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Warm laser shock peening without coating induced phase transformations and pinning effect on fatigue life of low-alloy steel

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ABSTRACT

The current study proposes warm laser peening without coating process utilizing decarburized surface as the protective ablation layer and is directly intended towards the experimental evolution of existing laser shock peening technology. The interlath-retained austenites are transformed into martensites during warm laser peening. Also, the depth-wise compressive residual stress and its thermal relaxation behavior are comparatively prevailing. The scanning and transmission electron microscopic analysis identify the severe plastic deformation features of microstructures. So, the grain refinement and pinning force mechanisms on the mechanical properties are recognized. Further, the micro and nano-hardness studies provide a significant improvement in the surface and sub-surface mechanical properties. Moreover, the optimized fatigue life of low-alloy steel is achieved through the thermal engineering process. The present work increased the fatigue life of the specimen by 26 times and it is effectively repairing the partially pre-fatigued specimen.

1. Introduction

The surface modification technologies play a crucial part in designing materials for service applications in automotive and aircraft industries. The surface initiated cracks and corrosion pits on the material further propagating will lead to fatigue failure in many cases. Especially the heavy vehicle automotive suspension parts have to undergo high loading and continuous vibrations due to different road conditions. Shot peening based surface modification technology considerably improved the fatigue life of metallic materials over the last few decades. In general, it is well known that the process exhibits desirable property enhancement of engineering materials/components through induction of compressive residual stresses (RS) [1–6]. Since this technology introduces poor surface finish and less magnitude of penetration of compressive RS. Predominantly, relaxation of RS at moderate temperature is the drawback among the shot peening based surface modification technologies [2,6,7]. The advanced laser ablation based surface modification technology, namely: laser shock peening (LSP) has been getting greater attention over the last decade within the aircraft industries. In particular, it significantly improved the fatigue life and resisted the stress corrosion cracking [8,9]. The laser ablation, which produces intense plasma shock waves generates deep compressive RS. This compressive RS induced deformation mechanism is solely a cold working process which improves the fatigue, wear and corrosion properties of metallic materials [5,9–11].

The evolved decarburization on the hardened and tempered metal surface is removed completely during the laser ablation process [3]. The multiple laser shock peening without coating (LSPwC) using decarburized surface as an ablation protective layer on the low-alloy steel substantially increases the fatigue life of the specimen. The LSP producing grain refinement induced plastic deformation is liable to the fatigue life enhancement of metallic materials [13]. The ambient condition LSP treatment induced internal RS relaxation affects the mechanical properties of metal materials under exposed thermal conditions [14]. Considerable efforts have been directed towards low-alloy steels to enhance the fracture toughness in the past decades [15]. Thermal engineering based shot peening technology improved the fatigue life with low-stress relaxation. The optimum working temperature for dual phase spring steel was evaluated for shot peening process [16–17]. The thermal engineering based warm laser shock peening (WLSP) has advantages such as dynamic strain aging (DSA), and dynamic precipitation (DP) hardening of low-alloy steel which contributes an extensive improvement in fatigue life cycle [14,18–20,51,52]. LSPwC method of producing high compressive RS works efficiently with low energy lasers. Also, it is economical for commercial applications [5,21–24].

The current experimental process provides a constant warm condition to the working specimen and also the variations may not be more than 5–10 °C. The weaker decarburized surface is particularly focused to utilize for the laser ablation process [25,26]. The ferrite–martensite dual phase low-alloy steel is considered in the present investigation.

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The current research established an attempt to find a solution through investigating key microstructural properties in order to understand the fatigue life of metallic materials. Thus, fundamental understanding of the process could be established by further optimization of the process. Therefore, the motivation of this paper is first to conduct optimization of the WLSP without coating conditions to overcome the current issues with an ambient condition laser peening process. Then, the task is to evaluate the residual stress relaxation during thermal exposure conditions at the application stage. Thereafter, an efficient utilization of the decarburized surface as an ablative layer for the WLSP without coating process is investigated. The microstructural and mechanical properties of WLSP without coating specimens are then evaluated. Finally, post-shock tempering heat treatments are conducted in order to enhance the fatigue life of WLSP specimen.

2. Experiments and methods

2.1. Warm laser shock peening without coating

A high content of Si & Mn medium carbon low-alloy spring steel SAE 9254 (hardened at 900 °C and tempered at 400 °C) is used for the laser surface modification process. The LSPwC is performed on specimens at room temperature (25 °C) and on pre-warmed (250 ± 15 °C) specimens with a low energy Nd: YAG laser (Litron, UK) (300 mJ) of pulse duration 10 ns with a fundamental frequency of 1064 nm. The smooth and uniform surface is prepared for warm LSPwC. The thickness of BK7 glass confinement layer is 1 mm. In this case, WLSP parameters are being tuned to get a match of shock impedance between confinement glass layer and decarburized surface steel, in order to attain peak pressure (Table 1) [5,14,18–20,51,52]. The laser power density used for the current experimental process is 5.97 GW cm^{-2}. For industrial application higher pulse repetition mode can be chosen without causing an adverse effect. And for low energy laser higher repetition mode operation is comparatively easy. i.e., instead of 10 Hz repetition higher repetition rate can be chosen without compromise on the result for industrial application. There was no significant variation found among the treated samples with 5 Hz and 10 Hz pulse repetition rates during the optimization process [5,12,21]. The borosilicate glass (BK7) with around 90% of transmittance is used as the confinement layer for both the experiments which is confirmed using the Ultraviolet-visible (UV–Vis) spectrometer as shown in Fig. 1. In order to avoid fast cooling of the pre-heated specimen during WLSP experiments, the electrical dryers are used for continuous heating of target specimen holder surroundings. Subsequently, the WLSP treated specimen are slowly cooled from the processing temperature to avoid RS relaxation [14,18–20,51,52]. The authors earlier work investigated that direct laser ablation on the mirror polished surface works efficiently but, an anisotropic problem during the shock wave production is identified [5,21,24,27]. The reason is mirror polished surface would not act as an opaque medium. So, there might be a shock wave pressure anisotropic problems involved in the context of producing deep and high RS. A mild portion of decarburized black opaque layer surface is left for the current process and the high intense laser ablation removes it. Attending decarburized surface acts as a protective layer to avoid re-solidification and surface melting. Decarburized layer is removed partially by grinding it until getting a thin enough (100–150 μm) to avoid the effects of impedance mismatch for the full ablation and entire form of plasma for warm LSPwC operation. The current WLSP process holding aluminum foil is not an opaque medium and there exist an experimental coating problem during high-temperature processing of the material. In the case of high energy laser, the optimized thickness of protective surface needs to be maintained. The WLSP experimental working setup is shown in Fig. 2.

Table 1
Laser shock peening without coating experimental parameters.

Pulse energy	Pulse duration	Repetition rate	Power density	Pulse density	Spot diameter
300 mJ	10 ns	10 Hz	5.97 GW cm^{-2}	2500 pulses cm^{-2}	0.8 mm

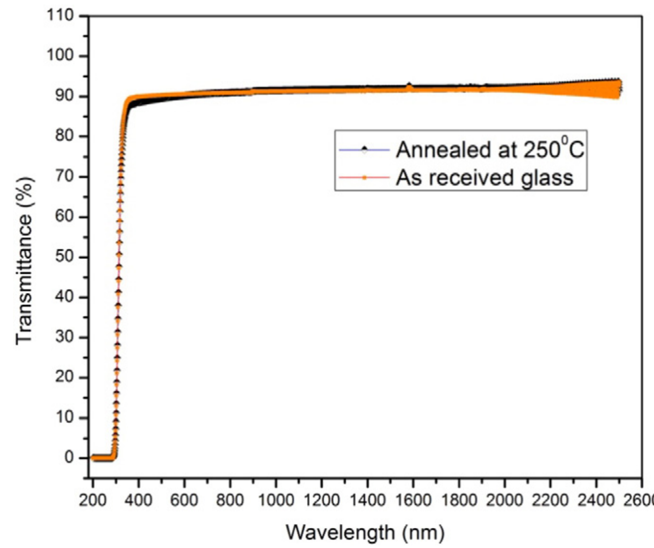

Fig. 1. The UV–Vis spectroscopic wavelength vs transmittance rate of BK7 glass.

2.2. Characterization methods

High-resolution X-ray diffraction is accomplished to investigate the phases of unpeened, LSP and WLSP specimens employing Cu$_{K\alpha}$ radiation as X-ray source (Bruker D8, USA). The compressive RS through the thickness was measured using X-ray diffraction sin$^2\Psi$ method. The X-ray irradiations at the diffractive angle (81.92°) are measured by X'pert Pro system (PANalytical, Netherlands) using Cu$_{K\alpha}$-radiation [32–33]. The electrolyte polishing successive layer removal technique was adopted for depth analysis of compressive residual stress. It is carried out by applying 80% methanol and 20% perchloric acid solution by controlling the voltage (18 V) with constant electropolishing speed. The depth level uncertainty during electropolishing in the surface layer (within error bar) is not considered for clarity of discussion. The Scanning Electron Microscopes (SEM, Hitachi S-4700 and Zeiss EVO 18 & FE-SEM, Carl Zeiss Ultra-55) and the high-resolution transmission electron microscope (HR-TEM, FEI, Tecnai-G^2 20, Netherlands) are used to analyze the key microstructural properties. The surface cross-sectional TEM samples are prepared by using precision ion polishing system. In order to study the laser peened plane surfaces, the mirror-like polishing is suggested after laser peening using a wet cloth to remove the ablated surface without any cause to the original surface. The average surface roughness measurements are carried out by a surface profilometer (MarTalk). According to ASTM: E384 standard, the transverse cross-sectional specimens are used to measure Vickers microhardness (Mitutoyo, Japan) with a constant load of 1.96 N (200 g). The depth-wise nanoindentation test is carried out using Berkovich nanoindenter (Hysitron Inc. Minneapolis, USA) by a successive layer removal technique using electropolishing method. Although, the depth level uncertainty during electropolishing in the surface layer (within error bar) is not considered for clarity of discussion. The fully reverse conditioned dynamic loading room temperature high cyclic fatigue tests are carried out utilizing the universal material testing servo-hydraulic machine (INSTRON 8801). The fatigue studies are performed according to ASTM standards ASTM: E466-07 and ASTM E-8/E8M. The dynamic load of tensile and compressive stress at a constant frequency and its average mean load are fixed to be zero. In order to complete the studies in a reasonable time frame, the testing parameters like load