EFFECTS OF LASER SHOCK PROCESSING ON MATERIAL'S PROPERTIES①

Dai Shujuan, Liu Furong, Yang Xiao, Zou Hongcheng
National Laboratory of Plastic Forming Simulation and Die & Mould Technology,
Huazhong National Laboratory of Laser Technology,
Huazhong University of Science and Technology, Wuhan 430074

ABSTRACT The effects of laser power density on the mechanical properties of the LY12CZ aluminum alloy (including surface hardness and fatigue strength) were described. The results showed that with the increase of the laser power density, the material's hardness and fatigue strength increased. By microscopic analysis, the microstructures of the shocked and unshocked materials were compared. In addition, the building-up of the shocked wave was studied and explored.

Key words laser shock processing (LSP) fatigue strength power density shock wave (stress wave)

1 INTRODUCTION

As a new technology, the laser shock processing (LSP) has been studied by many scholars[1-3]. The LSP can increase material's surface hardness and especially fatigue strength significantly. Clauer[4] found that laser shock could improve the 7075-T6 aluminum plate's fretting fatigue lives by 30~100 times.

Considering the actual application, we studied the effects of the small-power and multi-point laser shock on the LY12CZ aluminum alloy. The specimen surface can be protected and peak pressures can be further modified by applying an opaque coating which is easy to remove after laser irradiation. The coating was formed by chemical method; the solution composition was: 1 g/L $Mn(H_2PO_4)_2 \cdot 2H_2O$ (1 g) and 1~2 g/L NaF (1~2 g).

When the intense laser beam strikes the metal surface, the surface layer is instantaneously vaporized. The rapidly expanding high temperature vapor exerts a pressure on the target surface which then propagates into the specimen as a stress wave. Higher surface pressure is obtained by placing a transparent overlay on the opaque coating. Here water was chosen as the overlay which confined the "blow-off" material between it and the specimen surface for the duration of the laser pulse.

2 EXPERIMENTAL

The LY12CZ aluminum alloy (Cu 4.61, Mg 1.51, Mn 0.58) was chosen for the LSP, which consists of a solution treatment and natural aging at ambient temperature. Its normal mechanical properties are: $\sigma_{0.2}$= 372 MPa, σ_b= 487 MPa.

To imitate the actual shape of the spare parts with the hole and notch, (a) and (b) specimens were used and their geometric sizes are shown in Fig. 1.

The LSP experimental arrangement is shown in Fig. 2. Excimer Laser, YAG Laser and Pumping Dye Laser were adopted to strike the material; the laser shock parameters are listed in Table 1.

3 RESULTS AND ANALYSIS

3.1 Shock hardening

The experiment was carried out on an NMT

① Received Mar. 12, 1996; accepted May 13, 1996

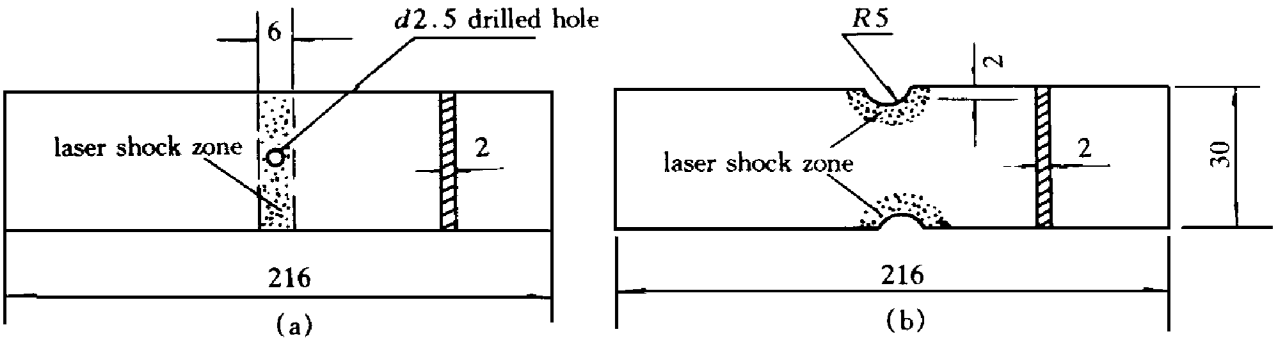

Fig. 1 Specimen shape and geometric sizes (in mm)

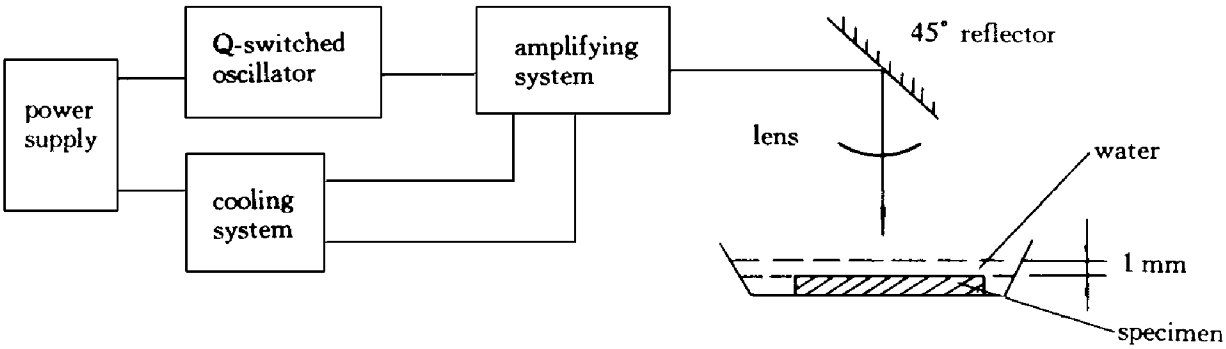

Fig. 2 Experimental arrangement of LSP

Table 1 Laser shock parameters

Group	Laser model	Export energy / mJ	Pulse width / ns	Beam size / mm	Power density / $W\cdot cm^{-2}$	Wave length / μm	Sample shape
I	EMG201MSC Excimer Laser	90	28	1 × 3	1.06×10^{8}	0.308	a-type
II	YAG Laser	193	5	*d*1	4.92×10^{9}	1.06	a-type
III	U2M Pumping Dye Laser	20	0.15	*d*0.31	1.77×10^{11}	0.532	b-type

-1 Hardness Tester. The surface hardness of the shocked specimens and the unshocked specimens was measured. The results were presented in Fig. 3. It is very evident that the hardness of the LY12CZ aluminum alloy is improved greatly after LSP. By the data processing, the imitating curve equation of laser power density vs surface hardness was obtained as follows:

$$Hv = 32.96\lg^2 P - 549.56\lg P + 2349.93 \quad (1)$$

3.2 Fatigue test

The fatigue specimens were prepared in accordance with Fig. 1. With PW3-10 high frequency almighty fatigue machine, the fatigue lives of the unshocked and shocked specimens were measured under the conditions of $\sigma_{max}=$

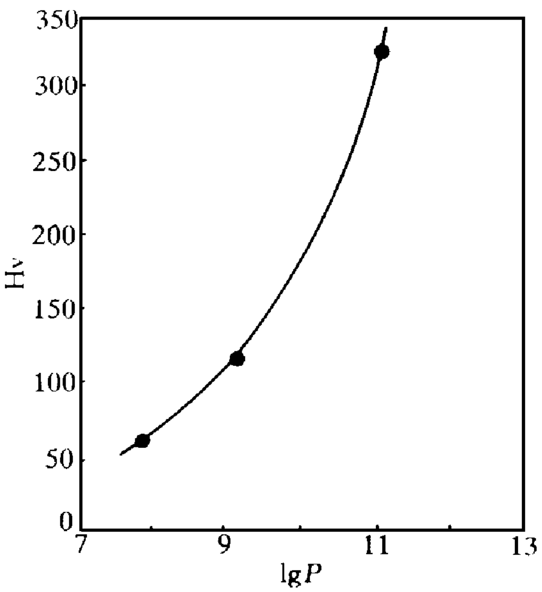

Fig. 3 Curve of laser shock power density vs surface hardness

135.2 MPa, σ_{min} = 11.5 MPa and stress ratio R = 0.085.

The fatigue test results were summarized in Table 2.

By processing these data using the statistics method[5], it can be seen that after the LSP, the specimens' median fatigue lives were improved by 1.073~ 2.065 times for Group Ⅰ, by 1.52 ~ 2.925 times for Group Ⅱ, and by 1.374~ 13.996 times for Group Ⅲ.

The fatigue lives of Group Ⅲ were also measured under different loads, the data were drawn in Fig. 4. In the range of chosen stress, the fatigue lives of the shocked specimens could be improved much more than those of the unshocked specimens.

By processing these data, we obtained the following equations:

for unshocked specimens:

$\sigma = 650.91 - 90.91 \lg P$

for shocked specimens:

$\sigma = 456.9 - 51.3 \lg P$

If we define the condition fatigue strength σ_{lim} as the stress under the condition of $N = 10^6$, σ_{lim} under the two treatments was calculated as follows:

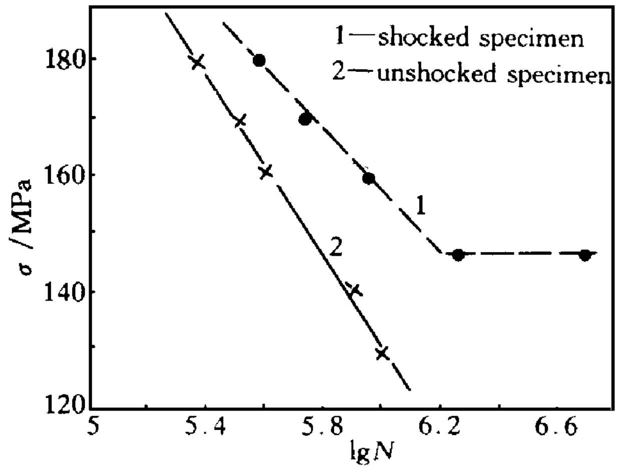

Fig. 4 Fatigue curve of σ vs lg*N*

for unshocked specimens:

σ_{lim} = 105.5 MPa

for shocked specimens:

σ_{lim} = 149.1 MPa

3.3 Microscopic analysis

With JEOL-100CX Ⅱ Transmission Electron Microscope, the areas which had been shocked or unshocked were observed, as shown in Fig. 5. Comparing these two photos, Fig. 5 (b) had higher dislocation density than Fig. 5 (a), which indicated that after the LSP, quite a lot of dislocations were formed in the LY12CZ aluminum alloy. In the laser shock process, the laser pulse transmits energy to the material surface, where it is absorbed. When some of the surface atoms vaporize and break off the surface, a hydrodynamic stress wave is created, which makes the material surface deform (< 5 μm); at

Table 2 Fatigue lives of three groups of specimens (kilo-cycle)

Group	Unshocked						Shocked							Remarks
Ⅰ	228	188	195	190	270		279	318	285	235	338	588	264	a-type specimen
Ⅱ	220	229	148	210	195	201	350	310	650	360	356	600		a-type specimen
Ⅲ	85	350	330	1200	218	*	950	650	1650	3000	1500 *			b-type specimen

* This group of specimens were measured at σ_{max} = 142.1 MPa, R = 0.085.

the same time a lot of dislocations are produced, the altered dislocation density is responsible for the observed changes of properties in the material.

The improvement of the strength is related to the dislocation density as follows[6]:

$$\Delta\tau = \alpha G b \rho^{1/2} \qquad (2)$$

where $\Delta\tau$ is an additional value of the shearing stress to resist the barrier of the dislocations, α is a constant, G is the shear modulus, b is the Burgers vector and ρ is the dislocation density.

This equation clearly shows that $\Delta\tau$ increases with the increase of the dislocation density. In other words, the material strength is improved. That is the reason why the fatigue strength is improved after the LSP. At every stress level, the quantitative dislocations prevent the forming of the persistant slip band, so as to delay the fatigue crack initiation and propagation.

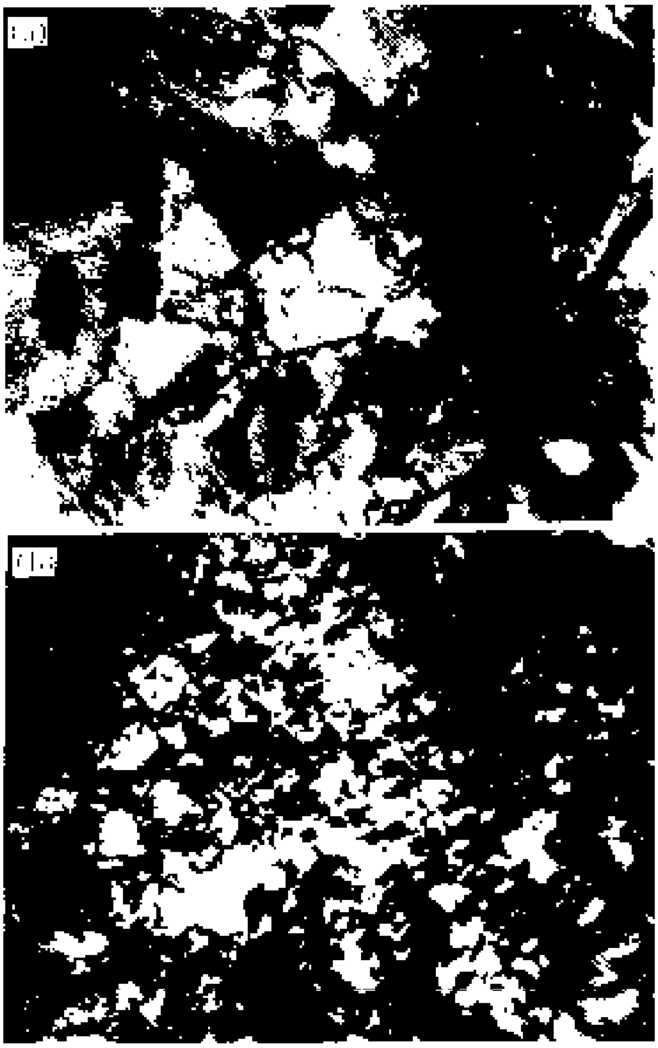

Fig. 5 TEM photos
(a) —Unshocked specimen, ×36 000;
(b) —Shocked specimen, ×48 000

Fig. 6 was taken under the stereo microscope, some main cracks in the shocked specimens were observed; the main cracks splitted some less cracks during the propagation, which evidently proved that quite a lot of dislocations produced by the laser shock interacted with each other to prevent the fatigue crack from forming and propagating.

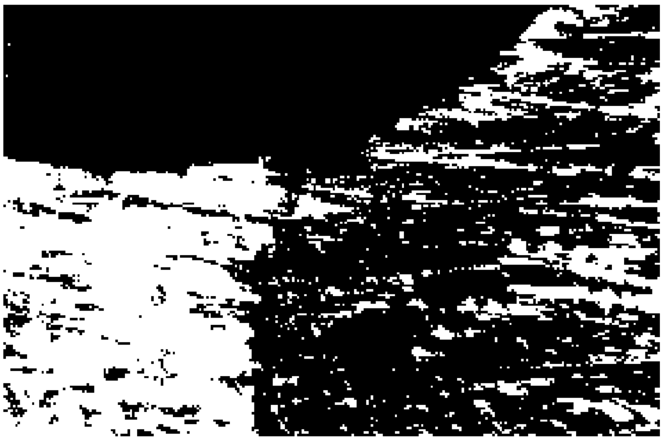

Fig. 6 Stereo microscopic photo, ×50

3.4 Stress wave

With the quartz pressure transducer and 2 440 instantaneous storage oscilloscope, the laser shock wave was measured in the LY12CZ, as shown in Fig. 7. The first peak showing negative oscillation in the oscilloscope is due to the heat elastic shock wave which comes from the heat expansion stress, the second peak is due to the mechanical pressure which arises from the

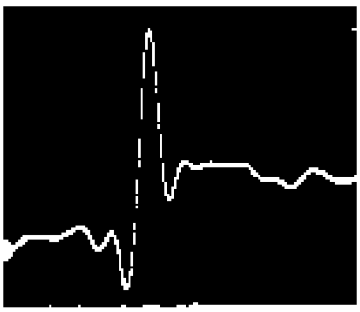

Fig. 7 Stress wave photo
(specimen thickness: 0.1 mm;
50 ns/div; 100 mV/div)

laser pressure and the antishock pressure of vaporation; the results of the interaction between the expansion stress and the mechanical pressure show positive oscillation in the oscilloscope. In comparison with the building-up of the wave, the attenuation of the stress wave is very slow.

4 CONCLUSIONS

(1) LSP can effectively improve LY12CZ aluminum alloy's mechanical properties.

(2) With the increase of the laser power density, the material's surface hardness and fatigue strength can be improved evidently.

(3) After the LSP, there are quite a lot of dislocations forming in the materials, which is the main reason to improve the material's fatigue strength.

(4) The stress wave includes two parts: one is the heat elastic shock wave which comes from the expansion stress, the other is the mechanical pressure which arises from the laser pressure and the antishock pressure of vaporation.

REFERENCES

1 Willian F Bate Jr. Appl of Laser in Material Processing Proceeding of Conference. Washington, DC: AMS, 1979: 317- 330.

2 Fairland B P, Wilcox B A. Appl Phys, 1972, 43(9): 3893- 3895.

3 Fairland B P, Clauer A H. Appl Phys Lett, 1974, 25: 431.

4 Clauer A H, Fairland B P. Metall Trans A, 1977, 8A: 119.

5 Gao Zhentong *et al*. Fatigue Application Statistics, (in Chinese). Beijing: National Defence Press, 1986: 282- 304.

6 Hertzberg R W. Deformation and Fracture Mechanics of Engineering Materials. John Wiley & Sons, 1987.

(Edited by Peng Chaoqun)

(From page 119)

will shift to − 700~ − 750 mV[10] as pH values decrease to 7.2 (due to the attachment of marine organism, for example). In that case, the specimens treated by Tec. A will suffer severe local corrosion.

4 CONCLUSION

The chair-like and network-distribution (Mn, Fe) Al_6 and silicate compound precipitated at grain boundaries in the specimens heat-treated by particular technology can severely deteriorate the corrosion resistance of LF6M Al-Mg alloy exposed to natural seawater.

REFERENCES

1 John E. Aluminium-Properties and Metallurgy. Ohio: Metals Park, ASM, 1984.

2 Chen Zuxiu. In: Proc Sec Inter Conf on Al Alloys. Beijing: 1990: 682.

3 Li Jiuqing, Tu Yidong. Cailiao Baohu, (in Chinese), 1994, 27(4): 1.

4 Zhang Baochang. Nonferrous Metals and Their Heat-treatment. Beijing: Nat Def Ind Pub, 1981: 8.

5 Zhu Zufang (ed). Corrosion Resistance of Nonferrous Metals and Their Application. Beijing: Chem Ind Pub, 1995: 6.

6 Lin Leyun, Song Wensang. In: 7th APCCC Proceedings. Beijing: 1990, 1: 541.

7 Yan Yumin, Lin Leyun, Wang Xiaohua. Corr Sci and Prot Tech, (in Chinese), 1995: 7(3): 225.

8 Czirki A *et al*. In: Proc Sec Inter Conf on Al Alloys. Beijing: 1990: 508.

9 Zheng Yuzhen *et al*. Eng Mater, (in Chinese), 1994, 8- 9: 7.

10 Rowland H T *et al*. Corrosion, 1980, 36(9): 458.

(Edited by Li Jun)