Numerical simulation of fatigue life of 2A02 aluminum alloy treated by overlapping laser shock processing

Songbai Li, Chong Wang, Zijian Kang and Cheng Zhang

School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China
E-mail: namewangc@csu.edu.cn

Abstract. Laser shock processing (LSP) has been now recognized as an efficient surface strengthening technology to improve fatigue, corrosion and wear resistance of metals. In this paper, the effect of residual stress on the fatigue life of 2A02 aluminum alloy specimens subjected to LSP was investigated by the finite element method (FEM). This investigation was split into two parts, numerical simulation of the LSP process and the fatigue analysis. The LSP simulation was performed using the commercial code ABAQUS. The fatigue analysis, using the residual stresses obtained in the previous LSP simulation as input, was performed by the commercial node nCode Designlife. The simulation results indicate that under the fatigue loading of maximum axial stress of 365MPa and the stress ratio of R=0.1, the fatigue life of specimens with LSP was extended up to 205.7% from 12,290 times to 25,280 times. It was observed that the residual compressive stresses induced by LSP can significantly prolong the fatigue life of 2A02 aluminium alloy specimens. It is found that simulation results are well agreement with available experimental data. It indicate that FEM calculation of specimen life with LSP is feasible.

1. Introduction
In order to improve the reliability of aerospace equipment under service conditions and prolong its service life without changing the quality of the matrix material, the surface strengthening technology has been increasingly researched and applied internationally. Laser shock processing, as a new surface strengthening technology, can significantly improve its fatigue life, so it has been widely studied and applied.

Currently, researches on the effect of LSP on the fatigue life are mainly based on the fatigue test method. However, this method usually has the disadvantages of long test period, high cost, etc. Moreover, the results are poor in repeatability and consistency due to too many factors affecting fatigue life.

With the rapidly development of the finite element software, numerical simulation using finite element software can meet certain requirements. At present, researches on LSP simulation [1, 2] have been reported at home and abroad, but those mainly focused on the shock wave propagation and residual stress distribution under single laser spot, and the dynamic response process of materials and plastic deformation during LSP, and obtaining a higher and more uniform residual stress distribution by optimizing the LSP parameters. However, there is few report on the simulation of the residual stress distribution and fatigue life under overlapping laser shock processing.
In this paper, the commercial code ABAQUS combined with fatigue analysis software nCode Designlife were employed to predict the fatigue life of 2A02 aerospace aluminum alloy specimens with LSP, and the simulation results were compared with available experimental results.

2. FEA simulation of overlapping laser shock processing
The numerical simulation of overlapping laser shock processing by ABAQUS is mainly divided into two steps: The first step is to use ABAQUS/Explicit code to simulate and analyze the shock wave propagation and dynamic response of material. Then, the dynamic stress distribution obtained in the previous step is taken as the initial state, and it is imported into ABAQUS/Standard code to perform springback analysis and obtain a stable residual stress distribution under static equilibrium. When simulating the impact of multiple spot laps, the residual stress distribution obtained from the previous impact is taken as the initial state of the next impact. Repeating the above process can obtain the residual stress distribution under multi-beam overlapping.

2.1. The establishment of finite element model
In accordance with the standard GB/T 3075-2008 "Metallic materials - Fatigue test - Axial force - Control method", the geometric model of the 2A02 aluminum alloy specimen was established. The specific dimensions are shown in figure 1. Due to the axial symmetry of the laser shock treatment area, only half of finite element model has been created. The diameter of the laser spot used in simulation is 6mm, the overlapping ratio is 50%, and the size of the impact area is 9mm×18mm. Therefore, six spots were totally defined on the model. The specific overlapping path is shown in figure 2. The C3D8R hexahedral element was used for the model. According to the literature [3], when the ratio of the element feature length to the laser spot diameter is approximately 2.5%, the simulation results gradually stabilized. Therefore, the model was divided into 70 equal parts in the entire z direction and y direction and x direction to 10.5 mm area, and the element size was 0.15mm. The rest region of x axis gradually coarsening, the largest element size was about 3 mm, the total number of elements were 86,229. The full-constrained boundary condition was applied on the bottom surface of the specimen, and the symmetric boundary condition was applied on the X-O-Y symmetry plane.

![Figure 1. Geometric model](image1)

![Figure 2. Finite element model](image2)

2.2. Material constitutive model.
The essence of LSP is the interaction of high-pressure plasma shock wave with metal materials. Under this ultra-high strain rate condition, the strain rate of metal materials exceeds $10^6$ s$^{-1}$, the mechanical behaviour of the material under impact is clearly different from the quasi-static condition. The constitutive equation used in this paper is the Johnson-Cook (J-C) model. It is the most commonly used constitutive model for the dynamic performance of materials. It can be well applied to high-pressure and high-speed impact processes, the relationship is simplified as equation (1):

$$
\delta_y = \left( A + B \varepsilon^n \right) \left[ 1 + C \ln \left( 1 + \frac{\varepsilon'}{\varepsilon_0} \right) \right]
$$

Where $A$ is the yield strength, $B$ is the strengthening modulus, $n$ is the hardening index, $C$ is the strain sensitivity coefficient, $\delta_y$ is the yield strength, $\varepsilon$ is the plastic strain, $\varepsilon'$ is the strain rate, and
\( \dot{\varepsilon}_0 \) is the reference strain rate. For 2A02 aluminum alloy, the J-C parameters are shown in table 1 [4]. The other parameters of 2A02 aluminum alloy are as follows: Elastic modulus \( E = 69520 \) MPa, Poisson's ratio \( \mu = 0.3 \), Density \( \rho = 2850 \) kg/m\(^3\).

| Material | \( A/\text{MPa} \) | \( B/\text{MPa} \) | \( n \) | \( C \) | \( \dot{\varepsilon}_0 \) |
|----------|----------------|----------------|------|------|----------------|
| 2A02     | 265            | 426            | 0.34 | 0.015 | 1              |

### 2.3. Laser shock wave pressure

The precise definition of the laser shock wave pressure is the primary factor which can guarantees the reliability of LSP simulation results. In this simulation, the laser spot diameter was 6mm, the laser pulse width was 23ns, and the peak shock pressure was 1.5GPa. According to the available research results [5], the pressure-time of the shock wave under the constrained model is approximately Gaussian, and the duration of the shock wave is 2 to 3 times the laser pulse width. Therefore, the duration of the shock wave pressure in this paper was approximately 70 ns. The specific parameters are shown in figure 3. In the previous laser shock simulation, a simplified uniform distribution space model was generally used. In order to obtain a more accurate spatial pressure distribution model, ZHANG et al. [6] studied the distribution of the laser shock wave pressure in the radial direction of the laser spot. The results show that the laser shock wave pressure obeys the Gaussian distribution in space, and the specific expression is as shown in equation (2). Therefore, this simulation chooses to use a more accurate Gaussian spatial distribution model. Creating a spatially resolved distribution was applied in ABAQUS in order to define precisely the shock wave pressure spatial distribution.

\[
 f(x, y) = \exp\left(-\left(x^2 + y^2\right)/ 2R^2\right)
\]  

(2)

Where \( x, y \) is the rectangular coordinate distance from any area to the spot centre, \( R \) is the diameter of the spot.

![Figure 3. Pressure pulse profile](image)

### 2.4. Results and discussion

In the solution control, the settings of the total step time and increment step are the main parameters. In ABAQUS/Explicit, the total step time was 4500 ns and the stable incremental step was 6 ns. The remaining parameters could use the software default settings. The static residual stress distributions after each shock were obtained respectively. The residual compressive stress \( S11 \) is shown in figure 4. It can be seen from figure 4 that the surface has a stress distribution close to the spot diameter after the first spot, and the maximum residual compressive stress was -119.7 MPa. After the second spot, the maximum residual compressive stress was -128.7 MPa. The maximum residual stress of overlapping region was basically same as the centre of the spot, because the area was subjected to two shock,
indicating that the overlap shock can improve the uniformity of the residual stress distribution. After the shock of the 6th spot, the maximum residual compressive stress on the surface was -133.2MPa, which was well agreement with the experimental results in literature [7].

![Figure 4. Distribution of surface residual compressive stress S11 after point-by-point impact](image)

3. Fatigue analysis
Under the conditions of axial loading maximum stress of 365MPa, stress ratio of R=0.1, and the frequency of f=1.5Hz, nCode Designlife was used to predict the fatigue life of 2A02 aluminum alloy specimens with LSP. The specific steps are as follows: the first step is to create a finite element model of the specimen in ABAQUS in order to obtain the linear stress under the maximum load. Moreover, the ODB results file in ABAQUS including the maximum load linear stress and the residual stress with LSP were imported into nCode Designlife. The second step is to define the load spectrum by using the TSGenerator module coupled with the Arithmeticl module in nCode Designlife. The load was a sine wave which the amplitude was 164.25 MPa, the mean was 200.75 MPa and the frequency was 1.5 Hz. The third step is to define the material parameters. The strain life $\varepsilon$-N curve was estimated by inputting the strength limit of 2A02 aluminum alloy of $\sigma_b = 455$MPa and setting the material type as aluminium alloy. The fourth step is to set the analysis method as the strain fatigue analysis, considering that most of the materials used in the aviation distribution are mainly low-cycle fatigue failures. Meanwhile, the load spectrum was related to the maximum load linear stress, and the residual stress of the specimen with LSP was linearly superposed as the static stress.

3.1. Static calculation under maximum load conditions
The axial force was 7300N, i.e., the nominal maximum stress was 365MPa. The numerical results are shown in figure 5. Seen from figure 5, there was a stress concentration at the arc transition of the specimen and the maximum stress was 408 MPa. However, due to the fact that the stress concentration area is small and the cross-sectional area is large, it is not the smallest area of the specimen life and the effects of stress concentration can be ignored here. The hazardous area of the specimen should be at the smallest cross section where the maximum stress was 365.87 MPa. Compared with the nominal stress of 365 MPa, the error is 0.2%. The simulation results are close to the theoretical values and can be used to calculate the subsequent fatigue life.
3.2. Numerical calculation of fatigue life on specimens without LSP

The fatigue life contours of specimens without LSP is shown in figure 6. The minimum fatigue life cycles shown in figure 6 was 12,290 times. The average fatigue life of specimens without LSP in the experimental results of literature [7] was 11,690 times. The error between the predicted fatigue life and the experimental life was 5.1%, which was verified the reliability of using nCode Designlife to calculate fatigue life. Comparing figure 5 to figure 6, it is verified that the stress concentration in figure 5 does not affect the fatigue life.

Figure 5. Stress distribution after applying a maximum load

Figure 6. Specimen life without LSP

3.3. Numerical calculation of fatigue life on specimens with LSP

The fatigue life contours of specimens with LSP is shown in figure 7. The minimum fatigue life of the laser shock area of the specimen surface was 25,280 times, and the fatigue life was extended up to 205.7%. Comparing the predicted life to the experimental results of literature [7], the experimental average fatigue life of specimens with LSP was 26,881 times, and the error was 6%, which indicates that the numerical simulation of specimen life with LSP by means of nCode Designlife is feasible.

Comparing figure 4 to figure 7, it is found that the residual compressive stress region of the specimen is basically consistent with the fatigue life improvement region, which indicates that the residual compressive stress induced by LSP is the main factor for the improvement of the specimen fatigue life. In addition, the predicted fatigue life are slightly smaller than the available experimental results, probably due to the lack of consideration of surface dislocation and nanometerization.
Figure 7. Specimen life with LSP

4. Conclusions
(1) Laser shock processing will induce compressive residual stress on the surface of specimens. When the laser spot diameter is 6mm, the laser pulse width is 23ns and the peak shock pressure is 1.5GPa, the maximum residual compressive stress on the surface of specimen is approximately -133.2MPa.

(2) Numerical simulation results show that the fatigue life of specimens without LSP and specimens with LSP were 12,290 times and 25,280 times, respectively, the fatigue life was extended up to 205.7%.

(3) It is found that the residual compressive stress region of the specimen is basically consistent with the fatigue life improvement region, which indicates that the residual compressive stress induced by LSP is the main factor in improving the fatigue life of 2A02 aluminum alloy specimens.

(4) The numerical simulation results are well agreement with the experimental results, verifying the reliability of the numerical simulation.

Acknowledgements
This work was financially supported by the Hunan Science and Technology Plan Project (Grant No.: 2016GK2005).

References
[1] Ding K 2003, Three-dimensional Dynamic Finite Element Analysis of Multiple Laser Shock Peening Processes, Surface Engineering. 19(5), 351-358
[2] Keller S, Chupakhin S and Staron P 2017, Experimental and numerical investigation of residual stresses in laser shock peened AA2198, Journal of Materials Processing Technology
[3] Yongxiang Hu, Zhenqiang Yao 2006, The Time Step Choosing for FEM Simulation of Laser Shock Processing, Journal of Shanghai Jiaotong University. 40(10), 1743-1747
[4] Zhikai Zhang 2016, Study on the Dislocation Density and Grain Size of Metal Surface by Laser Shock Peening, Jiangsu University. Chapter3 pp16-17
[5] Peyre P, Fabbro R and Merrien P 1996, Laser shock processing of aluminum alloys. Applications to high cycle fatigue behavior, Materials Science & Engineering A. 210(1-2), 102-113
[6] Wewu Zhang, Yao Y L and Noyan I C 2004, Microscale Laser Shock Peening of Thin Films, Part 1: Experiment, Modeling and Simulation, Journal of Manufacturing Science & Engineering. 126(1), 10-17
[7] Xinmin Luo, Jingwen Zhang and Guangzhi Zhao 2009, Effect of Laser Shock Strengthening on Fatigue Behaviors of 2A02 Aluminum Alloy, Chinese Journal of Lasers. 36(12), 3323-3328