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ARTICLE

Finite Element Analysis of Surface Roughness Generated by Multiple Laser Shock Peening

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Abstract: Laser shock peening (LSP) is a novel surface processing technique for improving the fatigue properties of metal parts, and surface roughness is a critical parameter when fatigue strength resistance is concerned. In this paper, a three-dimensional (3D) finite element model was developed in order to assess the surface roughness evolution induced by multiple LSP. A modified finite element analysis (FEA) method was used to compute the vertical displacements profiles, and discrete data obtained from the numerical simulations were subsequently input to the proposed discretized formula to calculate the surface roughness R_a. The results obtained from the numerical simulations are in good agreement with the experiment data from open literatures, which validates the proposed approach. After the validation of the numerical model, a parametric study was conducted in order to predict the effects of overlap rates, number of impacts, and pulse energy on surface roughness R_a.

Key words: laser shock peening; surface roughness R_a; numerical simulation

Laser shock peening (LSP) has emerged to be a new and promising technique because it can significantly improve the fatigue behavior of metallic components by inducing compressive residual stresses[1,2]. Other applications of LSP are aimed at improving the corrosion resistance and wear resistance of the material[3,4]. Comparing with other traditional surface treatment methods, LSP produces deeper compressive residual stress to the surface of the metallic targets, more uniform stress distribution, and less risk of microstructure damage [5-7].

Surface roughness from the LSP process plays a highly important role on fatigue lives of metallic components, and many investigations have concentrated on experimentally to investigate the influences of the LSP process parameters on surface roughness of the target. For instance, Petan et al.[8] investigated the effects of laser pulse density and spot diameter on the surface roughness of X2NiCoMo18-9-5 Maraging steel. Irizalp et al.[9] analyzed the influences of LSP parameters, including number of laser impacts and spot size on the surface roughness. Salimianrizi et al. [10] analyzed the effects of beam overlapped rates, number of laser shots and scanning pattern on surface roughness. Shadangi et al.[11] investigated the influences of LSP time on surface roughness of interstitial free steel through an experiment. Kalainathan et al.[12] investigated the influences of LSP pulse density on surface roughness of 316L steel.

In most cases, the effect of LSP parameters on surface roughness is studied by means of experimental trials which are expensive and time-consuming. Recently, the finite element analysis (FEA) method has been used to study the effect of LSP parameters on residual stress and surface displacement in metallic components[13-16]. However, few studies have focused on the influences of LSP parameters on surface roughness by FEA method. In this paper, the mean arithmetic roughness (R_a) was obtained from the statistics of nodal vertical displacements along some sample paths based on the presented discretized formula. The nodal vertical displacements were predicted by a modified FEA method[17]. Benchmark simulation for the mean arithmetic roughness was validated by comparing the computed results with available

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LSP experimental results. After the validation of the numerical model, the effects of overlap rates, number of impacts, laser pulse energy on surface roughness of 2050-T8 aluminum alloy processed by multiple LSP with square spots were discussed.

1 Definition of the Surface Roughness Parameter

Among all the parameters for quantifying roughness, the mean arithmetic roughness (R_a), defined by Eq.(1), is by far the most frequently chosen surface parameter[18,19].

$$R_a = \frac{1}{l}\int_0^l f(x,z)\mathrm{d}x \quad (1)$$

where $|f(x,z)|$ represents the distance between the target surface node coordinate (*x, z*) and the mean line within sampling length, *l* (see Fig. 1).

According to the definite integral theory, the discretized formula of the mean arithmetic R_a can be expressed as:

$$R_a = \frac{1}{l}\sum_{i=1}^{m}|f(x_i,z_i)|(x_{i+1}-x_i) \quad (2)$$

where *m* represents the number of the nodes, $(x_{i+1}-x_i)$ represents node spacing, and z_i represents the vertical displacement along the direction of LSP.

The mean line is usually written as:

$$z = Kx + D \quad (3)$$

where *K* is the slope of the straight line and *D* is the *z*-axis intersection, the mean line can be obtained by least square method in commercial software Matlab. $|f(x_i,z_i)|$ can be defined by:

$$|f(x_i,z_i)| = \frac{|z_i - Kx_i - D|}{\sqrt{1+K^2}} \quad (4)$$

when node spacing $(x_{i+1}-x_i)$ is constant, after some manipulation , this leads to the following expression for R_a:

$$R_a = \frac{1}{m\cdot\sqrt{1+K^2}}\sum_{i=1}^{m}|z_i - Kx_i - D| \quad (5)$$

2 Numerical Simulation

2.1 Description of FEA model

A three dimensional (3D) model developed using commercial finite element code ABAQUS was used to simulate the process of 25 square laser spots impacting on the target surface. The target was modeled as a rectangular body (40 mm×40 mm×5 mm) and the shocked region was located in the center of the upper face (Fig.2a). Target mesh was set up by 25322495, C3D8R finite elements and CIN3D8 infinite elements (Fig.2b). The element size of 150 μm×150 μm×100 μm was used near the shocked region.

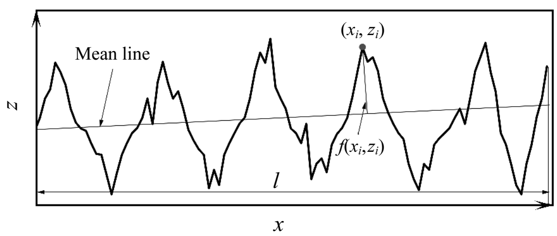

Fig. 1 Calculation of the profile roughness parameter R_a

2.2 Material model

The material used in this study is 2050-T8 aluminum alloy. Young's modulus, poisson's ratio, and density of 2050-T8 aluminum alloy are 72 GPa, 0.33, and 2750 kg/m^3, respectively. The typical strain rate is as high as 10^6/s in the LSP process. In this work, the dynamic behavior of the material is defined with a Johnson-Cook model[20], which is widely used to represent high strain rate phenomena. The Johnson-Cook equation is as follows:

$$\sigma = \left(A + B\varepsilon_p^n\right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \quad (6)$$

where σ is the equivalent flow stress, ε_p is the equivalent plastic strain, $\dot{\varepsilon}$ represents dynamic strain rate, and $\dot{\varepsilon}_0$ is the quasi-static strain rate; *A*, *B*, *C* and *n* are considered to be the material constants called Johnson-Cook constitutive constants. The parameters of Johnson-Cook model for the material are listed in Table 1[21].

2.3 LSP pressure loading

During the LSP process, the high magnitude stress wave is generated by the interaction between the high power densities, short pulsed lasers and materials, the peak shock pressure (*P*, GPa) can be calculated by Eq.(7)[22]:

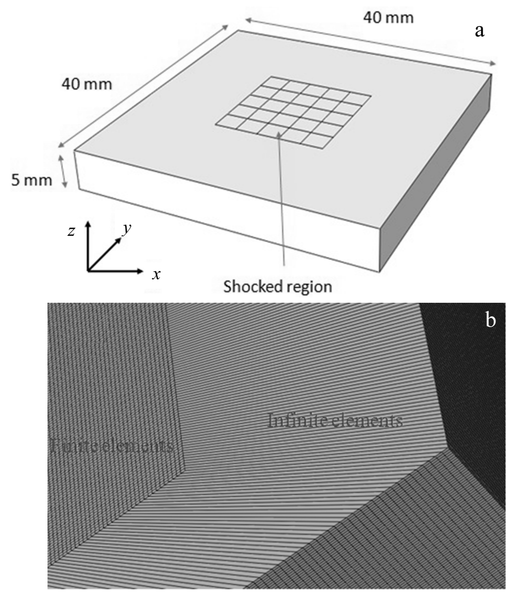

Fig.2 3D FEM (a) and 3D FEM mesh (b)

Table 1 Johnson-Cook model constants for 2050-T8 aluminum alloy[21]

A/MPa	*B*/MPa	*n*	*C*	$\dot{\varepsilon}_0$/s^{-1}
510	200	0.45	0.02	0.01

$$P = 1.65\sqrt{I_0} \tag{7}$$

where I_0 is the absorbed laser power density, GW/cm^2.

In this study, because square spot shows better homogenous in intensity, the spatial distribution of shock pressure was presumed to be uniform. The temporal profile of the impact pressure evolution obtained from experiments is shown in Fig.3 [21].

In the work, we imposed 25 pressure pulses impacting the target surface successively as shown in Fig.4. The overlapping rate φ was defined by the equation:

$$\varphi = \frac{\Delta d}{d} \times 100\% \tag{8}$$

where d is laser spot size, and Δd is the distance between two adjacent laser impacts.

2.4 Numerical model validation

A modified explicit procedure [17] was adopted to get the coordinates (x_i) of the nodes on the whole impact area and their assigned vertical displacement (u_3=z_i). The modified explicit simulation approach adopted for LSP contains two analysis steps. The first is used for each LSP with a short duration explicit approach until the kinetic energy approximates zero. The second is used for the final shot with an extended-duration explicit approach instead of implicit analysis.

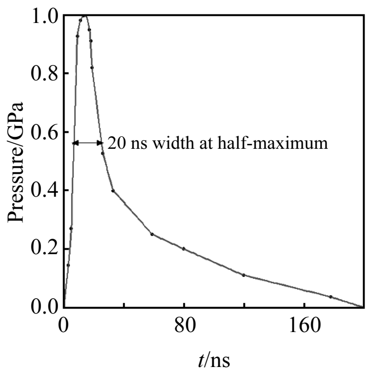

Fig.3 Normalized pressure pulse induced by a 8~10 ns laser pulse used in ABAQUS

A VDLOAD subroutine was used to generate impact position and the impact sequence in ABAQUS/Explicit. In addition, another routine has been developed in Matlab software, by which the surface node data (x_i, z_i) obtained from ABAQUS are imported to get the mean line. Having defined the position of mean line, the data (x_i, z_i) are chosen to calculate the surface roughness R_a by Eq.(5) and at last make an average of surface roughness R_a. The schematic diagram for the roughness parameter calculation is presented in Fig.5.

The numerical model was validated by comparing the computed results with available LSP experimental results[23], in which two samples of 2050-T8 aluminum alloy with 14 mm diameter-8 mm thick cylinders and 30 mm × 30 mm × 10 mm square shaped plate were treated by LSP. In the experiments, a power density of 5 GW/cm^2, a laser spot diameter of 1.5 mm, two overlapping rates of 50% and 25% were used for 14 mm diameter-8 mm thick cylinders; a power density of 5 GW/cm^2, a laser spot diameter of 5 mm, and the overlap of 25% were used for 30 mm×30 mm×10 mm square shaped plate in the LSP process. The results obtained from FEA were compared with the experimental data in Fig.6. As can be observed in Fig.6, the comparison of the experimental and numerical surface roughness values shows a good correspondence. This correspondence confirms the validity of the numerical model.

3 Results and Discussion

After the validation of the numerical model, a parametric study was conducted in order to predict the effect of overlap rates, number of impacts, and pulse energy on surface roughness R_a. Fig.7 shows the contour plot of the vertical displacements (u_3=z) of the surface when overlapping rate is 5%, and spot size is 3mm, and pulse energy is 8.75 J. The corresponding vertical displacements (u_3 = z) are considered using the inserted black dot lines (see Fig.7), the data (x_i, z_i) are chosen to calculate the surface roughness R_a by Eq.(5) and at last make an average of the surface roughness R_a .

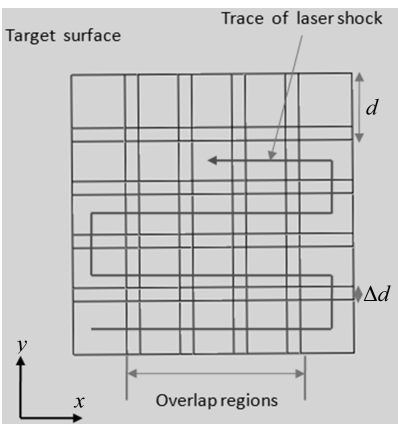

Fig.4 Overlapping laser shock processing

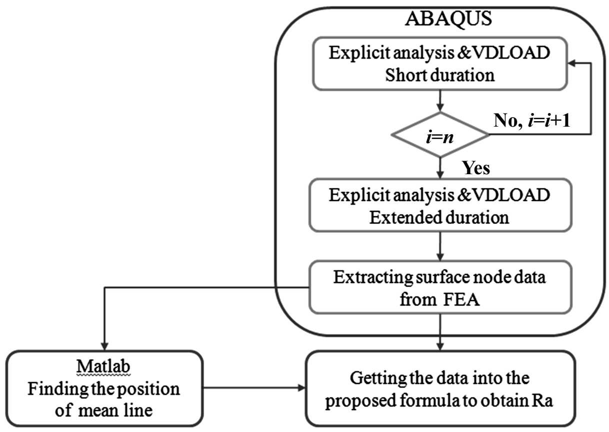

Fig.5 Schematic diagram for roughness parameter calculation

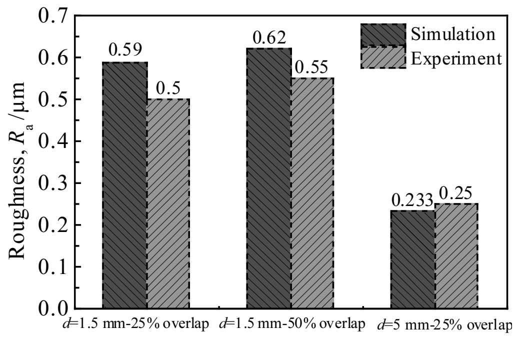

Fig.6 Comparison of computed and experimentally measured surface roughness R_a [23]

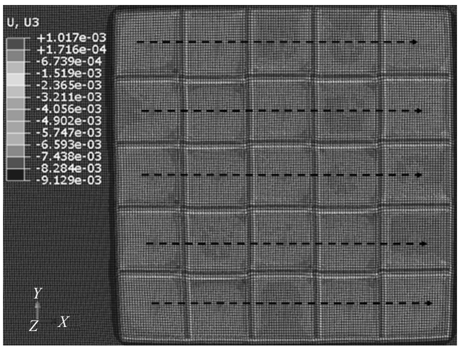

Fig.7 Vertical displacements u_3 caused by LSP treatment

3.1 Effect of overlap rate

The simulation was performed to evaluate the effect of overlap rate on the surface roughness R_a under the same pulse energy of 8.75 J, spot size of 3 mm, and pulse duration of 10 ns. The overlapping rate was assumed to be 5% and 50%. Fig.8 shows the variation of the vertical displacement of the surface for 5% overlap and 50% overlap. Fig.8 shows that the vertical displacement and indentation width are more larger for 50% overlap. Similar results were observed in the previous literature report [24]. In Fig.9, the surface roughness of two specimens treated by two overlap rates is compared. As illustrated, the overlap rate could affect the surface roughness

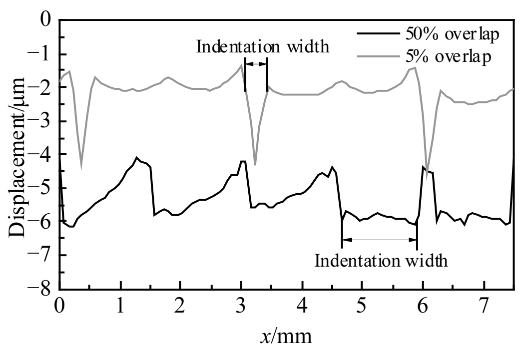

Fig.8 Vertical displacements profiles with different overlap rates

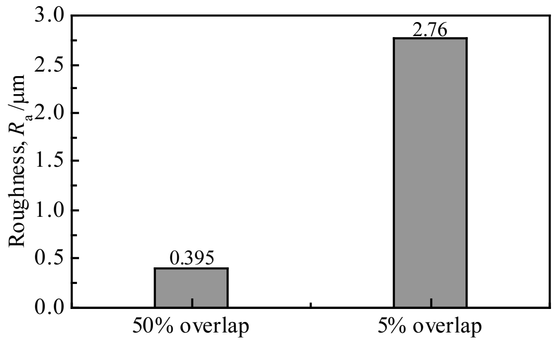

Fig.9 Effect of overlap rate on surface roughness

and 5% overlap increases the roughness, which is verified by Salimianrizi et al.[10].

3.2 Effect of multiple impacts

To evaluate the effect of multiple laser impacts on the surface roughness, the pulse energy, spot size, pulse duration, and overlap rate are defined to be 8.75 J, 5 mm, 10 ns, and 50%, respectively.

Fig. 10 shows the vertical displacement increases with increasing the number of impacts. Fig. 11 shows surface roughness increases with the increase of the number of impacts. Similar results have been reported by several researchers[9,25]. These results can be explained as a result of local plastic deformation which is induced by the increasing

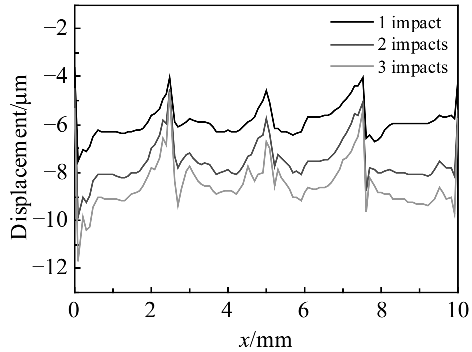

Fig.10 Vertical displacements profiles for multiple impacts

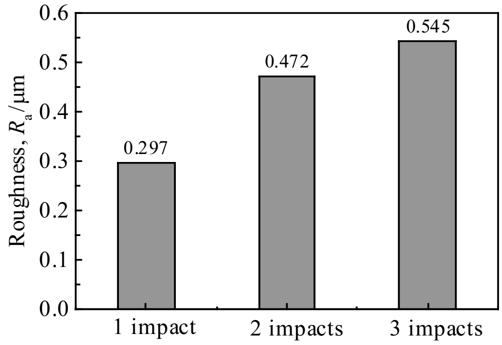

Fig.11 Effect of impact number on surface roughness

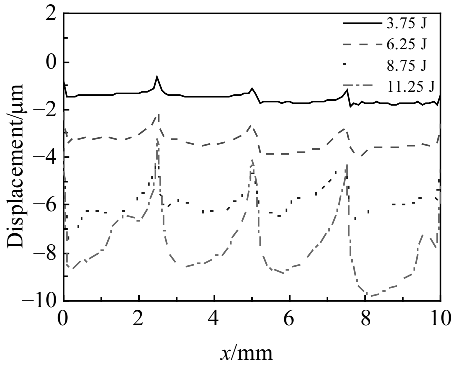

Fig. 12 Vertical displacements profiles for pulse energy

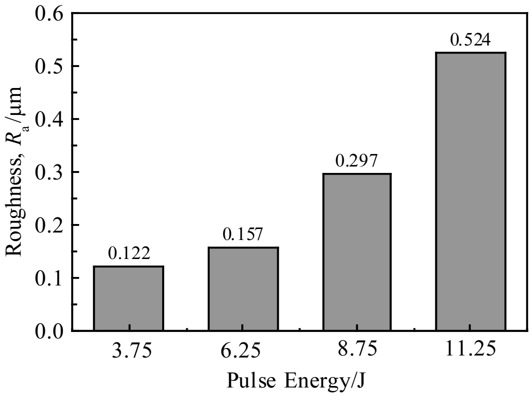

Fig.13 Effect of pulse energy on surface roughness

LSP number, because the vertical displacement is introduced onto the target surface by the increase of LSP number.

3.3 Effect of pulse energy

The surface roughness is influenced by the pulse energy. In this work, the surface roughness was calculated (spot size 5 mm, pulse duration is 10 ns, and overlapping rate 50%), and the pulse energy used for the simulation was assumed to be 3.75, 6.25, 8.75, and 11.25 J, respectively.

Fig. 12 shows the surface indentation becomes more pronounced and vertical displacements increase with the increase of the pulse energy, which is verified by Chu et al.[26]. Fig. 13 shows surface roughness increases with increasing laser pulse energy. Qiao et al.[27] reported a similar effect of the pulse energy on the surface roughness. To explain this phenomenon, the local plastic deformation caused by the plasma-induced shock waves should be taken into consideration. The shock waves induced by LSP increase with the increase of pulse energy.

4 Conclusions

1) A modified FEA method is used to compute the vertical displacements profiles.

2) The discretized formula for surface roughness R_a is proposed based on the definite integral theory.

3) The numerical model is used to predict the surface roughness by applying the computed results as inputs to analytical equations. The comparison with experimental results allows to affirm that the model is a useful tool to predict surface roughness parameters.

4) The vertical displacements increase with the increase of overlap rates, the number of impacts, and pulse energy.

5) Surface roughness increases with increasing the number of impacts and pulse energy; compared with 5% overlap, 50% overlap can generate lower roughness.

References

1 Huang S, Zhou J Z, Sheng J *et al*. *International Journal of Fatigue*[J], 2013, 47: 292

2 Zhao J, Dong Y, Ye C. *International Journal of Fatigue*[J], 2017, 100: 407

3 Caralapatti V K, Narayanswamy S. *Optics & Laser Technology* [J], 2017, 93: 165

4 Sanchez-Santana U, Rubio-Gonzalez C, Gomez-Rosas G *et al*. *Wear*[J], 2006, 260(7): 847

5 Montross C S, Wei T, Ye L *et al*. *International Journal of Fatigue*[J], 2002, 24(10): 1021

6 Zhigang C, Jie Y, Nan T *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(12): 2962

7 Gujba A K, Medraj M. *Materials*[J], 2014, 7(12): 7925

8 Petan L, Ocaña J L, Grum J. *Surface and Coatings Technology*[J], 2016, 307: 262

9 Irizalp S G, Saklakoglu N, Yilbas B S. *The International Journal of Advanced Manufacturing Technology*[J], 2014, 71(1-4): 109

10 Salimianrizi A, Foroozmehr E, Badrossamay M *et al*. *Optics and Lasers in Engineering*[J], 2016, 77: 112

11 Shadangi Y, Chattopadhyay K, Rai S B *et al*. *Surface and Coatings Technology*[J], 2015, 280: 216

12 Kalainathan S, Sathyajith S, Swaroop S. *Optics and Lasers in Engineering*[J], 2012, 50(12): 1740

13 Cao Ziwen, Che Zhigang, Zou Shikun. *Rare Metal Materials and Engineering*[J], 2013, 42(S2): 222

14 Kim J H, Kim Y J, Lee J W *et al*. *Journal of Mechanical Science and Technology*[J], 2014, 28(5): 1803

15 Kamkarrad H, Narayanswamy S. *Journal of Mechanical Science and Technology*[J], 2016, 30(7): 3265

16 Ocana J L, Morales M, Molpeceres C *et al*. *Applied surface Science*[J], 2004, 238(1): 242

17 Vasu A, Hu Y, Grandhi R V. *Surface and Coatings Technology*[J], 2013, 235: 648

18 Schmähling J, Hamprecht F A, Hoffmann D M P. *International Journal of Machine Tools and Manufacture*[J], 2006, 46(14): 1764

19 Anselme K, Davidson P, Popa A M *et al*. *Acta Bomaterialia*[J], 2010, 6(10): 3824

20 Johnson G R, Cook W H. *Proceedings of the 7th International Symposium on Ballistics*[C]. The Hague: Johnson-Cook Model, AISI, 1983, 21: 541

21 Hfaiedh N, Peyre P, Song H *et al*. *International Journal of Fatigue*[J], 2015, 70: 480

22 Berthe L, Fabbro R, Peyre P *et al*. *Journal of Applied Physics*[J], 1997, 82(6): 2826

23 Peyre P, Hfaiedh N, Song H *et al*. *International Journal of Structural Integrity*[J], 2011, 2(1): 87

24 Cao Ziwen, Xu Haiying, Zou Shikun *et al*. *Chinese Journal of Aeronautics*[J], 2012, 25(4): 650

25 Qiao Hongchao, Zhao Jibin, Gao Yu. *Chinese Journal of Aeronautics*[J], 2015, 28: 609

26 Rigsbee J M, Banaś G. *Materials Science and Engineering A*[J], 1999, 260A: 8

27 Qiao H, Zhao J, Zhang G *et al*. *Surface and Coatings Technology* [J], 2015, 276: 145

多点激光冲击强化表面粗糙度的有限元分析

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摘　要：激光冲击强化技术是一种新型的表面处理技术，它能够改善金属零件的疲劳性能，当考虑材料的抗疲劳性能时，表面粗糙度是一个关键参数。为了评估多点激光冲击强化表面粗糙度的变化规律，建立了三维有限元模型。采用一种改进的有限元分析方法获得零件表面节点的垂直位移，由数值模拟得到的离散化数据带入提出的表面粗糙度离散化公式，得到表面粗糙度 R_a 的值。数值模拟的结果与已有文献中的实验数据具有较好的一致性，验证了仿真模型的可行性。在此基础上，研究分析了搭接率、冲击次数和脉冲能量对表面粗糙度的响。

关键词：激光冲击强化；表面粗糙度R_a；数值模拟

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