Applied Mathematical Modelling 38 (2014) 145–167

Contents lists available at SciVerse ScienceDirect

Applied Mathematical Modelling

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

Statistical evaluation of forming limit diagram for annealed Al 1350 alloy sheets using first order reliability method

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

[a] Department of Mechanical Engineering, Kongunadu College of Engineering and Technology, Thottiyam 621 215, Tiruchirappalli District, Tamil Nadu, India
[b] Department of Chemistry, N.K.R. Govt. Arts College (W), Namakkal 637 001, Tamil Nadu, India
[c] Department of Mechanical Engineering, PET Engineering College, Vallioor 627 117, Tirunelveli District, Tamil Nadu, India
[d] Department of Mathematics, National Institute of Technology, Tiruchirappalli 620 015, Tamil Nadu, India
[e] Department of Production Engineering, National Institute of Technology, Tiruchirappalli 620 015, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 4 August 2012
Received in revised form 17 March 2013
Accepted 31 May 2013
Available online 26 June 2013

Keywords:
Non-ferrous metals
Alloys
Sheet forming
Plastic behavior
Monte Carlo simulation

ABSTRACT

This paper investigates the formability and forming limit curve of aluminium alloy sheet of grade Al 1350 with respect to annealing temperature and strain conditions through statistical approach. The uncertainty of forming limit curve (FLC) due to anisotropy parameter and strain hardening exponent have also been taken into consideration. The plastic instability criteria and its relevant equations given by Hill have been used to construct the theoretical FLC which is compared with experimental FLC. The stochastic modeling has been made on the statistical evaluation of the FLC with a high confidence level. First Order Reliability Method (FORM) and Monte-Carlo simulation (MCS) methods have been used to compare the probability of the data points determining FLC by considering normal distribution of material properties.

1. Introduction

Aluminium alloys play a major role in determining the modern engineering materials, based on their various desirable properties, availability and wide application. It is the task of the researchers to predict and formulate the properties of these alloys with various composition, size and working condition their practical implementation. Nowadays, in manufacturing engineering applications, the sheet metal components and their products are essential. Alan et al. [1] state that the industrial implementation will be the futuristic work on sheet metal forming. Hence the scientific investigations on sheet metal properties and behavior help to have a control over the manufacturing methods through scientific approach. Ponalagusamy et al. [2] and many other researchers [3–7] have proposed new causes for the failure of this criterion on sheet metals by modifying the theory of localized necking given by Hill and Swift. The yield theory and plastic behavior were later modified and used by many researchers [8–10].

The forming limit analysis and the study of Forming Limit Diagram (FLD) have been made extensively by the researchers [11–16]. The effect of annealing temperature and preheating was studied in various literatures and found that as the temperature of annealing increases the formability also increases [14–21]. The experimental investigation was moved on to the analytical and numerical studies [21–26]. This involved many theoretical studies and viewing of researches on formability

* Corresponding author. Tel.: +91 4326 277571, mob.: +91 9994020525; fax: +91 4326 277572.
E-mail addresses: velmanirajan@gmail.com (K. Velmanirajan), anuvmrajan@yahoo.co.in (K. Anuradha), pet.engg@gmail.com (A. Syed Abu Thaheer), rpalagu@nitt.edu (R. Ponalagusamy), narayan@nitt.edu (R. Narayanasamy).

0307-904X/$ - see front matter
http://dx.doi.org/10.1016/j.apm.2013.05.050

Nomenclature

σ_1	major stress
σ_2	minor stress
$\sigma_x, \sigma_y, \sigma_z$	principal stresses along x, y, z axis
σ_n	standard deviation of n-value
σ_R (or) σ_r	standard deviation of R-value
σ_{HT}	standard deviation of homologous temperature
$\gamma_{xy}, \gamma_{xy}, \gamma_{xy}$	shear stress on respective planes between x, y, z axis
σ_t	true stress
ϵ	true strain
ϵ_1	true major strain
ϵ_2	true minor strain
ϵ_3	true thickness strain
$\epsilon_1^p, \epsilon_2^p$	critical point major and minor strain
$\bar{\omega}$	reliability index
N	number of samples
J	limit state function
D	distance from the reduced variate point to the origin
D_{min} or a	minimum distance from the reduced variate point to the origin
X	distance form limit state function to the origin of reduced variates
Y	yield stress in tension
f	plastic potential identifier
Z	random variable
d_i	perpendicular distance of a point from reference FLC
m_i, n_i	coordinate in the FLC plot
A, B	coefficient of x–y axis
Wtc, Wps, Wtt	width of formability test specimen for TC, PS and TT regions
t_i, W_i, L_i	initial thickness, width and length of formability specimen
d_o	initial diameter of grid circle in mm
d_1, d_2	major and minor diameter of deformed grid circle in mm
α_i	direction cosines along the X_i axis
β	ratio of minor strain increment to major strain increment
α	ratio of minor stress to major stress
λ	plastic multiplier
HT	homologous temperature (ratio of annealing temperature to melting point)
F, G, H, L, M, N	anisotropy parameter
R-value	plastic strain ratio (ratio of width to thickness strain)
n-value	strain hardening index value
K	strength coefficient value
R_{av} (or) $\bar{R}$	average plastic strain ratio or normal anisotropy = $(R_0 + R_{90} + 2R_{45})/4$
n_{av} (or) $\bar{n}$	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
TT	strain condition of tension-tension region
PS	plane strain condition
TC	strain condition of tension–compression region

[27–29]. The studies were extended to the fracture limit [30] and uncertainty study of the sheet metals [31] like anisotropy [32–34]. Prediction of forming limit and yield locus on plastic theory were derived [35–37]. The variables namely material orientation, strain conditions and tensile properties that affect the sheet metal formability were studied [38–41].

Exact analytical solutions for metal forming processes and operations are extremely difficult to obtain and assumptions are inevitable. Limit analysis is an alternative analytical approach that has received increased acceptance and is being used with increased frequency [42]. The reliability and statistical approach have been attempted on formability studies with many assumptions and with less experimental data [42–46]. Strano et al. [42] have made a survey on the statistical attempts made for evaluation of FLD since 2004 and have concluded that in most of the cases, the average value of cloud points used for plotting FLDs were not sufficient and clear enough for direct industrial interpretation. Kleiber et al. [44] have made reliability assessment for sheet metal forming operations in sheet stamping simulation using Monte-Carlo Simulation (MCS) technique.