Residual stress induced by multi-micro laser shock peening under overlapping process

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In order to investigate the effect of multi-micro laser shock peening on residual stress of copper materials, surface residual stress is measured, and distribution of residual stress under different overlapping rates and laser energies is explored. Surface mean residual stress is proposed as characteristic means according to the defect of test equipment in existence. Numerical simulation is carried out to display residual stress distribution on top surface and depth in the overlapping process of microscale laser peening. The results show that overlapping rate and laser energy greatly influence the distribution of residual stress, and the surface mean residual stress is an effective characteristic means according to the residual stress distribution along typical paths and mean stress formula.

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Laser shock peening (LSP) has been effectively used to introduce residual compressive stresses into the surface of metals to improve fatigue performance since 1960s[1−3]. The previous studies were focused on the treatment of macro-components with laser beam diameter at the order of millimeter. Recently the expanding applications of small devices with dimensions of several millimeters make the mechanical properties of such devices an increasing concern. Processes that can improve the mechanical properties at microscale are required. Micro laser shock peening (μLSP)[4] with laser beam diameter at the order of micron can modify surface properties of such metal components and enhance fatigue life. Experiments of μLSP have been carried out in Columbia University since 2002[5−7] The results show that μLSP imparts beneficial residual compressive stress in the surface layer of copper by properly choosing process parameters, and residual stress distribution is regarded as the main characteristic means because residual compressive stress takes key effect on balancing tensile stress to improve fatigue life. Moreover, to implement strengthening treatment of larger area, multi-μLSP is adopted. Distribution of peening times in shock region is different under different overlapping rate conditions, which leads to the result that there is great difference in residual stress distribution. So it is important to investigate the influence of overlapping on residual stress in multi-μLSP.

In this letter, changes of surface mean residual stress in multi-μLSP were explored experimentally, residual stress distribution on top surface and depth was displayed in numerical simulation.

The feature size of shock region is at micron order, but the tube diameter of X-ray stress analyzer is mostly at about 1 mm, it is difficult to precisely measure the stress in single spot shocked region. As a result mean residual stress considered as characteristic parameter of strengthening effect in multi-μLSP is a simple and practical means.

According to overlapping process of LSP, shock region is repeated by the combination of four adjacent spots, two along the x direction and two along the y direction according to characteristic of circle spot overlapping, stress representative unit is selected as Fig. 1.

Square composed by four spot centre is partitioned into many regions, with different overlapping rates and different partition regions n. When overlapping rates are −50%, 0, and 50%, n is 5, 5, and 9, respectively. Mean residual stress can be expressed as

$$\bar{\sigma}_s^{rc} = \sum_{i=1}^{n} \frac{\vec{\sigma_i}\, s_i}{S}, \tag{1}$$

where s_i is the area of partition region i in the square, S is the area of square, $\vec{\sigma_i}$ is the residual stress of partition region i in the square, and n is the number of partition regions in the square.

Spitlight 2 000 Nd: YAG laser was used with pulse duration of 8 ns and wavelength of 1 064 nm. Samples were pure copper sheet with size 15×10×1 (mm), and black paint was spread on the surface as energies absorption layer. Three different energies of 515, 675, and 835 mJ were considered in the experiment, three different overlapping rates of 50%, 62.5%, and 75% were used, and spot diameter was 800 μm. Schematic of multi-micro laser shock processing is shown as Fig. 2, where η is the overlapping rate, a, b, c, and d represent the directions of peening paths, respectively, and shock region is 10×8 (mm).

X-350 stress analyzer was used to measure the residual stress of the shocked region. Tube diameter adopted in measurement is 1 mm. As a result that every measuring

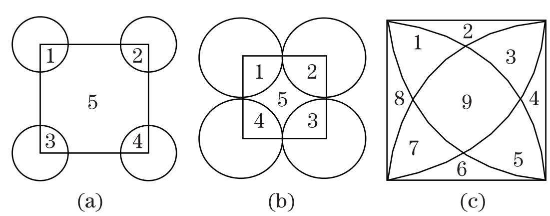

Fig. 1. Representative unit with different overlapping rates of (a) –50%, (b) 0, and (c) 50%.

point involves influence region of 6–15 laser spots. Arrangement of measuring points for X-ray diffraction is shown in Fig. 3.

Figure 4 shows distributions of surface mean residual stresses under different overlapping rates. As seen, surface mean compressively residual stress increases by –40 MPa with overlapping rate increasing from 62.5% to 75% and –80 MPa with overlapping rate increasing from 75% to 87.5%. Obviously it increases with the increase of overlapping rate. This is directly related to peening times. Single-spot μLSP experiment was conducted by Zhang *et al.*[8] under the condition of laser energy E=240 μJ, spot diameter d=12 μm, and peening times n=1, 3. The results indicated that compressive residual stress increases from –50 to –75 MPa with n increasing from 1 to 3. Peening times of partition region in representative unit is different with different overlapping rates. When overlapping rate increases, proportion of partition regions with higher peening times increases, which leads to the increase of mean residual stress. So the results agree with that of Ref.[8] based on Eq. (1).

Figure 5 shows surface mean residual stress field under

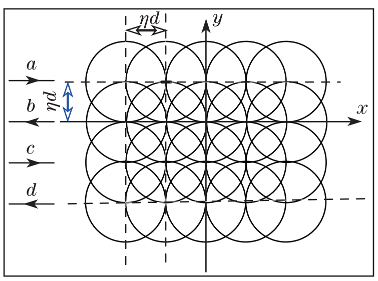

Fig. 2. Schematic of multi-micro laser shock processing.

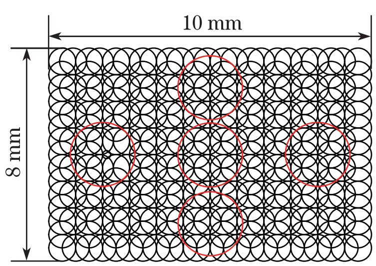

Fig. 3. Arrangement of measuring points for X-ray diffraction.

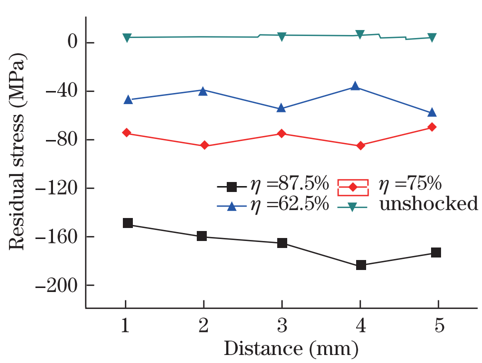

Fig. 4. Surface mean residual stress field under different overlapping rates. (d=800 μm, E=515 mJ)

Table1. Material Performance Indexes

Material	ρ(kg.m^{-3})	ν	E(GPa)	σ_b(Mpa)
Cu	8 960	0.3	136	259

different energies with overlapping rate of 62.5%. Surface mean compressive residual stress increases from –45, –75 to –120 MPa with laser energy increasing from 515, 675 to 835 mJ, respectively, it increases obviously with the increase of energy. When laser irradiates the surface of materials, large amounts of laser energy are added suddenly to a material system, creating intense sound or pressure waves that become shock waves. Beneficial residual compressive stress is imparted into the processed surface layer of metal or alloy parts when the peak pressure created by the shock wave is above the dynamic yield stress of the material. Usually, the range of peak pressure induced by μLSP is about 1–10 GPa, which confines within the impact of elastic-plastic mechanism. Peyre *et al.*[9] showed that magnitude of residual stress on metal surface increased with the increase of peak pressure, while peak pressure induced by laser depends on laser energy. Surface mean residual stress is resulted by the interaction of single points, so the result agrees with the research of Ref. [9].

Finite element analysis software ABAQUS was used. Pure copper material performance was shown in Table 1. The laser beam diameter was 800 μm, the laser energy 515 mJ, the overlapping rate is 62.5%, and shock processing is shown as Fig. 2. The strain rate and rate effect on yield strength were considered while temperature was taken as room temperature, material was assumed as isotropic and homogeneous and obeyed Von Mises' yield criterion, C3D8R element was selected for the high strain rates (10^7 s^{-1}).

Typical paths along the x direction were chosen based on symmetry distribution of schematic of multi-micro laser shock processing along both the x and y directions. According to characteristic of circular spot overlapping, two typical paths O-O and A-A were selected as shown in Fig. 6, where O-O passes through centre of spots, and A-A is 1/2R parallel to path O-O.

Figure 7 shows residual stress nephogram along path O-O and A-A at surface and depth of sample. Residual compressive stresses distribute at top surface and two typical paths, and influence depth of both paths almost coincides.

Figure 8 shows residual stress distribution along path

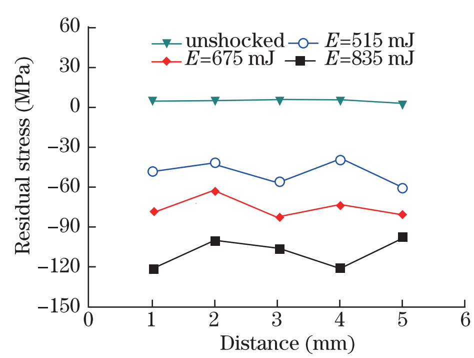

Fig. 5. Surface mean residual stress field under different energies. (d=800 μm, η=62.5%)

O-O and A-A at top surface. Compressive residual stress magnitude is from –20 to –40 MPa along path O-O, less than from –40 to –60 MPa along path A-A. This shows stress of representative units is –20––60 MPa. According to Eq. (1), mean residual stress should be between the minimum and maximum values of residual stress in representative unit. Surface mean compressive residual stress obtained from X-ray diffraction is about –46 MPa, within the stress magnitude range of paths O-O and A-A. So the simulation result is in agreement with the experimental result, and numerical simulation can provide good guidance on prediction of residual stress distribution in multi-micro laser shock peening.

Figure 9 shows residual stress distribution at different depths along paths O-O and A-A. Figure 9(a) shows that magnitude of residual stress increases with the increase of depth and reaches a maximum value at 0.2-mm depth along path O-O, when depth is 0.4-mm magnitude of residual stress decreases to zero. Figure 9(b) shows that residual stress distribution tends to coincide from the shocked surface to 0.2-mm depth. The different residual stress distributions of two typical paths are also resulted

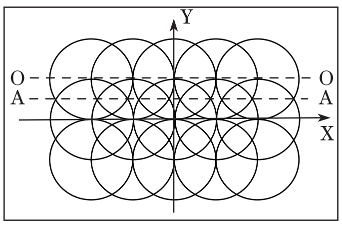

Fig. 6. Typical paths in shock region.

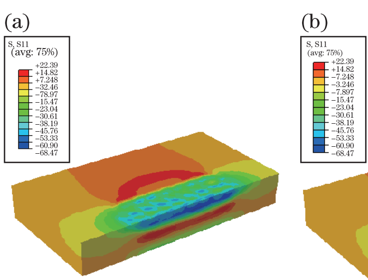

Fig. 7. Residual stress nephogram along paths (a) A-A and (b) O-O.

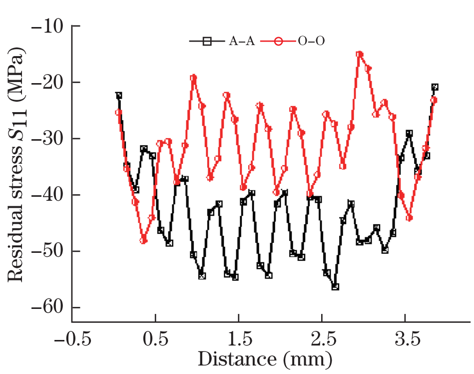

Fig. 8. Residual stress distribution along paths O-O and A-A at top surface.

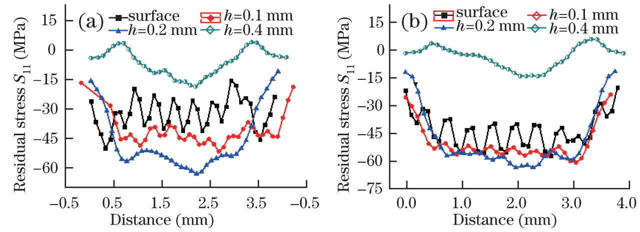

Fig. 9. Residual stress distribution at different depths along paths (a) O-O and (b) A-A.

by the variation of peening times.

In conclusion, with experimental and numerical simulation studies on distribution of residual stress induced by multi-micro LSP, influence of overlapping rate and laser energy on residual stress distribution is obtained. Overlapping results in the nonuniform distribution of residual stress in multi-μLSP. Surface mean residual stress is an effective characteristic means to evaluate strengthening effect. When overlapping rate increases from 62.5% to 87.5% surface mean residual stress increases by two times. Meanwhile surface mean compressive residual stress increases with the increase of laser energy. Numerical simulation displays residual stress distribution on top surface and depth, and efficiently predicts the strengthening effect of multi-μLSP. With reasonable characteristic of residual stress, good guidance for further control of surface mechanical performance and parameter optimal selection is provided.

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References

1. J. Lu, K. Luo, A. Feng. J. Zhong, G. Sun, L. Zhang, and X.. Qian, Chinese J. Lasers (in Chinese) **37,** 2662 (2010).
2. X. Luo, J. Zhang, G. Zhao, X. Ren, and Y. Zhang, Chinese J. Lasers (in Chinese) **36,** 3323 (2009).
3. W. Li, W. He, Y. Li, C. Wang, and Z. Yang, Chinese J. Lasers (in Chinese) **36,** 2197 (2009).
4. W. Zhang and Y. Yao, J. MANUF. SCI. E. **124,** 369 (2002).
5. H. Chen, Y. Yao, and J. W. Kysar, J. MANUF. SCI. E. **126,** 226 (2004).
6. W. Zhang and Y. Yao, in *Proceedings of the Transactions of the North American Manufacturing Research Institution of SME,* 413 (2001).
7. W. Zhang, Y. Yao, and I. C. Noyan, J. MANUF. SCI. E. **126,** 18 (2004).
8. W. Zhang and Y. YAO, J. MANUF. SCI. E. **124,** 369 (2002).
9. P. Peyre, R. Fabbro, P. Merrien, and H. P. Lieurade, Materials Science and Engineering **210,** 102 (1996).