Experimental and Numerical Investigation of Residual Stresses in low pulsed Laser Shock Peening on AA7075 T651

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Abstract
Laser shock peening (LSP) is the emerging technology among several severe surface treatment processes for improving mechanical characteristics of metallic materials by producing compressive residual stresses. Though several LSP experiments have been done on compressive residual stresses, scare amount of studies concentrated on numerical investigation of residual stresses in LSP. The objective of this article is investigation of the experimental and numerical study of compressive residual stresses on AA 7075 t651. In the experiment, residual stresses analysis is performed. The sin²Ψ method was utilized for measuring residual stresses. The three-dimensional (3-D) finite element method (FEM) analysis was applied to simulate the LSP on AA 7075 t651. The simulated and measured results showed good agreements. The numerical study was utilized to determine the compressive residual stresses.

1. Introduction
Laser shock peening (LSP) is a severe surface treatment process used to enhance the surface properties of the materials such as fatigue, wear and corrosion as result of induction in compressive residual stresses on the surface [1,2]. The objective of LSP is to acquaint compressive residual stresses in dangerous zones of fatigue. Though, the disadvantage of LSP is numerous process parameters which pay the resulting residual stress field. Therefore, the experimentation based on the optimization is a time-consuming process.

The numerical simulation on LSP such as FEA can speed up the optimization process and support to identify the mechanisms which are difficult to measure. Braisted and Brockman are reported on FEA analysis on LSP and found prediction of the residual stresses [3]. Dig and Ye studied the laser focus size and the influence of overlap and reported reasonable agreement to the experimental data [4]. Sathiyajith et. al investigated LSP on AA 6061, and reported high pulse laser shock peening process provides reliability issue due to its thermal effect [2]. Prabhakaran et. al reported low pulsed LSP process improved the mechanical properties of steel-based alloy [5].

From the literature survey, the low pulse energy on LSP is not done on non-ferrous materials and it provides better mechanical and surface properties so the study on low pulse LSP with non-ferrous material is important at this time and the simulation also necessary to predict the compressive residual stress with low pulse energy.

This study concentrates the Experimental and Numerical Investigation of Residual Stresses in low pulsed Laser Shock Peening on AA7075 T651.

2. Experimental techniques
2.1 Material
AA 7075 T651 material is thermo-mechanical treated so it possesses good mechanical property than other therefore it is selected for the experimental work. The sample was purchased from PMC Corporation,
Bangalore. The sample dimensions are 10mm×10mm×8 mm. before LSP, It was ensured that the surface of the sample is smooth and original. Table (a). and Table (b) shows the chemical composition and mechanical property of the sample.

2.2 Laser shock peening

The Nd: YAG laser with 1064 mm wave length was utilized in the LSP process. The beam quality factor (M^2) value is 2 and 08 mrad is beam divergence. Top hat profile was selected for shape of beam and a TEM00. Therefore the laser beam brightness is 345.04 mW cm^{-2}Sr^{-1}μm; this methodology used form literature [6,-8]. The black paint coating with 1 mm thick is used as an ablative layer and the thin 1-2 mm thick water layer was used confinement medium, which is also used for eliminate the ablated material constantly. The laser beam is passed on the material surface. The bi convex lens with 300 mm focal length and dichromatic mirror with kept 45° was utilized to deliver the laser beam on the target. The blower is placed nearer to the lens due to protect the lens from the water drops during LSP process. The sample holder was placed on XY translation stage, which is controlled by computer [9-12].

2.3 Test of Residual Stress

The magnitude compressive residual stress is calculated by X-ray Diffraction sin2Ψ method. X-pert Pro-system is used for computing the X-ray radiations of 4 mm^2 at the diffractive plane of (422). It is worked 40 mA and 45 kV voltage current utilizing Cu-Kα radiation (λ= 1.54 Å).

3. Modeling and Finite Element Analysis (FEA)

3.1 Simulation Parameters

The vital parameters involved in the FEA analysis on LSP process includes i) the laser spot shape and size, ii) the pressure pulse shape and duration, iii) geometric modelling and meshing, and iv) the material model. Except the mesh convergence study, the other parameters are selected on the basis of the experiments conducted in this research.

3.1.1. Laser Spot Shape & Size

If the spot diameter is in the range of 0.5 -1 mm it will create a high shock pressure, whereas the larger spot diameter will resulted in a lesser shock pressure. Hence, the laser spot size of 0.8 mm diameter (from Experiment) is used in this study and the shape of the laser spot used is the circle.

3.1.2. Pressure Pulse Magnitudes and Duration

A high amplitude and short- duration pulse are the key parameters with respected to the LSP processing. The magnitude of the shock pressure for the FEA is calculated as per the equation 2.1 and presented in Table 1.

Figure 1 depicts the pressure-time history. It is obtained from the experimental pulse duration and pressure formation. The simulation procedure does not change the explicit model of the physical process. Typically, the pressure pulse of the laser spot is relatively uniform over the complete surface, regardless of whether the laser spot is square or circular. It is owing to the narrow duration of the pressure pulse induced by LSP. The pressure--time history is demonstrated as a triangular ramp Gaussian temporal shape FWHM in the FEA simulation. The pressure increases linearly to a maximum value over the time of the pressure pulse FWHM and it then decays to zero.
Table 1. Magnitude of Shock pressure

| Pulse Energy (mJ) | Magnitude of Shock Pressure (GPa) |
|------------------|----------------------------------|
| 200              | 2.033                            |
| 300              | 2.45                             |
| 400              | 2.835                            |
Figure 1. Pressure (y axis) vs time history (x axis) of pulse energies a) 200 mJ b) 300 mJ c) 400 mJ

3.1.3. Geometric Modeling and Meshing

The modelling is done using ANSYS workbench19.2, with a dimension 10 x 10 x 6 mm and laser spot diameter of 0.8 mm as shown in figure 2.
Figure 2. Geometric model of AA 7075 T651

Figure 3. Meshed model of AA 7075 T651

The model is then meshed using ANSYS mechanical with a tetrahedral shape, containing about 1 lakh elements. A finer mesh of face size 0.2 mm used in the region where the laser beam pressure is applied. Whereas the remaining regions are meshed using a biased condition as shown in Figure 3.

3.1.4 Material Modeling

LSP makes strain-rates exceeding 106 s⁻¹ within the material target. The material model contributes a critical role in accurately FEA simulating the process with such a high strain-rate. In this research, two material models are explored for use in LSP simulation. The first model uses perfectly elastic-plastic material properties. In this model, Young’s modulus and dynamic yield strength are used to define material properties. The dynamic yield strength depends upon the Hugoniot Elastic Limit of the material. While the second model uses a bi-linear isotropic model analysis.
3.1.5. Loading and boundary conditions

A triangulated pulsed load is applied to the model on the region where it interacts with laser beam for this analysis with a varying peak pressure and 75% overlapping. A triangulated pressure load of 2.033 GPa, 2.45 GPa and 2.835 GPa for a pulse energy of 200 mJ, 300 mJ and 400 mJ respectively. The boundary conditions are fixed at bottom side of the model.

4. Results and Discussion

4.1 Residual Stress measurement

The maximum compressive residual stresses of unpeened and peened specimens with pulse energies 200 mJ, 300 mJ and 400 mJ are conferred in the Table (b)

| Pulse energies (mJ) | Compressive residual stress(MPa) |
|---------------------|---------------------------------|
| Unpeened (0)        | 50                              |
| 200                 | 168.78                          |
| 300                 | 262.35                          |
| 400                 | 317.38                          |

Table (b). Maximum residual values for diverse pulse energies

The T651 condition induces a compressive residual stress of around -50 MPa in the unpeened sample [4]. The compressive residual stress in the LSP phase, on the other hand, is much higher than in the unpeened sample. The degree of the compressive residual stress is directly proportional to the pulse energy, and at the same time, increase in depth for evaluating compressive residual stress with decreasing magnitude for the same, according to the trend result.

4.2 FEA Simulation of Residual Stress induced by LSP

FEA simulation of the compressive residual stress distribution in AA 7075 T651 peened with pulse energies of 200 mJ, 300 mJ and 400 mJ are shown in Figure 5, 6 & 8 respectively. It can be observed
that the maximum compressive residual stress value increases with the laser pulse energy, due to the increase in the energy imparted and profound compressive residual stress induced during the LSP.

Figure 5. FEA effect of compressive residual stress at pulse energy 200 mJ

Figure 6. FEA effect of compressive residual stress at pulse energy 300 mJ
Figure 7. FEA effect of compressive residual stress at pulse energy 400 mJ

4.2.1 Comparison of Experimental and Simulation Results

The comparison of the magnitude of compressive residual stress in the FEA and the experimental values of the peened specimen with pulse energies of 200 mJ, 300 mJ and 400 mJ are shown the Figure 8. The percentage error of the stress is 8.8 %, 6% and 5.3 % respectively; therefore the magnitude of compressive residual stress is attained using FEA model is in good compatibility with the experimental value for LSP process.

Figure 8. Comparison of compressive residual stress of FEA and Experiment results.

Conclusion

- The maximum residual stress induced in the 400 mJ used sample during LSP is 317 MPa which is 5.3 times that of compressive residual stress present in the as-received specimen.
- The prediction in maximum compressive residual stress in the 400 mJ used sample during LSP is -345 MPa and the variation from the experimental and predicted values obtained between 5 – 10 %.
- In FEA model analysis the magnitude of compressive residual stress is attained in good agreement with the experimental value for the LSP process

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