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Fabricating protruded micro-features on AA6061 substrates by hot embossing method

Nhat Khoa Tran, Yee Cheong Lam, Chee Yoon Yue, Ming Jen Tan

***Abstract*—**Metallic micro parts are playing an important role in micro-fabrication industry. Recently, we have demonstrated a new deformation mechanism for micro-formability of polycrystalline materials. Different depressed micro-features smaller than the grain size have been successfully fabricated on 6061 aluminum alloy (AA6061) substrates with good fidelity. To further verify this proposed deformation mechanism that grain size is not a limiting factor, we demonstrate here that in addition of depressed features, protruded micro-features on a polycrystalline substrate can similarly be fabricated.

***Keywords*—**Deformation mechanism, grain size, micro-fabrication, polycrystalline materials

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I. Introduction

THE trend towards further miniaturization in electronics production, micro-systems technology (MST), and medical sector, is progressing rapidly [1]. Recently, much research has been conducted in metal-forming technologies, which offer the potential for mass production with controlled quality and low cost, for the production of micro-parts [2]. Micro-forging and micro-extrusion have been employed in mass production of metallic micro-parts with reasonable precision [3]. Micro hot embossing can be applied to make metallic micro heat exchanger, a crucial component of many micro-electromechanical systems (MEMS) [4]. Other typical examples of micro metal forming include the manufacture of pins for IC-carriers, fasteners, micro-screws, lead-frames, micro-cups and connectors, as well as medical implants [5].

The widely accepted deformation mechanism in micro-forming of polycrystalline metallic alloys is grain boundary sliding and grain rotation in polycrystalline aggregates [2, 4-8]. As such, grain size is believed to be a limiting factor on the minimum size of the geometrical features that can be produced by micro-forming [3]. With this perception, ultra-fine grained alloys were employed for the fabrication of micro-scale features [2, 4, 6]; alternatively, amorphous alloys (bulk metallic glasses), which have no crystal structure, have also been demonstrated for the fabrication of micro-scale features [7]. Fig. 1 illustrates the current concept of deformation of coarse polycrystalline, ultra-fine grained and amorphous metals in a micro-forming process. Ultra-fine grained alloys were fabricated by severe plastic deformation (SPD) techniques [9], which could reduce the alloy grains to submicron scale [2]. As such, these alloys have been employed to manufacture micro-parts with features in the range of 5-50 μm [4]. With their unique characteristic, namely the absence of grain boundaries, amorphous metals have been demonstrated to have no difficulties in filling the micro-cavity of the mold with good fidelity [7].

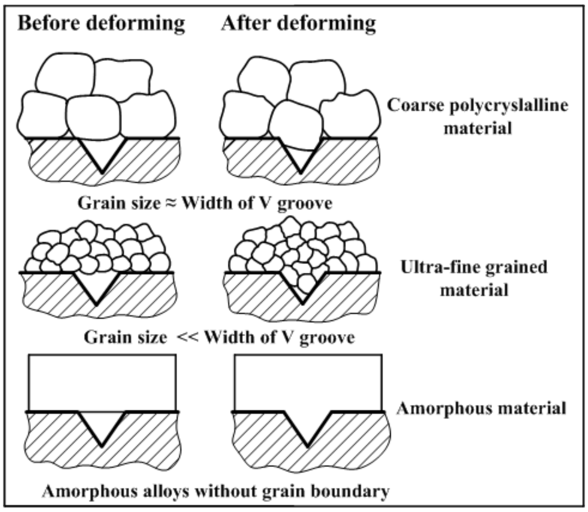

Fig. 1 Illustration of micro-formability of coarse polycrystalline, ultra-fine grained and amorphous metals [7]

The production and preparation of ultra-fine grained and amorphous alloys are more involved and costly as compared to normal polycrystalline alloys. This drawback poses limitations in their wide adoption for mass production of metallic micro-parts as compared to the potential offered by normal coarse grained polycrystalline alloys. Our previous research [10] reports a new deformation phenomenon in micro hot forming of a polycrystalline metal, AA6061. In contrast with conventional mechanism for metallic micro forming, namely grain boundary sliding and grain rotation, it was hypothesized that by proper choice of the processing condition, namely a processing temperature close to the solidus temperature and sufficient loading pressure, cooperative plastic deformation in adjacent grains even across their shared grain boundaries is possible such that continuity across the grain boundary is maintained. Some micro-features (straight channels, X, O, Y shaped features) have been fabricated to verify this hypothesis [10, 11]. However, we have hitherto examined only depressed features fabricated in

Nhat Khoa Tran is with the Singapore-MIT Alliance, Manufacturing Systems & Technology Programme, Nanyang Technological University, 65 Nanyang Drive, 637460, Singapore (phone: 065-67904273; e-mail: tran0065@e.ntu.edu.sg).

Yee Cheong Lam is with the Singapore-MIT Alliance, Manufacturing Systems & Technology Programme, School of Mechanical & Aerospace Engineering, Nanyang Technological University, 65 Nanyang Drive, 637460, Singapore (e-mail : myclam@ntu.edu.sg).

Chee Yoon Yue is with the Singapore-MIT Alliance, Manufacturing Systems & Technology Programme, School of Mechanical & Aerospace Engineering, Nanyang Technological University, 65 Nanyang Drive, 637460, Singapore (e-mail: mcyyue@ntu.edu.sg).

Ming Jen Tan is with the School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore (email: mmjtan@ntu.edu.sg).

AA6061 substrates. In industry, metallic micro-parts are employed widely with protrusive micro-features. One typical example is the micro-mold for making polymeric microfluidic devices; the metallic die must have protruded micro-channels so as to emboss depressed micro-channels onto the polymeric substrates. As such, the purpose of this investigation is to explore the ability of making protruded micro-features on AA6061 substrate. In particular, we will employ a hot embossing process with a silicon master to fabricate the protruded micro-features on AA6061 substrates.

II. Experiment Procedure

A. Experimental equipment

The hot-embossing experiment was carried out on a servo-hydraulic INSTRON testing machine equipped with compression platens inside an air furnace that can reach up to 1000°C, see Fig. 2. The hot-embossing temperature was measured and controlled by two thermocouples attached to the compression platens.

Fig. 2 INSTRON testing machine

B. Silicon master preparation

Silicon masters were fabricated from a 1.5 µm thick silicon wafer. Thick silicon wafers were employed to avoid the breakage of silicon master during the demolding process. The fabricating process consisted of three steps: photolithography, deep-reactive ion etching (DRIE) and wafer dicing. Firstly, the reversed patterns of the desired channel were transferred onto the surface of the silicon wafer by UV-photolithography and developed. With the DRIE process, the silicon wafer was etched to the depth of 30 µm. Finally, the 4 inch silicon wafer was diced to 20 mm x 20 mm individual silicon masters.

C. AA6061 preparation

AA6061-T6 is a precipitation hardened aluminum alloy, containing 0.84% magnesium and 0.7% silicon as its major alloying elements. Differential scanning calorimetry (DSC) indicated that its solidus temperature is about 603°C, see Fig. 3. AA6061 specimens were polished using SiC papers: grit 800, 1200, 2400 and 4000 respectively, and then followed by 6 µm and 1µm diamond pastes. The surface roughness of AA6061 specimen, measured by PLµ Confocal Imaging Profiler, was approximately 40 nm.

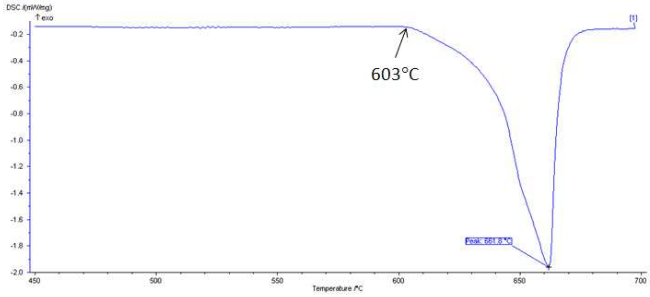

Fig. 3 DSC graph of AA6061

Measured by Electron Backscatter Diffraction (EBSD), Fig. 4 shows a projection of the grain structure and texture, as the grain orientations are colored according to the inverse-pole-figure color map shown. Employing Tango software, the average grain size of AA6061 was measured to be approximately 46.27 µm, which is in good agreement with the grain size value of 45.07 µm reported [10].

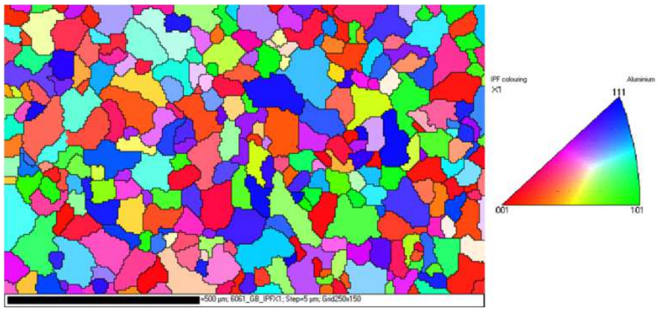

Fig. 4 Microstructure of 6061 aluminum alloy prior to hot embossing experiment. The image was colored using a X1 inverse-pole-figure color map, where X1 is the horizontal direction.

III. Results and Discussion

In this investigation, the depressed features in the silicon masters, which had an aspect ratio 1:1, were hot-embossed onto the AA6061 substrates. The feature depth and feature width were approximately 30 µm, which were smaller than the average grain size of AA6061. At first, individual silicon master and AA6061 specimen were aligned and placed between the compression platens. The sandwich Si-AA6061 was heated up to the embossing temperature of 500°C. After a suitable length of time (approximately 10 minutes at the embossing temperature), the load was ramped up to 24,000 N to produce a nominal pressure of 60 MPa in 60 s, and held for 30 s before unloading. Subsequently, the silicon master was demolded manually. More details about the hot embossing procedure of silicon master on AA6061 substrate can be found in [11, 12].

Fig. 5 to Fig. 8 show the SEM micrographs of the different depressed micro-features on the silicon masters and corresponding embossed protruded micro-features on the AA6061 substrates.

Fig. 5 and Fig. 6 show the successful replication with good fidelity of the simple protruded features such as square, concentric circles, triangle and cross micro-features. Similarly,

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Fig. 7 and Fig. 8 indicate the successful replication with good fidelity of the more complicated protruded features such as micro-channels and micro-mixer shaped features. These protruded embossed features had width of approximately 30 μm, which is less than the average grain size. As such, we have demonstrated here the possibility of making protruded micro-features on a polycrystalline substrate with their feature size less than the grain size of the substrate material.

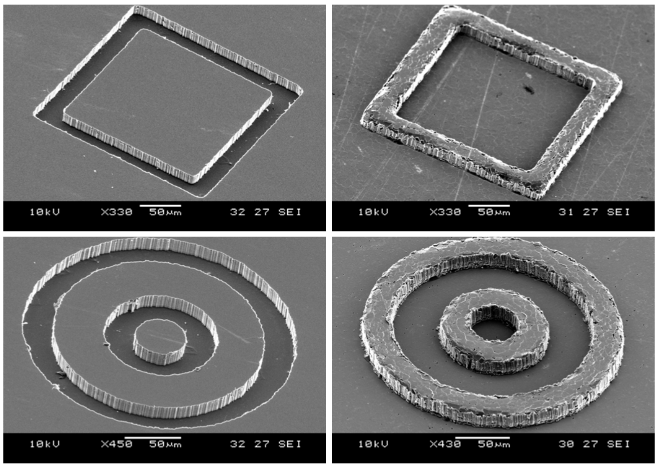

Fig. 5 Square and concentric circle features on silicon masters (left) and corresponding embossed features on AA6061 substrates (right)

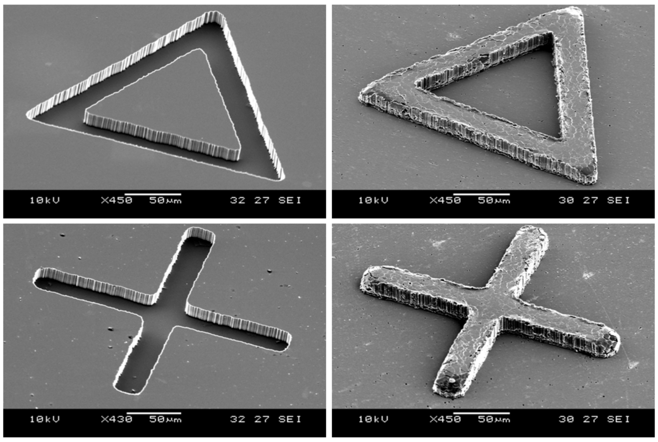

Fig. 6 Triangle and cross shaped features on silicon masters (left) and corresponding embossed features on AA6061 substrates (right)

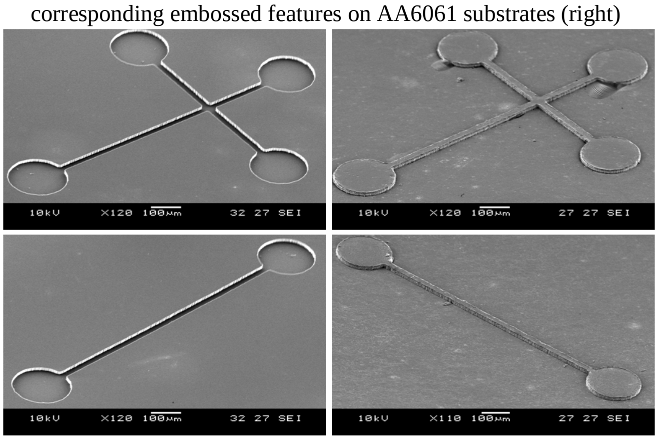

Fig. 7 T shaped and I shaped features on silicon masters (left) and corresponding embossed features on AA6061 substrates (right)

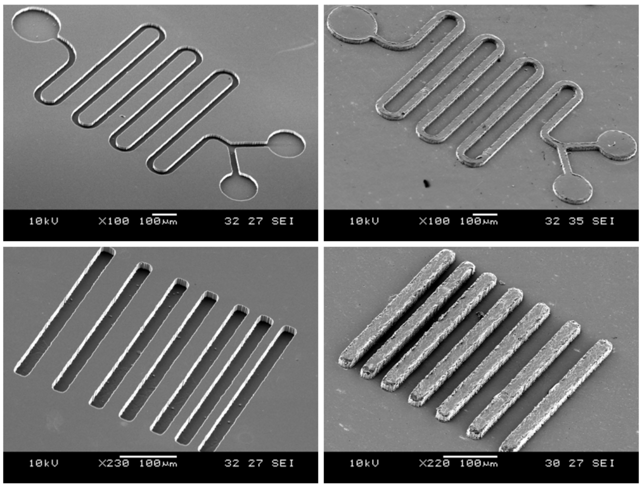

Fig. 8 Micro-mixer shaped features and micro-channels on silicon master (left) and corresponding embossed features on AA6061 substrates (right).

IV. Conclusion

In this study, by hot embossing, the fabrication with high fidelity of protruded features smaller than the average grain size on AA6061 substrate has been demonstrated. We have previously demonstrated that depressed features smaller than the grain size can be similarly fabricated [10]. Together, these results show that by proper choice of the embossing parameters, (embossing temperature, embossing rate and embossing load), it is possible to fabricate, by hot embossing, both depressed and protruded features with good fidelity on polycrystalline materials regardless of their average grain size. The applicability of this research is not limited to the area of mold-making with fine features, but also in the field of fabricating aluminum micro-parts for microelectromechanical systems (MEMS) or micro-systems technology.

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