning electron microscope (SEM, JEOL JSM-7001 F). The elemental analyses of the sample surfaces decorated with the micro/nanostructures were carried out by EDX. The analytical elements included Fe, O, C, Si, Cr, N and Ar. The acquisition time was fixed at 2 min for each measurement.

3. Results and discussion

Fig. 1 shows the digital photographs of the colored surfaces of the stainless steel, processed by the nanosecond laser in four gaseous environments, including air, O_2, N_2 and Ar. The scanning speed was varied from 10, 20, 30, 40, 50, 60, 70, 80 to 90 mm/s. The laser fluence was fixed at 0.8 J/cm^2. When the laser texturing was carried out in air, the colors of the stainless steel surfaces varied from black, orange, yellow to light yellow as the scanning speed changes as shown in Fig. 1(a). For the laser texturing in O_2, the treated surfaces also exhibited a color change from black, orange, green, blue to yellowish-green at the different laser scanning speeds as shown in Fig. 1(b). The surfaces prepared in O_2 present much richer colors than those being prepared in air. The stainless steel surfaces do not demonstrate the similar color change when treated in N_2 and Ar. As shown in Fig. 1(c), the colors of the surface treated in N_2 varied from light blue to dark blue, and then changed back to light blue with increasing scanning speed. Meanwhile, the surfaces treated in Ar shown in Fig. 1(d) only exhibited a color change from light gray to dark gray. The laser texturing parameters are the same for all the treated surfaces in Fig. 1(a)–(d) except for the gaseous environments. Therefore, it can be concluded that the gas environment is responsible for the color difference.

Fig. 2 shows the measured reflectance spectra of the stainless steel surfaces after the laser texturing in various gases at the scanning speed changing from 10 to 90 mm/s. The reflectance spectra of the textured surfaces are normalized against those of the non-treated surfaces. The reflectance spectra are highly related to the laser scanning speed and gas environment. It can be seen that the reflectance of the surface being textured in air and O_2 has a similar monotonic increase with scanning speed, while the reflectance of the surface being textured in N_2 and Ar are characterized with an initial drop and a subsequent rise as the scanning speed increases from 10 to 90 mm/s. For the textured samples in air and O_2 at a scanning speed of 10 mm/s, the reflectance is very low, corresponding to a black surface. The surfaces processed in these two gases also show a different relationship between the reflectance peak and the scanning speed. Textured in air, the peak of the spectra shifts from 711, 658, 650, to 645 nm as the scanning speed increases from 20 to 50 mm/s, after which the peak position stabilizes at 630 nm for the scanning speeds of 60, 70, 80 and 90 mm/s. Textured in O_2, the peaks appear in the spectra at 720, 660, 560, 520 and 653 nm for the scanning speed changing from 20 to 60 mm/s, and then stay at 580 nm for the scanning speed of 90 mm/s. The peak shifts from 535 to 575 nm and changes back to 530 nm for being textured in N_2, while it shifts from 540 to 560 nm and changes back to 500 nm for being textured in Ar. The dependence of the reflectance spectra on the processing parameters in Fig. 2 corresponds to the color change in Fig. 1.

Fig. 3 shows the morphological evolution of the featured surfaces characterized by SEM, which are prepared at the scanning speeds of 10, 40 and 80 mm/s. When treated in air at a scanning speed of 10 mm/s, there is no obvious microripple on the ablated area, but microprotrusions can be clearly observed at the edges, indicating a drastic ablation and materials' redeposition [8,16]. The microripples appear at a scanning speed of 40 mm/s and the distance between neighboring microripples increases when the scanning speed increases from 40 to 80 mm/s. Meanwhile, the size of the microprotrusions experiences a gradual decrease with the increase of the scanning speed. The features of the microripples and microrpotrusions formed in air are similar to those in O_2, N_2 and Ar. The similarity of the features of these microstructures is ascribed to the combined effect of thermal melting and materials' redeposition with the multiple pulse laser irradiations.

When a nanosecond laser pulse irradiates on a surface, a high-temperature melting area is formed due to intense energy transfer in the irradiated area. In a few hundred nanoseconds, the melting area gradually solidifies, and the density in this area abruptly changes, resulting in an obvious boundary between the melted and unmelted areas [17,18]. The periphery of the melted area is higher than the center. It is because the melting materials in the center are pushed outside by the strong shock wave, resulting in more materials being redeposited in the periphery. The modified area looks like a microdisk. When the successive pulse is applied, the thermal