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Surface morphology of micro stepped components in micro cross wedge rolling

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Abstract

A novel microforming process - Micro Cross Wedge Rolling has been proposed, which is very promising in producing micro stepped components. It is inevitable to confront with huge challenges in the development of micro cross wedge rolling technology. The influences of miniaturization, especially size effect, on process, accuracy control and product quality have to be studied. A micro cross wedge rolling testing rig has been designed and manufactured. Micro stepped components have been fabricated successfully by adopting flat wedge tools on this rig. The effects of surface roughness of tool, grain size in workpiece and cross sectional area reduction on surface morphology of rolled workpiece have been investigated.

1. Introduction

From the viewpoint of production engineering, microforming is considered an effective process to manufacture micro components which are essential when a high volume of components is required (Geiger, 2002; Allwood et al., 2006). In general, there are three sections - micro massive forming, micro sheet metal forming and micro profile forming. Research on micro profile forming has been insufficient till now (Vollertsen et al., 2004). Stepped rotational microparts like micro shafts which have widespread applications in MEMS and other MST facilities may

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be manufactured by micro forging, micro extrusion or even micro machining. However, multi-passes are required and the efficiency is low.

Cross wedge rolling is a material forming technology in which a cylindrical billet is plastically deformed into an axisymmetrical part by the action of wedge shape dies moving tangentially relative to the workpiece (Li et al., 2008). Cross wedge rolling has a significant potential in technology and applications in the field of materials manufacturing. However, fundamentals of cross wedge rolling have not been fully understood (Li et al., 2008).

The advantages of microforming technology include high production rates, minimised material loss, excellent mechanical properties of the final product and close tolerances (Geiger et al., 2001). Unfortunately, metal forming technologies established in the macro world cannot be simply scaled down to be applied in the micro world, because it is impossible to scale down all parameters in the process according to similarity theory (Geiβdorfer et al., 2006). A huge challenge exists because of geometrical sources, physical sources, and the change in the ratio between the surface and volume, as well as the increasing influence of Van der Waals and gravity forces (Geiβdorfer et al., 2006). Specific effects of miniaturisation have been observed in all areas of material, process, tools and machines/equipment, which have been well reviewed (Geiger et al., 2001; Vollertsen et al., 2004; Vollertsen et al., 2006; Engel et al., 2002; Williams et al., 2005).

Firstly, scaling down a process from conventional size to micro scale incurs size effects, i.e. material behaviour, including flow stress, anisotropy, ductility and forming limit depends on the specimen size. Flow stress decreases in general with decreasing specimen size, which has been explained by the surface layer model (Geiger et al., 2001). Secondly, materials characteristics influence process, e.g. forming forces, tribology, spring-back and product accuracy. One of the most important process parameters is friction (Engel, 2002). Friction increases with decreasing specimen size. This behaviour has been explained by the model of open and closed lubricant pockets (Sobis et al., 1992). Thirdly, tool manufacturing is a factor crucial to microforming processes as it affects the accuracy in shape and movement or control of the forming tools.

Whatever forming technologies are applied in microforming, all the above problems cannot be avoided. However, the appropriate technologies may be adopted to reduce the number of passes of the microforming process as many as possible, which not only simplifies the manufacturing of tools but also the handling system. Cross wedge rolling is one of the technologies. One important characteristic is that the cross wedge rolling process is highly combined and automated (Li et al., 2008). The feeding, rolling and cutting end of the billet can be accomplished in a single pass, resulting in higher productivity and material utilisation than the traditional machining, forging and casting processes. Scaling down cross wedge rolling to micro scale and the effects of surface roughness of tool, grain size in workpiece and cross sectional area reduction on surface morphology of rolled workpiece have been investigated.

2. Experimental procedure

The application of microforming to the production of micro parts requires suitable production systems with high accuracy. A micro cross wedge rolling machine was designed and manufactured as shown in Fig. 1(a).
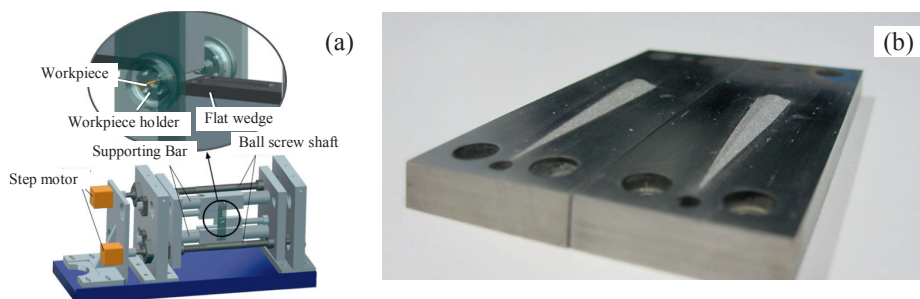

Fig. 1. Micro cross wedge rolling test rig.

A simple and effective automatic control system has been adopted, which consists of positioning, displacement and velocity controls. The tools are a pair of flat wedge of tool steel for simplifying machine design and improving accuracy, as shown in Fig. 1(b). The driving force on the wedge and the displacement can be captured by the load cell and position sensor respectively.

Micro cross wedge rolling tests were conducted using cylindrical workpieces of stainless steel, pure copper and pure aluminium with a diameter of 0.8 mm. Various processing parameters including rolling velocity, cross-sectional area reduction, wedged-tool geometry and surface roughness of workpiece and tool were tested. Two key parameters are forming angle α and stretching angle β. It was determined that $\alpha = 28°$ and $\beta = 8°$ by optimization using numerical simulations (Lu et al., 2013). Workpieces of pure copper underwent heattreatment to obtain different grain sizes. The velocity of flat wedge ranged from 0.1 to 10 mm/s and the area reductions were 34.0, 52.7 and 75.0 %. The surface morphology of rolled workpiece was examined under Keyence VHX-100 Digital Microscope (DM). The received workpiece was cold drawn and its surface morphology is shown in Fig. 2(a) while that after polishing is shown in Fig. 2(b). Each micro cross wedge rolling test was repeated 10 times and the surface roughness was obtained by measuring twenty lines that are evenly distributed on the surface. As an example, Fig. 3 shows the profile and surface morphology of one workpiece after micro cross wedge rolling.
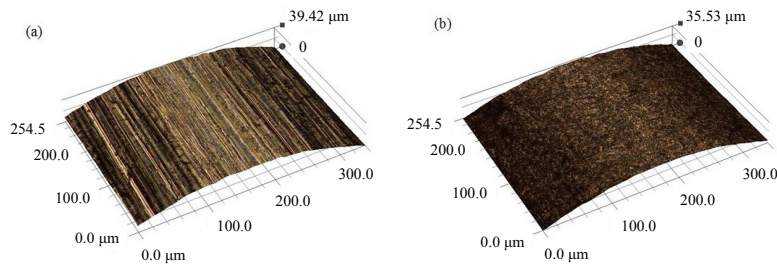

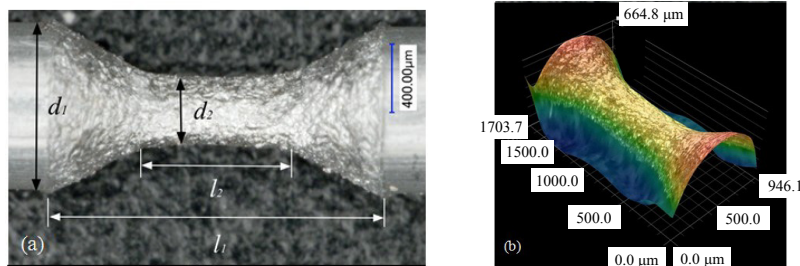Fig. 2. Surface morphology of workpiece (a) as received, (b) after polishing.

Fig. 3. One workpiece after micro cross wedge rolling (a) profile, (b) surface morphology.

3. Results and discussion

Due to significant size effects in micro forming, it is essential to analyse the evolution of surface morphology of workpiece in micro cross wedge rolling by considering the interaction between the workpiece and tools, microstructure and heterogeneity of material etc. The effects of surface roughness of tool, grain size and cross sectional area reduction are presented in the following.

Fig. 4. Surface morphology of workpiece before and after micro cross wedge rolling when tool roughness R_a = 3.2 (a) stainless steel, (b) pure copper, (c) pure aluminium.
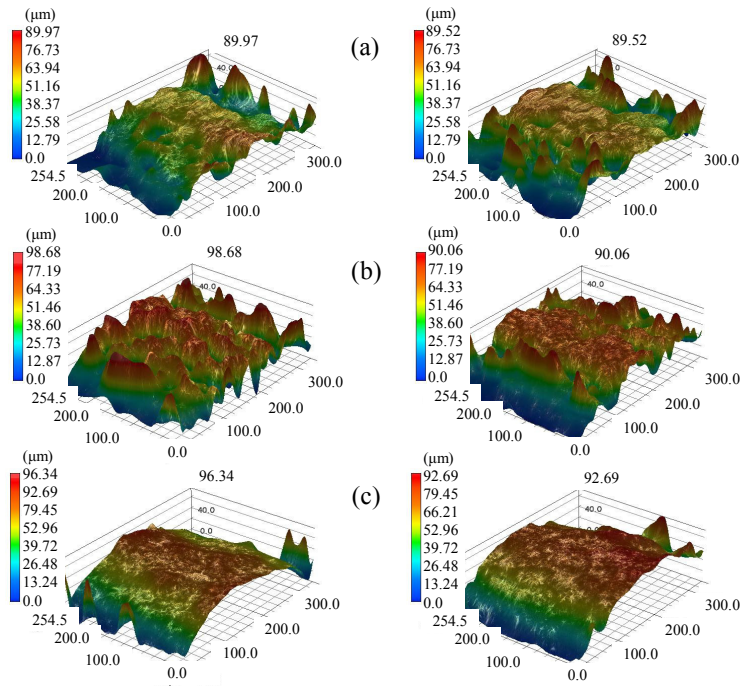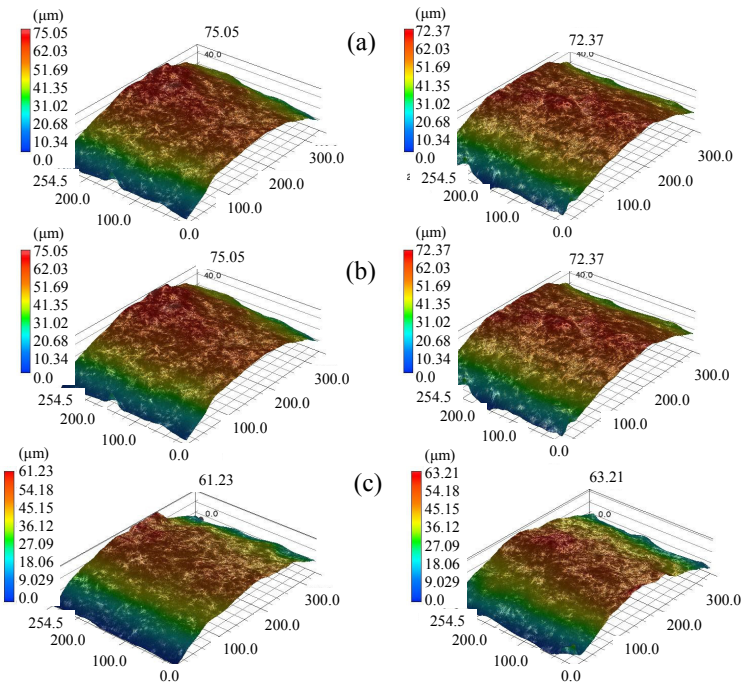

Fig. 5. Surface morphology of workpiece before and after micro cross wedge rolling when tool roughness R_a = 1.6 (a) stainless steel, (b) pure copper, (c) pure aluminium.

3.1. Effect of surface roughness of tool

The surface roughness of tool influences friction and deformation at the interface, which affects the final surface topology of micro workpiece significantly. The surface roughness of flat wedge R_a = 0.8, 1.6, 3.2, which were prepared by taking into account material transfer, rotation criteria and required surface quality in the process of micro cross wedge rolling. Figs. 4 and 5 show surface morphologies of workpieces before and after micro cross wedge rolling.

In the case when the grain sizes are close, the surface roughness of workpiece increases with an increase of surface roughness of tool, as shown in Fig. 6(a). Stainless steel workpieces show smoothest surface after rolling, followed by pure copper then pure aluminium. When surface roughness of tool increases from 1.6 to 3.2 μm, the surface roughening of workpieces of pure copper and pure aluminium is more rapidly than that of stainless steel. The maximum surface roughnesses of pure aluminium and pure copper reach 2.5 and 2.25 μm, respectively while that of stainless steel is only 1.5 μm. This indicates that the control of surface morphology for materials with high strength will be easier than that with low strength in microforming.
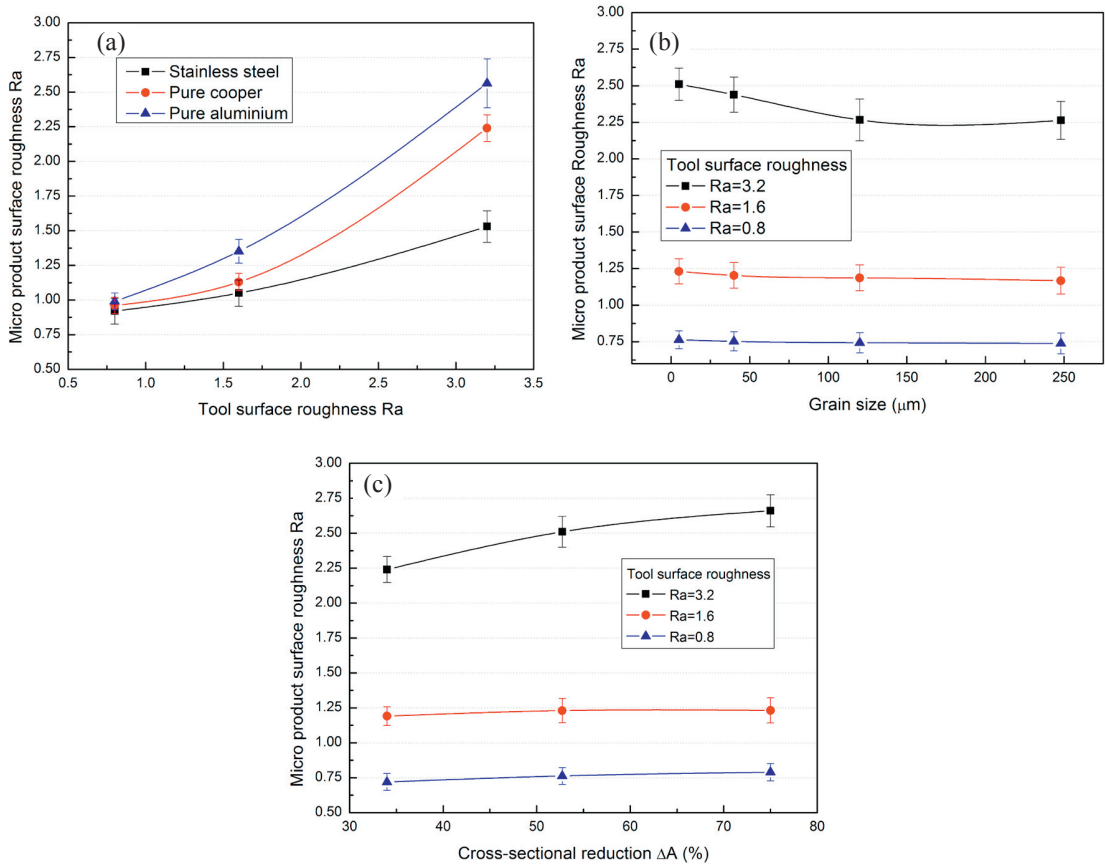

Fig. 6. Relationships between surface roughness of rolled micro workpiece and (a) initial surface roughness of tool, (b) grain size, and (c) cross sectional area reduction.

3.2. Effect of grain size in workpiece

Fig. 6(b) shows the relationship between grain size and surface roughness of rolled workpiece in the case of

pure copper. The surface roughness of the rolled workpiece is relatively sensitive to grain size when the surface roughness of tool is 3.2 μm and it has significant increase when grain size decreases. When surface roughness of tool is 0.8 or 1.6 μm, the effect of grain size on surface roughening of workpiece is not apparent and the average surface roughness R_a only increases slightly with the decrease of grain size. These results do not agree with the view that large grain size causes more inhomogeous deformation in micro forming then high surface roughening. The reason is still being investigated.

3.3. Effect of cross sectional area reduction

The cross sectional area reduction represents the amount of the deformation during rolling process. Fig. 6(c) shows the relationship between cross sectional area reduction and surface roughness of rolled workpiece of pure copper. When the surface roughness of tool is 3.2 μm, there is a significant increase in the surface roughness of workpiece with an increase of area reduction. However, when the tool surface roughness is 1.6 or 0.8 μm, the fluctuation of surface roughness is very limited.

3.2. Surface morphology

Fig. 7 shows surface morphologies of workpieces of pure copper and pure aluminium after micro cross wedge rolling, which were obtained under SEM. Deformation, adhesion and ploughing can be observed on the surface of workpieces. Adhesion is regarded as interface damage and may be caused by capillary, electrostatic, van der Waals forces and other kinds of 'chemical' forces (Lilly et al., 2008; Paulo Davim, 2010). Rough tool surface aggravates more transfer of softer work material and causes more adhesion than smooth tool surface, which builds up layers or formation of lumps of work material on the tool that accounts for increasing tendency of the surface roughness of workpiece and even causes surface defects of workpieces. Metal of low strength is easy to be scratched and transferred to the tool surface. Among the three tested materials, stainless steel has highest strength, followed by pure copper then pure aluminium.
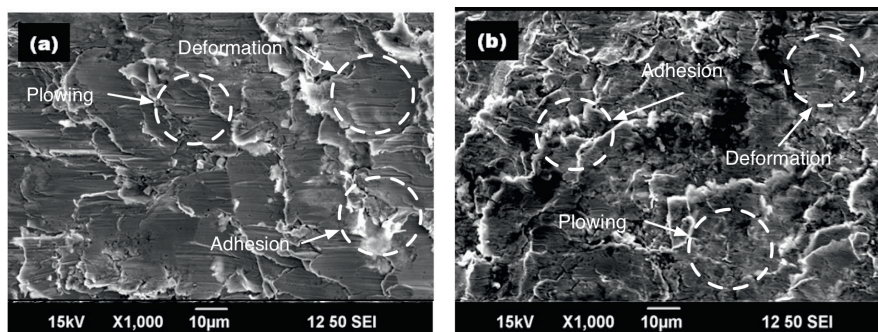

Fig. 7. Surface morphologies of workpieces after micro cross wedge rolling under SEM (a) pure copper, (b) pure aluminium.

4. Conclusions

Micro cross wedge rolling has been developed and micro stepped components have been fabricated successfully on a testing rig by adopting flat wedge tools. When surface roughness of tool is 3.2 μm, the surface roughening of workpiece of pure copper and pure aluminium was more rapidly than that of stainless steel. The maximum surface roughness of pure aluminium and pure copper reached 2.5 and 2.25 μm respectively while that of stainless steel was only 1.5 μm. The control of surface morphology for materials with high strength is easier than that with low strength in micro cross wedge rolling. In the case of pure copper, the surface roughness of the rolled workpiece was relatively sensitive to grain size when the surface roughness of tool was 3.2 μm. When the surface roughness of tool was 3.2 μm, there was an apparent increase in the surface roughness of workpiece with an increase of area

reduction, while the change of surface roughness was very small when the tool surface roughness was 1.6 or 0.8 μm.

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