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[INVITED] A review: Warm laser shock peening and related laser processing technique

Yiliang Liao [a,*], Chang Ye [b], Gary J. Cheng [c]

[a] Department of Mechanical Engineering, University of Nevada, Reno, Reno, NV 89557, USA
[b] Department of Mechanical Engineering, University of Akron, Akron, OH 44325, USA
[c] School of Industrial Engineering, Purdue University, West Lafayette, IN 47906, USA

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ABSTRACT

This paper reviews the recent progress in warm laser shock peening (WLSP) and related laser processing technique. The process design, enhanced mechanical performance, and microstructure evolution of WLSP are discussed in details. The fundamental process mechanism is reviewed by building the processing-microstructure-property relationship. In particular, the precipitation kinetics during WLSP is discussed to study the effect of process parameters on the nucleation of nano-precipitates, and multiscale discrete dislocation dynamics (MDDD) simulation results are summarized to investigate the dislocation multiplication and propagation behaviors as well as the dislocation pinning effect. In addition, the research progress of thermal engineered laser shock peening (TE-LSP) technique is reviewed with a focus on the coarsening of precipitates, the extended fatigue life, and more importantly, the fundamental process mechanism.

1. Introduction

Laser shock peening (LSP) is an effective laser-based surface processing technique used to treat metallic materials for the enhanced surface strength, improved wear and corrosion resistance, and extended fatigue life [1–18]. These superior mechanical properties are mainly attributed to the laser-induced surface compressive residual stress and work-hardened layer. Compared with other plastic deformation processes utilized for improving fatigue performance such as shot peening (SP) [19–26] and ultrasonic impact peening (UIP) [27–32], LSP holds advantages including: (1) a high magnitude and a deep depth of compressive residual stresses, (2) the capability of processing components with complex geometry, (3) the ability to precisely control the pulsed laser energy, and (4) the essentially undamaged target surface due to the existence of ablative coating layers. Therefore, LSP has been extensively applied for industrial applications.

Despite these advantages, the efficiency of LSP is mainly restricted by the major challenge that: the compressive residual stress as well as work-hardened layer are prone to relax under a mechanical loading or thermal heating process [1,2,4,33–35]. Half the initial compressive stress may be relaxed in less than only 10 min even at moderate engine temperatures. Three mechanisms are highlighted as primary causes of residual stress relaxation: (1) compressive or tensile over loading; (2) cyclic loading near or above the endurance limit; (3) exposure to thermal cycling. From a physical metallurgy point of view, the stress relaxation is associated with microstructure rearrangement through dislocation propagation and multiplication. Therefore, in order to improve the process efficiency and effectivity of LSP, it is of special importance to develop novel laser peening processes to improve the compressive residual stress stability.

To tackle the challenge of LSP in the aforementioned discussion, warm laser shock peening (WLSP) has been developed by Chengs research group at Purdue University since 2009 [36–47]. WLSP is a thermal–mechanical surface processing technique, which integrates the advantages of LSP, dynamic strain aging (DSA) and dynamic precipitation (DP) to generate unique microstructures with a high stability. As a strengthening mechanism, DSA promotes the dislocation multiplication through the interaction between mobile dislocations and diffused solute atoms. This results in more uniform and highly dense dislocation structures. DP, also known as the strain-induced precipitation, is a thermal–mechanical precipitation effect leading to the nucleation of precipitates during the deformation process. In WLSP, the nucleation process of DP is assisted by the presence of highly dense dislocations from DSA [48–50]. DP-induced nano-precipitates could resist the movement of nearby dislocations through the elastic interaction between dislocation and precipitates, the so-called dislocation pinning effect. This pinning effect makes the major contribution to

* Corresponding author.
E-mail address: yliao@unr.edu (Y. Liao).

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the improve stability of microstructure as well as residual stress. As a result, WLSP further improves the mechanical performance of metallic materials.

During WLSP, the DP-induced nano-precipitate size is normally 5–10 nm in diameter [36–38]. This is determined by the short DP time (on the order of nanoseconds) associated with the laser pulse duration. The dislocation pinning strength is strongly affected by several precipitate parameters including the size, number density, inter-particle spacing and volume fraction. In order to optimize the dislocation pinning strength, thermal engineered laser shock peening (TE-LSP) is further developed, which combines WLSP with a post-shock heating process to further improve the fatigue performance of metallic materials through tailoring precipitate parameters by extending the precipitation kinetics from the nucleation stage to the coarsening stage [43,44].

In this paper, WLSP and related laser processing technique are reviewed through discussions on the process design, enhanced mechanical properties and microstructure evolution. More importantly, the process mechanism is discussed through establishing the relationship among the process, microstructure and property. The knowledge gained from this review paper could provide important insights and guidance for the design of novel laser processing and/or thermal–mechanical processing techniques.

2. Warm laser shock peening

2.1. Process design

Fig. 1 shows a schematic view of WLSP experimental setup. The target material is heated up to a certain processing temperature during WLSP. Various heating methods could be applied to provide the thermal energy. A layer of ablative coating materials is placed on the top surface of target sample to absorb the laser energy, and protect the sample surface from any undesired damage. Once the focused pulsed laser energy reaches the sample surface, the ablative coating layer is vaporized and ionized to form the laser-induced plasma. The hydrodynamic expansion of laser-induced plasma is confined by the existence of the transparent confining media placed above the ablative coating layer. As a result, the laser-induced shockwave is generated and propagated into the target materials, resulting in beneficial plastic deformation. For the experimental setup, various materials could be used as the ablative coating layer, such as aluminum foil, black tape, graphite, etc., while the transparent confining media could be chosen from glass, water, silicon oil etc. Similar to conventional LSP process, Q-switched Nd-YAG nanosecond pulsed laser systems are feasible to carry out WLSP [36,38].

For WLSP experiments, the laser power intensity and processing temperature are the two most critical processing parameters for the process optimization. A higher laser power intensity normally leads to a greater magnitude of compressive residual stress, however a saturation point will be reached once the laser intensity is up to a certain level. The WLSP processing temperature should be sufficiently high for effective DA effect, but not too high to induce the thermal relaxation and microstructure rearrangement. In addition, several other laser processing parameters should be manipulated for WLSP process optimization, including the laser beam size, wavelength, overlapping ratio, etc.

2.2. Enhanced mechanical properties

The enhanced surface strength is one of the most important beneficial surface characteristics generated after WLSP. WLSP experiments have been carried out by researchers on aluminum alloy 6061 and 7075 (Fig. 2a and b) [36,40], and carbon steel AISI 4140 and 1042 (Fig. 2c and d) [38,41], and Titanium alloy Ti6Al4V [47]. As observed in Fig. 2, compared with the LSP samples, the WLSP samples exhibit a greater surface strength. For instance, with a laser intensity of 2 GW/cm^2, the surface hardness of AA6061 sample processed by WLSP at 160 °C (130 VHN) is 27.5% higher than that of LSP sample (102 VHN); with a laser intensity of 4 GW/cm^2, compared with LSP, WLSP can further enhance the surface hardness of AISI 4140 by 9.4% from 385 to 421VHN. This surface hardening phenomenon is attributed to both the strain hardening effect through the surface plastic deformation and the precipitation hardening effect through the generation of second phase nano-precipitates. Since the surface hardness test is relatively easier to carry out than other mechanical testing methods, the hardness test is normally employed to guide WLSP parameter optimization.

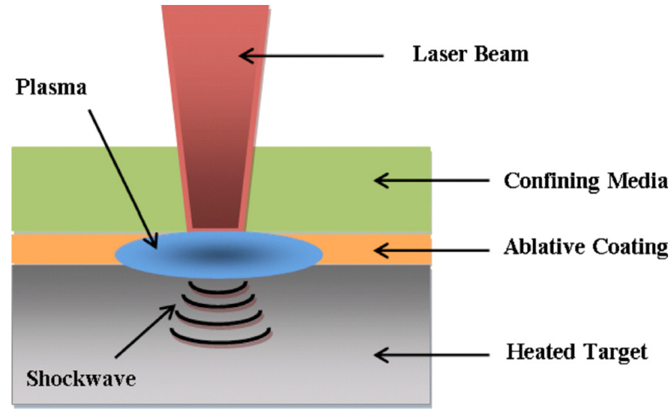

Fig. 1. Schematic view of WLSP experimental setup, adopted with permission from [37].

Besides the surface strength, the improved stability of compressive residual stress after WLSP makes the major contribution to the extended fatigue life. Fig. 3 shows the improved cyclic stability of compressive residual stress of AA6061 and AISI 4140 after WLSP [36,38]. As shown in Fig. 3a, WLSP-treated samples exhibit a higher cyclic stability of residual stress than that of LSP-treated samples, particularly at a high cycle region. For instance, the residual stress magnitude of LSP AA6061 sample decreased by 38% after 200,000 cyclic loading, while that of WLSP sample only decreased by 23% [36].

As per the aforementioned discussion, not only the magnitude and depth but also the stability of laser-induced compressive residual stress play critical roles on the determination of the fatigue performance of metallic materials. Fig. 4 shows the extended fatigue life after WLSP. Compared with LSP, after one million loading cycles, WLSP can further improve the fatigue strength of AA6061 (Fig. 4a) from 180 to 200 MPa. It is also observed that for the case of aluminum alloy, the improved fatigue performance is more significant in the high cycle region than the low cycle region [36]. For the case of carbon steel 4140, as observed in the stress-lifespan (*S–N*) curves in Fig. 4b, the fatigue limit of WLSP sample (1200 MPa) is 75 MPa greater than that of LSP sample (1125 MPa) [38]. For titanium alloy Ti6Al4V, as the low cycle fatigue performance shown in Fig. 4c, the fatigue performance of WLSP samples at 100–300 °C is better than that of room temperature LSP sample, however if the WLSP processing temperature reaches 400 °C, a significant fatigue life deterioration is observed [47].

Of specific interests, it is reported recently by Ye and co-workers that compared to room temperature LSP, WLSP of AA7075 has the capability of improving the material strength without sacrificing the ductility [40]. As shown in Fig. 5, WLSP sample has a higher strength of 557 MPa compared to LSP sample of 421 Mpa,