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Study the stress enhancement effect of sacrifical coating in laser peening

Nghiên cứu hiệu ứng tăng cường ứng suất của lớp bọc bảo vệ trong phương pháp rèn bằng tia laser

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Abstract

Photoelasticity images of laser peening using sacrificial coating were simulated by the Finite Element Method. The Von Mises stress distribution in the coated target is deduced from the simulated images and is compared with the stress-induced in the non-coated target. The result shows that sacrificial coating can enhance the induced stress by a factor of 1.2.

Keywords: Sacrificial coating; laser peening; photoelasticity images; Finite Element Method.

Tóm tắt

Hình ảnh quang đàn hồi của quá trình rèn bằng tia laser sử dụng lớp bọc bảo vệ được mô phỏng bằng phương pháp phần tử hữu hạn. Phân bố ứng suất Von Mises trong mẫu có sử dụng lớp bọc được rút ra từ hình ảnh mô phỏng và được so sánh với trường hợp không sử dụng lớp bọc bảo vệ. Kết quả xác nhận rằng lớp bọc bảo vệ có thể làm tăng ứng suất sinh ra trong mẫu với hệ số 1.2.

Từ khóa: Lớp bọc bảo vệ; phương pháp rèn bằng tia laser; hình ảnh quang đàn hồi; phương pháp phần tử hữu hạn.

1. Introduction

Focusing an intense, short laser pulse onto a rigid surface produces high-pressure plasma, which drives a shock wave into the surrounding environment during its expansion. When the laser ablation is carried out under liquid, the liquid phase acts as a restricting medium to restrain the plasma expansion [1]. The expansion of ablation plasma in liquid drives an impulse momentum into the target, which can exceed several GPa and produce changes in in-depth microstructures of materials [2, 3]. One popular application of under-liquid laser-induced ablation is for surface treatment, also known as laser peening [4].

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In laser peening, a sacrificial coating is used to protect the target surface from being ablated by the hot plasma [5]. In addition to their protective effect, the absorptive coatings are expected to increase the shock pressure [6]. At laser intensities below 1 GW/cm^2, some enhancement in the amplitude of stress was observed if materials with high absorptivity, low thermal conductivity, and low heat of vaporization were used as the coating [7]. At higher laser power densities, it has been believed that the shock process is controlled by properties of the ionized plasma that is created on the target surface rather than by the properties of the target materials themselves. As such the absorptivity of coating materials should not affect the energy absorption and thus provide less or no stress enhancement effect.

In our previous work, we showed qualitatively that a sacrificial coating can still significantly increase the laser-induced transient stress at laser intensities over 1 GW/cm^2 [8]. In this research, we aim to use simulation method to quantify how much the tress is enhanced by a sacrificial coating.

In this work, we first carry the simulation to reconstruct the experimental images obtained by photoelasticity imaging technique for laser peening using coated target and non-coated target. Then, we compare the induced stress between the two ablation regimes. The result confirms that the sacrificial coating can enhance the induced stress by a factor of 1.2.

2. Material and methods

The ablation was carried out using a 1064 nm laser pulse, with full width at half maximum (FWHM) = 13 ns. Target is an epoxy-resin block ($\mathbf{20 \times 5.8 \times 28}\ \boldsymbol{mm^3}$). In one regime, the laser pulse was focused directly on the target surface (non-coated target). In the other regime, the target surface was coated by a thin layer of black paint which serves as the sacrificial coating (coated target). The ablations were carried out in the water. The pulse energy was from 20 mJ to 90 mJ. Photoelasticity images were obtained by using a pump-and-probe imaging system together with a polariscope. The images were captured at 2000 ns after irradiation. Details of the technique and imaging system can be found in our previous work [9].

The simulation was carried out using the Finite Element Method. The plasma pressure is given as initial displacement to a prescribed small area representing the ablated region. The program then calculates the stress state of each element. Based on stress values, the light path was calculated and the photoelasticity image is reproduced. We chose the images obtained for underwater radiation of no coated sample, at 20 mJ to be the basic images to carry simulation. Ablation at different configurations was simulated basing on this condition with increasing the stress factor. Details can be found in our previous works [10, 11].

3. Results and discussion

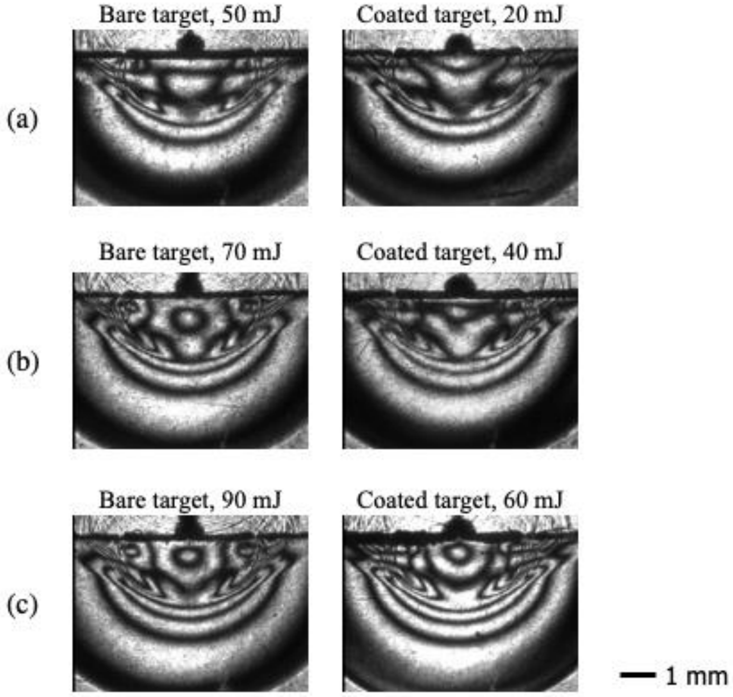

Figure 1. Compare ablation of bare target and coated target. Images were obtained at 2000 ns after irradiation.

In Figure 1, we compared the images taken for bare target and coated target at different pulse energies from 20 to 90 mJ. In the photoelasticity imaging technique, the number of photoelastic fringes shows semi-quantitatively the strength of induced stress. We thus base on the number of fringes to compare the induced stress in the two ablation regimes: the induced stress is considered the same if the photoelasticity images have the same number of fringes. Coated target irradiated by a 20 mJ laser pulse gave the same number of fringes as bare target irradiated by a 50 mJ laser pulse (Fig. 1a). As such, we can say that with sacrificial coating, a 20 mJ laser induced a stress as strong as a 50 mJ laser pulse without using the coating.

Similarly, our results showed that with black paint coating, a 40 mJ laser pulse induced a stress as strong as a 70 mJ laser pulse in case there is no coating (Fig. 1b). However, without the use of coating, a laser at 90 mJ cannot induce a stress as strong as 60 mJ laser can in case black paint coating was used (Fig. 1c). This observation confirms that the sacrificial coating does increase the laser-induced stress.

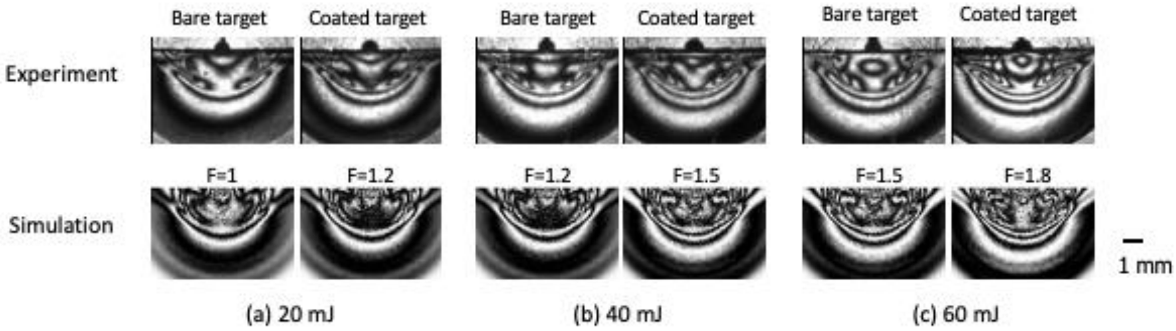

Figure 2. Simulation result for ablation of bare target and coated target at different pulse energies.

To quantitatively investigate the increase of induced stress, we simulated the ablations with and without the use of sacrificial coating at pulse energies from 20 to 60 mJ. From the basic simulation data for ablation of bare target at 20 mJ laser pulse energy, we applied increasing stress factor from 1.0 to 1.9. The simulated images were then compared with the experimental results based on the number of fringes. The results are shown in Figure 2. The simulation reconstructed the photoelasticity images to a certain extend.

In Figure 2, we can see that a bare target ablated by a 20 mJ laser pulse can be simulated with stress factor F=1.0. However, a coated target ablated at the same pulse energy need to be simulated by a stress factor of 1.2. Similarly, stress factors F=1.2 and F=1.5 were required to simulate ablation of bare target and a coated target at pulse energy of 40 mJ (Figure 2b); and stress factors of F=1.5 and F=1.8 were required to simulate ablation of bare target and coated target at pulse energy of 60 mJ (Fig. 2c). This result suggests that, the sacrificial coating can enhance laser induced stress by a factor of approximate 1.2.

4. Conclusion

We investigated the stress enhancement effect of sacrificial coating using simulation method. The experiments were carried out using photoelasticity imaging technique with black pain used as sacrificial coating. Finite element method was used to simulate the photoelasticity images. The simulation result shows that the sacrificial coating can enhance laser induced stress by a factor of approximate 1.2.

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