G Model
APSUSC-27837; No. of Pages 10
ARTICLE IN PRESS
Applied Surface Science xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Applied Surface Science
journal homepage: www.elsevier.com/locate/apsusc

Plastic deformation mechanism of polycrystalline copper foil shocked with femtosecond laser

Y.X. Ye [a,b,*], Y.Y. Feng [a], Z.C. Lian [a], Y.Q. Hua [a]

[a] School of Mechanical Engineering, Jiangsu University, Zhenjiang 21203, PR China
[b] Jiangsu Provincial Key Laboratory for Science and Technology of Photon Manufacturing, Jiangsu University, Zhenjiang 212013, PR China

ARTICLE INFO

Article history:
Received 21 February 2014
Received in revised form 27 March 2014
Accepted 2 May 2014
Available online xxx

Keywords:
Femtosecond laser
Laser shock forming
Plastic deformation
Copper foil
Stacking fault
Twin

ABSTRACT

Plastic deformation mechanism of polycrystalline copper foil shocked with femtosecond (fs) laser has been characterized through optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Experiments of ns laser shocking copper (Cu) and fs laser shocking aluminum (Al) were also conducted for comparison. Dislocations arranged in multiple forms, profuse twins and stacking faults (SFs) coexist in the fs laser shocked copper. At small strain condition, dislocation slip is the dominant deformation mode and small amount of SFs act as complementary mechanism. With strain increasing, profuse twins and SFs form to accommodate the plastic deformation. Furthermore, new formed SFs incline to locate around the old ones because the dislocation densities there are more higher. So there is a high probability for new SFs overlapping on old ones to form twins, or connecting old ones to lengthen them, which eventually produce the phenomena that twins connect with each other or twins connect with SFs. Strain greatly influences the dislocation density. Twins and SFs are more dependent on strain rate and shock pressure. Medium stacking fault energy (SFE) of copper helps to extend partial dislocations and provides sources for forming SFs and twins.

1. Introduction

Since 1960s, it has been found that strong mechanical shock wave can be induced through high-power pulsed lasers interacting with solid targets [1,2]. So laser driven shock wave has been widely researched in manufacturing and material processing, such as strengthening metal surface (laser shock processing, LSP) [3–5] and directly forming metal parts (laser shock forming, LSF) [6–8]. Until now, laser shock applications mainly used nanosecond (ns) pulsed lasers [3–8], and a few use picosecond (ps) pulsed lasers [9]. Microsecond (ms) or longer pulsed lasers are not appropriate for inducing intense shock wave because of their lower peak power and very serious heating effect. As a more intense laser, fs laser can generate more higher amplitude shock wave on material surface, which has been verified earlier [10–13]. However, manufacturing through fs laser-induced shockwave has not been attached as much attention as ns lasers, because of its too short laser pulse duration. And the machining ability of fs laser shock processing or forming has once been doubted [14,15].

In recent years, with the application of ultrashort laser in other material machining field. There is growing evidence that fs laser has its unique advantages in comparison to ns or longer-pulses laser, due to its high machining precision and little heat affected zone [16,17]. This is also true for laser shock processing, especially in laser shocking micro parts. On the one hand, short-duration shock wave induced by fs laser is not enough to blow away a micro part [18]. On the other hand, small penetrating depth of fs laser induced shock wave gives more opportunity for machining flexibility and precisely controlling the machining process. Deeper compressive residual stress and larger plastic deformation can be obtained through impacting parts more times with fs laser gradually. These properties are favorable for forming or processing micro parts [18,19]. So with the development of MEMS, application of fs laser driven shockwave in manufacturing field has attracted researchers' attention.

As we reviewed in Ref. [20], the strengthening effects of fs laser shock process has been verified through theoretical and experimental research [14,21], and bending sheet metal through fs laser shock forming also been realized successfully [18–20]. During our previous research [20], we have obtained pit on copper and aluminum foil through fs laser shock forming. And the influences of some technique parameters on the plastic deformation have been thoroughly researched experimentally. Destroy mechanisms

* Corresponding author at: School of Mechanical Engineering, Jiangsu University, Zhenjiang 21203, PR China. Tel.: +86 511 88797898; fax: +86 511 88780241.
E-mail addresses: yeyunxia@mail.ujs.edu.cn, yx_ye@163.com (Y.X. Ye).

http://dx.doi.org/10.1016/j.apsusc.2014.05.019
0169-4332/© 2014 Elsevier B.V. All rights reserved.

Please cite this article in press as: Y.X. Ye, et al., Plastic deformation mechanism of polycrystalline copper foil shocked with femtosecond laser, Appl. Surf. Sci. (2014), http://dx.doi.org/10.1016/j.apsusc.2014.05.019

of confining layer during fs laser shock process have been analyzed too.

In spite of this, research on fs laser shock has just begun. Ultrashort pulse duration and high peak power of fs laser make the ablation mechanisms and interacting process of fs laser with targets largely different from ns laser. Ultrafast process makes it difficult to monitor or detect some important processes or parameters. In addition, it is well known that the strain rate of ns laser shock can reach up to $10^7\,s^{-1}$ [10], which leads to microstructural evolution of metal materials significantly different from low strain rate process. However, the strain rate obtained through fs laser is thought to be much higher than ns laser. In this case, what's the response of the material? How do the material microstructure evolve? These problems all need in-depth study.

This paper presents a first attempt to observe the microstructures of polycrystalline copper shocked with fs laser and analyze the plastic deformation mechanism under ultrahigh strain rate. In order to clearly recognize the shock effect obtained through fs laser, the copper material was firstly annealed to decreasing original defect density in the grain. TEM (transmission electron microscopy), OM (optical microscopy) and SEM (scanning electron microscopy) have been conducted to characterize the microstructures. 3D profiler has been used to measure the deformation for coarsely evaluating the orders of magnitude of strain rate induced by fs laser. Ns laser shock on the same material has been conducted as comparison to fs laser shock. Because pure copper owns medium stacking fault energy (SFE), aluminum (Al) with SFE, was chosen to observe the influence of SFE on plastic deformation mechanism at the conditions of ultrahigh strain rate.

2. Experimental methods

Rolled pure copper (Cu) foils and pure aluminum (Al) foils with the dimensions of about 15 mm × 15 mm were used as metal targets. Their thicknesses were about 20 μm. To enhance the formability of the specimen, Cu foils were annealed at 800 °C for 1 h and Al foils were annealed at 550 °C for 1 h. Then the specimens were exposed to furnace cooling to room temperature. To avoid oxidation, the heat treatments were conducted in vacuum condition.

Black paint was chosen as surface absorbent layer. In our experiments, adhesive tape, the main component of which is polypropylene, acted as confining layer. In our previous research [20], we used gum water of the main component polyvinyl alcohol. Because acoustic impedance of polypropylene is $0.19 \times 10^6\,g\,cm^{-2}\,s^{-1}$ [22], bigger than that of glue $0.16 \times 10^6\,g\,cm^{-2}\,s^{-1}$ [23]. Therefore the confining effect of adhesive tape is expected to be better than glue. Furthermore, the thickness of flexible confining layers can be adjusted quantitatively through simply changing the layers of adhesive tapes. Our experiments used two layers of adhesive tape, and the total thickness was about 20 μm.

The same experimental setup as in Ref. [20] was used in our experiments. The central wavelength of laser was about 800 nm and its maximum energy about 550 μJ. Laser pulse frequency could be changed from 1 Hz to 1 kHz. In our experiments, 1 kHz was used for obtaining continuous scanned area through moving the specimens along x and y directions as shown in Fig. 1. The moving parameters (speed or feeding distance) along x and y directions were carefully adjusted to guarantee overlapping rate of laser beam. One shocked sample with continuously scanned area is shown in Fig. 1. For studying the influence of strain on material microstructures, we firstly impacted some specimens only one time and then selected some of them to conduct the second shock scanning. So that specimens with different strains were obtained. Laser repetition rate 1 Hz was only used once for obtaining pit on copper foil through laser shocking one point on the target surface. According to our previous research results [20], we choose laser pulse energy 500 μJ and pulse width 350 fs to guarantee fs laser shock effect. The diameter of output laser beam from laser is about 6 mm and then laser was focused onto the specimens by a focusing lens with 1 m focal length. The spot diameter on specimen is about 400 μm. Ns laser shock experiments were carried out with Nd^{3+}:YAG, with the wavelength 1064 nm, 20 ns pulse width, 300 mJ impact energy, 1 Hz repetition rate and 3 mm spot diameter on the specimen surface.

After laser shock experiment, the samples were all cleaned with acetone, removing the absorbent and confining layers. During the cleaning process, particular attention must be paid to the removal of the tape in order to avoid extra plastic deformation. For estimating strain and strain rate, 3D profiler Keyence VHX-1000 was used to measure the 3D profiles of pits obtained through fs laser shock and ns laser shock. Epoxy resin embedded samples were prepared for observing the microstructure with S-3400N (SEM) and Leica DM2500M (OM). Solutions with 5 g $FeCl_3 \cdot 6H_2O$ dissolving in 5 ml HCl and 100 ml pure water was used for etching pure copper. Specimen preparation for TEM was conducted as follows: 3 mm diameter disks were directly cut from the interested area on the foil. For fs laser shocked target, the disks were located at the continuously scanned area, while for ns laser shocked target, the disks were chose at the bottom of the pit because ns laser induced pits are large enough. Then the disks were thinned to perforating from the specimen backs, opposite to laser irradiated surface. So that most laser shocked material was left. The perforated disks were observed on JEM-2100 (TEM) operating at 200KV.

3. Experimental results

3.1. The strain, strain rate and peak pressure evaluation

Fig. 2 shows the profiles of laser shock induced pits on copper foil through fs laser and ns laser. Profile lines in the lower parts of Fig. 2a and b, represent the material deforming at the central symmetry axis. Although the deforming process is complex, and there exist radial, tangential and thickness strains with different values at different locations, we will use a simple deep drawing model to evaluate the strain obtained through fs laser shock, shown in Fig. 2c. According to theory of deep drawing [24], among all strains, the tangential strain $\varepsilon = \ln(R_1/R_0)$ has the maximum value, which is used to evaluate the deformation degree. Then the strain rate $\dot{\varepsilon} = \varepsilon/\tau$. R_1 is the pit diameter obtained after laser shock, R_0 is original diameter of shocked region and τ is the duration of shock wave. According to Fig. 2a and b, the diameter R_1 is 580 μm and 5356 μm in Fig. 2b. R_0 is the lengths of red curves in Fig. 2a and b. The line shapes of both curves are not regular. So it is difficult to calculate their accurate lengths. We will further simplify the calculating process through fitting the curved lines with several straight lines, as indicated by dashed lines shown in Fig. 2d. According to the fitting results in Fig. 2d. R_0 in Fig. 2a is about 586 μm, and in Fig. 2b about 5764 μm using simple geometric calculations. So the plastic strain of fs laser induced pit is about 0.005 (considering the pit was obtained through 2 times of fs laser shock, $\varepsilon = \ln(R_1/R_0)/2$). Ns laser induced strain is about 0.073.

For ns laser, the pulse duration of shock wave is about 2–3 times laser pulse [25], so we take $\tau = 2 \times 20\,ns = 40\,ns$ for ns laser shock experiment. Then the strain rate induced by ns laser is $\varepsilon/\tau = 1.8 \times 10^6\,s^{-1}$. For fs laser shock forming, the shock wave pulse width is about hundreds times of laser pulses [10], so we take $100 \times 350\,fs = 3.5 \times 10^{11}$ s. The evaluated strain rate is about $1.4 \times 10^8\,s^{-1}$, and this order of magnitude agrees with that in [10]. So the strain rate obtained through fs laser shock is about 2 orders of magnitude greater than that of ns laser shock.