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# Investigation of the Stability of the Compressive Residual Stress Generated by Warm Laser Shock Peening

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Is approved by the final examining committee:

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# INVESTIGATION OF THE STABILITY OF THE COMPRESSIVE RESIDUAL STRESS GENERATED BY WARM LASER SHOCK PEENING

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Chang Ye

In Partial Fulfillment of the

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of

Doctor of Philosophy



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To my parents, 叶远汉  胡多先

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# ABSTRACT

Ye, Chang. Ph.D., Purdue University, August 2011. Investigation of the Stability of the Compressive Residual Stress Generated by Warm Laser Shock Peening. Major Professor: Gary Cheng.

Laser Shock Peening (LSP) has been successfully used to improve component fatigue performance by bringing beneficial compressive residual stress to material surface since the 1990s. However, it has been found that the compressive residual stress generated by room temperature LSP (RT-LSP) is not stable during cyclic loading. Thus, it is necessary to improve the stability of the compressive residual stress generated by RT-LSP.

In this study, Warm Laser Shock Peening (WLSP) is proposed as a potential approach to improve the stability of the compressive residual stress. WLSP is to laser peen a component that is being heated to elevated temperatures. As a thermomechanical treatment (TMT) technique, WLSP integrates the advantages of LSP, dynamic strain aging (DSA) and dynamic precipitation (DP). Through DSA, more uniform and high density dislocations are generated. Through DP, highly dense nanoscale precipitates are generated. Experimentally, WLSP has been evaluated by AISI 4140 steel in terms of the microstructure, residual stress stability and fatigue performance. To investigate the effect of the precipitate particles generated by WLSP to crack propagation, an extended finite element method (XFEM) model was employed. To investigate the effect of temperature to the residual stress distribution, WLSP simulation of copper, a pure metal not applicable to dynamic strain aging, was carried out by finite element model (FEM) and validated by experiments.

Through these studies, it has been found that: (1) WLSP can generate high density nanoscale precipitate particles in alloy materials applicable to dynamic strain aging and

precipitate hardening; (2) the highly dense precipitate particles generated by WLSP leads to higher material strength than RT-LSP; (3) the pinning force exerted by the precipitate particles to the dislocations leads to higher stability of the compressive residual stress; (4) the highly dense nanoscale precipitate particles generated by WLSP can dissipate the stress concentration near the crack tip and thus decrease the crack propagation speed and improve component fatigue performance.

# CHAPTER 1. INTRODUCTION

## 1.1. Laser Shock Peening

Laser shock peening (LSP) has been successfully used to improve metallic component fatigue performance for more than two decades [1]. In the current medium-confined LSP setup (Figure 1.1), a sacrificial coating and a transparent overlay are put on top of the target component. During LSP, the pulsed laser penetrates through the transparent overlay and irradiates on the sacrificial coating, the surface temperature of which increases rapidly [2]. When the temperature reaches certain point (around 10,000$^{o}$C), plasma forms, which is confined between the target component and the confining medium. With the expansion of the high pressure plasma, shock wave propagates both in the target material and the confining media. In this way, the shock wave that goes into the material is stronger and lasts longer than free-expanding plasma in LSP without confining media. When the peak stress of the shock wave exceeds the Hugoniot elastic limit (HEL) of the material, plastic deformation occurs, which leads to the formation of compressive residual stress in component surface.

After LSP, the surface hardness of the metallic component increases, which is attributed to the work hardening induced by the high-strain rate deformation. Surface strength improvement combined with the presence of the compressive residual stress leads to fatigue performance improvement.

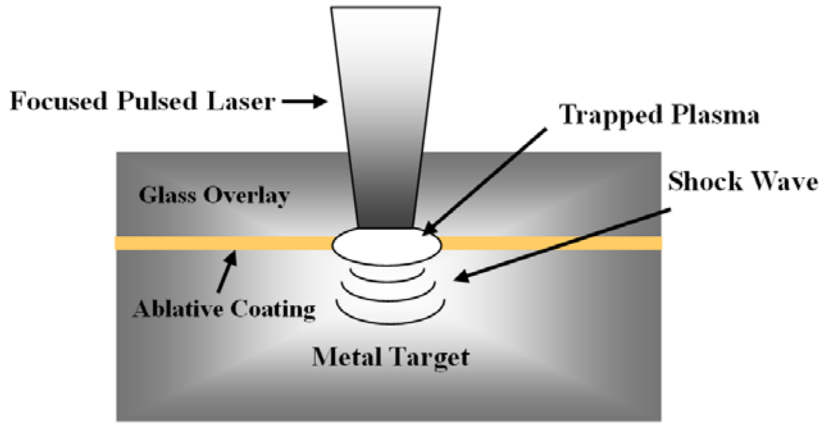


Figure 1.1 Schematic Representation of the Laser Shock Peening Process



## 1.2. Problem Statement

For effective fatigue life improvement by generating compressive residual stress by any surface processing technique (including LSP), two aspects are most important. Firstly, the magnitude of the compressive residual stress and secondly, the residual stress stability against cyclic loading, especially for cyclic loading at elevated temperatures.

The compressive residual stress magnitude generated by LSP is determined by the laser parameters and the material properties of the target component. The residual stresses generated by LSP are prone to decrease in magnitude during cyclic loading, especially at high loading temperatures [3]. If this happens, component fatigue performance cannot be effectively improved. Thus, it is very important to have stable compressive residual stresses.

## 1.3. Scope of this Research

Warm Laser Shock Peening (WLSP) is LSP while heating to target component to elevated temperatures, specifically the DSA temperature. WLSP integrates the advantages of LSP, dynamic strain aging (DSA) and dynamic precipitation (DP). By bringing compressive residual stress and nanostructures to component surface simultaneously, it is expected that WLSP can stabilize the dislocations and thus improve the stability of the compressive residual stress. The aim of this research is to investigate the stability of the compressive residual stress generated by WLSP and to study how WLSP affect component mechanical properties.

In this study, aluminum alloys and carbon steels, both are applicable to DSA, were used to evaluate the WLSP process. To investigate how the microstructures generated by WLSP affect crack propagation behavior during cyclic loading, extended finite element method (XFEM) was used to model crack propagation under the influence of the precipitates generated by WLSP. To investigate the effect of temperature to residual stress generated by LSP, pure copper was used, since copper is not applicable to DSA or DP, its microstructure is relatively simple and it does not experience phase change during LSP at elevated temperatures.

## 1.4. Structure of this Thesis

This thesis is structured as follows. In Chapter two, a literature review is carried out on LSP and the related research work. Chapter three reviews the material characterization methods used in this study. Chapter four presents the WLSP work of aluminum alloy 6061. Chapter five presents the WLSP work on AISI 4140 steel. Chapter six presents an XFEM study of the crack propagation behavior under the influence of the microstructure generated by WLSP. Chapter seven presents the WLSP work of copper. Chapter eight draws the conclusion of this thesis.

# CHAPTER 2. LITERATURE REVIEW

In Chapter one, the motivation of WLSP has been discussed and the scope of this research has been identified. In this chapter, a literature review is conducted on issues related to this research. This literature review includes, the generation of the compressive residual stress by LSP, how LSP affects component properties, the residual stress relief modes, the fundamental mechanisms of dynamic strain aging and dynamic precipitation, and the related work on high temperature surface processing in the literature.

## 2.1. From High Energy Pulsed Laser to Shock Wave

In LSP, the pulsed laser that is used to generate the high pressure plasma usually has high intensity (greater than 1 GW/cm$^2$) and short duration (a few to 10s of nanoseconds). When a high power pulsed laser irradiates on to a material surface, the first atomic layer of the target material is vaporized into a high temperature (10,000$^o$C) and high pressure (1-10 GPa) plasma. By performing a physical and mechanical study of the laser-induced plasma, Fabbro [4] described the relationship between the shock pressure P(t) and plasma thickness L(t) by:

$$\frac{dL(t)}{dt} = \frac{2P(t)}{Z} \qquad \text{Eq. 2.1}$$

$$I(t) = P(t)\frac{dL(t)}{dt} + \frac{3}{2\alpha}\frac{d}{dt}[P(t)L(t)] \qquad \text{Eq. 2.2}$$

Assume constant laser power density, $I_0$, the scaling law for the pulse pressure can be estimated by:

$$P(GPa) = 0.01\sqrt{\frac{\alpha}{2\alpha+3}}\sqrt{Z(g/cm^2s)}\sqrt{I_0(GW/cm^2)} \qquad \text{Eq. 2.3}$$

where P is the peak pressure and α (empirically value [4], typically, α=0.1~0.2) is the portion of absorbed energy contributed to the thermal energy of the plasma; Z is the reduced shock impedance between the material and the confining media, which is governed by Eq. 2.4:

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \quad \text{Eq. 2.4}$$

where $Z_1$ and $Z_2$ are the shock impedance of the confining media and the target component respectively. The shock impedances of common materials are shown in Table 2.1. Figure 2.1 shows an example of laser power temporal profile and the generated plasma pressure temporal profile with BK7 glass (Borosilicate crown glass) as the confinement material.

Table 2.1 Shock Impedance of Common Materials

| Material | Water | Aluminum | BK7 Glass | NiTi | Copper | Steel 4140 | Stainless Steel 304 |
|---|---|---|---|---|---|---|---|
| Shock Impedance ($10^6$g.cm$^{-2}$s$^{-1}$) | 0.165 [5] | 1.5* | 1.44[6] | 3.8* | 4.18* | 3.96* | 3.94* |

* Estimated by equation Z=ρ*D [7], where ρ is material density and D is shock wave propagation speed in material.

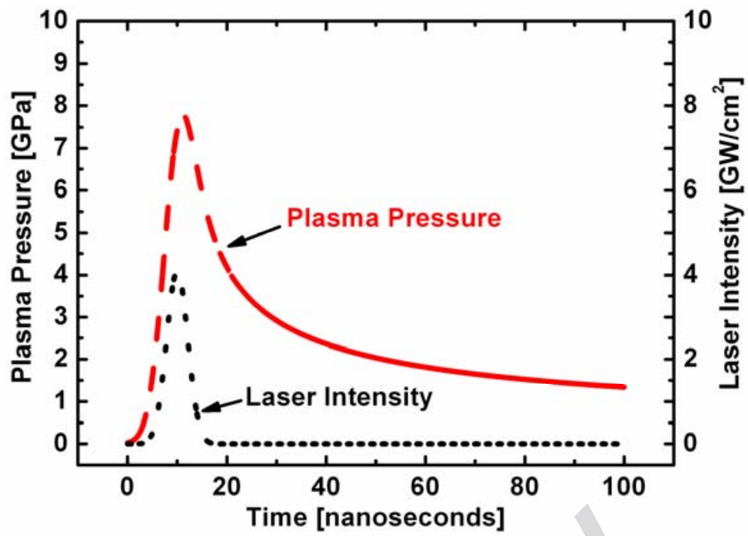


Figure 2.1 Time history of laser intensity temporal profile and the resulting plasma pressure temporal profile (Laser Intensity 4.1 $GW/cm^2$, Laser pulse width 5 ns, target material: copper, confining media: BK7 glass (Borosilicate crown glass), plasma peak pressure 7.8 GPa.)



## 2.2. Generation of Compressive Residual Stress by LSP

When a high pressure is suddenly applied to a metallic target, the pressure is accumulated in the wave front, since it cannot disperse away within such a short time. Thus, a discontinuous jump of pressure, density, and internal energy is formed across the wave front [8]. In this way, the shock wave is formed.

When the shock wave that propagates into the material exceeds the dynamic yield stress of the material, plastic deformation occurs, which induces compressive residual stress in the material and change the near-surface microstructure and properties. The generation of residual stress consists of two steps [9, 10] : step (1) the rapid expansion creates sudden uniaxial compression (Figure 2.2a) on the irradiated area and dilation of the surface layer and step (2) the surrounding material reacts (Figure 2.2b) to the deformed area, generating a compressive stress field.

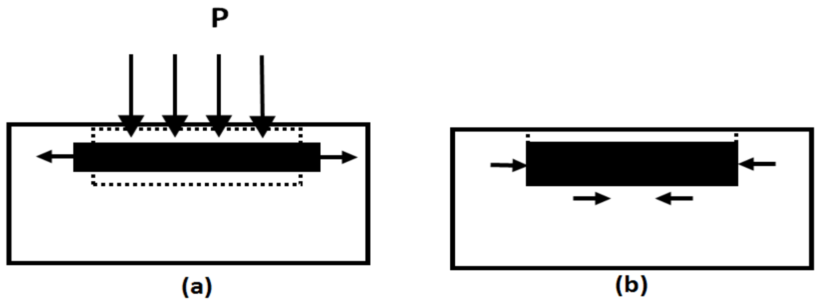


Figure 2.2 Generation of compressive residual stress by LSP, adopted from Peyre [9], reuse with permission from Elsevier

To evaluate the compressive residual stress, it is necessary to evaluate the plastic strain first. Figure 2.3 shows the material stress and strain behavior during LSP. In the loading process, the material stress increase linearly with the strain until the material yield point is reached. After that, the material work hardens and plastic strain occurs. In the unloading process, the stress-strain curve goes back to zero stress following a curve parallel to the elastic stress-strain line. At the end of the deformation process, some the elastic strain is recovered. The retained elastic strain corresponds to the residual stress after LSP. Ballard [11] analyzed the LSP process and proposed the relationship between the surface plastic strain and the peak plasma pressure as shown in Figure 2.4. The residual stress magnitude can be calculated by knowledge of the plastic strain, plastic affected depth and the material properties.

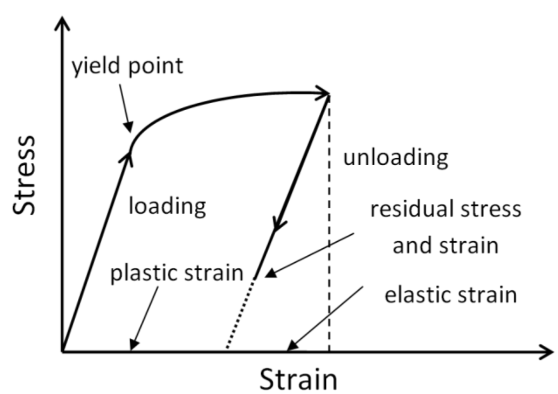


Figure 2.3 Stress and strain behavior of the material during LSP