Available online at www.sciencedirect.com

ScienceDirect

International Journal of Fatigue 30 (2008) 188–197

International Journal of Fatigue

www.elsevier.com/locate/ijfatigue

Massive parallel laser shock peening: Simulation, analysis, and validation

A.W. Warren [a], Y.B. Guo [a,*], S.C. Chen [b]

[a] Department of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL 35487, United States
[b] Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712, United States

Received 29 August 2005; received in revised form 11 December 2006; accepted 21 January 2007
Available online 25 February 2007

Abstract

Laser shock peening (LSP) is a transient process with laser pulse duration time on the order of 10 ns, real time in situ measurement of laser/material interaction is very challenging. LSP is usually performed in a massively parallel mode to induce uniform compressive residual stress across the entire surface of the workpiece. The purpose of this paper is to investigate the effects of parallel multiple laser/material interactions on the stress/strain distributions during LSP of AISI 52100 steel.

FEA simulations of LSP in single and multiple passes were performed with the developed spatial and temporal shock pressure model via a subroutine. The simulated residual stresses agree with the measured data in nature and trend, while magnitude can be influenced by the interactions between neighboring peening zones and the locations of residual stress measurement. A design-of-experiment (DOE) based simulation of massive parallel LSP were also performed to determine the effects of laser intensity, laser spot size, and peening spacing on stresses and strains. Increasing the laser intensity increases both the stress magnitude and affected depth. The use of smaller laser spot sizes decreases the largest magnitude of residual stress and also decreases the depth affected by LSP. Larger spot sizes have less energy attenuation and cause more plastic deformation. Spacing between peening zones is critical for the uniformity of mechanical properties across the surface. The greatest uniformity and largest stress magnitudes are achieved by overlapping of the laser spots.

Keywords: Laser shock peening; Laser/material interaction; FEA; Residual stress

1. Introduction

Laser shock peening (LSP) is a surface treatment process designed to improve the mechanical properties and fatigue performance of materials. LSP is primarily conducted on metallic components. The principle of LSP is to use a high intensity laser and suitable overlays to generate high pressure shock waves on the surface of the workpiece.

An increase in fatigue strength is accomplished by the creation of large magnitudes of compressive residual stresses and increased hardness which develop in the subsurface. The maximum compressive residual stress is often formed at the surface of the workpiece and decreases in magnitude with increasing depth below the surface. The transient shock waves can also induce microstructure changes near the surface and cause high density of dislocations to be formed. The combined effect of the microstructure changes and dislocation entanglement contribute to an increase in the mechanical properties in the near surface.

It has been shown by previous research [1–8] that improved fatigue life of metallic components such as bearings, gears, shafts, etc. can be accomplished by inducing compressive residual stress and work hardening in the subsurface. The compressive residual stresses also improve resistance to corrosion fatigue. An advantage of LSP is that the magnitude of affected depth is very deep as compared with other surface processes such as conventional shot peening. In the case of rolling contact such as bearings,

* Corresponding author. Tel.: +1 205 348 2615; fax: +1 205 348 6419.
E-mail address: yguo@eng.ua.edu (Y.B. Guo).

0142-1123/$ - see front matter
doi:10.1016/j.ijfatigue.2007.01.033

the residual impressions from the LSP can also improve fatigue life by acting as reservoirs for lubricant.

During LSP (Fig. 1), the surface of the test specimen is usually first coated with a thin layer of material such as black paint which is opaque to the laser beam. This opaque layer acts as sacrificial material and is converted to high pressure plasma as it absorbs energy from a high intensity laser (1–10 GW/cm^2) for very short time durations (<50 ns). If the specimen surface is also submerged in a transparent media such as water, the rapidly expanding plasma cannot escape and the resulting shock wave is transmitted into the specimen subsurface. These shock waves can be much larger than the dynamic yield strength of the material (>1 GPa) and cause plastic deformation to the surface and compressive residual stresses which can extend to a deep depth in the subsurface. Due to the high strains/strain rates that the material undergoes, there can also be significant microstructure changes thus causing the mechanical properties such as hardness, tensile strength, and fatigue strength to be improved. Because thermal rise in the specimen is nearly eliminated by the water overlay, LSP is a primarily a mechanical process. In order to make the improved material properties more uniform, massive LSP zones must be created. It may also be advantageous to perform multiple LSP passes in order to create larger magnitudes of residual stress and hardness.

Previous LSP simulations have focused on a single laser peened zone. While these simulations are valuable for obtaining insight of the physical process by which the shock wave is propagated through the specimen, they may not accurately reflect the real process of LSP. In actual applications, multiple locations of the workpiece are usually shock peened in a massive parallel mode to accomplish uniform surface properties across the entire specimen surface. Single LSP simulation is only applicable to cases where the spacing between consecutive peening zones is sufficiently large. If the LSP zones are denser, the interaction between consecutive peened zones will become a significant factor for estimation of LSP affected depth, residual stresses, surface properties, and surface profiles.

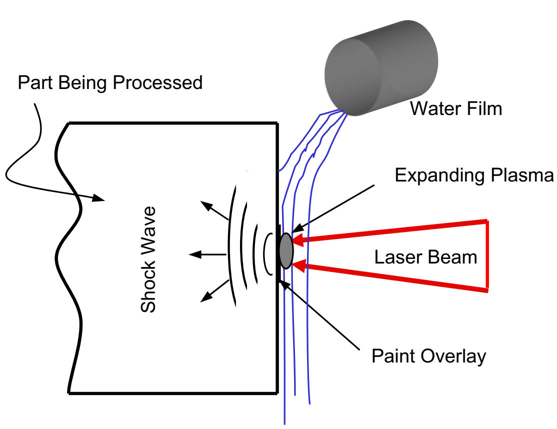

Fig. 1. Schematic of laser shock peening (LSP).

The objective of this research is to create a 3D finite element model to reveal the interactions between massive parallel laser shock peening of AISI 52100 steel. This will be accomplished in two steps. The first is to perform a simulation which can be compared to the experimental residual stress data [9]. A user subroutine has been created, for the first time, to model massive parallel laser shock pressure as a function of time and space. After this benchmark simulation was completed, a design-of-experiment (DOE) based sensitivity analysis was performed to test the effects of laser intensity, laser spot size, and peening spacing on stresses and strains.

This work sheds light on the complex interactions of massive parallel LSP to enable LSP process parameters to be properly selected to achieve optimal surface integrity. The effects of laser intensity, laser spot size, and peening spacing are critical to surface integrity characteristics such as residual stress, microstructure, and surface quality.

2. Literature review

A significant amount of LSP research has been conducted to investigate the surface integrity of metallic components. Most experimental work has focused on the determination of residual stress magnitudes and distributions at the surface and in-depth subsurface. The effect of LSP on mechanical properties such as hardness, fatigue strength, and fatigue life has been studied [10,11], however, more research is still needed. The resulting surface integrity can be correlated with the LSP process parameters such as laser intensity, laser spot size, peening pass, and peening spacing. The recent status of research and development on LSP of metals has been reviewed [12].

A primary goal of LSP is to induce deep compressive residual stress and work hardening in the surface of the workpiece. The depth and magnitude of compressive residual stress can vary depending on the LSP process parameters. Increasing the laser intensity increases both the magnitude and affected depth of the induced compressive stress in the subsurface. However, it has been shown that laser intensities greater than a particular threshold serve to decrease the surface stress magnitude, but continue to increase the magnitude and affected depth in the subsurface [3]. This was attributed to expansion release waves that are formed due to high energy shock waves. An investigation of laser spot size effect showed that energy attenuation is less for larger spot sizes allowing the stress shock wave to propagate deeper into the material [13]. Thus larger spot sizes increase the depth of plastic deformation. Laser peening across the entire specimen surface allows uniform mechanical properties. Peening spacing is critical to provide uniformity of mechanical properties across the entire surface. A study of overlapped laser spots [2,3,14,15] showed that the residual stress distribution is nearly uniform and is entirely compressive. Hardness decreases in the area between adjacent laser spots that do not overlap. When the spacing between adjacent peened zones is