ABSTRACT

An important manufacturing process in metal shaping industries is sheet metal forming, which has been widely used to produce consumer products, namely, washers, cabinets, electronic and computer parts, automotive components and aircraft components. Depending on the nature of the manufacturing process and dimension, the sheet metal may be subjected to different strain conditions. The information regarding the application of sheet metal in engineering and industrial implementation along with its formability, is important for both the manufacturers and the users.

This research work investigates the formability of commercially pure grades of aluminium sheets with different thickness, namely Al 8011 alloy (1.5 mm thickness), Al 1145 alloy (1.8 mm thickness) and Al 1350 alloy (1.2 mm thickness). These cold-rolled aluminium sheets are stretch formed until fracture, using the hemispherical punch to evaluate the Forming Limit Diagram (FLD) and fracture limit diagram. The FLD is an effective tool to evaluate the formability of aluminium sheet metal under various strain conditions. Initially from all grades of sheet metals, three sets of tensile and forming specimens were prepared as per the test requirements. Each set of specimens was subjected to annealing at different temperatures, namely, 200°C, 250°C, 300°C and 350°C by soaking for one hour, followed by furnace cooling. The tensile test was conducted separately for evaluating the strain hardening exponent (n-value) and plastic anisotropy (r-value), using the Hounsfield Tensometer. A formability test was conducted, using the punch and die set assembly. The experimental forming limit diagrams (FLDs) were plotted based on the results of the formability test. Using Hill’s criteria, theoretical FLDs were also plotted for making comparison. Microstructure and texture results were obtained for all the sheets annealed at different temperatures. All these results were analyzed and correlated with each other. These results were mathematically evaluated using Response Surface
Methodology (RSM) in order to predict the interrelations between the input and output parameters. Also the evaluations of the FLDs and their data points were compared with the reliability techniques such as the first order reliability method (FORM) and Monte Carlo Simulation method (MCS) by considering the normal distribution of material properties.

The chemical composition (by % weight), microstructural examination, tensile and forming test and void coalescence study were conducted. Hydrofluoric acid was used as an etchant for the study of the microstructure. By using the Hounsfield Tensometer the tensile tests were carried out. The samples were cut along three different directions specifically, 0°, 45°, and 90° to the rolling direction of the cold rolled sheets, and prepared as per the E8 ASTM standard. The forming process by the punch stretching experiment was conducted up to fracture occurrence, and it was carried out on a double action hydraulic press capacity of 2000 KN with the experimental setup. The chemical etching method was used to print the grid patterns of a grid size of 2.5mm. For describe the FLD, the width of the specimen chosen was 60 mm, 80 mm and 100 mm for permitting Tension-compression and 160 mm, 180 mm and 200 mm for taking the biaxial strain measurements. The remaining widths 120mm and 140 mm were used for the plane strain condition. The fractured surfaces on the specimens were observed using Scanning Electron Microscopy (SEM) which cut close to the fracture zone was exposing voids clearly. From the SEM analysis, the nature of the fracture voids could be observed as void parameters, and correlated with the formability parameters as a void coalescence study. Bulk texture measurements have been calculated using the Panalytical X’pert X-ray texture goniometer with Cu Kα radiation. Orientation Distribution Functions (ODFs) were calculated from the measured four incomplete pole figures of 111, 200, 220 and 311, using the Labotex® software based on the arbitrarily defined cells (ADC) method. The volume fractions of the individual texture components were estimated by the ODF integration method with a 10° Gaussian spread. Later, these results were analyzed with the
suitable RSM model and Probability studies, namely, the first order reliability method (FORM) and the Monte Carlo simulation (MCS).

The chemical composition, microstructural, tensile properties, formability properties, void coalescence parameters were studied and texture analysis was made on the commercially pure aluminium grade Al 1350, Al 8011 and Al 1145 alloys; and the following are the results.

- The n-value, R value, and the percentage elongation of the annealed alloy sheets increase on increasing the annealing temperature for all the samples. But the yield strength and tensile strength showed a decreasing trend. Similar studies were made for the three different grades of aluminium alloy sheets and a similar trend was found.

- It is clear that as the annealing temperature increases, the formability also increases. Similar studies were made for the three different grades and a similar trend was observed. At 350°C, the annealed sheet showed a fully recrystallized microstructure, which might be due to the relieving of the internal strain energy formed during cold working, and the forming of new strain free grains, which increased the percentage elongation.

- For the void parameter, the void size increased and the ligament thickness decreased, as the annealing temperature increased.

- Correlating the texture volume fraction plot with the formability plot, it can be inferred, that formability could be attributed to the evolution of the annealing texture components, especially the cube and the Goss. The presence of precipitates could significantly suppress the cube fraction in the microstructure, which in turn retains the deformation components at lower temperatures.

- The recalculated 111 pole figures from the ODF with imposed orthotropic sample symmetry showed that significant fractions of the deformation components had been retained up to 250°C, beyond which the evolution of the cube texture became prominent with the
annealing temperature. In $\varphi_2 - 0^\circ, 45^\circ, 65^\circ$ sections of the ODF, the intensity of the Cu, S components in the $\varphi_2 - 45^\circ, 65^\circ$ sections respectively, have minified with temperature. $\varphi_2 - 0^\circ$ section showed qualitatively the strengthening of the cube intensities as a function of temperature. The above interpretations of the ODF have been substantiated quantitatively by the volume fractions of the texture components calculated from the ODF.

- Further the RSM tool has been used to predict the effect of the input parameter to get the desirable output parameters.
- In this study, mathematical models have been generated by the RSM, for tensile property, formability, void parameters and volume fraction of the texture components of aluminium alloy sheets of different thickness, as a function of the forming process parameters, by using the multiple linear regression analysis. These predicted mathematical models are important for formability and texture studies with superior properties.
- The statistical tools used to predict the reliability were; FORM and MCS, which were used to evaluate the readings and results of the limit strains. Using the above mentioned material parameters, the stochastic modeling of the FLC with the given confidence level can be carried out. In addition, the FORM was employed for assessing the reliability of the FLC, and this was verified by the MCS method. As a result, the errors between the FORM and the MCS are less than 5% for any given variation of the material parameters. The probabilities of the limit strains fall within the marginal zone, and are in favourable agreement with the theoretical ones. Using the proposed approach the product designer can robustly evaluate the forming limit of the sheet metals.