Optics & Laser Technology 86 (2016) 93–102

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Full length article

The size effect on deformation behavior in microscale laser shock flexible drawing

Huixia Liu*, Xianqing Sun, Zongbao Shen, Cong Li, Chaofei Sha, Liyin Li, Shuai Gao, Youjuan Ma, Xiao Wang

School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China

ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form
8 July 2016
Accepted 18 July 2016
Available online 25 July 2016

Keywords:
Laser flexible micro-drawing
Size effects
Deformation behavior

ABSTRACT

A microscale laser shock flexible drawing (μLSFD) is a novel ultrahigh strain rate manufacturing technology that provides an effective means for fabricating complicated microparts shapes in foil. However, the size effect phenomenon in ultrahigh strain rate microforming is still largely unknown. In this work, the micro-mold and process parameters were designed to investigate the size effects based on the similarity theory. The parts were formed using annealed copper foils with four different grain sizes to study the grain size effect. The parts were fabricated by use of different micro-molds and copper foils with varying thicknesses but with the same annealing temperature to investigate the effect of feature size. The experimental results indicated that the depth of the formed parts increased with an increase in the grain size; the forming depth decreased significantly when the feature dimension was smaller than a critical value. The surface roughness and the thickness thinning ratio of the formed parts increased when the grain size and feature dimension increased. The maximum thinning ratio appeared at the bottom of the formed parts. The regression analysis revealed that the material deformation was more homogeneous with a decrease in the grain size and an increase in the feature dimensions when the μLSFD process was employed. This study provides a theoretical basis for the investigation of size effects in laser shock flexible forming.

1. Introduction

Micro metal components have been widely and increasingly used in micro-electro-mechanical systems (MEMS), micro systems technologies (MST), and electrical devices as a result of the miniaturization trend [1–3]. Compared with other microfabrication techniques, such as the lithographic technology and micro machining, microforming technology has recently become one of the promising micro manufacturing technologies mainly due to the advantages it offers, including high productivity, low rate of material waste, and excellent mechanical properties [4]. Nevertheless, when the workpiece dimensions are scaled down to microscale, there is evidence that the presence of size effects influences the microforming ability [5]. There are only a few grains located at the deformation region when the thickness of a workpiece decreases to the same order of magnitude as the grain size. Therefore, the deformation behavior of the material is no longer as homogeneous as a conventionally formed material [6].

To investigate the material size effects that occur in the microforming process, many experimental and numerical studies have been conducted. The influence of grain size, specimen dimensions and feature size on the deformation behavior of the material continues to be a concern for researchers. There is a classical formula, the Hall-Petch relationship, which was proposed by Hall [7] and Petch [8] to determine the effects of grain size on the material. Shan et al. [9] used the Hall-Petch equation to explain the decrease in bending force with the increase in grain size during micro-bending tests. Gau et al. [10] investigated the influence of size effects on the flow stress and formability by performing tensile and bending tests. Peng et al. [11] established a uniform constitutive model that considered size effects and precisely simulated the flow behavior of micro-sheet metal in the process of forming a micro U shape. Xu et al. [12] investigated the coarse-grained and ultrafine-grained effect on the flow stresses via micro-compression experiments of high purity aluminum. To investigate the effect of specimen dimensions on the material, the tensile tests of CuNi18Zn20 [13] and the compression tests of Cu-Zn alloy [14] revealed that the flow stress of the sheets decreased with a decrease in the thickness. These phenomena were explained by the surface layer model. Parasız et al. [15] investigated the effect of specimen size on deformation during microextrusion and found that miniaturization resulted in increased hardening of

* Corresponding author.
E-mail address: lhx@ujs.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.optlastec.2016.07.009
0030-3992/

the material. Molotnikov et al. [16] used a dislocation density based constitutive model to simulate the impact of sheet thickness on the load-displacement curves and the drawing limit ratio in micro deep drawing. Wang et al. [17] conducted U deep drawing experiments to investigate the influence of die cavity dimensions on the material. They found that the punch load increased with a decrease in the female radius. Fu et al. [18] explored the impact of the punch radius on the deformation load during micro compound blanking and deep drawing of copper sheet. Mahabunphachai and Muammer [19] investigated how the ratio of the bulge die diameter to the sheet thickness affected the material flow curve of thin sheet metals under hydraulic bulge testing conditions.

Recently, laser shock forming has become a prevalent method of microforming. This method allows for precise control the laser energy while avoiding the difficult aligning of the upper and lower die that is necessary in traditional microforming. Niehoff et al. [20] successfully executed the laser deep drawing process for the first time. Jiang et al. [21] researched the precision control of sheet metal forming by laser shock forming. Liu et al. [22] fabricated micro-gears during the laser shock punching process. Gao et al. [23] researched the fillet ratio and aspect ratio of mold impact on the deformation behavior in microscale laser dynamic forming. Wang et al. [24] investigated the influence of size effect on formability in the laser dynamic micro-bending process. Zheng et al. [25] investigated the fracture mode of materials under different ratios of laser beam diameter to die diameter in micro-scale laser shock punching. However, the experimental and numerical researches on size effects mentioned are confined to the microforming process with a low strain rate. Very few studies have been conducted on the effect of size on microforming under an ultra-high strain rate.

This paper presents the impact of grain size and feature dimension on the deformation behavior of copper foils in the μLSFD process. The micro-molds and process parameters were designed based on the similarity theory. Pure copper foils with three different thicknesses and four different annealing temperatures were selected as the experimental materials. Three different types of laser energy and a 3 mm spot diameter were used in this paper. The influence of the micro-mold feature dimensions and grain size on the forming depth and surface roughness of the formed parts was investigated. Furthermore, the thickness distribution of the formed parts was discussed.

2. Forming mechanism

The basic schematic of the μLSFD is shown in Fig. 1. The forming system consists of a laser beam, blank holder, confining layer, rubber pad with black paint coated on the surface, the specimen, and a micro-mold. The Spitligth 2000 a Nd:YAG Laser was used in the experiment and its technical parameters are shown in Table 1. When the black paint is irradiated by the laser, it absorbs the laser energy and produces high temperature and high pressure plasma. The produced plasma then expands in the limited space between the confining layer and the rubber pad and induces a shock wave. When the induced shock wave acts on the surface of the rubber pad, it propagates inside in the form of stress waves. A pressure enhancement effect is generated when the stress wave propagates from a small wave impedance medium (rubber pad) to a large wave impedance medium (workpiece). This is the impedance mismatch effect [26]. Finally, the workpiece produces a plastic deformation at the shockwave pressure and the impedance mismatch effect.

3. Experiment

3.1. Material and micro-mold

The pure copper foils with different thicknesses of 40 μm, 60 μm and 80 μm were annealed at 350 °C, 450 °C, 550 °C and 650 °C in a vacuum and held for an hour to obtain the different grain structures. The annealed specimens were mounted with low viscosity epoxy and then grinded and polished. Finally, the specimens were etched using a solution of 5 g $FeCl_3$, 15 ml HCl and 85 ml H_2O and the grain structures were observed through digital microscope (KEYENCE VHX-1000C). The grain structures of the copper foils with different thicknesses and different annealing temperatures are shown in Fig. 2. The grain sizes in the thickness direction of the copper foils were measured by the mean linear intercept method according to the ASTM E112 standard and are presented in Table 2.

Three different sizes of micro-molds were designed based on the similarity theory to investigate the influence of the mold dimensions on the deformation behavior of the copper foils during the μLSFD process. The micro-molds were fabricated by use of a

Table 1
The technical parameters of the Spitligth 2000 a Nd:YAG Laser.

Technical parameters	Value
Wave length	1064 nm
Single pulse energy	80–1900 mJ
Pulse width	8 ns
Repetition frequency	1–10 Hz
Exit spot diameter	9 mm
Energy stability	< ±1%

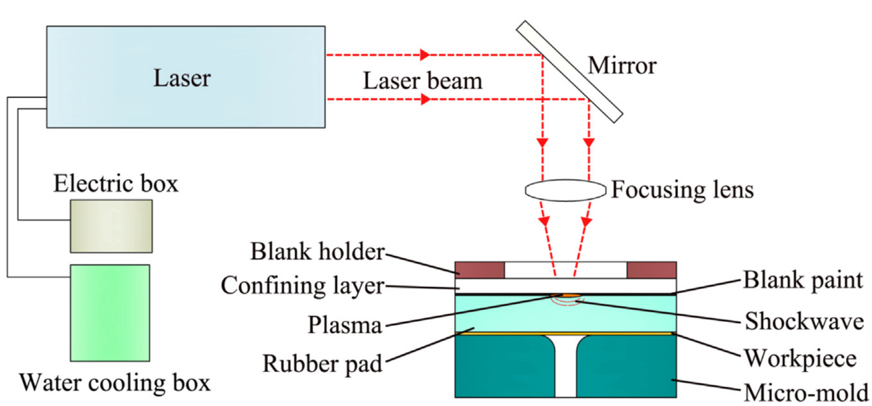

Fig. 1. The schematic diagram of the microscale laser shock flexible drawing process.