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Laser Shock Wave Assisted Patterning on NiTi Shape Memory Alloy Surfaces

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Laser Shock Wave Assisted Patterning on NiTi Shape Memory Alloy Surfaces

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ABSTRACT

An advanced direct imprinting method with low cost, quick, and less environmental impact to create thermally controllable surface pattern using the laser pulses is reported. Patterned micro indents were generated on $Ni_{50}Ti_{50}$ shape memory alloys (SMA) using an Nd:YAG laser operating at 1064 nm combined with suitable transparent overlay, a sacrificial layer of graphite, and copper grid. Laser pulses at different energy densities which generates pressure pulses up to 10 GPa on the surface was focused through the confinement medium, ablating the copper grid to create plasma and transferring the grid pattern onto the NiTi surface. Scanning electron microscope (SEM) and optical microscope images of square pattern with different sizes were studied. One dimensional profile analysis shows that the depth of the patterned sample initially increase linearly with the laser energy until 125 mJ/pulse where the plasma further absorbs and reflects the laser beam. In addition, light the microscope image show that the surface of NiTi alloy was damaged due to the high power laser energy which removes the graphite layer.

Keywords: laser-shockwave, plasma, drag friction, patterned surfaces

1. INTRODUCTION

Lasers have been used for fabricating one or more dimensional surface patterns on variety of components in industry including aerospace, automotive, and microelectronics [1, 2]. Surface patterning by lasers offers variety of advantages such as flexibility, cleanliness, precise modification of the surface, remote and contactless operation, and more accurate energy deposition [3]. Unlike the conventional patterning methods, the laser patterning is inexpensive, environment friendly, faster than former with the minimal distortion, and doesn't involve any heating or etching process [4]. In laser shock wave direct imprinting, expansion of plasma propels the underlying grid material into samples, creating patterned microindents [5, 6]. Any patterns of the template can be transferred into desired surface with high fidelity. Even a single laser pulse can create pattern once the power density exceeds the certain threshold. It was reported that the patterning process is highly scalable and feature size can be precisely controlled by changing laser properties [4].

The laser absorption depth and the amount of material removed by a single laser pulse depend on the material's optical properties and laser parameters. The properties of laser-produced plasma, such as degree of ionization and temperature of plasma species, can evolve quickly and strongly and depend on various parameters such as the laser wavelength, energy density, repetition rate, pulse duration, spot size on target, target composition, and surface quality. [7, 8].

The laser pulse energy is initially absorbed predominantly by the surface electrons which lead to a sharp temperature gradient in penetration depth and plasma formation. The material experiences a phase transformation from solid to vapor, thus a pressure (shock) wave is generated and propagates through the depth of the sample [9]. The energy is redistributed between energy of plume and shock waves during expansion which is usually around 100 ns [10, 11].

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In laser produced confined plasma, a transparent overlay is essential where enhanced pressure (4-10 times higher) on the material surface must be achieved in order to produce shock wave [12]. As shock wave travels through substrate, plastic deformations occur to a depth where the peak pressure drops below the Hugoniot elastic limit. Amount of deformation depends on the pressure. Therefore, it is important to estimate the peak pressure which is given by [13]

$$P\ (GPa) = 0.01[\frac{Z(gcm^{-2}s^{-1})I_0(GW/cm^2)\delta}{2\delta + 3}]^{1/2}$$

where I_o is the incident laser power density, P is the pressure, and Z is the reduced acoustic impedance between a target and medium, and δ is the efficiency of plasma material interaction.

SMAs can produce very high actuation strain (8% uniaxial strain), stress (~400 MPa) and work output (~10 MJ/m^3) as a result of reversible martensitic phase transformations [14, 15]. SMAs are also being used in aerospace industry for decades as; hydraulic tubing coupling, actuators for hingeless ailerons, wing twisting, tailoring the inlet geometry and orientation of propulsion systems, changing fan/nozzle area, noise mitigation at takeoff and landing, rotorcrafts, low-shock release devices and optimizing dynamic properties of aircraft panels [16, 17]. In 2009, the American Institute of Aeronautics and Astronautics (AIAA) named shape memory alloys as one of the ten emerging aerospace technologies [18]. Among these applications, morphing at micro and macro scales attracts considerable interest [17, 19]. The different shapes of wings, camber angles, textures and some other characteristics give the aircraft its own aerodynamic properties.

Laser patterning on shape memory alloys will generate controllable surfaces since SMAs are a class of active materials that can change their shape reversibly with a change in temperature, stress or magnetic field. Surface roughness and texture can drastically alter the characteristics of turbulent flow, and, thus, the drag and friction forces exerted on the surface of a moving object in a fluid [20, 21]. It has been reported that the “riblets” on the shark skin can reduce the wall shearing stress or wall friction up to 10% [22, 23] while many surface structures are known to increase friction and drag force. Consequently, it may be possible to optimize the flight characteristics of moving objects by reversibly controlling surface roughness and texture. For micro-morphing, shape memory surfaces can be produced by embedding SMAs into aircraft structure and forming “hybrid structures” [24-26]. The temperature change (e.g. triggered by electrical current) will activate SMAs and surface geometry will change upon phase transformation where transformed surfaces could generate very different drag or friction forces that can be optimized for aircraft operation. SMAs can produce reversible surface protrusions based on the phase change between martensite and austenite [26, 27]. Thermal cycling which may be repeated indefinitely, results in a ‘bumpy’ or flat surface. The geometry of the protrusion depends on the processing parameters.

A recent study has shown that patterned microindents can be generated on the surface of NiTi SMAs by laser shock assisted direct imprinting and it is much easier and faster than creating surface patterns with the nano/micro indentation techniques [4]. However, depth and shape of surface patterns generated by laser assisted shockwave imprinting respect to the laser properties have not been analyzed so far. In this study we analyzed the changes in depth of the generated patterns on NiTi SMA with respect to the laser energy density and report optimum conditions to generate smooth patterns with the highest depth.

2. EXPERIMENTAL METHODS

The nominal composition of Ni_{50} Ti_{50} alloys were from NASA Glenn Research Center. The alloys were firstly electrical-discharge machined to a circular plate with a diameter of 10 mm and thickness of 1mm.

The surface roughness of samples were reduced to 0.05µm in five steps by using Buehler EcoMet 250 Grinder-Polisher with an AutoMet 250 Power head. Transformation temperatures were determined by using a Perkin-Elmer Pyris 1 differential scanning calorimeter (DSC). The martensite and austenite start and finish temperatures (M_s, M_f, A_s, and A_f, respectively) are 78 °C, 45 °C, 85 °C, 122 °C.

NiTi SMAs were patterned by nanosecond Nd:YAG (1064 nm and frequency doubled 532 nm) pulsed laser assisted shock wave imprinting as shown in Fig. 1. A thin layer of graphite was sprayed on NiTi as a sacrificial layer to increase the pressure and to protect the material from damage caused by ablation and melting [12]. On top of the graphite layer, a copper grid (SPI Supplies) was used as both ablative material and punch. A piece of BK7 glass and water was used to confine the plasma generated by nanosecond laser. As a result, NiTi sample prepared were irradiated by laser energies between 25-200 mJ/pulse with a beam diameter of 3mm. The expansion of copper plasma is confined by confinement medium, mainly glass, pushes the grid into the NiTi surface. This highly dynamic force creates plastic deformation on the NiTi surface leading a surface pattern which is similar to the hole of the copper grid.

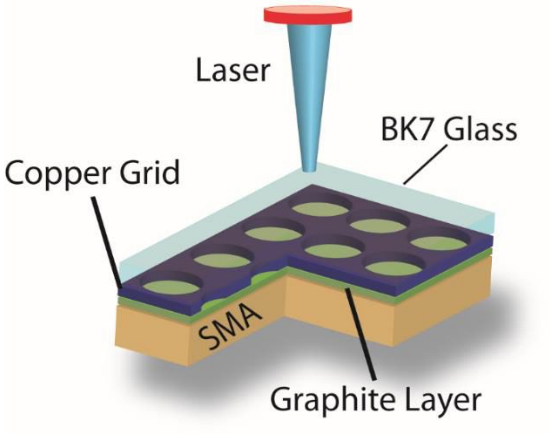

Figure 1. Illustration of laser shockwave assisted imprinting on the surface of NiTi SMA.

After irradiation, copper grid was peeled off and the graphite layer was washed off by acetone. Morphological properties of the surface were investigated by SEM (Jeol 6510LV) and a light microscope (Keyence VHX500F). Laser parameters was adjusted to optimize the protrusion heights.

3. RESULTS

Figure 2 shows the sample surface before irradiation (a), copper grid before (b and c) and after the laser imprinting (d). NiTi samples initially have smooth surface. After irradiation, patterned surface is visible with optical microscope. These patterns were generated under the outlined area of copper grid which shows the ablation of the copper and due to the punch of the copper grid into the sample.

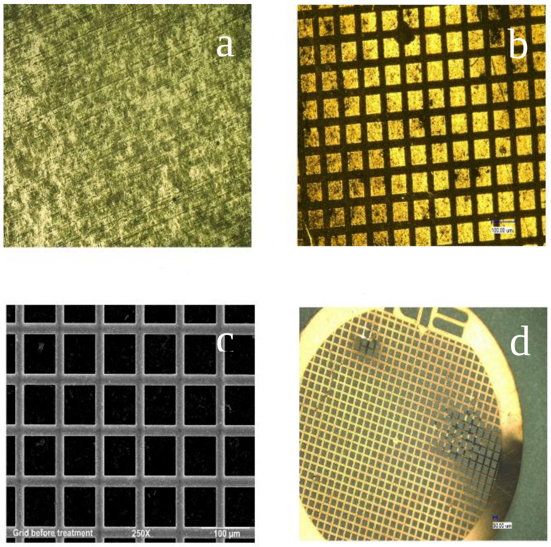

Figure 2. Sample surface before irradiation (a) and after irradiation (b) SEM image of copper grid (c) copper grid after irradiation with laser energy of 100 mJ/pulse (d).

Various sizes of copper grid with holes between 30 µm and 200 µm was used as a template to create patterned indents. Morphology of patterned surface was analyzed by optical microscope and SEM. Figure 3 shows the light microscope and the SEM images from the same area that patterns were achieved with its 3D map and line scan. As expected, patterns that was generated on the surface have the same dimensions as copper grid which is 62 µm square protrusions with 21 µm wide indents with average depth of 1.5 µm.

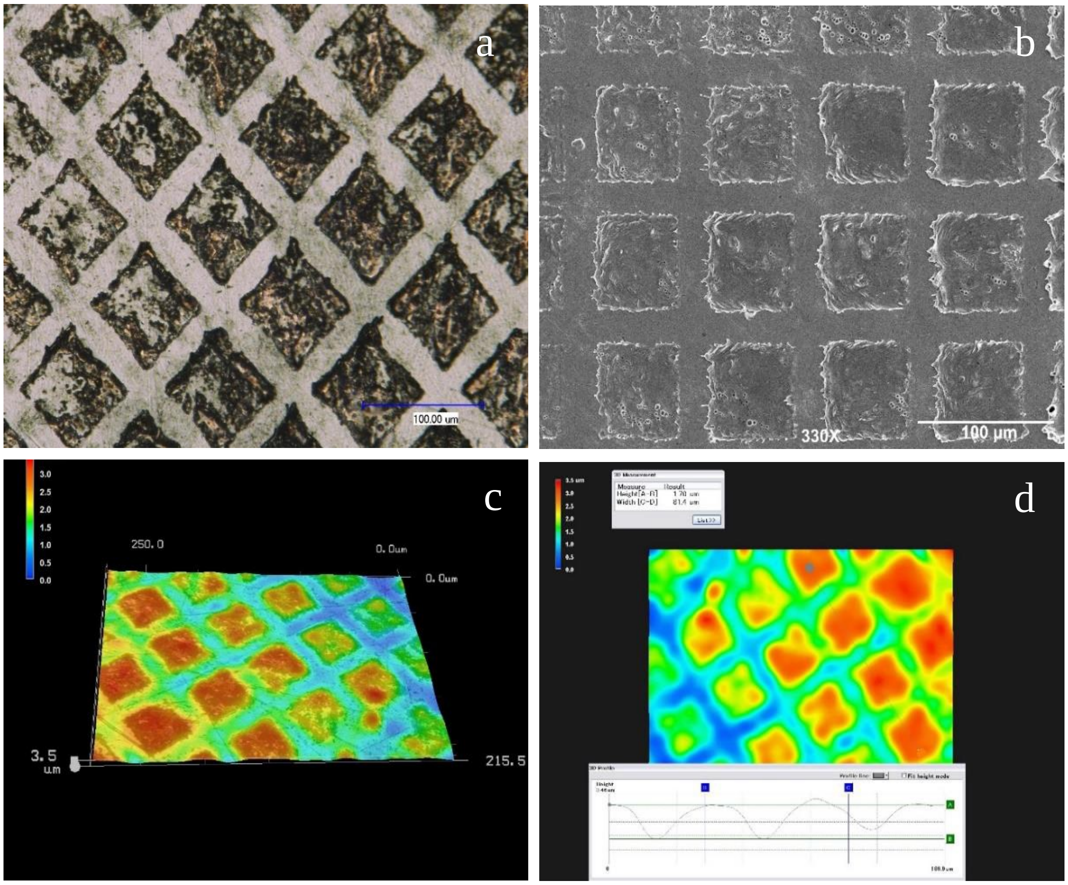

Figure 3. Light microscope 2D (a) and SEM (b) images of the surface at 100 mJ/pulse energy. Light microscope 3-D depth map (c) and 3-D line scan (d) analysis of the surface after being irradiated by 100 mJ/pulse laser energy.

In order to investigate and find the optimum laser parameters to achieve the highest and the smoothest patterns, pattern with different depths was obtained by changing laser energy between 25-200 mJ/pulse. Figure 4 shows the laser energy dependency of the depth of the patterns generated on the surface. These depth measurements are the average depth of 8 different points from 3 separate samples being irradiated by 25-200 mJ/pulse energies. Initially depth increases when the laser energy increases. However, this trend changes around 125 mJ/pulse, the depth reaches its optimum point with the highest depth of around 1.5 µm. After 125 mJ/pulse, the further increase in the laser energy produces smaller depth. It is well known that resonant mechanism could cause significant absorption of energy from intense laser pulses in plasma targets [28]. One of the reasons could be that at optimum energy (~125 mJ/pulse) optical breakdown of the transparent overlay occurs and plasma absorbs and reflects the laser beam which in return the part of the lasers energy was not transferred to the copper grid ablation. In that case, material may experience a transition from low intensity regime to high intensity regime where inverse-Bremsstrahlung is no longer negligible.

In addition, laser energy could be high enough to exceed the threshold of the protective graphite layer and damages the NiTi surface itself. To shade more light on this, additional test was performed by irradiating the surface with the graphite layer and without copper grid at the energy range of 100-200 mJ/pulse. Initially, there was no damage on the surface. However, when the laser energy reaches to 125 mJ/pulse, we noticed that laser pulses removes graphite layer and damages the surface itself.

It is known that increasing the laser energy increases the kinetic energy of the particles being ejected from the target and amount material removed. The laser energy as a control parameter was shown to significantly influence the morphology of the pattern and to cause changes in the crystal structure. Unlike the most direct imprinting technique which require high pressure which in turn results in damage to the sample, this technique can produce pattern without damaging the workpiece.

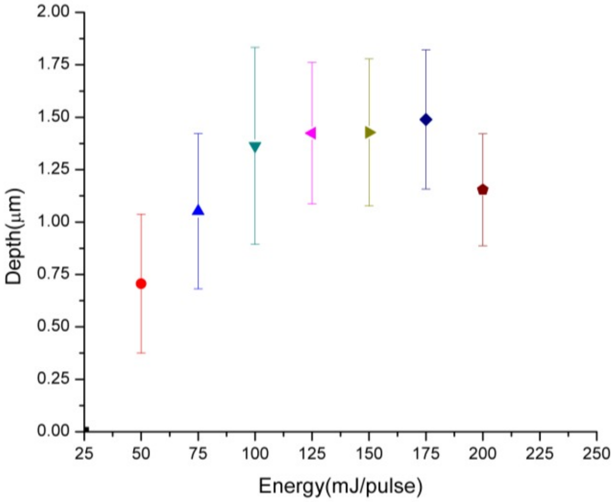

Figure 4. Laser energy dependence of the depth of the patterns generated on the NiTi surface.

Controlling the thickness of the depth by varying the laser parameters is a unique feature of laser assisted shock wave direct imprinting. In addition, no heating or etching is required in this technique. It is relatively easy to have scalable product and expected to be a competitive technique for high technology applications.

4. CONCLUSION

Square patterns on the surface of NiTi SMA were created by advanced direct imprinting method using nanosecond laser pulses with low cost, quick, and low environmental impact. Laser energy was shown to play an important role for surface patterning. Patterns generated on NiTi SMAs will allow to create controllable surface by temperature change (e.g. triggered by electrical current) which will activate SMAs and surface geometry will change upon phase transformation. Thus, transformed surfaces could generate very different drag or friction forces that can be optimized for aircraft operation. Further analysis is needed to find the optimum laser properties for recovery of the patterns and the influence of the shapes of the created patterns on friction and drag reduction.