Magnetically enhanced shockwave-assisted 3-dimensional imprinting and applications on NiTi Shape Memory Alloys

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ABSTRACT

Shape Memory Alloys (SMA) have unique characteristics to memorize their original structure and retain them when activated by heat or stress, however, there still much to be done in terms of fatigue life and phase modifiability. In this project, we propose a tunable treatment method using shockwaves created by nanosecond and picosecond pulsed lasers assisted with magnetic field to create 3-D structures on NiTi SMA. When the laser pulse hits the surface, its energy is partially absorbed, which ablates the surface resulting a plasma plume. By confining the plasma using dielectric medium and magnetic field, the shockwave is tuned for vertical transfer of the pressure gradient on the surface. Optical profilometer and SEM results confirm that the shockwave pressure became uniform when magnetic field was used. The less heat affected zones on the crater, and equal depth across the crater indicates a stable surface morphology due to magnetic field. Moreover, Shape-memory properties were also investigated with differential scanning calorimetry (DSC) measurements of NiTi samples, and the results indicate significant phase broadening, reaching up to 33% from the initial, and shifts in austenitic and martensitic phases of 5 °C. The tunability of the shockwave using magnetic field and water confinement expands the usage in treatment and imprinting of SMAs for biomedical and industrial applications.

Keywords: Laser Shockwaves, Shape Memory Alloys, Magnetic fields, 3-D imprinting, Laser Shock Peening

1. INTRODUCTION

With the development of lasers, the possibility of shockwave generation by confining the laser produced plasma plume in media such as water was explored [1-2]. As laser technology has gradually advanced, profound research has been conducted to use this idea for industrial applications. One of the main branches is Laser Shock Peening (LSP) that reached successful implementation in industry [3]. It is based on Q-switched, pulsed lasers where laser pulses are directed to targets. Once the energy is transferred to the material it instantly raises surface energy and ionizes the surface depending on the atomic and molecular composition of the material. The ionized portion produces plasma plume that can be confined to generate high pressure on the surface to peen or treat the bulk of the material.

We previously showed the imprinting of variety of structures and shapes using Nd:YAG laser with energy of 2 J/cm^2 and shockwaves reaching up to 10 GPas on NiTi Shape Memory Alloy as shown in Figure 1 [4-5]. Shape Memory Alloys have many potential applications in aerospace and biomedicine, thus, making SMAs material-of-interest to be treated for variety of purposes such as improving their shape-memorization properties or utilizing already built-in shape memorizing properties to produce dynamic structures and shapes with ultra-small resolution [6]. Although LSP is extensively developed up to the current treatment demands, direct control of the shockwave has never been achieved [3]. In current status of plasma plume, the shockwave is controlled by confining media such as water, glass, ambient gas, and with laser energy parameters [7, 8]. Direct manipulation of shockwaves gives possibility to tune and direct the pressure in certain directions by improving the resolution at the impact zone. Therefore, it plays important role at LSP when working in ultra-small and high-precision area of the target.

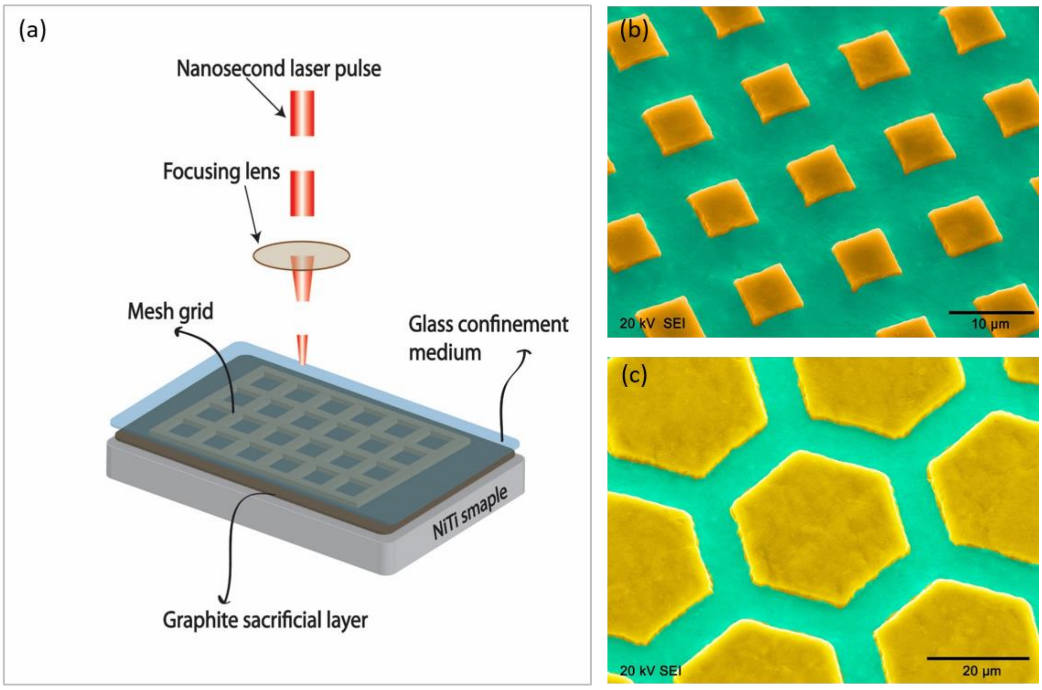

Figure 1. SEM images of 3D structures imprinted on NiTi Shape Memory Alloy using rectangular and hexagonal masks. Picture retrieved from Saidjafarzoda et al, 2018 [4].

Numerous works were done on utilizing magnetic field to improve laser-drilling and laser welding [9-13]. However, the controlling the shockwave using magnetic field in SMA imprinting has never been done. In this work, we present a direct shockwave controlling method using magnetic fields at different geometry and angles. The surface morphology images of the target material after treatment obtained by SEM and optical profilometer indicates the direct influence of magnetic field on the shockwave interaction with the surface. Moreover, Differential Scanning Calorimetry (DSC) has been conducted to observe the effect of shockwave's behavior with and without magnetic field by determining the phase shifts measured on austenitic and martensitic phases of NiTi SMAs. With minimal work conducted, investigation of the effect of magnetic field is still in progress, but the shockwave's effect on the SMA's phases is eminent through broadenings and shifts reaching up to 52.2% compared to initial phase temperature range. Finally, either a simulation of the magnetic field impact on the plasma plume behavior or real snapshots using ultra-fast cameras are proposed.

2. METHODS

The LSP was performed using Nd:YAG laser operating at energies of 50 mJ/pulse to 200 mJ/pulse, 10Hz repetition rate, and pulse duration of 5 ns. Magnetic fields were generated by neodymium solid magnets. Target material for the LSP was NiTi shape memory alloy disks and wires. The experimental setup is shown in Figure 2.

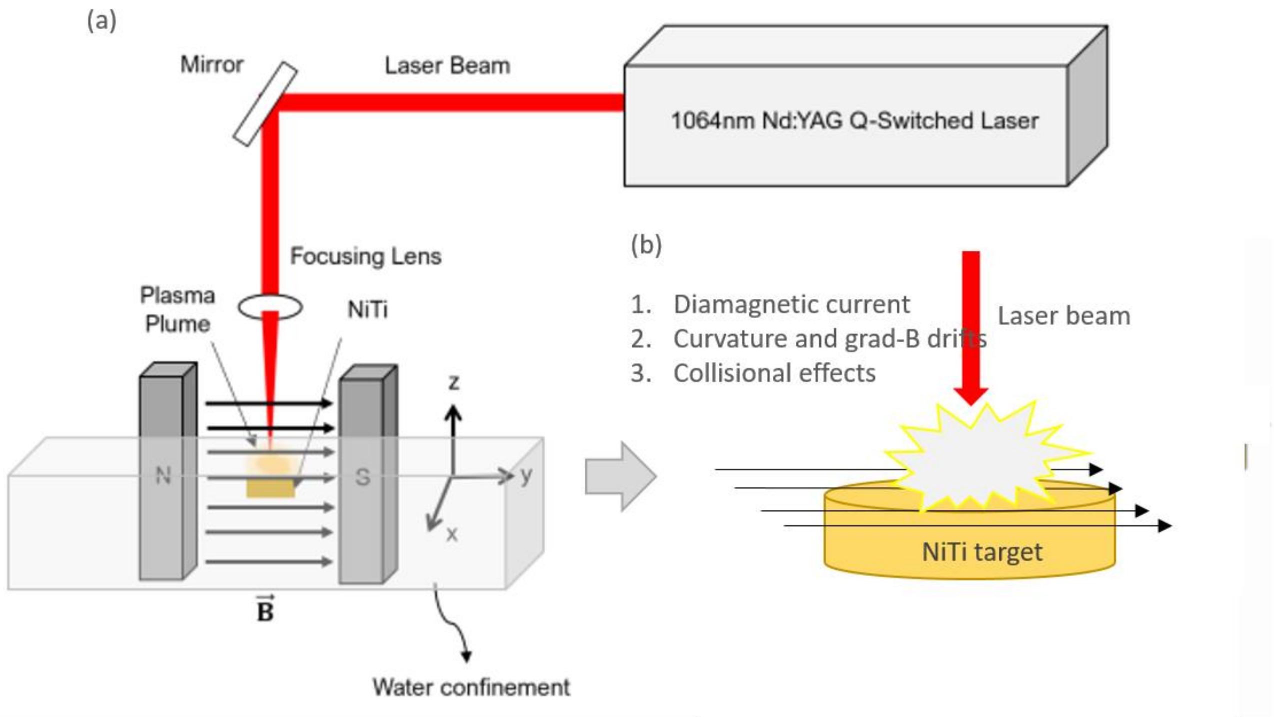

Figure 2. (a) Experimental Setup, (b) confinement of plasma in z-direction ignoring curvature drift & diamagnetic current, confinement in other directions.

3. RESULTS AND DISCUSSION

In order to understand the effect of magnetic field, LSP with and without magnetic field was observed on NiTi SMA wires. The optical profilometer images in Figure 3 show the craters formed on the surface of treated wires after 10 shots. From the surface morphology, it can be seen that as magnetic field was applied, impact from the shockwave dramatically changes from centralized to uniform overall distribution. When magnetic field is not present, craters have huge central melt region indicating an intense thermal heat transfer at the center, while with magnetic field, the central melt region became smaller. This phenomenon is theoretically explained in [8], however, the result contradicts to the data obtained by [9]. Singh, R. K. et al, 2016 [9] reported enlarged surface crater when B = 0.3 T compared to the case of B = 0 T.the difference in the observed result could be attributed to use of air medium on aluminum and copper targets as opposed to confined medium in our experiment. Their analysis indicates that magnetic field hinders the expansion by confining the plasma, which in turn serves as a reason for longer shockwave and target interaction. The Huguenot relation [2] explaining the plasma pressure generated by air showed higher pressure, but there is still an unclear contradiction related with enlarged crater size [9]. Our results, however, perfectly matches with the observations made by Ye, C. et al, 2013 [8] where the crater diameter got smaller from 200 μm to 150 μm when B = 0.7 T was introduced under the same geometrical setup. When the same experiment was conducted in glass confinement, it showed enlarged crater size, which advocates for the idea that confinement affected the interaction of the shockwave with the target, thus, explaining the contradiction found with the case of [9] where air and Ar gas was used as a confinement medium. In our case, the crater size has shrinked from 240 μm to 110 μm in water confinement when B = 0.3 T was introduced and is in well agreement with [8]. It should be noted for clarity that the works compared above are laser drilling, which aims on material removal via melt-ejection [17] serving different goal than LSP. In LSP, the primary purpose is to peen the material for bulk treatment and thus material removal is unwanted. In general, LSP involves only single shot treatment, rarely involving multiple shots. For the purpose of understanding the mechanism only, we treated with 10 shots in order to be able to see the impact much more effectively and compare with the results done on laser drilling experiments.

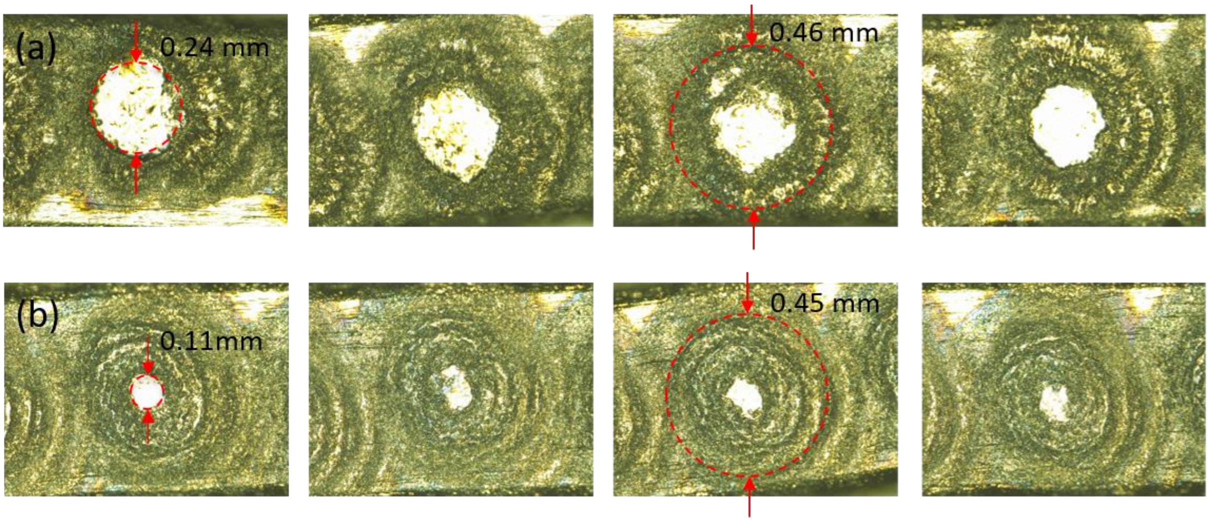

Figure 3. Laser Shock Peened NiTi wire (a) without and (b) with B = 400 mT magnetic field. At Laser energy 200mJ/pulse.

Angle measurements were performed to see the effect of magnetic field orientation on patterning. Results in Figure 4 show the possibility of tuning the shockwave. As magnetic field direction changes, the interaction between shockwave and target shows distinctive features. At 0 degrees with B = 0.25 T, the crater became smaller similar to the reported result in Figure 3. However, as magnetic field direction changed from 0 degrees to 45 degrees, the crater size got bigger. When the magnetic field direction was 87 degrees with respect to x-axis, the crater geometry turned into a narrow ellipse shape. These results strongly suggest the validity of curvature drift mechanism that is discussed below. Moreover, these results also account for $\vec{F} = \vec{J} \times \vec{B}$ term as well, where $\vec{J}$ is the induced diamagnetic current in plasma due to the existence of external magnetic field, and $\vec{B}$ is the external field.

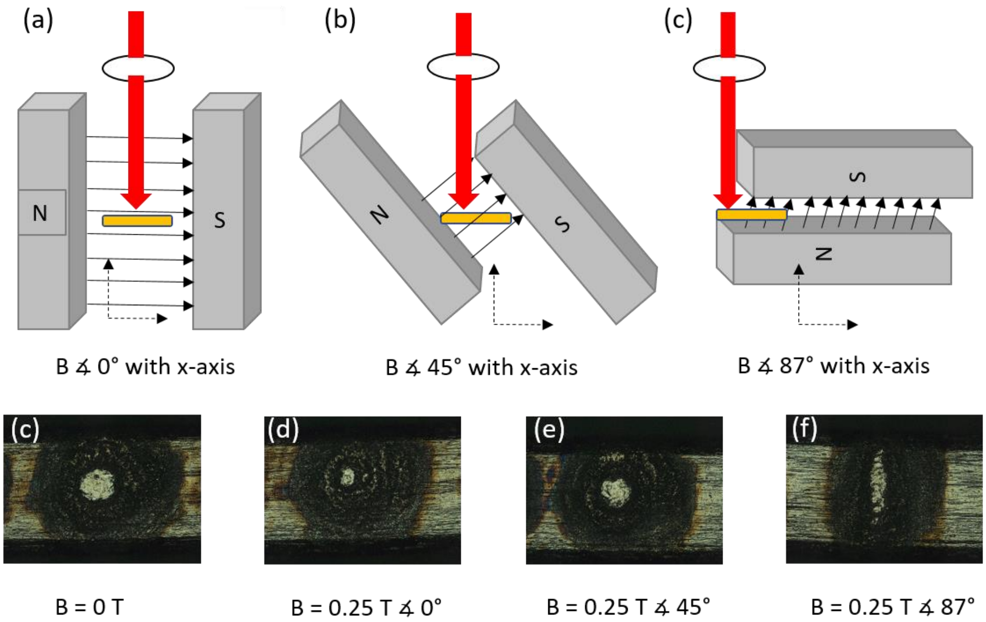

Figure 4. Magnetic fields directed at different angles. (a-c) B = 0.25 T at 0º, 45º, and 87º respectively. LSP results after 10 shots (c) B = 0 T, (d-f) B = 0.25 T at 0º, 45º, and 87º.

Numerous effects account for the magnetic field confinement. Three major effects will be proposed here. As high-intensity laser beam generates plasma plume that starts to expand. The expansion of plasma plume in magnetic field was investigated by many groups [12-17]. First effect is due to diamagnetic current [18]. When there exists external magnetic field, a diamagnetic current is induced to reduce the effect of external field. This accounts for heating up the plasma, but the interaction between diamagnetic current and magnetic field itself is key. It was investigated partially in [8] showing only confinement in z-direction for drilling. The diamagnetic current is given as

$$\vec{J} = \sigma(-\nabla\varphi + \vec{\upsilon} \times \vec{B}) \tag{1}$$

Where $\vec{\upsilon}$ is the particles velocity in plasma. We can assume $\varphi = 0$, ignoring the electrostatic potential for the sake of simplicity. The force between the induced current and external magnetic field is

$$\vec{F} = \vec{J} \times \vec{B} \tag{2}$$

Second effect is curvature and grad-B drifts of charged particles inside the plasma. It is more versatile because of the complexity in analyzing the curvature in the fields by solid neodymium magnets. Nevertheless, it is possible to quantify with the following equation

$$\vec{\upsilon}_B = \frac{m}{2qB}(\upsilon_{par}^2 + 2\upsilon_{perp}^2)\frac{\vec{B} \times \nabla B}{B^2} \tag{3}$$

Third, the collisional effects inside the plasma plume affect the temperature. [19] Wu, D. et al, 2020 studied the collisional effects in this particular case like in our experiment but via LIBS. This concept needs further investigation, both by calculation and experiment.

Additionally, the effect of shockwave on shape-memorization properties was investigated and our results show the consequential influence of the shockwave control. For this purpose, the differential scanning calorimetry (DSC) was performed. DSC is useful in analyzing the phases and phase shifts in multiphase materials. SMAs have two phases: austenite and martensite. Austenite phase corresponds to the high-temperature phase where the shape will be programmed to return to its initial structure upon reaching that temperature range. Martensite phase corresponds to lower temperature region where you can deform the structure to any shape. Additionally, SMAs are superelastic, which means they can afford hard deformations compared to inelastic or semi-elastic metals or alloys like aluminum.

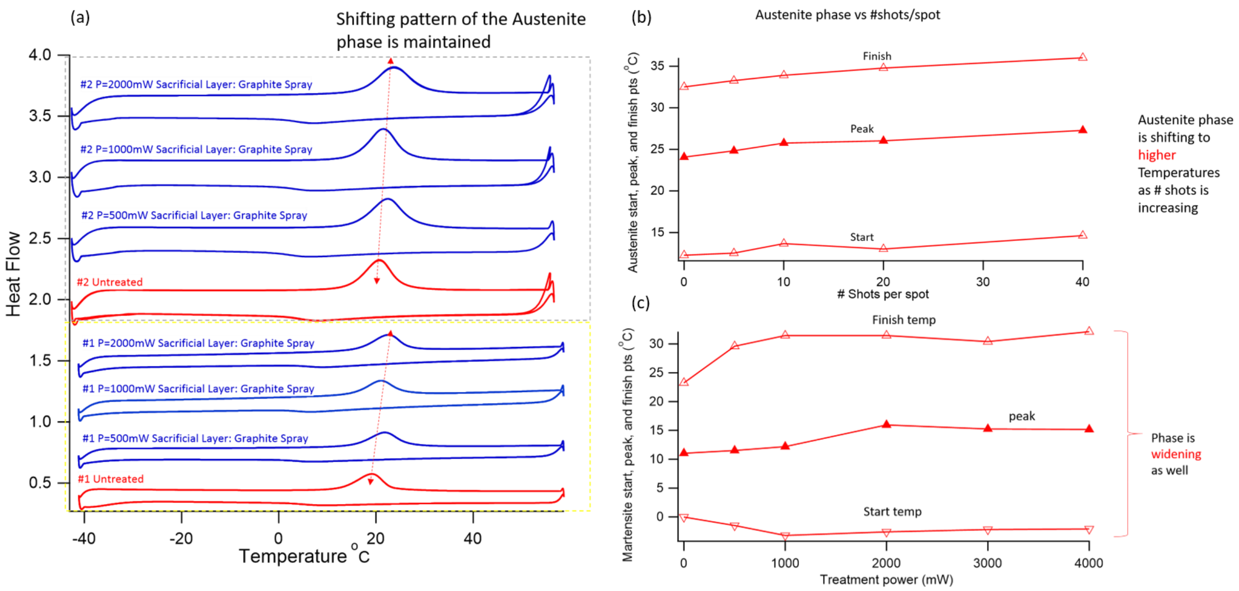

Figure 5. DSC results. (a) Laser Shock Peening done on 3M Unitek nitinol wires at increasing order of laser pulse energy from 50mJ/pulse to 200mJ/pulse, (b-c) parts show another measurement done on nitinol foils this time.

Figure 5 shows the DSC results obtained from Laser Shock Peened (a) NiTi SMA wires at different laser energies and (b-c) NiTi foils at different number of shots maintaining the laser energy constant. Both wires and foil results showed consistent shift of austenite phase into higher temperatures. In addition, phase widening in martensite phase was observed for nitinol foil when treated at various laser energies form 50 mJ/pulse to 200 mJ/pulse. The widening of 52.2 % compared with initial temperature range was evident. When the laser energy was kept constant, but number of shots was varied, austenite phase has shifted to higher temperatures reaching up to 3.5 – 4 °C. Phase width and temperature ranges are important in Biomedical applications of SMA such as orthodontic treatment with multibrackets [20]. 3M Unitek wires had weak martensite phase, so the results of phase shifts in martensite is omitted. DSC measurements confirm that treatments can be modulated to target certain phases and their characteristic behaviors although the effect of magnetic field was not completed yet.

Laser Shock Peening is a multi-step process involving multiple parameters. Being able to directly control the shockwave opens doors for precision treatments such as in 3D imprinting [4] or material property enhancements as in the case of SMAs.

4. CONCLUSION

In summary, we conclude that it is possible to modulate the shockwave using magnetic fields via versatile effects. This in turn, enables many opportunities such as in Laser Shock Peening. As a demonstration, we reported LSP on NiTi SMA foils and wires. The possibility of controlling and manipulation of the shockwave was shown with varying the magnetic field direction by observing the craters. LIBS, plasma plume simulations and ultra-fast imaging are being planned to study the plasma plume dynamics in detail. DSC results indicate that austenite and martensite phases of SMAs can be modified by treating them with LSP. Desirable shift or widening may be achieved using the right number of shots or laser energy. Magnetic control of LSP can enhance it for finely-tuned treatments.

5. ACKNOWLEDGEMENTS

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