Materials and Manufacturing Processes

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lmmp20

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Accepted author version posted online: 29 Oct 2013. Published online: 11 Feb 2014.

To cite this article: Chunju Wang, Chuanjie Wang, Debin Shan, Bin Guo & Jie Xu (2013) Manufacturing High Aspect Ratio Microturbine by Isothermal Microforging Process, Materials and Manufacturing Processes, 29:1, 42-45, DOI: 10.1080/10426914.2013.852217

To link to this article: http://dx.doi.org/10.1080/10426914.2013.852217

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Manufacturing High Aspect Ratio Microturbine by Isothermal Microforging Process

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An isothermal microforging process is proposed to manufacture a microturbine with high aspect ratio microblade. Two schemes with circular and circular ring preforms were performed by the proposed isothermal micro forging process. A microturbine with a higher microblade is manufactured when using the circular ring preform compared to that using the circular one. Then, the mechanical property of microturbine is evaluated via the shear strength of the micro blade. The mechanical property is improved by solid solution and aging treatment.

Keywords Deformation; Forging; Heating; Metalforming; Micromanufacturing; Microstructure; Nonferrous; Strength.

INTRODUCTION

Microturbine is a key component in the micropower units, especially in the micropumps and microturbine engines. Several micromanufacturing technologies have been applied for fabricating microturbines, such as lithography of Si or SiC [1], shape deposition of Si3N4 [2], EDM [3, 4], and miniature machining [5]. However, limitations of materials, high costs, and low efficiency of these methods restrict their applications in manufacturing microturbines. Microforming, as a promising technology for manufacturing micrometal components, is understood to fabricate microcomponents in the submillimeter range [6, 7]. Also, microforming offers many attractive virtues, e.g., higher manufacturing rate, higher precision, higher material utilization, lower cost, etc. [8, 9]. In the last two decades, a lot of research has been done on microforming of micrometal parts. Fu [10] developed a feature-based method for defect-free cold-forming process to manufacture a non-axisymmetrical micropart. Fu also investigated effect of the microstructure on deformation behavior of microcomponents in microextrusion [11, 12], microheading [13], and microscaled progressive processes [14], respectively. Kim [15] studied both acoustic softening and hardening behavior in micro/meso forming. Results showed that the overall forming stress reduced by 30% by applying high-frequency vibration. Engel [9] indicated that elevated temperatures can improve the material formability in microforming processes. Zhao [16] investigated the effect of electric conductive heating on microwarm coining of stainless steel numerically and experimentally. Shan [17] manufactured microgear and micro-double gears using microforging processes combined the developed floating female dies. Yang [18] studied the effect of high-energy assistance on the micro deep drawing and micro forging processes. The formability and the surface roughness were improved. In this paper, an isothermal microforging process is proposed to manufacture a rotationally symmetrical micro part--microturbine with high aspect ratio. The forming processes of the microturbine are investigated experimentally. Two types of preforms (circular ring preform and circular preform) are selected to study the influence of preform shapes on the plastic flow behaviors in the forming process of the microturbine. Then, a shear testing device is designed to measure the shear strength of the microblade. The mechanical property of the microturbine is evaluated by the shear strength of the microblade. Furthermore, a solid solution and aging treatment is performed to improve the shear strength of the microblade.

DESIGN OF ISOThERMAL MICROFORGING PROCESS

The microturbine is composed of a flange, a rotary table, and eight blades distributed on the rotary table uniformly. The two-dimensional (2D) and three-dimensional (3D) models of the microturbine is shown in Fig. 1. As the crucial component of microturbine, the quality of the microblade affects the whole performance of the microturbine greatly. The height and thickness of the microblade is 0.8 mm and 0.3 mm, respectively. The feature size of the microturbine is in the submillimeter range. It is hard to form the microblade with a high aspect ratio in the hundreds of microns range by
cold forming processes, because of size effects on friction and formability in microforming [6, 7, 19]. To minimize and control the size effects in microscale metal forming, an isothermal microforging process is proposed to manufacture the microturbine. Koc [20] indicated that the bulk plastic flow of the material has a key role on the formation of the surface microfeatures. To investigate the influence of pre-form shapes on the forming quality of the microturbine, circular ring and circular preforms are considered.

**EXPERIMENTAL RESULTS AND ANALYSIS**

**Experimental Setup**

The microforging device of the microturbine, including punch, ejection mechanism driven by a screw, die base, heating units, and female die manufactured with good surface quality by micro-electrical discharge machining (micro-EDM) is shown in Fig. 2. Cold rolling sheet of 7075 aluminum alloy is chosen and annealed at the temperature of 440ºC for 3 hours to eliminate work hardening. Based on the volume constant principle in plastic deformation process, the two preforms were prepared through the ultrafine machining process. The dimensions of the two preforms are shown in Table 1. To improve the material filling ability, both die set and the preform are heated to 450ºC. The lubricant graphite is applied to reduce friction. The punch velocity is assigned to 0.1 mm/s. The maximum punch load is assigned to 9,000 N. The experiments are carried out by a servo-driven apparatus with a load capacity of 10,000 N.

**Analysis of Isothermal Microforging Process**

Figure 3 is the digital photograph of the microturbine. The dimensions of the two microturbines manufactured through the two preforms are measured by a laser scanning confocal microscope (LSCM) (Olympus OLS-3000). Figure 4 depicts the three-dimensional topographies and the height distributions of the microblades. The maximum heights of blades in the two cases are 0.832 mm and 0.629 mm, respectively. The height scatters in the two cases are 0.188 mm and 0.34 mm, respectively. The microturbine with a higher height of the microblade and more homogeneous distribution of the microblade height is manufactured when using the circular ring preform. The void space of the circular ring preform enables the bulk material to flow into the cavities in the lower die and delays the full the contact between the punch and the preform compared to that using the circular preform.

**TABLE 1.—Dimensions of preforms used in the experiment.**

<table>
<thead>
<tr>
<th>Preforms</th>
<th>Outer diameter/mm</th>
<th>Inner diameter/mm</th>
<th>Height/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.90</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>5.90</td>
<td>2.0</td>
<td>1.09</td>
</tr>
</tbody>
</table>
It indicates that there is an advantage of forming high aspect ratio blade when using the circular ring preform compared to that using circular preform under the same punch loads. The blade heights at the centre (Points 7 and 8 in Fig. 4c) of the microblades are higher than those close to the ends of the microblades. The microblade height at the perimeter of the formed part (Point 1 in Fig. 4c) is lower than that approaching the centre of the parts (Point 12 in Fig. 4c) in both cases. These inhomogeneous distributions of the microblade heights are resulted from the combined contributions of compression stress distribution and die constraints. For both ends of the microblade, the constraints from the die are identical. The major difference is the punch stress. The compression stress is the highest at the center of the punch and decreases from the center to the edge of the punch. Thus, the microblade height at the center of the part is higher than that at the boundary of the part. As the both contributions, the highest blade height is at the center of the microblade inclining to the center of the part with a certain offset. Then the arc of the microblade is also measured by LSCM. The designed values of radius of inner arc and central angle are 1.10 mm and 120°, respectively. The measured values are 1.08 mm and 119°, just with errors of 1.82% and 0.83%, respectively. The surface roughness of the microblade is also measured by LSCM. The surface roughness of Ra is less than 0.6 µm. It is noticed that the formed microturbine by the proposed process has high accuracy of the microblade.

**Shear Strength Analysis of Microturbine**

Up to now, many microparts have been manufactured. However, fewer evaluating tests of mechanical properties of microparts were performed [10, 11, 13]. This part is focused on mechanical property analysis of the microturbine. Microturbine is a key component in the micropower units, whose working mode is rotation in a high speed. One of the main failures is broken under shearing stress. So, the shear strength of the microblades is chosen to characterize the mechanical properties of the microturbine. The evaluating tests are performed in a Zwick machine. The testing device is shown in Fig. 5. Then a solid solution and aging treatment (STA) is applied to the microturbine in circular ring preform case to study its effect on the shear strength of the microturbine. The microturbines are treated at 470°C for 0.5 h by a solid solution and at 120°C for 6 h and 165°C for 12 h by an artificial ageing process. The shear strength of the blade can be expressed in Eq. (1):

$$\tau = \frac{F}{S},$$

where $\tau$, $F$, and $S$ are shear strength, maximum shear load, and area of the blade in the cross-section, respectively.

The shear strength of the microblade with STA is 284 MPa, about 32% higher than that without STA ($\tau = 215$ MPa). The shear strength of the blade is improved by STA. Fracture morphologies of the blades are shown in Fig. 6. The backscatter images of microblades with and without STA are shown in Fig. 7. Before STA, the second phase in 7075 Al alloy arranges in a zonal distribution pattern along the height direction of the blade. However, the second phase reaches a polygon distribution after STA. This arrangement of the second phase can resist crack propagation during shearing stress.

**Figure 4.**—3D images and height distributions of the microblades: (a) circular preform case, (b) circular ring preform case, and (c) height distributions of the microblade.

**Figure 5.**—Shear testing device.

**Figure 6.**—Fracture morphologies of the blades: (a)–(c) without STA and (d)–(f) with STA.
shearing deformation effectively. Thus the microturbine with higher shear strength is obtained through STA.

CONCLUSIONS

An isothermal microforging process was proposed to manufacture the microturbine with high aspect ratio microblades. The flow pattern is improved when using the circular ring preform compared to that using the circular one. The microturbine with higher and more homogeneous distribution of the blade height is manufactured when using the circular ring preform compared to that using the circular one. The shear strength of the microblade was applied to evaluate the mechanical property of microturbine. The shear strength of the microblade is enhanced by about 32% for the microturbine with solid solution and aging treatment. This study provides a foundational method for forming more complicated microstructures and an attempt to evaluate the mechanical properties of microparts.

FUNDING

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (51105102 and 50835002).

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