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# Laser Shock Processing of FCC Metals

## Mechanical Properties and Micro-Structural Strengthening Mechanism

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# Preface

Laser shock processing, or laser shock peening (LSP), is the process of hardening or strengthening metal using a powerful laser. It can generate a layer of residual compressive stress on a surface of metallic materials and alloys that is four times deeper than that attainable from conventional shot peening treatments (shot peening), which has been successfully applied to improve fatigue performance of metallic components.

In the past three decades, LSP has been widely and intensively investigated over 200 scientific papers and reports. Most studies and investigations have been based on experimental approaches, influences of LSP on mechanical properties and in particular fatigue lives of metallic materials and alloys. Many researches have been focusing on analytical models and dynamic finite element models (FEM), to simulate the distribution of three-dimensional residual stresses in relation to materials properties, component geometry, laser sources, and LSP parameters in the last decade. LSP is also an effective surface treatment and post-processing method to eliminate tensile residual stress in the surface layer of metallic material and its weldment in order to improve their mechanical properties and tensile performances.

In this book, we take the face-centered cubic metals (FCC metals, including aluminum alloy and austenitic stainless steel) and stainless steel weldment as the studied objects. The aim of this book is to provide some foundational researches on the macro-property, micro-structure evolution, and plastic deformation induced by massive LSP impacts. These researches can provide some scientific insights into the industry application of LSP technology. Some different topics are involved, i.e., surface integrity and fatigue lives of FCC metals after LSP with different processing parameters, tensile property, and fractural morphology of FCC metals by LSP under different strain-rates, grain refinement mechanism based on the micro-structure evolution, and corrosion behaviors after multiple LSP impacts. Special attentions have been paid to the effects of LSP on mechanical properties and tensile performance of stainless steel weldment.

For a better understanding on the effects of LSP on the macro-properties and micro-structures, and in order to obtain the appropriate LSP processing criterion by addressing the various factors mentioned above, a lot of LSP experiments are carried out, and finite element simulation based on mechanistic modeling is currently recognized as an effective tool to analyze the distribution of residual stress. Some influential parameters associated with LSP are evaluated for the purpose of characterizing LSP processes. In particular, different methods of using LSP, such as one-sided, two-sided, and multiple LSP impacts on the FCC metals are elaborated in detail.

The research work from which this book arises was carried out at Laser Technology Institute in Jiangsu University supported by the National Natural Science Foundation of China (Grant Nos: 50735001, 51275220, 50675089, 50705038, 51105179). The work was based on research projects on evaluation and characterization of LSP for aerospace and engineering applications. Professor Yongkang Zhang at Southeast University finished Chaps. 1 and 5, Dr. Jinzhong Lu at Jiangsu University finished Chaps. 1–4 and 9, and Dr. Kaiyu Luo at Jiangsu University finished Chaps. 6–8. The authors would like to thank their colleagues and friends for useful discussions and help in the preparation of this book. The authors are particularly grateful to Dr. Fengze Dai, Dr. Lei Zhang, and Prof. Xinmin Luo due to their contribution to this book.

Finally, Dr. Jinzhong Lu would like to thank his family, for their love, understanding, and assistance over the years.

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# Contents

# Chapter 1
# General Introduction

**Abstract** This chapter presents the laser shock processing (LSP) process, recent development of LSP on alloys and metallic materials, typical applications of LSP and the scope of this book.

## 1.1 Laser Surface Treatment and Laser Shock Processing

Laser surface treatment is a flexible way of effectively protecting component and tool surfaces from wear and corrosion. Various surface treatment techniques can prolong tool life and improve component, tool or die performance.

Laser surface treatment is a novel and potential subject of considerable interest at present because it seems to offer the chance to save strategic materials or to allow improved components with idealized surfaces and bulk properties. Laser surface treatment shows many advantages compared to conventional techniques, e.g. a high flexibility with respect to the processed geometries or the possibility for a simple integration into existing production lines. Especially when only a small part of the surface of a workpiece shall be treated the laser process should be preferred.

Laser surface treatment can cause the changes in surface properties of alloys and metallic materials by generating temperature gradients, phase changes or mechanical influences. The most important processes are shown as following:

- *Laser transformation hardening* It is used for steel and cast iron. Heating by the laser above the austeniting temperature causes an $\alpha$-$\gamma$ transition of the material in the heated surface layer. Because of the high power density of the laser beam high temperature gradients are caused in the material which induces fast quenching when the laser beam moves ahead. This fast quenching causes the forming of hard surface layers consisting of martensite.
- *Laser remelting* In remelting the laser parameters are selected in a way that melting of the upper surface layer is occurring. There are several effects of the

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melting which can be utilized. For example inclusions can be vaporized or dissolved, the grain size can be adjusted and the hardness can be increased. Because of the flow of the produced melt the surface quality gets worse and usually additional processing is required.

- *Laser annealing* Laser annealing process is very similar to transformation hardening. In this process a material with a high martensite fraction is heated in order to dissolve a part of the martensite and thus to reduce the hardness.
- *Laser shock processing* Shock hardening occurs when laser pulses with a duration in the ns range are applied. In this case shock waves are induced which cause a kind of mechanical deformation connected to an increase of the hardness. The involved mechanisms are therefore similar to those occurring during cold working.

Figure 1.1 shows laser surface treatment processes in relation to other laser processes used in production engineering. It can be seen that laser surface treatment requires a relatively high energy laser beam. The interaction time is determined by the required heating and quenching rates, which is higher than that used for welding or cutting.

Among these laser surface treatment techniques, laser shock processing (LSP), also known as laser shock peening or laser peening, is a novel surface modification technique, which is successfully applied to improve the fatigue performance and mechanical properties of alloys and metallic materials due to the fact that LSP can impart a layer of compressive residual stress in the surface that is four times deeper than that attainable from conventional shot peening. After the treatment, the fatigue strength and fatigue life of metallic materials can be increased significantly

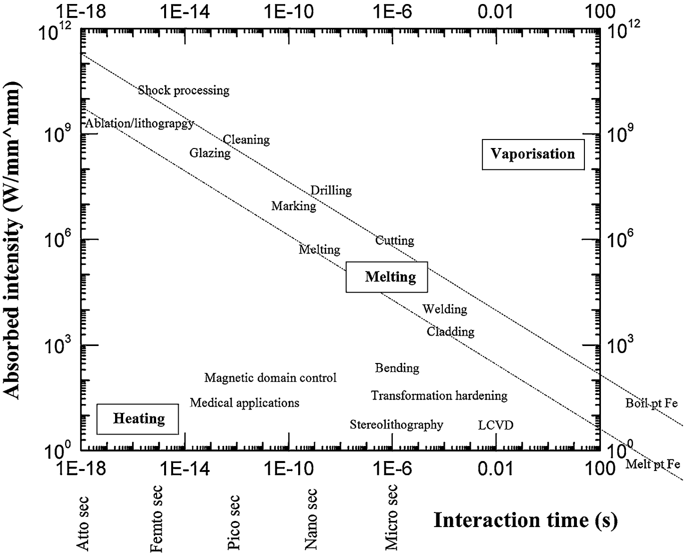

**Fig. 1.1** Overview over laser surface treatment processes

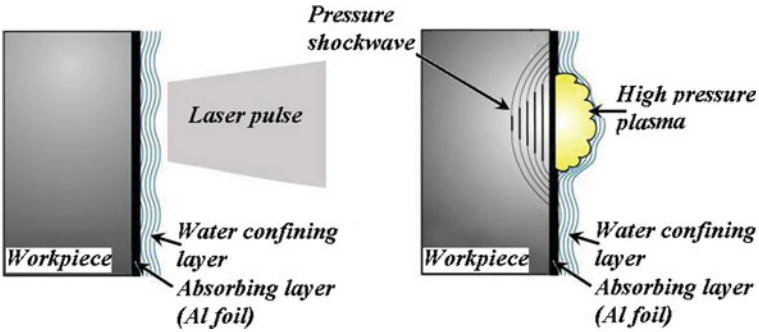

**Fig. 1.2** Schematic principle of laser shock processing

due to the presence of compressive residual stresses in the alloys and metallic materials.

The LSP process utilizes high energy laser pulses (several GW/cm$^2$) fired at the surface of a metal covered by two layers, namely an absorbing layer and a water confining layer. When a laser pulse with sufficient intensity passes through the transparent confining layer and hits the surface of the material, the absorbent material vaporizes and forms a plasma. The plasma continues to strongly absorb the laser energy until the end of the energy deposition. The rapidly expanding plasma is trapped between the sample and the transparent confining layer, creating a high surface pressure, which propagates into the material as a shockwave. When the pressure of the shockwave exceeds the dynamic yield strength of the metal, it produces plastic deformation in the near-surface of the metal. The LSP principle is schematically shown in Fig. 1.2.

The LSP technology has the following advantages: (1) less surface roughening compared to the conventional shot peening; (2) no embedded particles; (3) strengthening right into corners where shot could not reach; (4) no material to recycle, collect, grade and clean, as there is with shot peening; and (5) flexible laser pulse beam which can be adjusted and controlled in real time.

## 1.2 Recent Development of Laser Shock Processing on Alloys and Metallic Materials

A pulsed laser beam with a pulse width in the level of nanosecond can induce the shock wave, which was discovered and developed in the early 1960s for the first time [1, 2]. Subsequently, a lot of research focused on the improvement in mechanical properties (including micro-hardness, residual stress, fatigue life and yield strength) of alloys and metallic materials induced by LSP around the world. Anderholm et al. established the confined mode for an improved LSP process in 1968 [3]. Clauer et al. carried out LSP for the fastener holes in 1968–1981 at

Battelle–Columbus Laboratories (OH, USA) [4]. Banas et al. found that the hardness and yield strength of metallic materials can be increased by LSP due to high density arrays of dislocations [5, 6]. Fabbro et al. studied the shock breakout at the rear face of laser-irradiated metallic targets [7].

Since the early of 1990s, more and more systematic studies on engineering applications and underlying mechanism of LSP have been performed in other countries. In France, Fabbro and Peyre in France systematically studied the physics phenomenon and action mechanism generated by laser shock wave, including the laser-produced plasma in confined geometry [8], the generation of shock waves by laser-induced plasma in confined geometry [9], the shock waves from a water-confined laser-generated plasma [10], the laser-driven spallation process by the velocity interferometer system for any reflector interferometry technique [11, 12], laser-driven shock waves in stainless steels [13], and the wavelength dependent of laser shock-wave generation in the water-confinement regime [14]. In China, Zhang and Yu investigated the effects of LSP on 2024-T62 aluminum alloy [15], and results showed that LSP can increase the fatigue life and decrease the fatigue crack growth rates of 2024-T62 aluminum alloy, which results from the combinations of the surface compressive residual stress, reduced surface roughness, and increased dislocation density induced by the laser shock waves. In addition, they also proposed a novel measurement method to predict the effect of LSP on 2024-T6 aluminum alloy by comparing the surface toughness of the shocked region with that of the unshocked surface [16]. In Japan, Sano et al. developed the LSP of water-immersed material to improve the surface residual stress of metal components. The process changes the stress field from tensile to compressive by means of impulsive pressure of laser-induced plasma generated through the ablative interaction of the intense laser pulse with the material [17].

With the rapid development of the laser equipment, LSP is attracting comprehensive attentions of more and more researchers in the field of surface modification due to high-pressure (in the scale of GPa), high-energy (peak power is more than 1 GW), ultrafast (several tens nanoseconds) and ultra-high strain rate (more than $10^7$ $s^{-1}$) of the induced laser shock wave [5, 6]. There are many researchers who have been focusing on surface integrity, mechanical properties, microstructures, fatigue life of alloys and metallic materials induced by LSP. Cheng and Ye et al. at Purdue University systematically investigated fatigue lives, mechanical properties and microstructures of A6160 Aluminum alloy [18], SUS304 SS [19], copper [20], NiTi shape memory alloy [21] and AISI 4140 steel [22] in the elevated temperature, room temperature and low temperature before and after LSP, respectively. They found that LSP can refine and nanocrystallization the coarse grain in the surface layers of alloys and metallic materials in the above three temperatures, which can result in the improvement of mechanical properties and fatigue performance of alloys and metallic materials in the elevated temperature. Zhang et al. at Jiangsu University found that LSP changed the elastic properties of 2024-T62 aluminum alloy due to the distribution of microstructural changes induced by LSP [23]. Research results of Lu et al. at Jiangsu University showed that the values of the nano-hardness, elastic modulus and surface residual stress in the laser-shocked region and the laser-affected region were obviously improved compared to those in the non-shocked region [24]. Gomez-Rosas et al. studied the effects of LSP on wear and friction of 6061-T6 aluminum alloy, results showed that wear rate decreases as pulse density increases [25]. Lu et al. at Jiangsu University addressed the effects of multiple LSP impacts with different pulse energy on mechanical properties and wear behaviors of AISI 8620 steel [26]. Multiple LSP impacts can remarkably improve the wear resistance of AISI 8620 steel. The wear process of the unpolished sample subjected to multiple LSP impacts can be described as follows: the wear rate was big at the beginning of sliding dry wear, but then decreased after the micro-indention in the sample surface was polished to the disappear. Multiple LSP impacts on AISI 8620 steel had dual-function: the refinement of coarse grains in the near-surface region by dislocation movement and dispersion strengthening of C atoms which cut cementite and diffused into the ferrite by moving dislocations [27].

The change of residual stress on the surface and in the depth direction attracted more attention in the field of LSP. The effects of LSP parameters [28–34], including absorbing layer, pulse width, laser spot diameter, overlapping rate, pulse energy, wavelength and the time of LSP impact, on residual stress on the surface and in the depth direction were widely studied. Many alloys and metallic materials presented clear improvements in fatigue life after LSP treatment. The beneficial effects of LSP may originate from compressive residual stresses on the surface and in depth direction, which delayed the propagation of surface fatigue cracking and the growth of fatigue cracking in depth direction. Investigations on several different aspects of the fatigue behaviors, such as fatigue life, fatigue strength and fretting fatigue, were reported [35–42].

LSP can significantly improve the corrosion resistance and wear performances of alloys and metallic materials. Amar et al. at CNRS-Université de Bourgogne researched the corrosion behavior of AA2050-T8 after polishing and then LSP treatment using the electrochemical microcell technique and the SVET. Results revealed that LSP increased the pitting potential [43]. Trdan et al. in Faculty of Mechanical Engineering at University of Ljubljana studied corrosion resistance of AA6082-T651 aluminum alloy after laser shock peening by means of cyclic polarization and ElS methods, and they found that LSP can reduce pitting and completely prohibit the initiation of large surface pits to enhance corrosion resistance of AA6082 alloy [44, 45]. Zhang and Lu et al. investigated the effects of LSP on the stress corrosion cracking (SCC) susceptibility of AZ31B magnesium (Mg) alloy, and the SCC test in 1 wt % NaOH solution showed that LSP retarded the SCC initiation and growth in AZ31B Mg alloy [46].

There are some new developments in the plasma-related phenomenon and mechanism induced by laser shock wave. Wu and Shin et al. in the Center for Laser-Based Manufacturing at Purdue University paid attention to the plasma induced by laser shock wave in the past decade [47]. They proposed a self-closed numerical model which can simulate the laser pulse transmission through the breakdown plasma generated in water during LSP. This model can predict reasonably good experimental results. In addition, they also developed a physics-based predictive model to measure the early-stage plasma pressure and front propagation and the late-stage ($t > 30$ ns) plasma temperature and electron number density during LSP, which is very useful for the fundamental laser plasma study and relevant laser applications [48]. Wu et al. at Chinese Academy of Physics proposed a coupling pressure analytical model, in which the material constitutive models of confined layers and target material are considered, and this model can predict the plasma pressure profile at the surface of metallic target [49]. Thorslund et al. at University of Central Florida developed some mathematical models to calculate the temperatures, pressures and stresses during LSP for time-modulated (ramp-up, ramp-down and rectangular) laser pulses [50].

## 1.3 Typical Applications of Laser Shock Processing

LSP attracts strong interest in the field of commercialization application. Since two important patents were first issued in 1974 and 1983, LSP has been gradually used in industry. From 1996, the General Electric Company alone applied for a large number US patents based on laser shock processing.

In the aerospace industry, laser shock processing is an effective methods to improve the mechanical properties and fatigue lives of aerospace key products, such as turbine blades (as shown in Fig. 1.3) [51] and rotor components [52, 53], discs, gear shafts [54] and bearing components [55]. Laser shock processing could also be applied to strengthen fastener holes in cover parts. General Electric Aircraft Engines in the USA treated the leading edges of turbine fan blades [53] in F101-GE-102 turbine for the Rockwell B-1B bomber by laser shock processing in 1997, which enhanced fan blade durability and resistance to foreign object damage (FOD) without harming the surface finish [53]. Protection of turbine engine components against FOD [51] is a key priority of the US Air Force. In addition, it was reported that laser peening would be applied to treat engines used in the Lockheed Martin F-16C/D [56].

LSP Technologies Incorporation (Dublin, OH) also recently commissioned the ManTech Laser Shock Peening Manufacturing Cell (LSPMC). From 2004, LSP Technologies laser peened the airfoils on the Pratt and Whitney F119, 4th stage IBR that was flown on the F/A-22 Raptor aircraft. Implementation of laser shock processing increased the notched fatigue strength of IBR airfoils above the 55 ksi fatigue strength design criteria. Figure 1.3 shows an improvement of the notched fatigue strength of IBR airfoils [57]. The application of laser shock processing to the F119 IBR has reduced maintenance costs and eliminated the need for a costly redesign, estimated to be greater than $10 M (Fig. 1.4).

Laser shock processing can obviously improve the fatigue strength of the damaged blades which is equal to or better than that of undamaged blades [58], as shown in Fig. 1.5.

Laser shock processing has been shown to provide more than 2.5 times lifetime enhancement against fatigue failure for coupons replicating T-45 arrestment hook

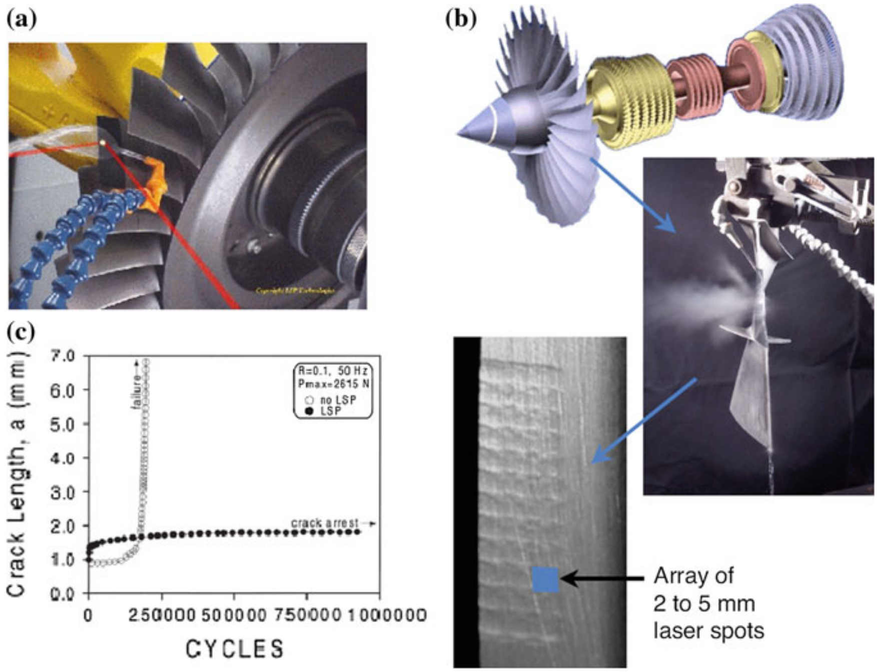

**Fig. 1.3** **a** Laser shock processing of F119 vane-integrated disk and blade. **b** Blade. **c** Crack length vs. cycles (a vs. N) data for baseline and LSP samples

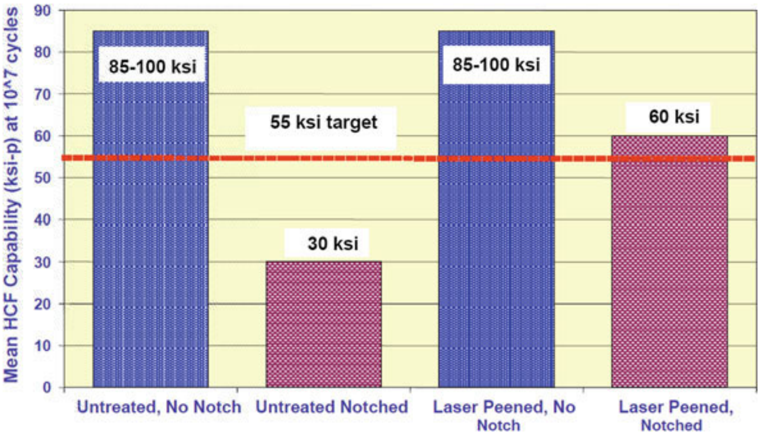

**Fig. 1.4** The effect of laser shock processing on F119 IBR fatigue life. A 0.050-inches deep EDM notch was used on the notched airfoils [57]

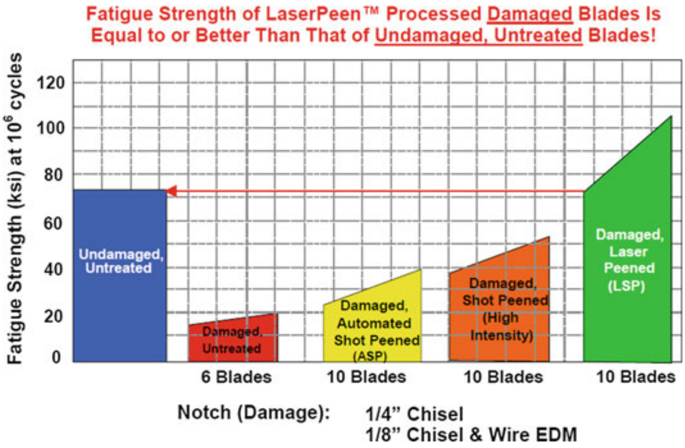

**Fig. 1.5** Laser shock processing improved the fatigue strength of the damaged blades [58]

shanks (as shown in Fig. 1.6). Employment of laser shock processing on aircraft would reduce maintenance costs and add to aircraft availability [59]. Since 2002, Metal Improvement Company (MIC) has processed over 35,000 wide-chord fan blades for commercial aircraft, and laser shock processing can extend lifetime of new and used Being 777 blades by more than 20 times (as shown in Fig. 1.6).

Laser shock processing without protective coating (LSPwC) was also developed and the practical effects (SCC and fatigue prevention). This technology has been applied to Japanese nuclear power reactors (BWRs and PWRs) as preventive maintenance against SCC since 1999 [60, 61] (Fig. 1.7).

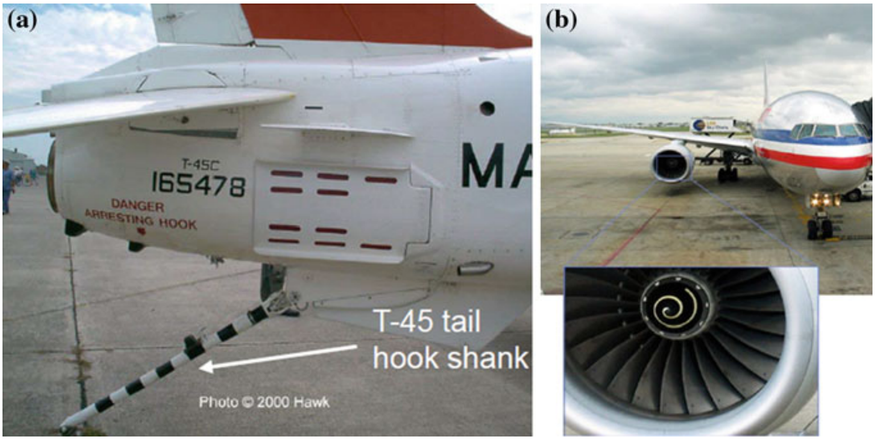

**Fig. 1.6** **a** The replicating T-45 arrestment hook shanks treated by laser shock processing. **b** The treated being 777 blades by laser shock processing