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Structural and mechanical behaviour of severe plastically deformed high purity aluminium sheets processed by constrained groove pressing technique

S.S. Satheesh Kumar *, T. Raghu

Near Net Shape Group, Aeronautical Materials Division, Defence Metallurgical Research Laboratory, Kanchanbagh, Hyderabad 500058, India

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High purity aluminium sheets (∼99.9%) are subjected to intense plastic straining by constrained groove pressing method successfully up to 5 passes thereby imparting an effective plastic strain of 5.8. Transmission electron microscopy studies of constrained groove pressed sheets divulged significant grain refinement and the average grain sizes obtained after five pass is estimated to be ∼0.9 μm. In addition to that, microstructural evolution of constrained groove pressed sheets is characterized by X-ray diffraction peak profile analysis employing Williamson–Hall method and the results obtained fairly concur with electron microscopy findings. The tensile behaviour evolution with increased straining indicates substantial improvement of yield strength by ∼5.3 times from 17 MPa to 90 MPa during first pass corroborated to grain refinement observed. Marginal increase in strengths is noticed during second pass followed by minor drop in strengths attributed to predominance of dislocation recovery is noticed in subsequent passes. Quantitative assessment of degree of deformation homogeneity using microhardness profiles reveal relatively better strain homogeneity at higher number of passes.

1. Introduction

Processing of bulk nanostructured materials by severe plastic deformation (SPD) techniques have emerged substantially in the recent years due to the superior mechanical properties exhibited by fine grained materials [1]. Though numerous methods for imposing intense plastic strain like equal channel angular pressing (ECAP) [2,3], high pressure torsion (HPT) [4], multiaxial forging (MAF) [5,6], cyclic extrusion and compression (CEC) [7], repetitive upsetting and extrusion (RUE) [8,9] and so on, have been proposed, only few methods exclusively purported for processing fine grained materials in sheet forms have been established. These methods include accumulative roll bonding (ARB) [10,11], constrained groove pressing (CGP) [12,13], repetitive corrugation and straightening (RCS) [14–16]. The application of ARB processed sheets are limited by the inherent problems associated with the process like de-lamination of bonded sheet layers, requirement of careful surface preparation, formation of edge cracks [12,17–19]. Of late CGP process stands out as a promising SPD technique for processing fine grained sheets and applicability of the method in achieving fine grained sheet materials have been demonstrated successfully in pure aluminum [12,20–22] and aluminium alloys [23], pure copper [18,24] and Cu based alloys [25,26], pure nickel sheets [13,27,28].

In CGP process [12,13], sheet material is subjected to repetitive shear deformation by deforming sheet specimens alternately between asymmetric grooved and flat dies under plane strain deformation conditions. A complete description of CGP process is schematically illustrated in Fig. 1. Sheet specimen of thickness t is placed between asymmetric grooved CGP dies (Fig. 1a) with groove angle of 45° and groove width, depth equivalent to sheet thickness (t). During first corrugation pressing (Fig. 1b), inclined region is subjected to shear deformation manifested by regions marked with vertical lines and an effective plastic strain of 0.58 is imparted, whereas regions labeled blank is undeformed (Fig. 1b). Subsequently corrugated sheet is pressed between flattening dies (Fig. 1c), wherein previously deformed inclined regions showed in Fig. 1b are subjected to shear deformation in reverse direction leading to a total accumulated strain of 1.16 (marked with horizontal lines). However the adjacent undeformed regions of Fig. 1b are left unstrained. Prior to second corrugation pressing, dies are shifted (Fig. 1d) to a distance equivalent to sheet thickness (t) in order to ensure shear deformation in undeformed regions. During second corrugation pressing (Fig. 1e), previously deformed regions (zones with horizontal lines) are left undeformed, whereas the adjacent unstrained regions (blank regions in Fig. 1b,c) are shear deformed thereby imposing a plastic strain of 0.58 labeled with vertical lines (Fig. 1e). In second flattening stage (Fig. 1f),

* Corresponding author. Tel.: +91 40 24586688; fax: +91 40 24340640.
E-mail addresses: sssatheesh12@rediffmail.com, ssatheesh@dmrl.drdo.in (S.S. Satheesh Kumar).

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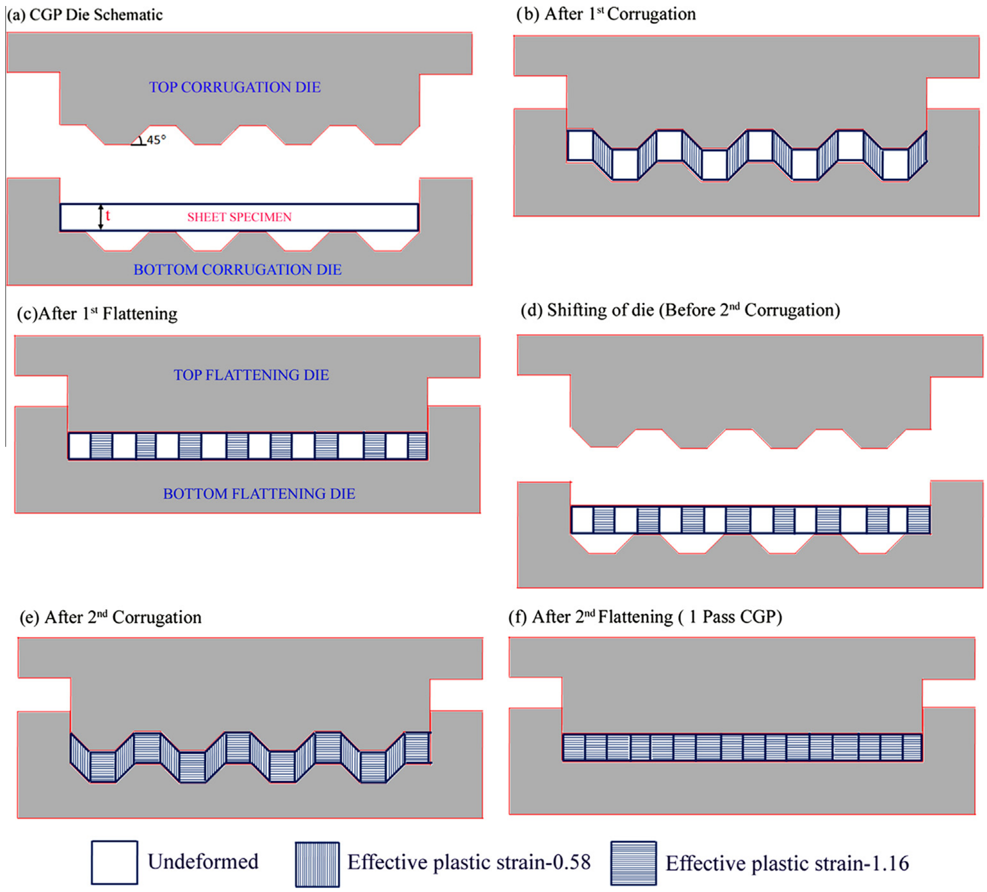

Fig. 1. Schematic illustrating the plastic strain evolution during CGP.

inclined zones are reverse shear deformed eventually resulting in uniform plastic strain distribution of 1.16 throughout the sheet material. An effective plastic strain of 1.16 is imparted to the sheet material at the end of one complete CGP pass comprising of two stages of corrugation and flattening.

Most of the earlier studies on the constrained groove pressing/ groove pressing of aluminium sheets are confined mainly to commercial purity grade aluminium sheets [20–22]. Meanwhile, in the present study the pertinence of CGP method to process high purity aluminium sheets (~99.9%) is studied. In the previous report on CGP processing of high purity aluminium, total strain imparted is limited to 4.64 [12], however in the present study aluminium sheets are constrained groove pressed successfully up to 5 passes thereby imparting a total effective plastic strain of 5.8. Microstructural characterization is carried out by transmission electron microscopy complemented with X-ray diffraction peak profile analysis. Severely deformed sheets are mechanically characterized by room temperature tensile tests and microhardness tests. The influence of CGP on the microstructural evolution of high purity aluminium sheets is investigated and correlated to mechanical behaviour.

2. Experimental procedures

Hot rolled high purity aluminium sheets (5 mm thick) with chemical composition (wt%) Si-0.074; Fe-0.05; Zn-0.0024; Mn-0.001; Cu-0.005; Mg <0.001; V-0.0084 and balance aluminium are annealed at 550 °C for 4 h in a muffle furnace whose temperature is maintained at ±5 °C followed by furnace cooling. The heat treatment is intended to homogenize the microstructure and relieve the residual stresses present in the sheet material. A CGP die with 45° groove angle capable of processing 5 mm thick sheet is fabricated out of H13 tool steel and assembled in a 250 Ton capacity hydraulic press. Rectangular sheet samples (130 × 70 × 5 mm^3) are extracted from the annealed sheet and subjected to severe plastic deformation by CGP technique at room temperature. The sheet surfaces are coated with Molykote prior to pressing to reduce the frictional effects and pressing is carried out at constant speed of 5 mm/s. In CGP process, sheet material is subjected to repetitive shear deformation under plane strain conditions by pressing the sheet alternately between asymmetric grooved dies and flat dies. The sheets are subjected to total number of 5 passes of CGP thereby imparting a total effective plastic strain of 5.8.

Small specimens extracted from the annealed aluminium sheet as well as CGP processed sheets are prepared following the standard metallographic procedures. The metallographic specimens are subjected to microstructural examination using light microscopy after etching in 12 ml HCl–6 ml HNO_3–2 ml HF–2 ml H_2O solution for 3 s at room temperature. Transmission electron microscopy (TEM) samples are prepared from CGP processed aluminium sheets (1 pass, 5 pass) and TEM images are captured utilizing FEI TECNAI G^2 20 transmission electron microscope operating at 200 kV. Sheet tensile specimens conforming to ASTM: E8M with 25 mm gauge length aligned along the longitudinal direction of sheet is EDM extracted and the room temperature mechanical properties are evaluated using Walter–Bai tensile testing machine. The tensile tests are carried out at initial constant strain rate of $1.67 \times 10^{-2}\ s^{-1}$. In order to investigate the microstructural evolution, X-ray diffraction experiments are performed using PHILIPS PW 3020 diffractometer operated using Cu $K\alpha_1$ radiation (λ = 1.542 nm). The peak broadening measured as full width at half