Micro-extrusion of ultra-fine grain aluminium

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Abstract

Microforming of normal, coarse grain (CG) metals leads to scale problems which originate from the fact that the grain size becomes comparable to the part size. A possible way of dealing with these problems is replacing CG metals with ultra-fine grain (UFG) metals. UFG metals can be produced in bulk by severe plastic deformation (SPD). This paper describes using UFG aluminium 1070 for preliminary trials of micro extrusion of a cylindrical cup. The process of producing bulk UFG aluminium by SPD is explained and the material obtained characterised. The preparation of micro billets for the extrusion operation is discussed. Backward extrusion is carried out for two types of material, CG and UFG. This enables a comparison of the material behaviour and product characteristics.

Keywords: microforming, micro-extrusion, ultra-fine grain metals, severe plastic deformation

1. Introduction

Microforming of metals is one of the emerging technologies, which increases the palette of micro components available. As with many micro manufacturing techniques, scaling down the existing technology is problematic. One aspect in particular has drawn attention for many years. It is the grain size of the material formed which becomes comparable with the size of micro component or the size of some of its geometrical features. Metal forming of a few grains rather than a polycrystalline material leads to an unusual material response, increased friction and reduced repeatability (scatter of results). These, and other technological problems, were reviewed by Geiger et al. [1] and Engel and Eckstein [2].

The focus of some publications was explicitly on the grain size effects. For example, Raulea et al. [3] carried out experiments for pure aluminium using a tensile test for specimens with different thicknesses and a given grain size and a bending test for one specimen thickness and different grain sizes. Kocanda and Prejz [4] studied the influence of the grain size in copper strip on the process of bending. More recently, Cao et al. [5] investigated behaviour of brass, with two different grain sizes, which was forward extruded into a micropin of two different sizes.

The above researches follow a certain pattern. The first approach used is to work with a material with one grain size and alter the dimensions of samples or products. This leads to the notion of a relative grain size. A more direct approach is to use one size of the product, as it is supposed to be, and experiment with different grain sizes. These different sizes are obtained by a thermo-mechanical process, which usually involves annealing at different temperatures. Such annealing leads to grain growth, which inevitably results in relatively large grains. The normally available grain sizes for many materials are measured in hundreds or tens of micrometres at best.

However, there is another way of addressing the problem of grain size in microforming. It is based on using nanometals or ultra-fine grain (UFG) metals produced by either powder metallurgy or severe plastic deformation (SPD). The powder metallurgy route, which involves nanopowders, enables obtaining grains smaller than 0.1 μm. However, the cost, residual porosity and health issues are the known concerns for this route. SPD, which is based on inducing a very large plastic deformation without basically changing the shape of the billet, can reduce the original grain size of the material to approximately 0.1 - 1 μm. SPD methods are related to traditional metal forming methods with all their formability, friction and tooling problems, however, they have a potential for cheap conversion of large quantities of all types of traditional coarse grain (CG) metals into UFG metals.

In the research reported in this paper, we used UFG aluminium produced by SPD. For comparison purposes, also the original CG aluminium was used. Both materials were prepared in the form of 1 mm thick plates, from which round blanks were punched out. Subsequently, these were subjected to backward extrusion into small cups and tested. All these steps are described in the chapters below.

2. Obtaining UFG aluminium

2.1 UFG metals

UFG metals possess unique properties including very high yield and ultimate strength and reasonable ductility. They excel at low temperatures (high impact strength) and become superplastic at elevated temperatures (high strain rate superplasticity). The existing and envisaged applications of UFG metals encompass sputtering targets, medical implants, structural parts for the automotive and aerospace industries, defence systems, MEMS and sports equipment. Application of UFG metals in microforming is relatively unexplored.

Nanostructuring of UFG metals by SPD involves generating multiple dislocation systems in the form of localised shear bands, which virtually subdivide the original large grains into subgrains (dislocation cells) and, eventually, lead to the creation of new fine grains with high angle boundaries. Only a relatively small strain is required to initiate this process, however, the
full conversion of the structure requires a very large strain (equivalent strain of 4-10 depending on the material) and, preferably, various spatial orientations of dislocation systems.

The research effort towards nanostructuring metals by SPD is worldwide and has resulted in hundreds of publications. Recently published three survey papers provide a lot of information on relevant issues [6,7,8].

2.2 Nanostructuring of aluminium by SPD

There are numerous SPD processes, which are used on a laboratory scale. There are no industrially accepted SPD processes as yet. The most popular SPD process is equal channel angular pressing (ECAP). It is based on forcing a metal billet through an L-shaped channel of constant profile (usually square or round). The mode of deformation is that of simple shear. It occurs at the intersection of the input and output passages of the channel. The amount of plastic strain generated depends on the angle between channel passages. For an angle of 90°, it reaches 1.15 (equivalent strain). This value is too small for all required microstructural changes to occur. Therefore, the material has to pass several times through a classical L-shape ECAP die.

An alternative system, which was used in this research, is based on four sequential channel passages orientated at 90° to each other and creating a 3-D path for the material. The system, proposed by Rosochowski et al. [9], incorporates three channel turns and thus fulfils the requirement of an increased strain in one pass of the material (3.45) and a spatial distribution of the shear planes (inclined at 60° to each other). The billet shown in Figure 1 represents the shape of the channel realised in a 3D-ECAP die.

The material used was commercially pure aluminium 1070 with the initial average grain size of about 300 μm (Figure 2).

After three consecutive passes through a 3D-ECAP die, the amount of plastic strain generated in the material reached 10.35. Such a large strain led to grain refinement with the average grain size of 0.6 μm, as illustrated in Figure 3. As this figure indicates, not all grain boundaries are of a high angle type (>15°), which means that some domains should be treated as subgrains rather than fully formed grains.

The mechanical properties of such produced UFG aluminium as well as the initial CG material were established by tensile testing of 2.5×12.5 samples. The measured values of the offset yield strength Re, ultimate tensile strength Rm, total elongation A5 and area reduction Z are presented in Table 1.

<table>
<thead>
<tr>
<th>Material (Al 1070)</th>
<th>Re (MPa)</th>
<th>Rm (MPa)</th>
<th>A5 (%)</th>
<th>Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG Al</td>
<td>56</td>
<td>73</td>
<td>39</td>
<td>97</td>
</tr>
<tr>
<td>UFG Al</td>
<td>173</td>
<td>188</td>
<td>16</td>
<td>72</td>
</tr>
</tbody>
</table>

3. Backward extrusion of miniature cups

Figure 4 presents the design of the part extruded. According to the classical definition, a micropart should be smaller than 1 mm. Thus the considered part is not exactly a micropart. However, it is small enough to give an indication of possible problems with micro-forming.

It is planned to miniaturise this part in the course of further research and reduce the outer diameter to 0.5 mm.

3.1 Billets for backward extrusion

Machining of pure aluminium, especially to the required billet size of 1.8×1.0, is problematic. In this research, a different approach has been tested. The method involved turning CG aluminium to produce 10 mm diameter bars and encapsulating them in resin. The same encapsulation was applied to square (8×8) UFG aluminium billets produced by 3D-ECAP. Next, the encapsulated materials were sliced and electropolished to the required size of about 1 mm. The whole procedure was designed to avoid inducing structural changes in the tested materials. Figure 5 displays the encapsulated materials after slicing.
Subsequently, such prepared plates were blanked using a 1.6 mm punch as described by Presz in [10]. A small punch/die clearance and a blankholder were used to avoid premature fracture. As can be seen in Figure 6, the smooth, plastic portion of the cut surface accounted for about 80% and 60% of blank thickness for CG and UFG material respectively. This difference was not unexpected taking into account that the UFG material was harder and less ductile. This also affected the blanking force for UFG aluminium which was higher and was dropping sooner (Figure 7).

3.2 Extrusion process

The blanked billets were first subjected to closed-die compression in the backward extrusion die before being extruded. The compression process was used to increase the billet diameter from 1.6 to 1.8 and rectify geometrical inaccuracies resulting from blanking. Finally, backward extrusion was carried out to produce the cups presented in Figure 8.

As it was the case with blanking, the UFG material exhibited higher resistance to forming. However, as can be seen from Figure 9, for a larger accumulated strain the difference between forming forces is getting smaller.

4. Characterisation of extruded cups

The extruded cups were encapsulated in resin, cut in half, electropolished and observed using optical microscopy. Some results of these observations are displayed in Figure 10 and Figure 11.

Grain boundaries in these figures are not readily recognisable. However, the non-even elevation of the revealed surface is associated with the heavily distorted individual grains. Judging by the size of these distorted areas, cups made of CG aluminium exhibit less uniform structure. Looking at the walls, they also seem to be less willing to assume the required shape. On the other
hand, since the cup shape is rather simple, this could also be related to the way metallurgical samples were prepared.

Scanning microscopy was used to observe some interesting details in the cups. Figure 12 gives the view of the cup’s edge for both materials. This edge is usually rough and has to be machined off in industrial applications. Nevertheless, looking at the surface discontinuities (cracks?) on this edge, one would appreciate a smaller scale of these for UFG aluminium.

In order to evaluate mechanical properties of the cups, micro-hardness HV_{50} measurements were carried out in the cups’ cross-sections. Figure 13 displays micro-hardness distribution in the bottom part (unfilled symbols) and at single measurement points in the middle of the wall (filled symbols) for both materials. The hardness distribution in UFG aluminium is more uniform, with an average value which is about 10 points higher than for the CG material.

This work was partly sponsored by Scottish Enterprise Proof of Concept Fund.

**References**


