



# Constrained groove pressing, cold-rolling, and post-deformation isothermal annealing: Consequences of their synergy on material behavior

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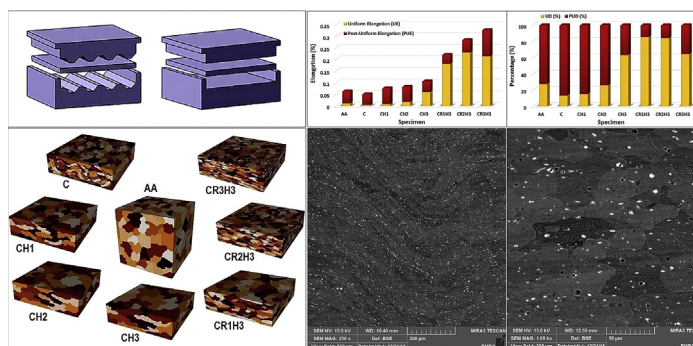
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## HIGHLIGHTS

- Different cold-rolling and annealing cycles were applied on CGPed specimens.
- The role of precipitates on microstructure and mechanical behavior were studied.
- Uniform deformation energy was calculated from examined stress-strain curves.
- Contribution of UD in Al-Mn-Si specimens was considered as formability criterion.
- Effect of thermal treatment and rolling strain on fracture behavior was analyzed.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Stress-relieved Al-Mn-Si specimens were constrained groove pressed (CGPed) and in the following, cold-rolled under different strains of 0.47, 0.8 and 1.27. Dual strained sheets were isothermally heat treated at 150, 250, and 350 °C. Microstructure survey revealed that generated shear-bands by CGP acted as talent sites for further strain-induced grain boundary migration (SIGBM) during annealing. SEM micrographs pointed out that coarse particles ( $1\ \mu\text{m} <$ ) had not preferential positions within the aluminum matrix and often comminuted into fine dispersoids ( $0.5\ \mu\text{m} >$ ) under heavy strains. Assessment of the softening fraction ( $R_{\text{rec}}$ ) depicted that greater accumulated strains along with higher post-annealing temperatures accelerated the thermal recovery and hence, reduced the  $R_{\text{rec}}$ . Tensile testing was performed repeatedly while fluctuation range for obtained stress-strain curves for each specimen as a criterion of structural uniformity was considered. It was found that post-deformation treatment of severely deformed sheets at 250 °C supplied maximum structural uniformity due to perfect restoration and evolution of inhomogeneity agents such as shear-bands, and precipitates within the matrix. In this regard, processing route contained cold-rolling by 0.8 strain of two-pass CGPed specimen and subsequent annealing at 350 °C ascertained to be an adequate combination of deformation and heat treatment with respect to achievement of the maximum uniform elongation (UE) of 22.96% and contribution of uniform

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deformation energy (UD) in total mechanically absorbed energy equal to 84.18% that provided the optimal formability for the applied alloy. Fracture analysis was performed by fracture angle measurement and SEM fractography. Thermal annealing of CGPed sheet at 150 and 250 °C declined its fracture angle from 55° to 50° and 46.5°, respectively. However, annealing at 350 °C changed the dominant fracture mode from shear to necking by incidence of fibrous morphology and enhanced the angle to 61°. Likewise, it was revealed that in spite of fracture angle increment by rolling reduction, post-rolling prevented the necking fracture in CGPed sheet treated at 350 °C and this might be shifted to higher temperatures.

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## 1. Introduction

Nowadays aluminum alloys are got attraction in many advanced engineering applications such as cryogenic systems, vehicle and aerospace industries [1]. Due to wide range and also variety of their utilizations, further improvement of mechanical properties in such alloys has been studied extensively [2]. In the last two decades, several severe plastic deformation (SPD) methods have been developed and studied by researchers [3–6]. Through the most of the processes, consecutive deformations by imposing considerable amount of strain lead to transformations in alloys' microstructure and their mechanical characteristics [7–9]. Besides, presence of extensive range of alloying elements in aluminum matrix made it susceptible for precipitates evolutions by which another reason for improvement would be provided [10,11].

SPD methods can significantly improve the strength-to-weight ratio of metallic alloys to be considered for specific applications. One special deformation technique without any dimensional change that could be applied to sheet products is CGP as introduced by Shin et al. [12]. CGP imposes repetitive shear plastic deformation on specimen by utilizing alternate pressings with asymmetric grooved and flattened dies [13]. Each CGP pass imposes  $\epsilon_{\text{eff}} = 1.16$  to metallic sheet and beside grain refinement, form remarkable micro shear-bands within microstructure due to its nature [14].

Cold-rolling could be considered as the most advantageous and applicable process for continuous production of bulky materials having diverse shapes such as plates, sheets and bars. The rolled structure is usually cellular-type having boundaries with low-angle misorientations; however, the ultrafine grained structure obtained by most of SPD methods are granular-type mainly contain high-angle grain boundaries [15,16]. It is reported that further rolling of SPDed material increases its fraction of high-angle misorientations results in higher uniformity in structure together with superior mechanical characteristics [17]. In this regard, authors have studied the combined effect of SPD and rolling as dual straining paths on Al-Mn-Si alloy [13,18]. Also, the impact of CGP and post-annealing on the dimensional changes of grains was thoroughly studied recently. It is concluded that non-uniform strain distribution pattern during CGP results in inhomogeneous grain growth via SIGBM mechanism eventuated in elongated structure rather than equiaxed morphology [19].

In the present study, authors have tried to fairly well study the function of post-deformation heat treatment and further straining through cold-rolling on the microstructure evolutions and mechanical properties of SPDed Al-Mn-Si alloy specimens subjected to two passes of CGP. Furthermore, the second-phase particles evolutions within aluminum matrix, their preferential positioning beside their role in material's mechanical response are investigated. Correlations of stress-strain curves by studying the structural uniformity and contributions of uniform deformation energy (UD) and post-uniform deformation energy (PUD) in examined curves

were surveyed. Meanwhile, the fracture analyses of fabricated specimens associated with failure angles of tensile samples were discussed. Ultimately, given discussions tried to answer the subject question regarding the synergy of applied processing routes to achieve the optimum formability condition for archetypal material.

## 2. Experimental procedure

Sheet specimens of Al-Mn-Si alloy having dimensions of 84 mm × 70 mm × 3 mm were cut and initially stress-relieved at 450 °C for 3 h in order to eliminate its production history. Treated samples were underwent two passes of CGP with  $\epsilon_{\text{eff}} = 2.32$ , and subsequently cold-rolled by strains of 0.47, 0.8 and 1.27. Schematic representation of SPD through CGP dies is illustrated in Fig. 1(a). Also, successive steps of one complete CGP pass are sketched in Fig. 1(b–g). As shown, two distinctive areas were formed in processed sheets owing to geometry and particular designation of grooving dies. Dead zones which are in contact to dents apex and remained undeformed at the end of the second cycle (Fig. 1(d)) along with the stretched zones between two adjacent dents (i.e. therein often shear-bands formation persuaded), are formed during first half-pass. Second half-pass continues by 180° clockwise rotation of deformed sheet around its normal surface axis (Fig. 1(e)). Further rotation lead to substitution of dead zones by previously strained areas and results in uniformly pressed sheet at the end of a complete pass (Fig. 1(g)). Congregation of precise architectonics of the grooving dies and grooved Al-Mn-Si sheet are illustrated in Fig. 2.

Cold-rolling direction was considered along the length of the

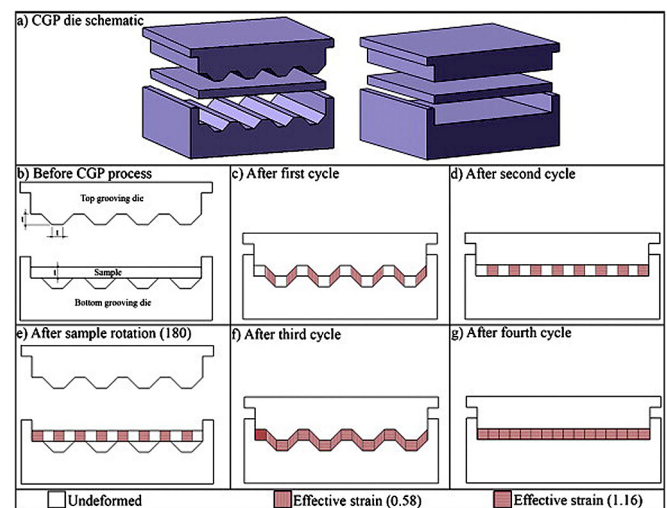


Fig. 1. Schematic representation of CGP dies (a), and consecutive CGP processing steps (b–g) [21].

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