Journal of Materials Processing Technology 220 (2015) 173–183

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Size effects on formability in microscale laser dynamic forming of copper foil

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ARTICLE INFO

Article history:
Received 10 August 2014
Received in revised form 17 January 2015
Accepted 23 January 2015
Available online 31 January 2015

Keywords:
Size effects
Microscale laser dynamic forming
Microforming
Formability

ABSTRACT

Unlike quasistatic loading of traditional microforming technology, microscale laser dynamic forming (μLDF) provides an efficient approach to fabricate microparts with enhanced mechanical properties. However, the size effects phenomenon is still inevitable in high strain rate microforming. It is thus necessary to investigate the size effects and dynamic deformation behaviour in μLDF. In this work, four different microchannels using annealed copper foils with four different grain sizes are manufactured simultaneously to investigate the size effects on formability in μLDF. The ratio of sheet thickness to grain size ($N = t/d$) is used to represent the interactive effects of grain size and specimen size, whereas the ratio of channel width to sheet thickness ($M = W/t$) is employed to characterize the feature size effect. Experimental results show that the N value and M value have an interactive effect on the normalized forming depth and the surface roughness value. When the M value decreases to the critical point of 4.5, the normalized forming depth is dramatically decreased and greatly influenced by the N value. Furthermore, the formability characterized by surface quality, thickness reduction and forming accuracy declines with the decrease of N value. The irregular thickness distribution and the inhomogeneous material flow of coarse-grained microchannel are attributed to the anisotropy and uneven grain distribution of microstructure. Despite the decreased formability, the coarse-grained microchannel with high necking ratio is still fabricated without failure and experiences more enhanced hardening effect than the fine-grained specimen, presenting the superplastic deformation behaviour in μLDF. When laser energy increases, the surface quality of the formed parts is improved by the intensive high speed sliding of asperities on the micro-die. The surface roughness value of the coarse-grained specimen is significantly reduced and therefore, the localized necking can be suppressed.

1. Introduction

The application of metallic microparts with micro-features such as micro channels and micro protrusions has been continuously increasing due to the current trend of miniaturization and integration in the fields of micro-electro-mechanical systems (MEMS), energy generation/storage and medical devices. With miniaturization, the number of grains of microparts decreases significantly. When the geometrical dimensions of microparts decreases to the same order as the material microstructure length scale, the plastic deformation behaviour is characterized by only a few grains located in deformed region. As the result, the material in microscale can no longer be considered as a homogeneous continuum. In this case, the friction condition, the material behaviour and the deformation mechanics have been changed due to size effects (Vollertsen et al., 2009). Therefore, the understanding of size effects on material deformation behaviour is critical in the design and development of qualified microparts.

Prior research has been conducted to explore the grain/specimen size effect on deformation behaviour. The grain size effect shows a strong influence on material response from macroscale to microscale. Petch (1953) revealed that the yield strength of material decreases with grain size, following the Hall–Petch relationship. Raulea et al. (2001) studied the grain size effect of thin metal sheet via tensile and bending test. They found an increased flow stress and strong scatter of process variables when the material was nearly one grain in the thickness. Chan and Fu (2012) focused on the grain size effect on the surface roughening and irregular plastic deformation in the embossing of microchannels. Wouters et al. (2005) further investigated the surface roughening of polycrystalline material via tensile deformation. It is found that surface roughening is the combination

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http://dx.doi.org/10.1016/j.jmatprotec.2015.01.020
0924-0136/

of a self-affine roughening related to grain size and a grain scale roughening caused by the crystallographic orientation differences between neighbouring grains. Besides the grain size effect, the specimen size effect was also examined by Stölken and Evans (1998) via tensile and bending test of nickel foil. They found that the flow stress appears to decrease with foil thickness in tensile test, whereas an increase trend of flow stress is observed in microbend test. Those two inversed relations between flow stress and foil thickness can be respectively explained by the surface layer model established by Geiger et al. (1996) and the strain gradient plasticity theory proposed by Nix and Gao (1998). Chen and Tsai (2006) conducted a microhardness test to study the specimen size effect on material mechanical properties. They concluded that both the hardness and the flow stress decrease with downscaled specimen size, confirming the theoretical proportionality between hardness and flow stress. In addition, Gau et al. (2007) carried out researches into the interactive effect of specimen size and grain size on the deformation behaviour of sheet metal via tensile and bending tests. It is found that the yield strength and the tensile strength decrease with the decreasing ratio of sheet metal thickness to grain size (T/D) when $T/D > 1$. Conversely, the yield strength increases with a large deviation when $T/D < 1$. Fu and Chan (2011) developed dislocation density models, which consider the interactive effect of specimen and grain sizes on the fracture behaviour of sheet metal. They identified that the slip number, the fracture stress and the fracture strain decrease with the decreasing ratio of thickness to grain size.

Apart from the above grain/specimen size effect, the feature size effect has been found considerably effect on the complicated material deformation behaviour when the feature size decreases to microscale. Mahabunphachai and Koç (2008) revealed that the material flow curve decreases when the ratio of bulge die diameter to sheet thickness decreases from 1961 to 191. However, the flow curve increases when the ratio further decreases from 191 to 49 in hydraulic bulge test. Kim et al. (2008) developed a flow stress model, which considers the grain and feature size effect to examine the forming behaviour in the coining process. The results revealed that the forming depth is affected by the specimen thickness, grain size and feature size. Wang et al. (2007) explored the feature size effect at the forming temperature of 400 °C in microcoining. They found that the formability is closely related to the ratio of the groove size to material grain size. Parasiz et al. (2007) investigated the feature size effect in microextrusion. Based on the microstructure evaluation, it is concluded that the deformation behaviour of specimen greatly depends on the location, size and orientation of individual grains when the grain size approaches the micropart size. They also revealed that the inhomogeneous plastic deformation and irregular hardness distribution occur in microbending (Parasiz et al., 2010). Justinger and Hirt (2009) established a model considering Taylor factors to estimate the influence of grain orientations on micro deep drawing. Experimental results show that the thinning of cup wall and the surface roughness increases with the decreasing formed part size. Xu et al. (2012) conducted experiments of micro deep drawing to investigate the size effects on formability. They found that the surface quality and irregular geometry shape worsens with the decrease in the feature size of the formed cup.

Based on the above reviewed studies, it can be seen that the experimental and modelling researches on size effects are limited to low stain rate forming under static or quasi-static loading conditions. Unlike quasi-static loading, microscale laser dynamic forming (μLDF) is a dynamic forming process and the material can be plastically deformed at an ultrahigh strain rate of approximately $10^7\ s^{-1}$. After laser shock processing, the refined subgrain structure and the large dislocation density dominate the microstructure of microparts (Cheng et al., 2007). It has also been found that the through-thickness large compressive stress of microparts can effectively improve fatigue resistance and inhibit the appearance of micro cracks. Gao and Cheng (2010) revealed that dynamic plastic deformation provides a practical approach for generating nano-scale twins in metals with low or medium stacking fault energies. They attributed the generation of nano-scale twins to the athermal plastic deformation at ultrahigh strain rates. The refined nano-scale grains and the nano-scale twins on the surface of specimen contribute to the further grain boundary strengthening and twin boundary strengthening (Zhao et al., 2005). Furthermore, the necking and fracture of the material are delayed by the inertia effects during high velocity deformation (Seth et al., 2005).

Table 1
Grain size and corresponding N value of copper foil with the thickness of 50 μm after different heat treatment conditions.

Temperature: T (°C)	400	500	600	750
Grain size: d (μm)	6.3	15.5	37.8	72.6
N value: t/d	7.9	3.2	1.3	0.7

Although it has been demonstrated that μLDF is a promising technology for the forming and strengthening of metallic microparts, size effects lead to many uncertainties in material dynamic response that is still inevitable under high strain rate loading. However, the investigation of size effects on dynamic deformation behaviours of thin sheet has not yet been extensively conducted. Only a few researchers discussed the size effects on material dynamic response. The yield strength, strain hardening and strain rate sensitivity of materials have been found to depend on the sample size and strain rate by multiscale modelling (Gao and Cheng, 2011). Furthermore, the grain size and laser spot also have a notable effect on the indentation depth under laser shock processing (Hu et al., 2012). There is still a lack of systematic research on the integrated size effects and inherent ultrahigh strain rate on dynamic deformation behaviour of thin metal sheet in μLDF.

The objective of this work is to investigate the size effects on dynamic plastic deformation and formability of copper foil in μLDF. As the effects of grain size, specimen size and feature size are coupled other than individual effect in microscale and therefore, they should be discussed concurrently. In this work, the ratio of sheet thickness to grain size ($N = t/d$) was used to represent the interactive effects of grain size and specimen size, and the ratio of channel width to sheet thickness ($M = W/t$) was employed to characterize the feature size effect. In the experiments, four different N values and M values were provided to investigate the grain size effect and feature size effect on formability in μLDF. In addition, three different sizes of the laser energy were loaded to analyse the effect of laser impact on the surface quality of formed parts.

2. Experiments

2.1. Experimental specimens and micro-die

In this work, T2 copper foil is chosen as the experimental material due to its relatively high ductility and wide application in microparts. To investigate the grain size effect on deformation behaviour, the as-received copper foils with the thickness of 50 μm are heat treated in a vacuum furnace at the temperature of 400 °C, 500 °C, 600 °C and 750 °C for 1 h to obtain the desired fine grain and coarse grain structures. After different heat treatments, the annealed copper foils are moulded into epoxy, polished and then chemically etched using 10% $FeCl_3$ solution. The grain size in the thickness direction is measured by mean linear intercept method according to the ASTM E112 standard. The obtained grain size, the corresponding N value ($N = t/d$) and the microstructure of annealed copper foil are given in Table 1 and Fig. 1, respectively.