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Forming limit diagram of Advanced High Strength Steels (AHSS) based on strain-path diagram

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ABSTRACT

Advanced High Strength Steels (AHSS) is a promising material for automotive applications due to its high strength-to-weight ratio compared to other steels. Recently third generation steels have been developed which show intermediate properties between first and second generation AHSS. Formability analysis was performed between first generation Transformation Induced Plasticity (TRIP) and second generation Quenched and Partitioned (Q&P) AHSS. The main objective of the study is to perform formability analysis of TRIP and Q&P AHSS. The chemical compositions of both the steels are almost similar but different processing conditions lead to microstructural variations. Experimental and simulated strain-path diagram (SPD) was plotted from drawing to stretching regions using Limit Dome Height (LDH) test and Finite Element Method (FEM) respectively. The formability of TRIP steel is higher when compared to Q&P steels. Stretching regions show large deviation between experimental and simulated SPD for both the steels. A new strain localization criterion is proposed to construct a forming limit curve (FLC) for both experimental and simulated SPD. The proposed failure criterion is compared with other failure criteria for FLC prediction. The FLC based on new strain localization criterion shows better agreement with experimental FLC compared to other failure criteria.

1. Introduction

Presently, the demand for lightweight structures in the automotive industry is enormously increased due to fuel economy, stringent safety and environment standards [1,2]. Many automotive industries are trying to replace some steel structures with light weight materials like aluminum, magnesium and composites [3–5]. Steel industries are also developing new grades of Advanced High Strength Steels (AHSS) with high strength to weight ratio as light weight structures [6]. First generation AHSS are Dual Phase (DP), Complex Phase (CP) and Transformation Induced Plasticity (TRIP) steels. These steels have an ultimate strength of 600–800 MPa and total elongation of 20-25% [7]. They are being used in automotive applications due to their good crash energy absorption capabilities and moderate strength [7]. The second generation AHSS are Twinning Induced Plasticity (TWIP) steels, lightweight Induced-Plasticity (L-IP) and austenitic stainless steels which have a very high ultimate strength of 1200–1500 MPa and elongation of 55-70% [8]. However, their cost effectiveness for automotive applications is very poor [8]. Steel industries have recently developed third generation steels, Quenched and Partitioned (Q&P) steels, which fall between the first and second generation steels, having an ultimate strength of 900–1100 MPa and elongation of 15-18% [9].

Two AHSS from the first generation (TRIP) and third generation (Q&P) are selected for formability analysis. TRIP steel is inter-annealed (IA) at the temperature of 820,850 and 880 °C for 60 s and then isothermal bainitic transformation is done at the temperature of 440,460 and 480 °C for 20, 30 and 60 s respectively [10–15]. The development of Q&P steel is a heat treatment process for steels which utilizes similar composition as TRIP or DP steels and achieves superior combinations of strength and ductility [9].The Q&P steel used in the present study is produced from a two-step heat treatment process; the first (Quenching step) is to heat the steel at 860 °C for 5 min and then coolit at 725 °C for 2–5 s to allow for ferrite formation. The material is then quenched at 140 °C/s to 260 °C which causes formation of martensite that is supersaturated with carbon. In the second step the steel is again heated at 350 °C partitioning temperature, and holding the material at that temperature for a period of 120 s causes carbon diffusion from the supersaturated martensite into austenite. This leads to a higher volume fraction of retained austenite upon cooling to 25 °C [16–19]. Both the steels have multiphase microstructure; TRIP steels consist of ferrite, bainite and retained austenite (5-20%) and Q&P steels consist of ferrite, bainite, martensite and retained austenite (5-8%). Retained austenite in both the steels transforms to martensite during plastic deformation which enhances the strength and ductility [10–15]. This transformation also helps in enhancing formability and energy absorption [16–19]. AHSS formability analysis has been done by many researchers [20–25]; however, very limited work has been reported for Q&P steels. Formability of the materials at different strain-paths can be represented by forming

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limit curves (FLCs) [26–28]. FLC is plotted between major and minor true strain at different strain-paths by applying different failure criteria. These criteria are mostly based on strain localization or crack initiations [29–31]. Forming a limit curve (using a failure criterion) shows the safe regions for materials to deform and regions of failure but does not show the complete strain-path from initial stages of deformation till the fracture. At the same time, the strain-path diagram shows complete deformation behavior or strain evolution of the materials from the initial stage till the fracture. The strain-path diagram can be plotted from the drawing region to the stretching region and different failure criteria can be applied to plot FLC. Forming limit diagram (FLD) of TRIP steels has been studied in detail [32,33] but very minimal work has been reported for Q&P steels. The objective of the present work is to compare the formability of both the AHSS since the chemical composition and phases are almost similar. Complete strain-path diagrams were constructed experimentally using LDH [34] and by simulation using FEM analysis. FLCs were also drawn using different necking criteria for the simulation. Based on strain localization a new necking criterion has been proposed to draw FLCs which can be applied for both experimental and simulation methods.

1.1. Experimental Procedure

Sheets of TRIP and Q&P AHSS having thickness of 1.05 mm and 1.2 mm respectively were selected for formability analysis. Chemical compositions of these steels are given in Table 1. The chemical compositions of these steels are almost similar except that Q&P steels have marginally higher Mn content than TRIP steel. However their microstructures are different due to processing conditions [10–19]. To study the mechanical properties of these materials, tensile tests were performed according to ASTM E 8 M standards using an Instron 5825 screw driven universal testing machine. Strain data were obtained using an extensometer mounted on the samples for accurate strain measurements. A minimum of three tests were performed for reproducibility of the results. For calculating the anisotropy, $\bar{r}$ tests were performed at 0°, 90° and 45° with rolling directions (RD) of the sheets according to the ASTM E 517 standard.

Limit Dome Height (LDH) tests were conducted using Electro Pneumatic 200 ton triple action servo hydraulic press. LDH samples were machined to different geometries using water jet cutting such that the different strain-paths from drawing region to stretching region can be generated [26]. Sample dimensions and their nomenclature are given in Table 2, where the maximum dimension (200 mm) is in the rolling direction of the sheet. For online strain measurements, using the digital image correlation (DIC) technique, one side of the samples were painted with black paint and then white paint was sprinkled on it to produce a random speckled pattern. To achieve zero friction condition between punch and blank an elaborate lubrication system comprised of alternate layers of grease, Teflon and PVC sheets were applied on the other side of the sample. Appropriate blank holding force was applied to avoid wrinkling and drawing. The samples were subjected to out of plane deformation till fracture in a hydraulic press with a hemispherical punch having a diameter of 101.6 mm. The strain development during deformation was captured using an online ARAMIS system [35] and further analysis was done by the digital image correlation technique. Major strain contour measured by the DIC technique on the deformed Q&P sample (US) is shown in Fig. 1a. Complete strain evolutions were captured from the initial stage of deformation till fracture and the strain-path curve was constructed for all the sample geometries (drawing to stretching).

Table 1
Chemical composition, in wt.%, of Q&P and TRIP steels.

Material	C	Si	Mn	P	S	Al	N	Fe
Q & P	0.20	1.49	1.82	0.017	0.0043	0.046	0.0039	Balance
TRIP	0.233	1.365	1.540	0.004	0.007	0.08	-	Balance

Table 2
Nomenclature of different LDH samples.

25 200	US
50 × 200	US1
75 × 200	US + PS
100 × 200	PS
150 × 200	PS + BS
175 × 200	BS1
200 × 200	BS

1.2. Simulation Procedure

To simulate complete strain-path diagram by LDH method for Q&P and TRIP steels a finite element analysis was performed using PAMSTAMP 2G solver. LDH tools punch, die, draw-bead and blanks were modeled using Solidworks CAD software. The geometries and dimensions were kept similar as in experimental LDH testing [34]. Simulations were performed for different geometries of the blank to develop complete strain-path diagram using appropriate boundary conditions. Major strain contour measured through simulation on the deformed Q&P sample (US) is shown in Fig. 1b. Hill 48 yield criterion and Hollomon hardening law were used in simulation for both the steels. Friction between punch and blank was assumed to be 0.01 which is very close to zero friction condition similar to LDH experiments. Friction between blank holder, blank and die was assumed to be 0.12, and a 24 ton blank holding force was applied on the draw bead as in the

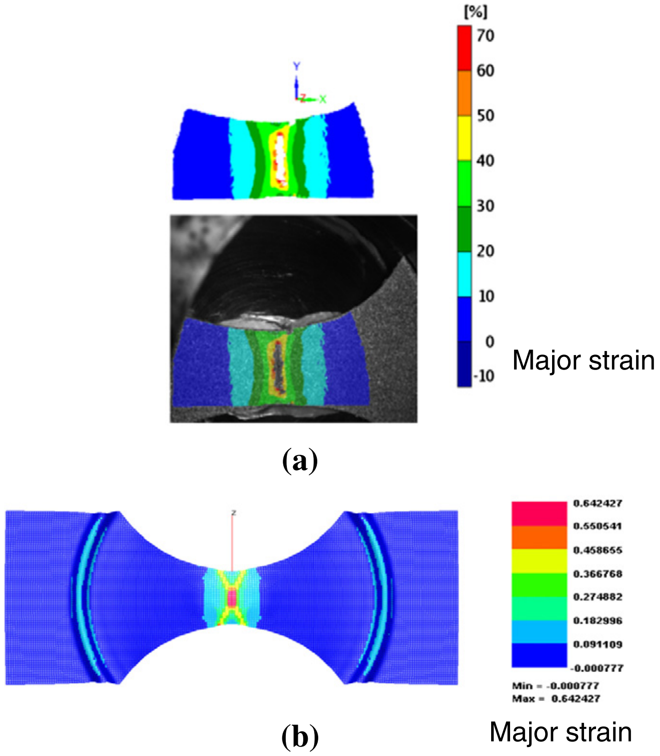

Fig. 1. Major strain contour measured by (a) DIC technique and (b) FEA simulation on the deformed Q&P sample (US).