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Studies on fatigue life enhancement of pre-fatigued spring steel specimens using laser shock peening

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ABSTRACT

SAE 9260 spring steel specimens after enduring 50% of their mean fatigue life were subjected to laser shock peening using an in-house developed 2.5 J/7 ns pulsed Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser for studying their fatigue life enhancement. In the investigated range of process parameters, laser shock peening resulted in the extension of fatigue life of these partly fatigue damaged specimens by more than 15 times. Contributing factors for the enhanced fatigue life of laser peened specimens are: about 400 μm thick compressed surface layer with magnitude of surface stress in the range of −600 to −700 MPa, about 20% increase in surface hardness and unaltered surface finish. For laser peening of ground steel surface, an adhesive-backed black polyvinyl chloride (PVC) tape has been found to be a superior sacrificial coating than conventionally used black paint. The effect of repeated laser peening treatment was studied to repair locally surface melted regions and the treatment has been found to be effective in re-establishing desired compressive stress pattern on the erstwhile tensile-stressed surface.

1. Introduction

Fatigue is one of the primary reasons for the failure of structural components. The life of a fatigue crack has two parts, initiation and propagation. In high cycle fatigue (HCF), with a polished part and no stress raisers, about 90% of the life is spent in fracture initiation [1]. In addition to enhancing fatigue life of components through various techniques, fatigue life extension of partly fatigue damaged in-service components remains area of high commercial interest. Fatigue life extension is usually achieved either by extending crack initiation period (before the appearance of a microscopic crack) or retarding crack propagation (after appearance of microscopic crack). Surface treatment has been identified as an effective tool for both delaying crack initiation as well for fatigue crack retardation. Both the approaches rely on modifying surface residual stress field or microstructure. Compressive residual stresses are known to significantly increases fatigue life and fatigue strength by inhibiting initiation and propagation of cracks [2,3]. Under fatigue loading conditions, compressive residual stress introduced in the surface layer by mechanical surface treatments (e.g. shot peening, autofretage, hole expansion, laser shock peening and low-plasticity burnishing [4]), experience cyclic relaxation [5]. Reintroduction of compressive stress field in partly fatigue-damaged specimens can set the clock back, thereby effecting extension of component's residual fatigue life. A local heating method is a popular technique for extending fatigue life in welded structures. It includes, spot heating and Linde's method [6]. In local heating method, the structure is heated locally so as to produce local yielding resulting in compressive thermal stresses. On the other hand, Linde's method is a low-temperature stress relaxation method [6]. Jang et al. demonstrated retardation of a through thickness fatigue crack by local heating [6]. There are also reports of rehabilitation of welds by hammer peening [7] and ultrasonic peening [8]. In recent years, laser has emerged as an effective tool for enhancing fatigue life [9–14]. Laser surface treatments which affect fatigue life rely on (i) generation of compressive residual stresses by phase transformation or by shock peening and (ii) tensile stresses from non-elastic thermal deformation [15,16]. Altus et al. used solid-state laser surface treatment to heal initial fatigue damage in Ti–6Al–4 V alloy [17]. Authors attributed healing to yielding and concluded that the laser treatment could be used multiple times as a practical repair method to erase fatigue damage up to the appearance of macro crack. Yee et al. reported an innovative solid-state CO_2 laser surface treatment to retard fatigue crack growth in 2024-T3 aluminum alloy [18]. Fatigue crack retardation was attributed to introduction of sufficiently high tensile residual stress at a region in front of the crack, which served to reduce magnitude of maximum

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Table 1
Nominal chemical composition and heat treatment conditions of the substrate.

Chemical composition (wt%)						Heat treatment temperature (K)	
C	Si	Mn	S	P	Bal.	Hardening	Tempering
0.56–0.64	1.5–1.8	0.7–1.0	⩽0.035	⩽0.035	Fe	1168–1208	723–763

Table 2
Experimental parameters of laser shock peening.

Pulse energy	Pulse duration	Repetition rate	Spot diameter	Scan speed	Track-to-track displacement
1.5 J	7 ns	2 Hz	1.5 mm	1.75 mm/s	0.7 mm

shear stress. In the last decade, laser shock peening has rapidly emerged as an effective surface treatment for enhanced fatigue life of engineering components [19–22]. The process exploits laser-generated shock waves to introduce high level of surface compressive stresses into the substrate. It involves irradiation of the substrate with high-energy short laser pulses causing instantaneous vaporization of the surface layer into high-temperature high-pressure plasma. Rapid expansion of the resultant plasma from the surface generates a high-pressure shock wave, which propagates into the substrate. When peak pressure of the shock wave exceeds dynamic yield stress of the substrate (Huguniot elastic limit), the metal is plastically deformed, thereby generating compressive residual stress on the surface of the substrate [23]. Tran etal [19] have reported that laser shock peening, in spite of being capital intensive with high running cost, is an effective fatigue life extension technology. An extensive survey conducted by Spradlin et al. [20] demonstrated fatigue life extension by laser shock peening (LSP) for a variety of specimen shapes, loadings, and materials. Hatamleh [21] used LSP to achieve significant increase in fatigue properties for failures involving surface-initiated cracks. Tan et al. [22] reported effective suppression of fatigue crack growth in Al alloys with various pre-existing notch configurations by LSP.

A recent study performed on SAE 9260 spring steel in authors' laboratory demonstrated significant increase in fatigue life over untreated as well as conventionally shot peened specimens [24]. The experimental study was carried to evaluate laser shock peening process as an alternative to existing shot peening practice for enhancing fatigue life of leaf springs. The present experimental study, an extension of the previous study, aims to evaluate laser shock peening process to rejuvenate partly fatigue damaged spring steel specimens.

2. Experimental details

The approach adopted for the present experimental study involved LSP of partly fatigue tested (about 50% of its expected fatigue life) specimens and comparison of their fatigue life with untreated specimens. The study was performed in 2 parts, viz. (i) characterization of fatigue life of the specimens, (ii) fatigue testing of specimens up to 50% of their expected life, followed by LSP of these partly fatigue-tested specimens and their fatigue testing. Similar approach has also been adopted by Spradlin et al. [20] for fatigue life extension of pre-fatigued 2024 aluminum alloy specimens through LSP.

The experimental study was performed on 6 mm thick plates of SAE 9260 spring steel in hardened and tempered condition. Table 1 presents chemical composition (in wt.%) and details of heat treatment condition of spring steel specimens, used for the experimental study. All heat treated specimens were subjected to surface grinding to remove soft decarburized layer [24] and surface oxide (with associated pits), developed during heat teat treatment. Uniform surface finish, without any decarburized layer, would serve to reduce scatter in fatigue life, thereby bringing out clear effect of LSP on fatigue life enhancement.

Laser shock peening was carried out with an indigenously developed 2.5 J flash lamp pumped Electro–Optically (E–O) Q-switched Nd:YAG laser system [25]. The experimental LSP setup comprised of (i) Nd:YAG laser system, (ii) beam delivery system consisting of a 45° plane mirror and a focusing lens of 400 mm (0.4 m) focal length, (iii) a 2- axis computer numerically controlled (CNC) workstation and (iv) a water recirculation system. The raw laser beam, emanating out of the laser system, is folded with a 45° plane mirror and focused with the help of a convex lens of 400 mm (0.4 m) focal length. Laser shock peening involved scanning painted surface of the specimen with a pulsed laser beam, while maintaining a layer of flowing water on the surface. The details of laser and experimental laser peening setup are provided elsewhere [24]. The optimized experimental parameters used for LSP [25] are summarized in Table 2.

Untreated and laser shock peened specimens were characterized by surface roughness measurements, residual stress measurements, nano-indentation, optical and scanning electron microscopy with energy dispersive spectroscopy and fatigue testing. Surface roughness measurements were performed with a diamond stylus based surface roughness tester. Residual stress measurements were performed with an X-ray diffraction based stress analysis system using Cr Kα radiation ($\lambda = 2.29$ Å). Standard d versus $\sin^2\psi$ method [26,27] was adopted for the determination of surface residual stresses along two orthogonal directions (along and across the direction of laser scanning). Depth profiling of residual stress involved sequential electro-polishing and stress measurement at regular intervals of about 50 μm. Microhardness measurements were carried out on the transverse cross-section of spring steel specimens as per ASTM: E384. Nanoindentation tests were performed on electro-polished surfaces of untreated (ground) and laser peened specimens using a nanoindenter at a load of 10 mN.

Fatigue tests were carried out on a 150 kN servo-hydraulic universal testing machine. A three-point bend loading configuration was selected for fatigue testing. In this particular fatigue test configuration, bottom surface of the specimen (refer Fig. 1) experienced cyclic tensile stresses while top surface was subjected to cyclic compressive stresses. Specimens were subjected to maximum stress in the range of 900–1200 MPa with a stress ratio (min. stress/max. stress) of 0.3 and tested at 10 Hz frequency. Under these loading conditions, fatigue failure was most likely to take place at the central part of the bottom surface experiencing maximum tensile stress, provided there were no defects like inclusions and microcracks around this region. Hence, central part of the tensile side of the spring steel specimens (dimensions: 80 mm × 50 mm × 5 mm) was subjected to LSP treatment (refer Fig. 1).