Journal of Materials Processing Tech. 255 (2018) 294–307

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Experimental and numerical investigation of residual stresses in laser shock peened AA2198

S. Keller[a,*], S. Chupakhin[a], P. Staron[a], E. Maawad[a], N. Kashaev[a], B. Klusemann[a,b]

[a] Helmholtz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Max-Planck-Straße 1, 21052 Geesthacht, Germany
[b] Leuphana University of Lüneburg, Institute of Product and Process Innovation, Volgershall 1, 21339 Lüneburg, Germany

ARTICLE INFO

Keywords:
Laser shock peening
AA2198
Residual stress
Hole drilling
X-ray diffraction
Focus size
Tempering conditions
Finite element analysis

ABSTRACT

Laser shock peening (LSP) is a surface treatment which improves the fatigue performance of metallic structures by introducing compressive residual stresses. The aim of this paper is the investigation of LSP of the aluminium alloy AA2198. This investigation includes the variation of the laser power density (2.78–25 GW/cm^2) and the square laser focus (1 mm × 1 mm and 3 mm × 3 mm). Additionally, two different temper stages (T3 and T8) and thicknesses (3.2 mm and 4.8 mm) of AA2198 are considered. The study of the LSP process is split into two parts; at first, LSP experiments are performed to clarify the influence of the temper stage, the focus size, the laser power density and the thickness of the specimen on the residual stress field. Secondly, a process model based on the finite element method is employed which requires in particular the adjustment of a suitable laser induced pressure pulse. Due to the different yield strength and strain hardening behaviour of the different temper conditions, AA2198-T8 shows a lower penetration depth of compressive residual stresses compared to AA2198-T3. A smaller focus size leads to higher compressive residual stresses near the surface but a lower penetration depth. To investigate possible shock wave reflections, different base layers in the LSP process are investigated considering a free, a clamped and a glued back-side of the specimen. No differences in terms of resulting residual stresses were observed. The experimental study provides some preliminary assumptions which are used to simplify the simulation set-up. Residual stresses are measured by the incremental hole drilling method using electronic speckle pattern interferometry (ESPI) as well as synchrotron X-ray diffraction. The calculated residual stresses in the simulation are averaged layer-wise over a sample area for comparison with the measured residual stresses. The model is used to simulate the LSP process for the considered temper stages and focus sizes to predict the resulting residual stresses. Simulated and measured residual stress profiles show for the different cases very good agreement.

1. Introduction

Laser shock peening (LSP) is a contact-free surface enhancement technique. Peyre et al. (1996) showed the improved fatigue performance on the cycle properties of different aluminium alloys. Clauer and Lahrman (2001) provided an overview of the surface enhancement properties achievable by LSP such as an increased corrosion resistance of the aluminium alloy AA2024-T3, which is investigated by Clauer et al. (1977). Handling fatigue and corrosion failure causes in light weight structures are main challenges in the aerospace industry as documented by Reid (2003). The aim of LSP is to generate compressive residual stresses in critical regions of fatigue. Crack driving tensile stresses have to overcome these compressive stresses to cause failure of the structure. Hence, addition of compressive residual stresses on possible tensile stresses caused by service loads leads to an increased fatigue life.

After the discovery of the effect of laser beam pulses on a target (Askar'yan and Moroz, 1963) followed by early publications (Fairand et al., 1972) which are focused on the microstructural and mechanical property changes in the material, LSP has been investigated continuously. This work contains the investigation of the LSP process of thin sheets consisting of AA2198 using an high energy laser enabling a laser power density up to 25 GW/cm^2. Dursun and Soutis (2014) provided recently a review on developments in advanced aircraft aluminium alloys. AA2198 is an aluminium-lithium alloy of the third generation and were developed for the aircraft industry to substitute common used aluminium-copper alloys such as AA2024. The advantage over traditionally used procedures (e.g. shot peening) is a higher penetration depth (in mm range) of compressive stresses in conjunction with a high surface quality (Peyre et al., 1996). Additionally, LSP allows

* Corresponding author.
E-mail address: soeren.keller@hzg.de (S. Keller).

https://doi.org/10.1016/j.jmatprotec.2017.11.023
Received 7 February 2017; Received in revised form 18 September 2017; Accepted 16 November 2017
Available online 20 November 2017

to treat complex geometries and does not involve any direct physical contact. A main difficulty in LSP are the many process parameters which influence the resulting residual stress field. Hence, experimental based optimization of LSP is a time consuming process.

Therefore, numerical simulation of LSP can speed up optimization processes and help understanding mechanisms which are difficult to measure (e.g. shock wave propagation). The first finite element (FE) simulation of LSP has been reported by Braisted and Brockman (1999). Depending on the specific research question of the simulation (e.g. prediction of the residual stresses, wave propagation or fatigue behaviour) several LSP process models based on the FE method were developed. Especially the discretised geometry and related simplifications (e.g. the use of symmetry conditions) influences the numerical effort. Using the rotational symmetry of circular laser spots two-dimensional FE models are resource effective tools to predict residual stresses. Thus, Ding and Ye (2006) used a two-dimensional-axisymmetric FE model which was in reasonable agreement to experimental data. The authors investigated the laser focus size and the influence of overlap, i.e. multiple laser pulses at the same spot. Sticchi et al. (2015) compared results of two-dimensional-axisymmetric and three dimensional FE model for LSP with overlap. It was concluded, that the fast and simple two-dimensional model can be used for first estimations. Three-dimensional models simulating a half space of the material using infinite elements were used to calculate detailed residual stress fields of pressure pulse-material configurations which the two-dimensional approach did not allow (e.g. square laser focus, specific laser pulse sequences or anisotropic material properties). Ocana et al. (2004) simulated deformations and residual stresses with a three-dimensional semi-infinite FE model. It is stated that a three-dimensional treatment of the LSP process is necessary for an effective assessment of the LSP technology. The use of an semi-infinite three-dimensional model is effective to determine the influence of the LSP conditions and material properties on the residual stress field but do not consider the specific geometry of a component. Three-dimensional discretisations of the whole component (Bhamare et al., 2013) or a part of it (Spradlin et al., 2011) lead to resource consuming simulations. Though, these allow the determination of the influence of complex geometries on residual stresses and enable the simulation of following process simulations (e.g. bending or tensile tests).

The LSP process simulation can be divided into two phases. The first phase is named laser-pulse-phase and includes the laser pulse simulation followed by all plastic deformation. The laser-pulse-phase is commonly simulated using an explicit solver due to the high dynamic short time events. The second phase (relaxation-phase) includes the dynamic relaxation of the system, where the material reaches static-equilibrium. The stresses of the static-equilibrium are the residual stresses if no external forces are applied. In the relaxation-phase only elastic deformations occur. Some authors are using an explicit solver to calculate a state sufficiently close to the equilibrium. Peyre et al. (2007) used an explicit solver for the simulation of multiple laser impacts in a pure mechanical model. Thermal effects were considered in a second implicit simulation. The results of both, thermal and mechanical simulation were combined in a thermo-mechanical simulation to solve the coupled problem. Brockman et al. (2012) and Bhamare et al. (2013) added damping to the system during the explicitly solved relaxation-phase to reduce the computing time. Another possibility is the use of an implicit solver for the relaxation-phase to calculate the equilibrium as shown by Braisted and Brockman (1999). A third method is demonstrated by Achintha and Nowell (2011). Here, the plastic strains of an explicit analysis of the laser-pulse-phase were extracted and put into a second implicit analysis as eigenstrains to determine the resulting residual stress field. Most of the numerical discretisation techniques do not model the the vaporisation of the material. However, Fabbro et al. (1990) demonstrate an analytical one dimensional model to predict the pressure pulse based on a defined laser pulse.

Independently from the modelling technique, major challenges are the material behaviour at high strain rates and the simulation of the laser impact. Both, material behaviour and laser impact conditions are often not precisely known and very difficult to determine experimentally. These uncertainties make the validation of simulations by experiments more difficult.

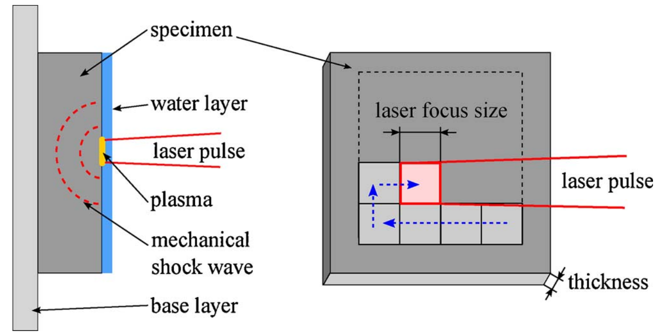

Fig. 1. Schematic of the LSP-process. The pulse leads by vaporization of the material to a plasma below the water layer which introduces shock waves into the material which lead to a characteristic residual stress field. The laser pulses are applied in a specific pattern.

This work is focused on the determination of the influence of tempering condition, material thickness, base layer, focus size and laser power density on the residual stresses in AA2198. Firstly, experimental results based on hole drilling measurements of the residual stresses are presented which are validated by X-ray diffraction. These results are used to set up a FE model which fits well to the measured data. Finally, comparisons between experiment and simulation for different temper conditions and focuses are shown.

2. Experimental techniques

2.1. Laser shock peening

A schematic of the LSP process is shown in Fig. 1. The first layer of the material is vaporized and turned into plasma by a pulsed laser. This high energy input leads to thermal expansion of the plasma which induces pressure shock waves propagating into the material. These shock waves lead to local plastic deformations close to the surface which cause residual stresses. The efficiency of the process is increased by transparent overlay, in this case a thin water film. The transparent overlay increases the duration and the maximum of the plasma pressure. In this work laser pulses were placed next to each other without overlap in the shown pattern.

LSP was performed at the Helmholtz–Zentrum Geesthacht with an Nd:YAG laser and a square laser focus with the focus size 1 mm or 3 mm. The laser pulse energy was varied between 0.6 J and 5 J with the Full Width at Half Maximum (FWHM) of 20 ns and a Gaussian profile. These laser pulse parameters lead to laser power densities between 2.78 GW/cm^2 and 25 GW/cm^2. The laser pulse energy and the FWHM are kept constant during the experiments. The experimental set-up is shown in Fig. 2. LSP specimens were fixed with a clamping device made of steel. To guarantee a laminar water film, water is sprayed above the area which will be peened. The material behind the specimen, the base layer, was varied during the experiments. It was investigated if the base layer affects the reflected shock wave. The superposition of reflected and initial shock waves could influence the resulting residual stress field. In this work three kinds of base layer were used, namely steel, air and a glued base layer.

Fig. 3 shows the used geometry of the specimens. The specimens dimensions are 90 mm/100 mm × 50 mm × 3.2 mm/4.8 mm. The investigated material is rolled AA2198 in T3 or T8 heat treatment condition. T3 condition was the delivery state of the material. Heat treatment to T8 condition was performed according to the material supplier