EXPERIMENTAL AND NUMERICAL ANALYSIS ON STRAIN DEVELOPMENT DURING HOLE EXPANSION

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Abstract

High strength steel (HSS) and advanced high strength steels (AHSS) were preferred over conventional steel in the automotive industries. However due to its strength and brittleness many challenges occurred during forming of those steels. Common challenges experienced are high spring-back, edge cracking, sudden failure and many more. In this paper hole expansion process was chosen to determine some of the properties of these HSS and Mild steels and favorable conditions to form these metals. Hole expansion process was considered as one of the method to determine the crucial mechanical properties such as strain development and edge cracking along with hole expansion ratio. These mentioned properties matches well with what high strength metal characterization needs. Previous research on hole expansion provides some observation on process dependability on materials ductility and some on hole surface quality. Crack generation is one of the common failures in this process. In this paper hole expandability and edge cracking will be analyzed experimentally on HSLA440 steel and compare with 1020 mild steel. Further results comparison will be provided with numerical analysis.

Keywords: Hole expansion, HSS, edge cracking, strains

1 INTRODUCTION

One of the property defines the formability in sheet metal forming is hole expansion [1-2]. During deformation the hole expands and fails at the hole edges. This quantity is calculated as percentage expansion of initial hole. This percentage expansion of hole is a useful mechanical property and experimented for many automotive sheet steel applications. Few studies have been conducted in order to characterize mechanical properties, sheet formability and crack propagation for HSS and AHSS steels [3-6].

According to literature [3], hot rolled high strength steels (HSS) nucleate cracks in the hole edges due to immense circumferential strains. The hole expansion capability is not only dependent on the material ductility. It`s dependent on the surface quality of the hole edge surface because the surface regions can create favorable conditions for nucleation and growing of radial cracks if the hole quality is not adequate.

The highest stresses developed during the expansion process are concentrated in the strained hole periphery and it increased the initial hole diameter while the thickness in this region is reduced [7]. The tractive tensions developed in the circumferential direction of the hole are the general cause to failures by cracking and tearing on the hole [7]. In other experiments with respect to temperature for C-Mn steel, the tensile strength decreases linearly but no changes in yield strength with increase in tempering temperature from 150 to 450^{o}C. The favorable condition for increase in hole expansion was found in between the tempering temperature of 200 to 300^{o}C [8]. The hole expansion property was improved remarkably when the pearlite in HSLA steel was replaced by bainite [9-10].

In stamping of mild and conventional high strength steel, the typical failure mode is localized necking, resulting splitting. This type of failure can be related to critical levels of strain in a part. Studies performed on advanced high strength steels (AHSS) have shown that the failure behaviour can be accurately described using FLD curves in cases where localised necking occurs [11].

In this paper the Nakazima method with reduce geometry is used to estimate the forming limit diagram (FLD) of HSLA440 steel and 1020 mild steel. Further the hole expansion experiments are performed with the same geometry with hemispherical punch and analyzed the limit strains and compared with FLD. In addition numerical simulations are analyzed for hole expansion process and results are compared with experiments.

2 MATERIAL AND METHODOLOGY

The HSLA440 and 1020 mild steel sheets with an overall thickness of 1.5mm were considered in this investigation. The mechanical properties for both steels are tabulated in the Table 1 and 2 along with the power law parameters which were used to fit the material curve in numerical investigation. The anisotropic values for HSLA440 steel can be found in Table 3.

TABLE 1. Mechanical properties for HSLA440 steel

Yield Strength (MPa)	Tensile Strength (MPa)	K	n	E%
446	626	772	0.11	18.4

TABLE 2. Mechanical properties for 1020 mild steel

Yield Strength (MPa)	Tensile Strength (MPa)	K	n	E%
362	535	771	0.17	15.5

TABLE 3. Anisotropic values for HSLA440 steel

Strain ratio from experiment					Calculated stress ratio for ABAQUS [11]		
r_0	r_{45}	r_{90}	$\bar{r}$	Δr	R_{11}	R_{22}	R_{12}
0.988	1.015	0.568	0.897	-0.237	0.854	0.852	0.848

To understand the forming and formability of HSLA440 grade steel during hole expansion process, Nakazima method with reduced geometry (due to lack of material availability) was used. Stretch forming tests were performed to evaluate the forming limit curve. Further hole expansion tests were performed to understand the formability. In addition above mentioned geometry was modeled and simulated for hole expansion using Abaqus/Explicit.

2.1 FORMING LIMIT DIAGRAM AND HOLE EXPANSION

To generate the limit strains from uniaxial to biaxial loading direction the H type 100 ton hydraulic press with the Nakazima tool (Figure 1) was used. Two sample geometries (137 x 50 mm and 130 x 130 mm) were used to plot the 3 points of FLD; uniaxial, plane and biaxial deformation path. 4.2 mm diameter circle grid was electrochemically etched on the sample. Mineral oil was used for lubrication purpose. Blank holding force of 1000kN was applied to lock the sheet and stretched by hemispherical punch until necking occurred in each test. The deformation of circles was evaluated using digital vernier caliper and the FLD was obtained by plotting the line between the strains for necked points. Using the same set-up the hole expansion test was performed.

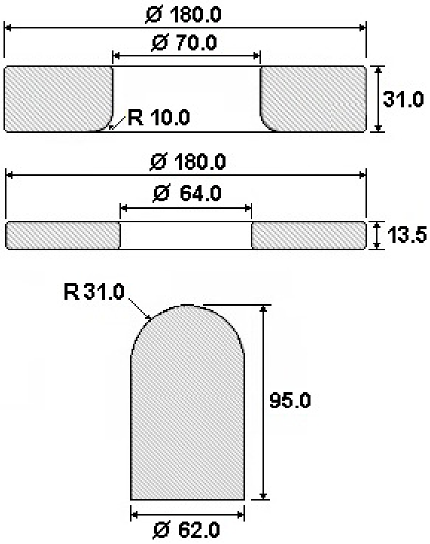
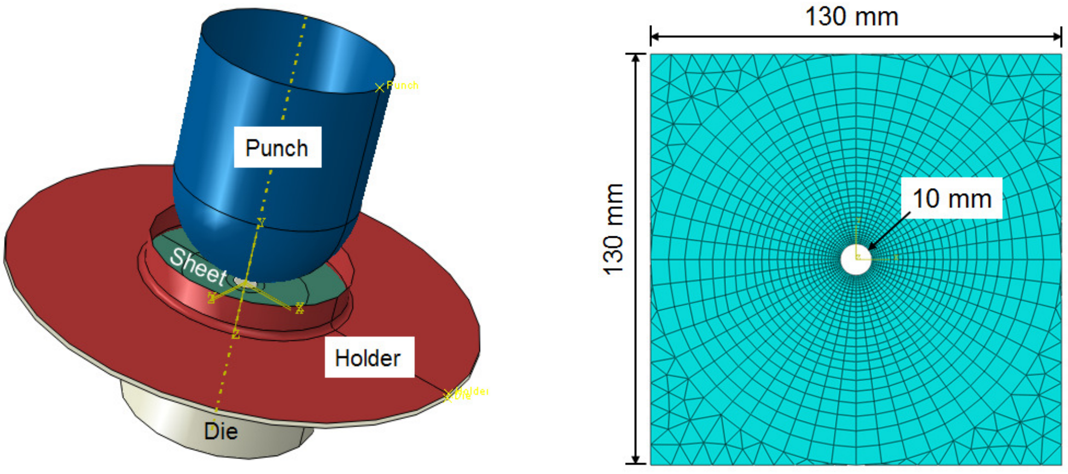


FIGURE 1. Experimental set-up for forming limit diagram

2.2 NUMERICAL METHOD

Using ABAQUS/Explicit 6.13-2, the hole expansion tests were investigated with a three-dimensional model approach. The tooling was given as rigid surfaces (Figure 2 (a)), while S4R shell elements (4-node quadrilateral, reduced integration) were used to mesh the circular blank partition and triangle elements S3R were used for remaining blank (Figure 2(b)). The average sheet thickness measured experimentally for the 1020 mild steel and HSLA 440 and was detailed in the model. The true stress-strain data, determined in the tensile tests, was replicated by power law and applied to define the material properties with isotropic hardening for all simulations.

All conditions and process parameters as present in the experimental tests were applied in the numerical model. As in experiments the process was lubricated with oil, the interaction between the blank and the rigid bodies was assumed very low and kept frictionless.



(a) (b)

FIGURE 2. (a) Simulation model for hole expansion and (b) hole expansion sample with 10mm hole for simulation.

3 RESULTS

Deformed specimen through hole expansion simulation for 1020 mild steel and HSLA 440 are shown in the figure. Both steel numerically showed necking at approximately 24 mm. The sheet thickness legend is also shown in the figure. The thickness strain observed in 1020 mild steel is 39.7% and for HSLA 440 steel is 36.9%. It seems that HSLA 440 steel is having more uniform thickness distribution as compared to 1020 mild steel.

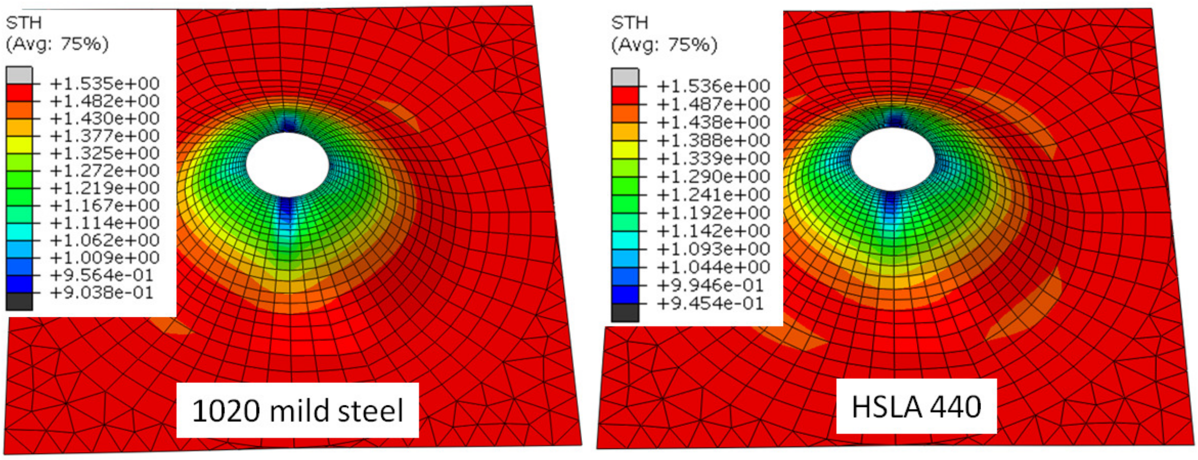
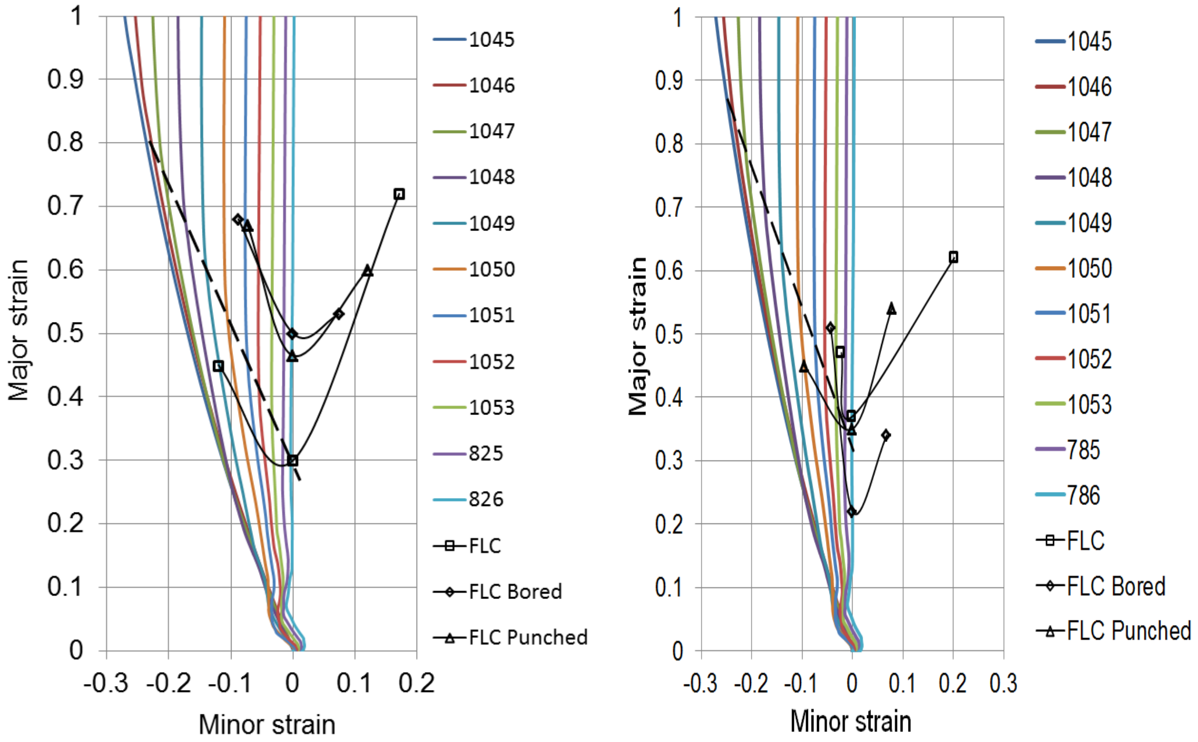


Figure 3. 1020 mild steel and HSLA 440 deformed simulated blank

The strain path of the necked elements (shown in blue in Figure 3) were extracted and plotted with the experimental conventional, bored and punched hole FLC (Figure 4 (a) for 1020 mild steel and Figure 4 (b) for HSLA 440). It can be seen that the strain paths deviate at necked stage and flow straight upward i.e., mostly increase the major strain. The approximate points of deviation of each element strain path were picked and the dotted line was plotted. This dotted can be considered as left side FLC. Note that this line was plotted by simulating only one sample and can be consider as a one-step experiment to plot the tensile to plane strain FLC. It can be seen that this FLC provides approximate good agreement with the conventional FLC.



(a) (b)

Figure 4. (a) Conventional, bored and punched FLC with strain paths from simulation for 1020 mild steel material and (b) conventional, bored and punched FLC with strain paths from simulation for HSLA 440 material

4 DISCUSSION

The experimental forming limit curves for the steels HSLA 440 and 1020 were raised in three different conditions of sheet: bored, punched and sheet without hole. In analyzing the results for 1020 steel, it is possible to verify that the processing conferred on the sheet led to a general increase of the limits of forming of the sheet. The area below the FLC of the sheet without holes is substantially less than that seen in the other two conditions, which means, generally, that the sheet resists strains lower levels in this condition until fracture. Considering a margin for possible experimental errors, the curves for the two conditions with holes are very close. The curve for bored condition has a sensible higher maximum amount of strain in the planar strain axis, being less steep in the two quadrants, and therefore being intercepted by the curve of punched condition, having smaller values of maximum strain when approaching the conditions of uniaxial and biaxial strains.

The HSLA 440 steel showed different behavior of the curves under different conditions, as compared with the 1020 steel. The portion of the curve of the bored condition which lies in the uniaxial strain area of the FLD is very steep, with the highest forming limit strain in this condition. However, in the quadrant representing the biaxial strain, the inclination is similar to other conditions and has substantially lower limits conformation. By comparing the curves of sheet without hole condition and punch condition, the limits on the planar strain axis are close, wherein the punched sheet condition has higher forming limits in the area of biaxial strains. This is clearly reflected in the fact that the sheet without hole behaves better under deep drawing conditions, and the sheet with punched condition supports larger deformations under stretch condition.

5 CONCLUSION

The forming and formability of HSLA440 and 1020 mild steel were studied in this paper through hole expansion process. Further the numerical simulation for hole expansion was performed. Experimentally, three different conditions of sheet were used to raise forming limit curves: bored, punched and without hole (conventional FLC). The presence of the central hole in the sheets of both materials increases the critical strain curves at the left side of FLC. Although different behaviors have been observed between the three experimental curves for each material, the limit strain predict numerically provides approximate good agreement with the conventional FLC. It was also observed that the element at the inner circumference has uniaxial strain while plane strain for elements towards the outer circumference along the crack.

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