Vacuum 148 (2018) 178–183

Contents lists available at ScienceDirect

Vacuum

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

Effects of laser shock peening on mechanical behaviors and microstructural evolution of brass

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ARTICLE INFO

Article history:
Received 9 September 2017
Received in revised form
26 October 2017
Accepted 14 November 2017
Available online 15 November 2017

Keywords:
Brass
Laser shock peening
Mechanical behaviors
Grain refinement

ABSTRACT

The mechanical behaviors and the microstructures of brass induced by laser shock peening (LSP) are investigated systematically. The compressive residual stresses (CRS) and the micro-hardness in surface layers are performed using X-ray residual stress tester and hardness tester respectively. The microstructures of the deformation layers are characterized using transmission electron microscopy (TEM). It is found that the CRS and the micro-hardness increasing are accompanied by improving laser pulse energy. The deformation layer induced by 4.5J LSP is divided into top surface layer, SPD layer and MPD layer according to the microstructures and CRS. The equiaxed grain size in the top surface layer after 4.5J LSP impacts is approximately 20 nm to 30 nm. The grain refinement process during LSP impacts can be described as follows: (i) dislocation structures are generated by strain and strain rate induced laser shock wave; (ii) original coarse grains subdivide into sub-grains with dislocation tangles (DTs) and dense dislocation walls (DDWs) forming at their grain boundaries; (iii) dynamic recrystallization (DRX) in sub-grain boundaries takes place due to the dislocation array transitions; (iv) new grain boundaries are formed in sub-grains, then they are subdivided into nano-scale equiaxed grains with the accumulation of plastic deformation.

1. Introduction

Brass characterized by its excellent workability, high thermal conductivity, as well as exceptional fatigue resistance and wear resistance properties are therefore widely used for applications in machinery parts that are subjected to transmission and brake contact (e.g. bearing liners, bushings, etc.) [1–5]. With the development of modern industry, the requisitions on fatigue resistance and wear resistance of brass increase significantly. Particularly, the excellent surface properties of machinery parts can ensure the machine stable running-in harsh conditions. In order to improving the fatigue resistance and wear resistance properties of brass, surface strengthen technologies (e.g. shot peening, rolling, equal channel angular press, etc.) of brass have been investigated [6–8]. However, these treatment technologies require the shape of components to be relatively flat without obvious grooves and holes. LSP is a novel surface modification approach, which can effectively improve surface mechanical behavior of metal alloys [9–11]. Compared with other surface strengthen technologies, LSP, which can apply in macro and micro fields of components, is substantially more flexible. In addition, LSP produces higher plastic deformation, which has a notable effect on surface properties improvement with less risk of microstructure damage on the component surfaces [12,13].

The impacts of LSP on the mechanical behaviors and microstructures of metal alloys have attracted great attention [14–17]. A. Salimianrizi et al. found that high-lever CRS of Al6061-T6 was induced by the LSP on the surface layer, and moreover, LSP turned out to be an effective approach to enhance the micro-hardness in the higher depth [18]. K. Y. Luo et al. investigated the effects of LSP treatment on microstructure of ANSI 304 austenitic stainless steel. Results showed that with the increase of the distance to the treated surface, the grain size increase, and micro-structure morphology of the plastic deformation layer subjected to a single LSP impact obviously differ from that in the substrate [11]. Besides, high-density dislocation and equiaxed grains with a size of 5 μm of 316L stainless steel were also observed in the surface layer after

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https://doi.org/10.1016/j.vacuum.2017.11.024
0042-207X/

massive LSP impacts, leading to the improvement of local micro-hardness and CRS [19]. However, little work exists in the application of LSP on copper and copper alloys because of its properties of high thermal conductivity and high light reflectivity. In brief, these investigations mainly focused on the microstructure deformation and mechanical properties near the surface during LSP process. Although the surface grain refinement can effectively improve mechanical properties of the metal alloys, its effect on mechanical properties of metal alloys especially brass and the grain refinement mechanism induced by laser shock wave lag well behind so far [20–22].

The purpose of this research is to investigate the effects of the pulse energy on mechanical behaviors and microstructures of brass induced by LSP impacts, especially its grain refinement mechanism during the LSP impacts. The distributions of CRS and micro-hardness of brass were studied, while the microstructures of brass were investigated by means of TEM. In addition, the surface grain refinement mechanisms of the brass induced by LSP were proposed.

2. Experimental methods

2.1. Preparation of the specimens

The brass specimens (62.1% copper and 37.9% Zinc) with a size of 10 mm × 10 mm × 5 mm were annealed at a temperature of 290 °C for 45min to homogenize the composition and eliminate the residual stress. Then the brass plates were polished in order to ensure uniform finishing (Ra = 50 nm). Prior to LSP treatment, the specimens were cleaned with citric acid to remove the oxide layers.

2.2. LSP equipment and processing parameters

LSP was performed using a Q-swithed Nd: YAG laser with an irradiation wavelength of 1060 nm and 10ns pulse width. Pulse energies used in the experiment were 2.5J and 4.5J respectively. At the same time, the laser spot diameter was adjusted to 3 mm. In the LSP process, a water layer with about 1.5 mm thickness was used as the transparent confining layer, in the meantime an Al foil with a thickness of 0.1 mm was used as the absorbing layer. The illustrations of the LSP process and laser shock path are shown in Fig. 1(a) and (b).

2.3. Measurements of CRS and micro-hardness

CRS in deformation layer of brass was determined by XRD technique with the sin2φ method using an X-ray residual stress tester (X-350A). For X-ray measurement of residual stress, the surface layers of brass were selected to measure, and the residual stresses were calculated from the formulas as follows [23]:

$$\sigma = -\frac{E}{1+\nu}\cdot\frac{1}{\sin 2\eta}\cdot\frac{1}{\sin 2\psi}\left(\frac{\partial\varepsilon_\alpha}{\partial\cos\alpha}\right) \quad (1)$$

$$\psi = \psi_0 + \eta \quad (2)$$

Here, σ is the residual stress, E is material's elastic modulus, ν is Poisson's ratio; η is the intersection angle between incident X-ray with the diffraction surface, ψ_0 is the intersection angle between incident ray with normal direction of sample surface; α is the measuring angle of Debye-Scherrer ring and ε_α is residual strain at a specific measuring angle. The X-ray source was Cu-Kα ray, and meanwhile the diffraction plane was (220). Furthermore, lattice strain and peak broadening at LSP surface were analyzed using a high resolution X-ray diffractometer employing Cu-Kα ray over the 2θ range of 120°–125° with step size of 0.10°. The X-ray beam voltage and electricity were 20.0 kV and 5.0Ma respectively. Each group is repeated three times under the same conditions in order to obtain the consistent results.

The micro-hardness in depth direction was measured using a Shimadzu HMV-2000 hardness tester, which 25g load and 15s hold were applied. The distance between each micro-hardness indent was 25 μm (in depth). In order to determine the LSP treatment effect on micro-hardness distribution, each average micro-hardness value was determined based on 5 indentation measurements.

2.4. Microstructural observation

The microstructure of brass subjected to LSP was characterized using a JEOL 2100 transmission electron microscope (TEM) operated at a voltage of 200 kV. In order to obtain the microstructure of deformation surface, preliminary preparation technique is applied. The specimens are first hand-grinded with 2500 grits of abrasive paper, and then the samples are grinded by the disc grinder (Gatan-623) until its thickness reaches 60–100 μm. Subsequently, the specimens are chemistry-milled by the twin-jet electro-polisher (TenuPol-5) with appropriate electrolyte. Two specimens with LSPed surface are bonded face-to-face to protect the determination depth surface during chemistry-milled in particular. More details about TEM specimens preparation can be found in Ref. [24].

3. Results and discussion

3.1. Compressive residual stress

CRS profiles in depth direction of the brass before and after LSP treatment are presented in Fig. 2. The negative value indicates that the residual stress is compressive. It can be observed that the untreated specimens are approximately at low stress level which the value is about −18 MPa, while the CRS in depth direction increase with the increase of laser pulse energy. After LSP with the laser

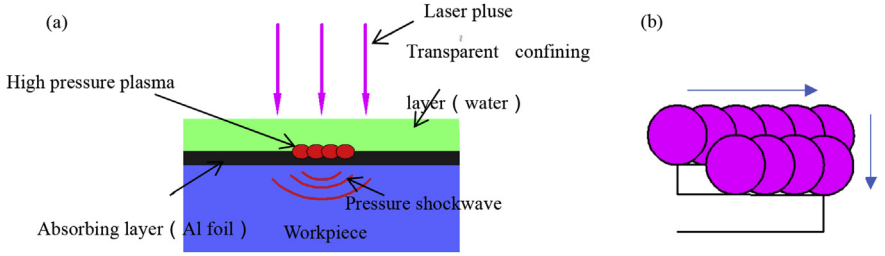

Fig. 1. (a) Schematic illustration of LSP process, and (b) laser shock path.