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Indirect confirmation and theoretical application of plasma shock−cavitation principle of pulsed laser shock

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Abstract: The coupling strengthening principle of the double physical effect of plasma shock−cavitation was proposed, and the rationality of the cavitation effect in pulsed laser shock treatment under liquid−confined conditions needs to be confirmed urgently. The XRD testing method and 304 stainless steel, which is easy to obtain diffraction peaks, were selected to quantitatively detect and characterize the residual stress distribution in the action area of a single pulse laser beam. The test results and literature analysis show that the different process conditions of laser shock processing bring about different strength matching of the two stress effects of plasma shock and cavitation, and the main source of stress effect of femtosecond laser shock without coating is the cavitation effect. The actual effects of the laser pulse width and other process parameters such as the absorption layer and the constraint layer affect or determine the material modification principle of the pulsed laser surface treatment.
Key words: laser materials processing; plasma shock; cavitation; surface strengthening

1 Introduction

When the metal surface is coated with a specific coating, the pulsed laser can produce a super-strong instantaneous shock wave on the surface. Researchers [1,2] have gradually applied the stress effects of a pulsed laser to the field of material strengthening or forming, and laser shock processing (LSP), as an effective surface-strengthening technology, was newly developed. By using laser-induced shock waves, large and deep residual compressive stress, and structural changes are formed on the metal surface, which can significantly improve the service performance of metal materials, enhancing fatigue resistance, stress corrosion resistance, and fretting wear resistance.

In LSP, to reduce the cost of equipment, a circular spot laser is often used. However, the appearance of a residual stress hole phenomenon renders the nearly perfect LSP defective. After the circular laser beam interacts with the material surface, the residual compressive stress distribution appears in most areas irradiated by the laser beam. Nonetheless, the central area of the laser beam exhibits residual tensile stress individually.

Simply speaking, the phenomenon of residual stress holes is that after the laser-induced plasma shock wave loading disappears, sparse waves propagate to the center due to the boundary effect of the shocking zone, resulting in reverse plastic

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deformation and reverse loading in the center area [3]. This phenomenon is prominent in the numerical simulations of LSP, but the residual stress hole in most published experimental results is not obvious. LU et al [4,5] compared and analyzed the experimental tests and simulations of residual stress distribution induced by single-spot laser shocking involved in a large number of relevant literature reports. By enumerating the actual test process conditions that cannot be included in the numerical simulation, LU et al [4] derived the scientific hypothesis that the cavitation detonation wave in the liquid-confined layer can weaken or suppress the residual stress hole. Based on the direct observations in the field of laser spectroscopy on the cavitation effect in the water environment, combined with the basis of the previous research, the researchers [6−8] proposed that it is necessary to update the physical principle of LSP under the condition of liquid constraint.

In this study, the physical mechanism of coupling regulation of plasma shock−cavitation in pulsed LSP will be further refined. Specifically, the authors will conduct a more accurate quantitative test on the residual stress on the material surface treated by single-beam LSP in the water confinement layer, and indirectly verify the actual effect of the pulsed laser-induced cavitation effect from the perspective of the treatment effect. Importantly, the principle of the strengthening technology of LSP under different process conditions was discussed, and the classification principle of LSP was re-determined.

2 Methods

The sample selected for the LSP test was the 304 stainless steel block used in Ref. [9]. A single laser spot impact region was selected as the research object, and the surface residual stress of the sample was tested by X-ray diffraction. The XL-640 ST X-ray stress analyzer was adopted, and Cr K_β radiation, the {311}-Bragg peak, and stress constant of −366 MPa were used. Importantly, to truly reflect the stress distribution trend, the selected collimator tube had a diameter of 0.5 mm. The numerical simulation of single-point laser shock was performed using Abaqus commercial software, and the specific simulation methods and related parameters were referenced [10,11].

The process conditions of LSP used in the actual test and numerical simulation are set to the same state, that is, the laser energy, pulse width, and single spot size used in the pulsed LSP treatment were determined to be 8.5 J, 18 ns and 3 mm, respectively. In addition, the constraint layer material selected in LSP was deionized water with a certain thickness, and the impact load used in the numerical simulation was calculated by converting the pulsed laser-induced peak pressure using an empirical formula.

3 Results

The block of 304 stainless steel material was used as a target to carry out simulation and experimental research on the LSP. Referring to the HEL calculation formula and data provided by the relevant pieces of literature [12,13], the selected test parameters ensure that the experiment satisfies the mechanical conditions of the stress hole proposed by the predecessors.

Figure 1 shows the results of experiment and simulation. It should be noted that the test residual stress is smaller than that in the previously published reference. The test locations selected are located in the central area of a single spot, and there is a possibility of a weaker boundary effect affecting the residual compressive stress at the center of the spot. Specifically, three spot areas are randomly selected as the test objects on the shocked surface of the sample, and the distribution tendency of the residual stress of the spot center is shown in Fig. 1(a). The result shows that the areas at the center of the laser spot have residual compressive stress, and the residual compressive stress is not much different at varied positions. In contrast, the residual compressive stress at the center of the spot shown in Fig. 1(b) is clearly missing.

In the previous study, LU et al [4] proposed a hypothesis that the cavitation bubble detonation wave induced by a pulsed laser can weaken the residual stress hole on the material surface. The research results show that, different from the numerical simulation results, there is no obvious uneven stress distribution on the material surface under laser shock in the actual test. This result fits and corresponds to the scientific conclusion that there are physical effects other than plasma shock in the process of laser shock, which makes the residual stress hole disappear.

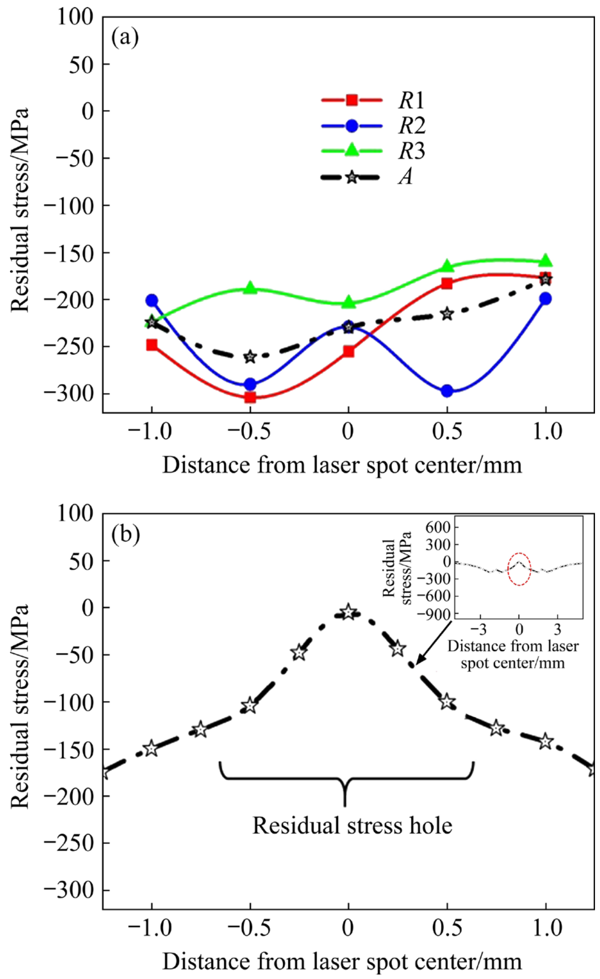

Fig. 1 Surface residual stress distribution of impact region of sample after laser shock treatment: (a) Test results [9]; (b) Simulation results (*R*1, *R*2, and *R*3 represent the radial paths of the central areas of three different spots, respectively, and *A* represents a virtual radial path formed by averaging the residual stresses of specific positions of the above three spots)

4 Discussion

The previous research results further illustrate the rationality and correctness of the cooperative-regulation principle of the dual-physical effect of plasma shock−cavitation of pulsed LSP. In essence, plasma shock and cavitation can be regarded as two distinct stress effects, or as two stages of the formation process of pulsed laser shock, and this recognition will not make a significant difference for researchers to understand the process of liquid-confined LSP. To elaborate the surface strengthening mechanism more clearly and intuitively, the plasma shock and cavitation were taken as two physical effects according to conventional cognition.

Based on the strengthening principle of dual-physical effects, the difference in the surface strengthening principle of LSP under different process conditions can be explained more perfectly. The variables of process condition described here include but are not limited to pulse laser parameters and the materials and specifications of the absorption layer and constraint layer. As mentioned above, during the LSP treatment, the high-temperature and high-pressure plasma in the ns stage are formed based on the material of the absorption layer. In the current research, the researchers [14] also generally believe that the plasma during the ns laser shock without the absorption layer (LSPwC) is formed based on the burning surface of the material to be processed. In industrial applications of lasers, ultrafast lasers with pulse widths of ps or fs have attracted the attention of researchers. In material processing based on the stress effect of a pulsed laser, the most important advantage of the ultrafast laser is the absence of ablation of the surface of the material. However, when using ultrafast lasers for the surface processing of materials, some researchers [15,16] have proposed laser shock treatment without an absorption layer ((μ)LSPwC). Then, in the LSP treatment without the coating of an absorption layer and without material surface ablation, what forms the impact pressure of the material surface?

Figure 2 and Table 1 answer the above question. In Fig. 2, the blue and black lines represent the liquid confining layer and the solid absorption layer covering the surface of the target, respectively. The yellow lightning pattern represents the plasma shock wave, the blue spherical pattern represents the cavitation bubble, and the blue radial line represents the distribution of the stress field inside the material. The size of the different patterns indicates the degree of physical effect or the intensity of the stress field. Among them, it is an ultrafast laser (ps or fs) in Figs. 2(a)−(d), and it is ns laser in Figs. 2(e)−(h). The actual physical mechanisms of the "(μ)LSPwC" and the traditional "LSP" technologies are shown in the dashed box.

Specifically, Fig. 2 shows that the solid absorption layer and the material to be processed itself make the surface have a material basis for the occurrence of a plasma shock effect, while the presence of a liquid absorption layer determines the possibility of a cavitation effect. As shown in Fig. 2, the surface strengthening effect of conventional ns-LSP techniques should be attributed to the synergy of the two physical effects of pulsed laser-induced plasma shock and cavitation, while other laser shock technologies have very different surface strengthening principles due to different processing conditions. Especially, for the (μ)LSPwC technology, the cavitation effect is its main physical mechanism. Of course, this will require later researchers to work on the path of validation. Based on the analysis of Fig. 2, Table 1 is constructed as a summary display, which shows the core processing principles of different laser shock-surface technologies that have been developed at present.

The above scientific understanding proposed will provide a theoretical reference for technicians to more accurately adjust the processing effect of LSP technology, and also help the germination and development of more new laser surface processing technology.

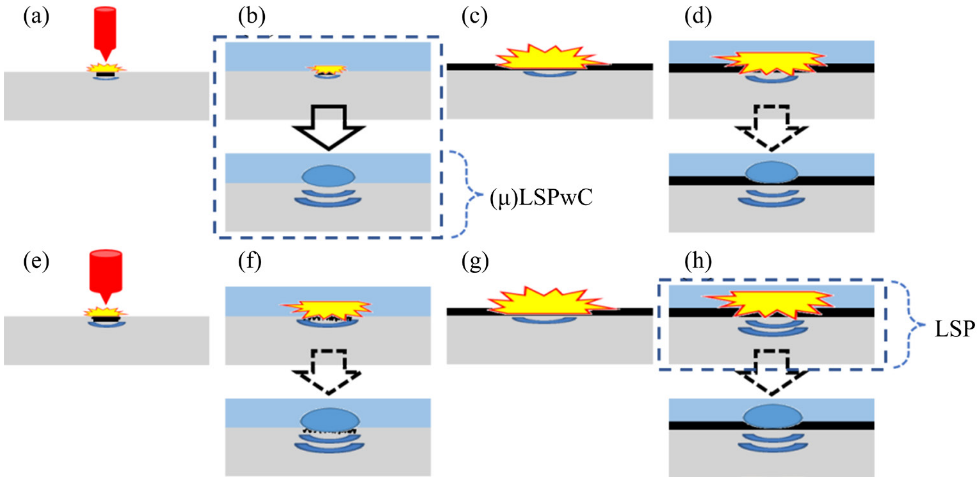

Fig. 2 Formation mechanisms of shock waves based on pulsed lasers displaying schematic diagram of varied physical effects under different pulse widths: (a−d) ps, fs laser; (e−h) ns laser

Table 1 Physical mechanisms of LSP treatment (with or without absorbing layer and with or without confining layer)

Pulse width	Absorbing layer	Confining layer (water)	Ablation of material surface	Plasma shock wave	Cavitation effect	Physical principle	Developed technology
ps, fs	√	√	×	√	√	A+ B(depending on conditions)	(μ)LSP [17,18]
		×		√	×	A(weakening) [19]	–
	×	√	×	×	√	B(depending on conditions)	(μ)LSPwC [16]
		×	√*	–	–	A(weakening)*	(μ)LSPwC* [20]
ns	√	√	×	√	√	A+ B(depending on conditions)	LSP
		×		√	×	A(weakening) [21]	–
	×	√	√	√	√	B(depending on conditions)+ A(weakening)	LSPwC [14]
		×	–	–	–	–	–

Note: "√" represents "with" or "exist"; "×" represents "without" or "non-exist"; "A" represents the plasma shock wave; "B" represents the "cavitation" effect; "–" indicates that the current condition is not feasible, or the result is pending validation; "*" represents some of the new findings that have emerged, and under these conditions, a very small part of the material ablation on the target surface essentially produces a role equivalent to that of the absorbent layer

5 Conclusions

(1) The strengthening effect of LSP under different process conditions depends on the coordinated regulation of the two physical effects of plasma shock and cavitation.

(2) Different processing processes obtain completely different effects of surface strengthening or modification by changing the occurrence conditions of the different physical effects.

CRediT authorship contribution statement

Guo-xin LU: Conceptualization, Methodology, Software, Writing − Original draft preparation; **Xue-kun LUO:** Data curation, Investigation, Writing − Original draft preparation; **Qiang WANG:** Visualization, Investigation; **Ji-de LIU:** Investigation, Software, Validation; **Zhong JI:** Software, Validation; **Feng LU:** Validation, Writing − Reviewing and Editing; **Xiao-feng SUN:** Validation, Writing − Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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脉冲激光处理等离子体冲击−空化原理的间接验证和理论应用

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摘　要：提出等离子体冲击−空化双物理效应耦合强化原理，在液体约束脉冲激光冲击中空化效应存在的合理性有待证实。选择 XRD 测试方法和较易获得衍射峰的 304 不锈钢，定量检测和表征单脉冲激光作用区域的残余应力分布。试验结果与文献分析表明，激光冲击强化的不同工艺条件导致等离子体冲击与空化两种应力效应的强度匹配不同，无涂层飞秒激光冲击应力效应的主要来源是空化效应。激光脉冲宽度以及吸收层和约束层等工艺参量的实际作用影响或决定脉冲激光表面处理的材料改性原理。

关键词：激光材料加工；等离子体冲击；空化；表面强化

(Edited by Xiang-qun LI)