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Full Length Article

High temperature thermal radiation property measurements on large periodic micro-structured nickel surfaces fabricated using a femtosecond laser source

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ABSTRACT

Microstructures enable many kinds of surface modifications with unique physical characteristics. The difficulties in fabricating microstructures on large metallic surfaces, however, may limit their wide use. This work measured the thermal radiation characteristics of large, three-dimensional microstructured metal surfaces where the microstructures were fabricated by a femtosecond laser to investigate the influence of the surface microstructures on the thermal radiation properties at elevated temperatures. The microstructured nickel surfaces with the microholes having the periods of 100 μm (aligned array) and 71 μm (staggered array) were fabricated by different femtosecond laser pulses (200 and 2000) and fluences (0.138 J/cm^2 and 0.276 J/cm^2). The microhole diameter was close to 20 μm and the depth was 50–120 μm with large aspect ratios above 2.5. Measurements of the thermal radiation properties of a polished bare nickel surface and surfaces with microholes showed that the topography greatly affected the surface radiation properties with increased emissivities (maximum increase of 55%) at temperatures from 700 K to 1200 K. It mainly arises from the multiple reflections inside the microholes and even cavity resonance inside some of the microholes. The work provides a valuable reference for fabricating 3D periodic microstructures on large metallic surfaces and shows how the engineered microstructure surfaces affect the thermal radiation at elevated temperatures.

1. Introduction

Microstructures are being used to modify the surface characteristics of materials [1,2]. Nanowires or nanoparticles [3], nanopyramids [4], constructed microstructures such as one-dimensional gratings [5] and 2D photonic crystals [6] have been widely used in electronics [7], microelectromechanical systems [1], batteries [8] and solar thermophotovoltic cells [9–11]. These micro-scale structures are fabricated using physical vapor deposition, chemical etching, lithography or nanoimprint, and ion beams [12–14]. However, the complicated procedures and the high costs of fabricating such materials with the specified microstructures greatly limit the use of the micro-scaled materials in large quantities for practical applications.

Ultrashort pulsed lasers, such as femtosecond (fs) and picosecond lasers, may enable fabrication of microstructures in one step [15], with very precise accuracy [16], high removal efficiencies [17], minimal damage to the material [18], and lower fabrication costs than other micro-manufacturing methods. The interactions between the femtosecond laser and various materials have been studied with analyses of the interaction mechanisms as well as some peculiar characteristics of the processed surfaces [19–21]. For instance, microstructures such as parallel microgrooves [22,23] and craters [24,25] directly modify the surface morphology [26], which impacts the tribological and hydrophilic properties [27,28] with super wettability and enhanced capillary forces [22] and the bioactivity of the materials [29].

Microfabrication of pure metals and alloys has aroused much interest [30,31]. Li et al. [4] used a template stripping method to fabricate nickel nanopyramids using laser interference lithography to first etch nanopyramids on silicon and then sputter nickel onto the silicon and then remove the silicon template to replicate the microstructures on large metallic surfaces. Unlike microfabrication of semiconductors or other non-metal materials, ideal deep surface microstructures on large machined metallic surface areas are quite

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difficult due to the material hardness and the size of the machinery. Therefore, better methods with ultrashort pulsed lasers are needed to directly fabricate large aspect ratio (ratio of the depth to the diameter) microstructures on metal surfaces because the negligible thermal diffusion due to the short pulses allows efficient, precise ablation and controllable morphology design [17,32–34].

The thermal radiative properties of microstructured metals are another area of concern. Thermal radiation, a fundamental energy transport process, is often significant in industrial processes (gas turbines, industrial furnaces, combustion systems, and others) and even in everyday life (such as solar energy applications) [35]. The surface thermal radiation properties, strongly correlated with the surface microstructures [36,37], must be accurately known to understand and control the heat transfer in many applications. Studies have been conducted to investigate radiative heat transfer in micro/nanoscale structures [38–40] with theoretical studies of spectrum tuning using surface microstructures or nanostructures or simulations of how to modify the spectral or directional thermal radiation and for selective absorption [41–43]. The microstructured surfaces were also used in the design of a high-quality blackbody cavity. For example, Ishii et al. [44] quantitatively illustrated that the effective emissivities of the triangular-grooved cylinder are higher than the rectangular-grooved cylinder using grooved cylinders for the construction of blackbody cavities. However, few researches have investigated the thermal radiation properties of microstructured surfaces at elevated temperatures. The effects of the surface microstructures on the thermal radiation properties at elevated temperatures need to be further investigated, especially for high-temperature applications involving metals and alloys.

Therefore, in this work, periodic 3D microstructures are fabricated with large aspect ratios (>2.0) on large machined nickel surfaces using femtosecond laser pulses. The processing parameters are varied to create various surface morphologies and topographies with measurements of the surface characteristics. The effects of the surface microstructures on the thermal radiation properties are quantificationally analyzed by measuring the total hemispherical emissivity at elevated temperatures. This analysis provides a valuable reference on the radiation properties of 3D periodic microstructures on large metallic surfaces at elevated temperatures.

2. Surface microstructures fabricated by a femtosecond laser

The 99.9% purity nickel samples were 300 mm (length) × 10 mm (width) × 0.25 mm (thickness). Seven substrates were first mechanically polished to mirror surfaces (surface roughnesses less than 50 nm). The center region of the sample front surface that was processed had an area of 50 mm (l) × 10 mm (w), as shown in Fig. 1(a). The ultrashort pulsed laser source was a femtosecond laser (TruMicro 5050) with a maximum average laser power of 40 W, a pulse duration of 800 fs, a wavelength of 1030 nm, and a repetition rate of 200 kHz. The Gaussian laser beam was deflected across the sample surface using a galvanometer scan system (intelliSCAN, Scanlab) and then focused on the surface via an f-θ-objective which gave a focal spot diameter of 34 μm.

One or several laser pulses will form spots or craters on processed surface [24,25]. The laser parameters, including the repetition rate, pulse fluence, single pulse duration and number of pulses, all affect the microstructure design. This study sought microstructures with large aspect ratios. The most direct way to create large aspect ratios is to create microholes by increasing the number of pulses, *i.e.* increasing the total irradiation duration. Periodic circular holes on substrates have many applications such as electromagnetic bandgap structures to modulate microwave frequencies [45,46] and spikes that can create blackbody sources [47].

In this study, the microholes were fabricated by multiple femtosecond laser pulses. The ablation threshold was much smaller with multiple pulses than with a single pulse, so multipulse ablation makes it feasible to fabricate surfaces using low fluences. Multipulse ablation can also drill holes with high aspect ratios [48]. The laser pulse fluence and the irradiation duration were varied to produce different microhole diameters and topologies. Three groups of laser parameters were investigated with different pulse energies controlled by irradiation power, and different numbers of ablation pulses controlled by irradiating duration. The three groups of parameters were: (a) an average laser irradiation power to the sample surface of 10 W, corresponding to a fluence of $0.138\ \mathrm{J/cm^2}$, and a total irradiating duration of 1 ms, corresponding to 200 pulses; (b) a fluence of $0.276\ \mathrm{J/cm^2}$ for 200 pulses; (c) a fluence of $0.138\ \mathrm{J/cm^2}$ for 2000 pulses. Aligned and staggered arrays were fabricated for each group of laser parameters, with staggered array having additional holes between each line of the aligned holes with various periods or densities, as shown in Fig. 1(c) and (d). The aligned arrays (samples S1, S2 and S3) had spatial periods of around $\delta = 100$ μm, while the staggered arrays (samples S4, S5 and S6) had larger densities with a period of $\delta/\sqrt{2} \approx 71$ μm. The microhole diameters, D, were all the same (~20 μm). The design parameters are listed in Table 1. S0, the bare nickel used as the control group, was not processed.

SEM images of the three aligned samples and the three staggered samples in Figs. 2 and 3, show the periodic microstructures.

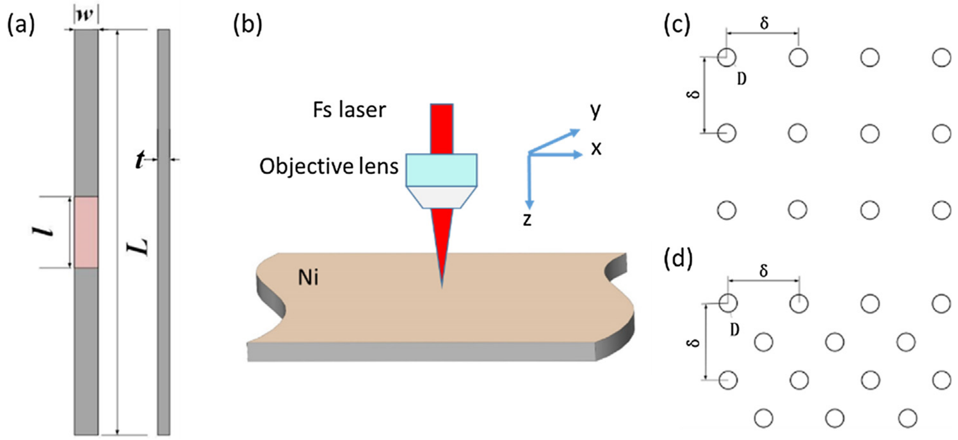

Fig. 1. Design of the laser processing system on the nickel sample. (a) Ni strip and processing area sizes. (b) Sketch of the femtosecond laser processing system. (c) Aligned array. (d) Staggered array.