Materials and Design 63 (2014) 471–478

Contents lists available at ScienceDirect

Materials and Design

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

Roll-formability of cryo-rolled ultrafine aluminium sheet

J. Marnette*, M. Weiss, P.D. Hodgson

Institute for Frontier Materials, Deakin University, Geelong Waurn Ponds, VIC 3216, Australia

ARTICLE INFO

Article history:
Received 5 February 2014
Accepted 15 June 2014
Available online 26 June 2014

Keywords:
Roll forming
Ultrafine-structured aluminium
Cryo rolling
Bending
Incremental forming

ABSTRACT

Ultrafine-grain aluminium sheet was produced by rolling at cryogenic (CR) and at room temperature (RTR). Commercial purity aluminium plate was reduced in 30 passes from an initial material thickness of 10 mm to a final thickness of 2 mm (80% reduction). Tensile stress and strength were significantly increased while total elongation was drastically reduced. It was found that despite the low tensile elongation both materials are able to accommodate high localised strains in the neck leading to a high reduction in area. The formability of the material was further investigated in bending operations. A minimum bending radius of 6 mm (CR) and 5 mm (RTR) was found and pure bending tests showed homogeneous forming behaviour for both materials. In V-die bending the cryo-rolled material showed strain localisations across the final radius and kinking of the sample. It has been found that even if the total elongation in tension is close to zero leading to early failure in V-die bending, ultra-fine grained and low ductile sheet metals can be roll formed to simple section shapes with small radii using commercial roll forming equipment.

1. Introduction

More than a decade ago Miller et al. [1] reviewed the application of light weight metals and noticed that aluminium structures are playing a key role in automotive design and are increasingly used as a substitute to steel. The disadvantage of light metals apart from high cost, is their lower strength compared to steel and this generally requires their use in higher gauges to meet the strength and rigidity requirements of structural components [2].

As well as others Liddicoat et al. [3] reported that the refining of the microstructure of light metals enhances the material strength and Severe Plastic Deformation (SPD) methods are commonly used to achieve a significant increase in material strength by generating an ultrafine-grained structure. Also, the work of Taylor et al. [4] as well as Zhao et al. [5] are some good examples of the significant improvement in strength to weight ratio that can be observed, especially for aluminium alloys.

The review paper of Sabirov et al. [6] gives a good summary on the benefits and drawbacks of numerous severely deformed alloys and shows the importance of the research that has been performed to date to produce ultrafine-grain metals and investigate their material properties.

Several approaches like the work of Zhao et al. [5] or Liddicoat et al. [3] have been made to produce ultrafine sheet metal. Most of these studies have been limited to the analysis of the material behaviour in tension and to a small scale sample production. However, structural components are commonly made by multi axial strain paths such as drawing or stamping. Taylor et al. [4] have shown that cryo-rolled aluminium can achieve higher formability in biaxial stretch forming than under pure tensile deformation. However, the actual production of parts from SPD processed sample material via sheet forming has not been performed yet and will be investigated in this work.

Panigrahi et al. [7–9], as well as Taylor et al. [4] and others [10,11] have reported the repeated cold rolling at cryogenic temperature that allows the bulk material production of ultrafine-grained metal sheet; however these materials show low tensile elongation and property variations through the thickness which complicate their forming in conventional processes [12]. Therefore, new forming processes need to be identified to form these high strength materials under cold forming conditions.

Wen [13] has shown that roll forming is a sheet bending technology that allows the forming of complex geometries from high strength and low elongation materials. It therefore has the potential to shape ultrafine-grained metal sheet to simple sections. However, currently there is only limited understanding of the role of material behaviour of ultrafine-grained metals in sheet metal forming.

---

* Corresponding author. Address: Institute for Frontier Materials, Deakin University, Locked bag 20000, Geelong, VIC 3216, Australia. Tel.: +61 433 183239.
E-mail address: jmarnette@deakin.edu.au (J. Marnette).

http://dx.doi.org/10.1016/j.matdes.2014.06.036

In this study commercial purity aluminium is rolled under cryogenic temperatures (CR) and at room temperature (RTR). The microstructure is determined and the material properties in tension are analysed. The formability of the alloys produced is then investigated for pure bending and for bending in a V-die for two different profile radii. Roll forming trials are also performed and the final radii are compared with the bending test.

2. Material preparation

Commercial purity aluminium (99.6%) in the form of a cast billet was hot rolled at 500 °C to a thickness of 10 mm and allowed to cool in air. Sections of 240 mm length and 90 mm width were cut from the plate and rolled in a two high rolling mill with a roll diameter of 365 mm at a set rolling speed of 15 rev min^{-1}. The aluminium plate was first kept in liquid nitrogen until bubbling stopped and was then rolled. After each rolling pass the sheet was submerged in the liquid nitrogen bath to keep the material at the cryogenic temperature (below −150 °C). The reduction from 10 mm to 2 mm was performed in approximately 30 steps using an average strain of −0.055 in each pass. Strips were also rolled at room temperature using the same rolling schedule. Both rolling processes produced aluminium strip with an approximate length of 900 mm and strips of 75 mm width were cut in the rolling direction using a guillotine. Bone shaped specimens for tension tests were prepared in the transverse and in rolling direction, while the samples for the pure and the V-die bend tests were pre-cut transverse to the rolling direction using a band saw followed by fine machining of the edges.

3. Experiments

3.1. Microstructure analysis

Samples were cold mounted in epoxy resin and polished with 6 μm and 1 μm Struers Dia-Duo diamond solution followed by OPS. Images were obtained using a Zeiss Supra 55 variable pressure FEG-SEM equipped with an angular selective backscattered (AsB) and an Electron Backscatter Diffraction (EBSD) detector at 20 kV, with an aperture of 60 μm in high current mode. The microstructures of the as received condition (AR), the room temperature (RTR) and the cryo-rolled (CR) material are shown in Fig. 1.

The grain size was determined manually. A grid with ten horizontal and vertical lines was sketched across the microstructure using Adobe Fireworks CS6. The number of grain boundaries was counted along the lines and was divided with the real length of the line across the image which was determined using the scale bar.

The initial grain size in the as hot rolled (AR) material was about 100 μm. After CR and RTR the microstructure shows elongated grains (especially for the RTR material) and is significantly refined (CR ~ 700 nm, RTR ~ 800 nm) compared to the AR material due to the heavy plastic deformation introduced during rolling. The CR material shows a smaller sub-grain size compared to the microstructure after RTR and a slightly smaller grain size in general. For both materials some sub-grains are as small as 200–300 nm.

The aspect ratio of the grains was obtained in a similar manner. The grain length (rolling direction) and width (normal direction) was measured on grains along the horizontal lines of the grid. The length and width were calculated by counting the image pixels lying in within the width and length of the grain. The scale bar relates to the real size of one image pixel allowing the measurement of the real size of the grain based on the pixel number.

The grain aspect ratio changes significantly with the plastic deformation and rises form 0.8 (AR) to 6.6 (RT). The ratio for the CR material is determined to be 2.1 and reflects therefore the in general smaller grain size and finer sub grain structure.

3.2. Tensile test

The tensile tests were performed in a 30 kN Instron machine at an initial strain rate of $10^{-3}\,\text{s}^{-1}$. A non-contact extensometer was used to measure the deformation at a gauge section of 20 mm × 5 mm. Three tests were performed for each sample direction to evaluate the average graph.

The reduction in area (RA) was determined using Eq. (1). The thickness (t') and the width (w') of the fracture tip and the thickness (t) and width (w) of the un-necked gauge (measured at a distance of $d = 7$ mm from the start of the gauge length) were taken using macroscopic images as shown in the schematic in Fig. 2. Adobe Fireworks CS6 was used to determine the dimensions on the images.

$$\text{RA} = \frac{(w \times t) - (w' \times t')}{(w \times t)} \times 100\ [\%] \tag{1}$$

3.3. Minimum bending radius

To determine the minimum bending radius small strips of 15 mm width and 50 mm length were bent over various die radii ranging from 1 to 15 mm. The strips were clamped as shown in Fig. 3 and bent using a swing folding device. Afterwards the samples were cold mounted in epoxy resin and polished with a Struers Dia-Duo diamond solution to 6 μm, 1 μm and finally to an OPS surface finish for optical microscopy. Pictures were taken using 5× magnification with an Olympus DP70 Digital Microscope to study the development of fracture as a function of the bending radius.

3.4. Pure bending test

Pure bend test were performed to investigate the material behaviour in bending and to analyse any type of inhomogeneous forming behaviour (e.g. kinking) similar to previous work performed by Hemmerich et al. [14] on highly aged steel. Samples

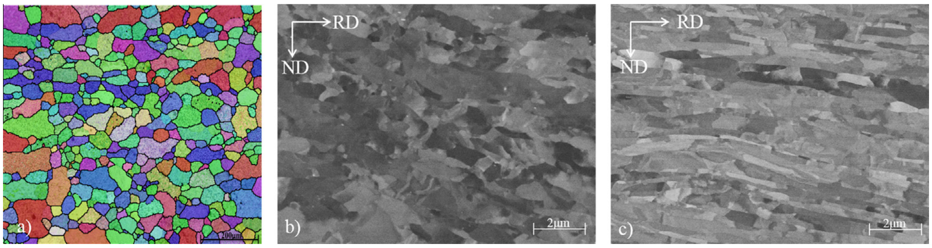

Fig. 1. (a) Microstructure of AR high purity aluminium (EBSD); (b) microstructure of RTR aluminium (AsB); and (C) Microstructure of CR aluminium (AsB). Rolling direction (RD), normal direction (ND).