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Experimental and Finite Element Forming Limit Diagrams for Interstitial Free Steels

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***Abstract*—**Interstitial free steels possess better formability and have many applications in automotive industries. Forming limit diagrams (FLDs) indicate the formability of materials which can be determined by experimental and finite element (FE) simulations. FLDs were determined experimentally by LDH test, utilizing optical strain measurement system for measuring the strains in different width specimens and by FE simulations in Interstitial Free (IF) and Interstitial Free High Strength (IFHS) steels. In this study, the experimental and FE simulated FLDs are compared and also the stress based FLDs were investigated.

***Keywords*—**Forming limit diagram, Limiting Dome Height, optical strain measurement, interstitial.

I. Introduction

THE forming limit diagram (FLD) is extensively used for the measurement of forming strains during deformation. FLDs were developed [1-3] initially as a tool to analyze the severity of sheet metal parts. Forming limit curve (FLC) is a graphical representation of the critical combination of two principal surface strains (major and minor strain) above which instability or necking is observed. It can be determined both by experimentally and theoretically.

Many researchers contributed towards the easier construction of FLDs rather than their experimental implementation. There exist strain-based and stress-based methods to construct them. The earlier experimental technique developed [4] was essentially an out of the plane method, comprising of a hemispherical punch and different width sheets, achieved in fewer steps. This method has friction component involved in it. The in-plane method of constructing the FLD was also developed [5-7] to avoid the friction component. Later the easier construction of FLD from a simple tensile test data was investigated [8]. Several numerical models were built by numerous researchers, to predict the FLDs theoretically, based on various failure criteria like ductile fracture criterion[9-12], thickness gradient criterion [13] etc. The strain based FLDs are path dependent and show certain limitations. The path independent stress based FLDs were developed [14] for accurate predictions of forming limits.

This paper deals with determining the experimental FLDs with the optical strain measurement system, comparing them with Finite Element simulations using PAMSTAMP and also investigating stress based FLDs, for interstitial free and interstitial free high strength steels.

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II. Experimental FLDs

Two grades of low carbon steel viz IF and IFHS steel sheets of 0.8mm thick were utilized for this research work. Material properties are listed in Table I. Tensile tests in all the three prime directions with the tensile axis being parallel (0°), diagonal (45°) and perpendicular (90°) to the rolling direction of the sheet were carried out according to ASTM standard E8M specifications. Mechanical properties obtained as listed in Table II. In all the tests, a constant crosshead speed of 0.1 mm min^{-1} was employed.

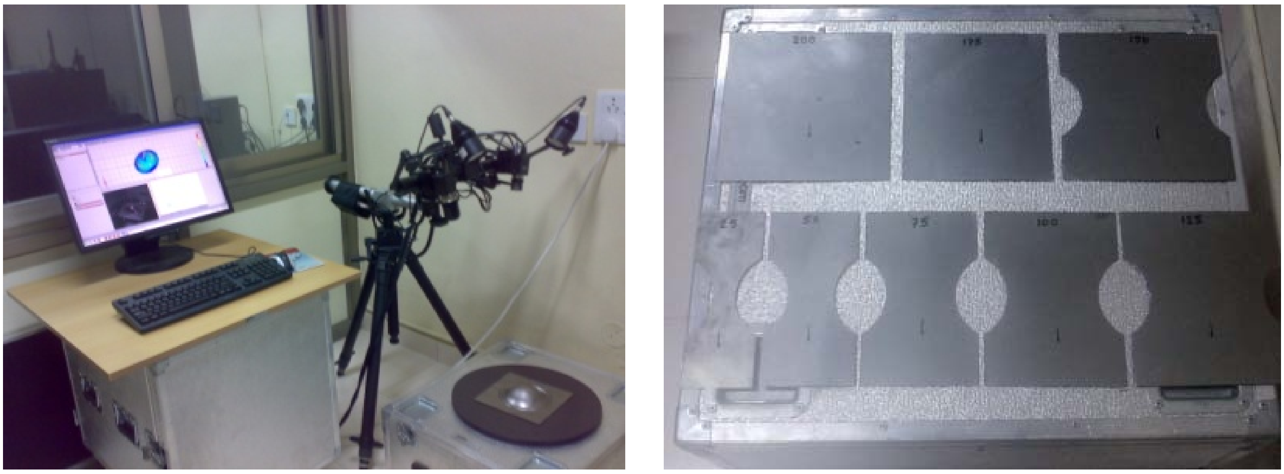
The normal anisotropy r-bar was calculated using (1).

$$R\ bar = (r_0 + 2r_{45} + r_{90})) / 4 \quad (1)$$

In this work, experimental FLDs are determined using a) marking the dot pattern (dots were of 1mm diameter, spaced equally at 2.5mm apart) on different width samples, b) image acquisition of undeformed sample, c) deforming the gridded samples up to failure or localization, d) Image acquisition of deformed sample and e) measuring strains.

Grid pattern on all undeformed samples were done using screen printing technique, followed by deforming the samples in LDH set up in a double action servo-hydraulic press of capacity (60+70T). Image acquisition and strain measurement were done using optical GOM system as shown in Fig. 1. Different width specimens were subjected to different modes of strain (drawing, plain strain and biaxial strain). Using optical strain measuring system [15], limit strains were noted to satisfy the thickness gradient criterion [13].

(a)



(b) (c)

Fig. 1 (a) undeformed, (b) deformed gridded samples of IF sheets, (c) Optical strain measurement system

TABLE I
CHEMICAL COMPOSITIONS, IN WT% ALLOYING ELEMENTS FOR TWO GRADES OF STEEL SHEETS

	C	Mn	P	S	Si	Al	N	Ti	Nb	Fe
IF	0.0022	0.05	0.008	0.007	0.004	0.04	0.003	0.053	----	Balance
IF-HS	0.0024	0.38	0.04	0.007	0.006	0.04	0.017	0.039	0.001	

TABLE II
MECHANICAL PROPERTIES OF IF AND IFHS STEEL SAMPLES CHOSEN FOR THE RESEARCH WORK

Mechanical Properties		IF	IFHS
Yield strength (MPa)		140	197
UTS (MPa)		289	372
% Elongation		51	40
Strain hardening index, n	0.32	0.32	0.26
	45°	0.29	0.23
	90°	0.31	0.24
	Avg.	0.3	0.25
r-values	0°	2.36	2.13
	45°	2.31	1.99
	90°	2.32	2.12
R-bar ($\bar{r}$)		2.34	2.34

The novice criterion for necking was adopted for prediction of FLD. During sheet metal forming a localized neck, is perceived by the presence of a critical local thickness gradient in the sheet. Such a perception of the neck is independent of the strain path, the rate of forming and the type of sheet metal (i.e. the material properties) being formed. If the thickness gradient at any location of the deformed sheet is less than the critical ratio, then it is considered as necked (fail) otherwise safe at that location.

Critical ratio (Rc) = tn /tn-1 = tn/tn+1 = 0.92

The optical strain measurement system has the option of measuring the strain directly from the deformed sample and the multistage method. The later method comprises of relating the strain on the deformed and undeformed samples by proper referencing of same two dots on both samples, with which an accuracy of 0.002 can be obtained. Finally, the experimental FLDs were constructed by separating the safe limit strains from the unsafe area containing the necked elliptic dots, as shown in Fig. 2.

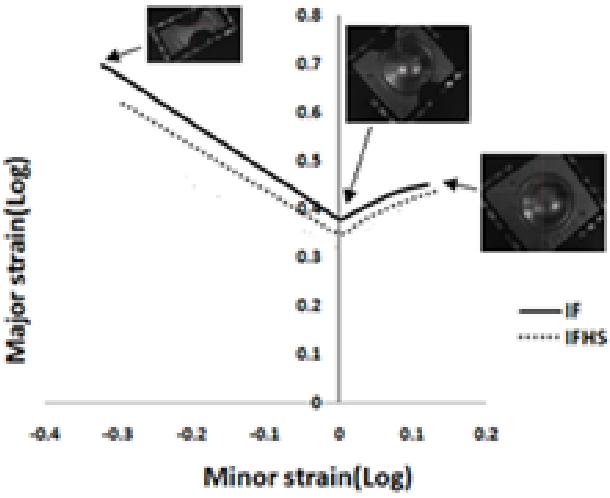


Fig. 2 Experimental forming limit diagrams of IF and IFHS steel sheets

III. PREDICTION OF FLDS USING FINITE ELEMENT METHOD

The simulation of LDH test was done in FE based commercial software (PAM-STAMP). CAD models of tool setup and blanks were generated with CAD package PRO/E. The surfaces of the tool parts were discretized by the triangle and quadrangle surface elements, assumed to be perfectly rigid. The blank sheet was discretized by quadrangle elements of size 2.5 mm, representing the material with an elasto-plastic constitutive law. For the material plasticity law, the orthotropic Hill-48 law was used. For the material hardening determination the Holloman law was used. Thickness gradient criterion was used as a failure criterion [13].

The simulation was done for eight different strain paths constituting standard LDH test, some of which failed near the draw-bead area that could not be taken for evaluating FLD. In the post-process module of simulation, thickness distribution are obtained and checked for satisfying the necking criterion. The ratio of thickness of two elements, near the necked area is checked after virtually pressing the sheet, to satisfy the thickness gradient criterion. At this stage the major strain value for all thicker elements were noted down from a pair of elements satisfying the criterion and the element having maximum major strain are chosen. This chosen element gives the limiting major & minor strain for that strain path. Similarly limiting strain for all the strain paths are obtained, and FLDs are constructed passing through these limiting strains. The comparison of FE is simulated, and the experimental FLDs are shown in Fig. 3.

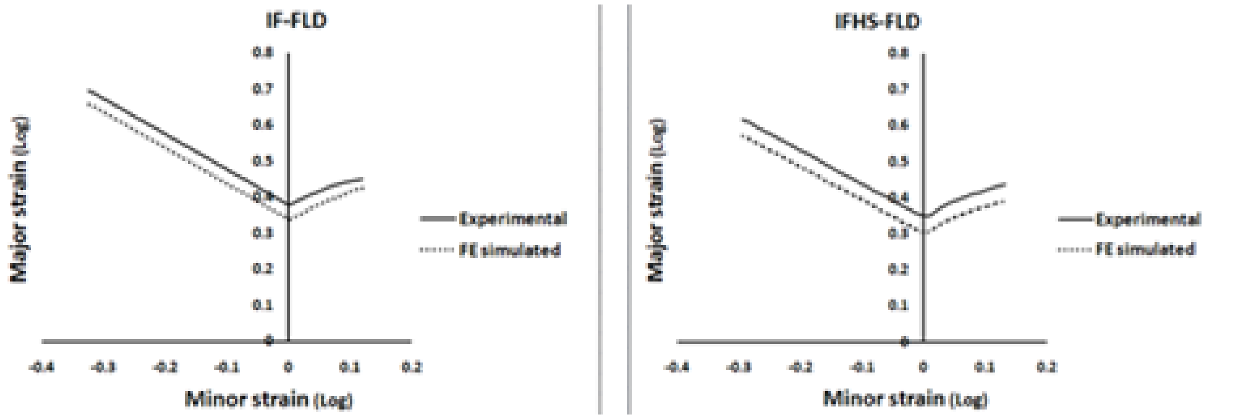


Fig. 3 Comparison of forming limit diagrams of experimental and FE simulations

IV. Stress Based FLDs

The major stress and the minor stress values were noted for the same element, which was chosen in FE simulation to note the limiting major strain and minor strain for the respective strain path, satisfying the thickness gradient criterion. The stress-based FLDs for the three materials are given in Fig. 4.

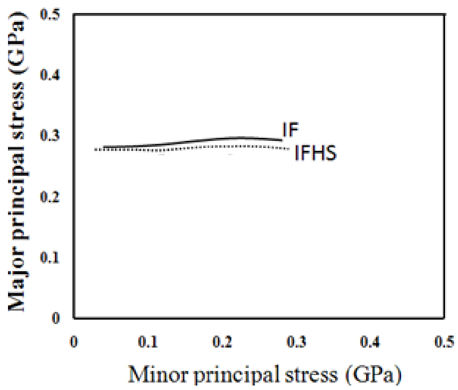


Fig. 4 Stress based FLDs for the DQ, IFHS, and IF materials

V. Discussion

Mechanical properties play a vital role in deciding the forming limits in any given material. The strain based experimental FLDs, as shown in Fig. 2, revealed the highest formability for IF steel than IFHS steel. This is because IF steel has higher values of both strain hardening exponent and the plastic anisotropy ratio than IFHS steel. The FE simulated FLDs as shown in Fig. 3, also captured the similar trend as of experimental diagrams but with lower FLD values. The path-independent stress based FLDs as shown in Fig. 4, are also depicted the similar nature as of experimental counterparts and again providing the valuable information of highest formability for IF steel sheet.

VI. Summary

Experimental and FE simulated forming limit diagrams were developed for the family of low carbon steels.

- Increase in ‘n’ and $\bar{r}$-values, lifts the FLD upwards.
- Formability of IF steel is higher than IFHS steel.
- FE simulated FLDs showed a similar trend as compared to their experimental counterparts.
- Stress based FLDs also predicted the increased formability for IF steel.

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