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# Experimental investigation of forming limit, void coalescence and crystallographic textures of aluminum alloy 8011 sheet annealed at various temperatures

K. Velmanirajan [a,*], K. Anuradha [b], A. Syed Abu Thaheer [c], R. Narayanasamy [d], R. Madhavan [e], Satyam Suwas [e]

[a] Department of Mechanical Engineering, Kongunadu College of Engineering and Technology, Thottiyam 621215, Tiruchirappalli District, Tamil Nadu, India
[b] Department of Chemistry, N.K.R Govt. Arts College(W), Namakkal 637001, Tamil Nadu, India
[c] Department of Mechanical Engineering, PET Engineering College, Vallioor 627117, Tirunelveli District, Tamil Nadu, India
[d] Department of Production Engineering, National Institute of Technology, Tiruchirappalli 620015, Tamil Nadu, India
[e] Department of Materials Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

In this work, a combined forming and fracture limit diagram, fractured void coalescence and texture analysis have been experimentally evaluated for the commercially available aluminum alloy Al 8011 sheet annealed at different temperatures viz. 200 °C, 250 °C, 300 °C and 350 °C. The sheets were examined at different annealing temperatures on microstructure, tensile properties, formability and void coalescence. The fractured surfaces of the formed samples were examined using scanning electron microscope (SEM) and these images were correlated with fracture behavior and formability of sheet metals. Formability of Al 8011 was studied and examined at various annealing temperatures using their bulk X-ray crystallographic textures and ODF plots. Forming limit diagrams, void coalescence parameters and crystallographic textures were correlated with normal anisotropy of the sheet metals annealed at different temperatures.



* *Corresponding author*. Tel.: +91 4326 277571; fax: +91 431 2500133; mobile: +91 9994020525.
E-mail addresses: velmanirajan@gmail.com, kvmrajanq@yahoo.com (K. Velmanirajan), anuvmrajan@yahoo.co.in (K. Anuradha), pet.engg@gmail.com (A. Syed Abu Thaheer), narayan@nitt.edu (R. Narayanasamy), satyamsuwas@materials.iisc.ernet.in (S. Suwas).

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## Nomenclature

| | |
|---|---|
| $\sigma$ | true stress |
| $\varepsilon$ | true strain |
| $\varepsilon_1$ | true major strain |
| $\varepsilon_2$ | true minor strain |
| $\varepsilon_3$ | true thickness strain |
| $\varepsilon_e$ | true effective strain |
| $\varepsilon_m$ | true hydrostatic or mean strain |
| R | plastic strain ratio (Ratio of width strain to thickness strain) |
| $n$ | strain hardening exponent value |
| K | strength coefficient value |
| $R_{av}$ (or) R-bar | average plastic strain ratio or normal anisotropy $((R_0 + R_{90} + 2R_{45})/4)$ |
| ΔR | planar anisotropy |
| $n_{av}$ | average strain hardening index $((n_0 + n_{90} + 2n_{45})/4)$ |
| $K_{av}$ | average strength coefficient $((K_0 + K_{90} + 2K_{45})/4)$ |
| RD | rolling direction |
| ND | normal direction |
| T–T | strain condition of tension–tension region |
| PS | plane strain condition |
| T–C | strain condition of tension–compression region |
| $V_a$ | void area fraction |
| L/W | length to width void ratio |
| $T$ | triaxiality factor |
| $\gamma$ | shear strain |
| $\delta d$ | relative spacing of the ligaments between two consecutive voids |
| $d$-factor | a parameter on the void analysis (ratio of δd to the radius of the void) |
| RMA | representative material area (i.e. the area chosen in the SEM image) |

## 1. Introduction

Forming metals is a conventional technique used to manufacture most of the sheet metal products. The forming operations of sheet metal include various types and conditions of strains, which can be evaluated to predict the properties of metal and the forming limit. This practice has been continuing in recent research works for finding the forming limits [1]. The effective tool used to evaluate the formability of sheet metal is the forming limit diagram (FLD), which is used to evaluate limiting strain in various strain conditions. The concept of FLD was introduced by Keeler and Backofen [2] and Goodwin [3] in the 1960s which was later simplified by Hecker [4] in 1975 and from then on it has been widely used for studying formability of sheet metals with some modifications [5,6] as a practice of theoretical prediction of FLDs. Pulsatory straining condition of the FLD was analyzed by Banabic and Dorr [7] and prediction of FLDs in anisotropic sheets was evaluated by Barata da Rocha et al. [8]. Banabic and Valasutean [9] analyzed new Hills yield criterion with respect to limiting strains while negative minor strain region was analyzed by Lian and Baudelet [10]. Chow and Jie [11] and Narayanasamy et al. [12] studied forming limits of aluminum alloy of grades 5086 and 19,000, respectively. They have also studied about the plastic strain ratio (R) to predict formability behavior [12]. The theoretical and experimental investigations of limiting strains of sheet metals were analyzed by Zhao et al. [13].

Three theoretical models are available to describe the localized necking mechanisms of sheet metal. Hill [14] proposed the first model which treats localized necking as a type of material instability and localized band forms along the zero extension direction as well. The second model called MK model was developed by Marciniak et al. [15], which postulates an initial through and localized necking band that develops on the outer surface. The practicing engineers widely employ this model and it is sensitive to size and depth of localized neck which needs to match the experimental and theoretical prediction. Vertex theory is the third model which develops and yields surface under a loading path [13]. The uncertainty of the plastic flow triggers in homogeneous deformation [15]. It is applicable to strain hardening materials, proportional to loading conditions and follows power law equation (1) at room temperature.

$$\sigma = K\varepsilon^n \tag{1}$$

where, '$\sigma$' is true stress, 'K' is strength coefficient value, $\varepsilon$ is true strain and '$n$' is strain hardening exponent value. By using this relation strain hardening exponent value can be calculated.

Prediction of forming limit of sheet metals is widely employed in manufacturing industries. Many researchers have predicted forming limit diagrams for different base materials. Simultaneously, enormous work is in progress in developing various analytical methods for the simulation of FLD analysis [15]. This work aims at predicting FLD and other relevant parameters on Al 8011 alloy, which mainly consists of Al–Fe–Si which is a commercially available Al alloy, with a wide variety of end applications owing to the fact that it is possible to control the microstructural evolution of the alloy by means of specific thermal and mechanical treatments [16]. Solid solution hardening, second phase precipitation hardening, grain refinement hardening and strain hardening may strengthen the Al 8011 alloy [16]. The dynamic and static recovery takes place in Al–Fe alloy [17]. Ravindran et al. [5] showed higher fatigue strength, vibration toughness and corrosion resistance in marine environment for alloy Al 5052. This paper deals with the variation in the material properties (namely n and R) of Al 8011 alloy sheet with respect to its void size in the fractured region measured using SEM image and correlated with Mohr's circle/shear strain and formability parameters. Further this analysis has been extended to texture properties as explained by Narayanasamy et al. [18].

The crystallographic texture can be controlled by suitable changes in the annealing temperature [18]. It has been recognized that, mechanical properties of metal sheets such as plastic anisotropy and formability can be improved by a proper crystallographic texture control [19]. It is known that the texture has great influence on the plastic anisotropy of the final recrystallized sheets that is usually represented by Lankford parameter (R-value). Moreover, the texture significantly affects the formability which is usually