Experimental and Numerical Investigation of Hole Expansion on CPW800 Steel

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Abstract. Many innovative processes and newer materials are preferred over conventional methods in sheet metal forming and automotive industry to increase the efficiency on many aspects. These innovative processes include complex strain loading on sheet metal during forming. On the other hand newer materials behave differently in these innovative process conditions. Due to these changes the material characterization came as crucial investigation. Hole expansion process is one of the materials mechanical characterization which was investigated in this paper. Hole expansion capacity of the material seems less dependent on materials ductility if the hole surface quality is poor. Crack generation is one of the common failures in this process. Advanced high strength steels which are oriented towards multiphase structure, found more prone to this factor. Due to complexity in material microstructure each phase behaves independent to each other during loading. In this paper multiphase steel CPW800 was investigated through hole expansion process. Hole punching test was performed with punching and broaching combo geometries which is not discussed in this paper. Limit strain was measured for the hole expanded sample and compared with the FLD of this material. Furthermore numerical simulations were performed to validate with experiments. In addition limit strains was predicted and compared with the experimental results.

Keywords: Hole Expansion, crack, nucleation, limit strains, numerical simulation.
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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 AHSS steel [3-6].

According to literature [3], hot rolled advanced high strength steels (AHSS) nucleate cracks in the hole edges due to immense circumferential strains. However the hole expansion capability is not only dependent on the material ductility if the punched hole is poor. The hole edge surface 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°C. The favorable condition for increase in hole expansion was found in between the tempering temperature of 200 to 300°C [8]. The big difference in strength in phases in multi-phase steel is the cause for low hole expansion [9].

In this paper the Nakazima method with reduce geometry is used to estimate the forming limit diagram (FLD) of CPW800 steel. Further the hole expansion experiment is 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.

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MATERIAL AND METHODOLOGY

The multiphase sheet steel CPW800 with an overall thickness of 1.7mm was considered in this investigation. The mechanical properties are tabulated in the Table 1 along with the power law parameters which were used to fit the material curve in numerical investigation. The anisotropic values can be found in Table 2.

TABLE (1). Mechanical properties for CPW800 steel

Yield Strength (MPa)	Tensile Strength (MPa)	K	n	E%
796	845	1200	0.11	16.8

TABLE (2). Anisotropic values for CPW800 steel

Strain ratio from experiment					Calculated stress ratio for ABAQUS [10]		
r_0	r_{45}	r_{90}	$\bar{r}$	Δr	R_{11}	R_{22}	R_{12}
0.749	0.83	0.576	0.746	-0.167	0.9239	0.872	0.926

To understand the forming and formability of CPW800 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.

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. Three sample geometries were used to plot the 3 points of FLD; uniaxial, plane and biaxial deformation path. 5 mm diameter circle grid was electrochemically etched on the sample. Mineral oil was used for lubrication purpose. Blank holding force of 200kN 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. The sample for hole expansion is shown in Figure 2(a).

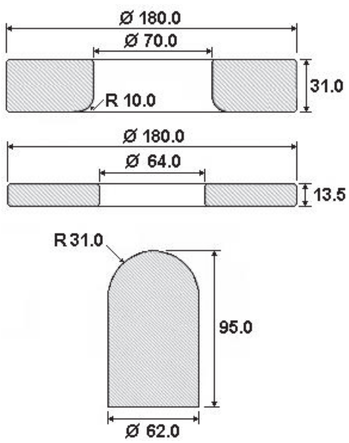

FIGURE 1. Experimental set-up for forming limit diagram

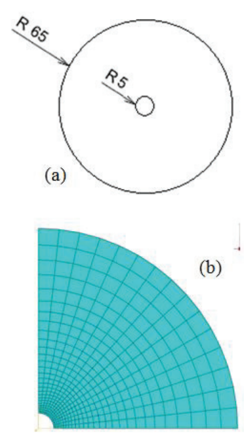

FIGURE 2. Samples for Hole Expansion (a) for experiments (b) quarter geometry for numerical simulation

Numerical Method

Using ABAQUS/Explicit 6.12-2, the hole expansion test was investigated with a three-dimensional model approach. The tooling was considered as rigid surfaces, while S4R shell elements (4-node quadrilateral, reduced integration) were used to mesh the blank. Quarter model (Figure 2(b)) was used to reduce computational time. The average sheet thickness measured experimentally for the CPW800 steel 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 for simulation. The anisotropy data was fed as stress ratios as given in Table 2.

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 mineral oil, the interaction between the blank and the rigid bodies was assumed very low and kept frictionless. For quarter geometry 50 kN blank holding force was applied. The limit strain was predicted by thickness gradient criterion detailed in next paragraph.

Thickness Gradient Criterion

To predict the forming limit strains from the simulation, this work considered the thickness gradient criterion (TGC). A localized neck is recognized by the presence of a critical local thickness gradient in the sheet metal during forming. At the onset of a visible local neck the existence of the critical local thickness gradient $R_{critical}$ is occurred. During the deformation, a thickness gradient, "$R_{thickness\ gradient}$" develops in the sheet which is expressed in Eq. 1.

$$R_{thickness\ gradient} = \frac{Current\ thickness\ of\ neck\ element}{Current\ thickness\ of\ neighbour\ element} \tag{1}$$

This thickness gradient keeps on reducing from initial thickness value during forming. At the onset of localized necking the thickness gradient becomes steeper. Thus a critical value attains at this transition from diffused necking. The criterion is represented in Eq. 2.

$$R_{thickness\ gradient} \leq R_{critical} \tag{2}$$

The $R_{critical}$ is experimentally estimated as 0.92. If $R_{thickness\ gradient}$ is less than 0.92, the component is considered as necked [11-12].

RESULTS AND DISCUSSION

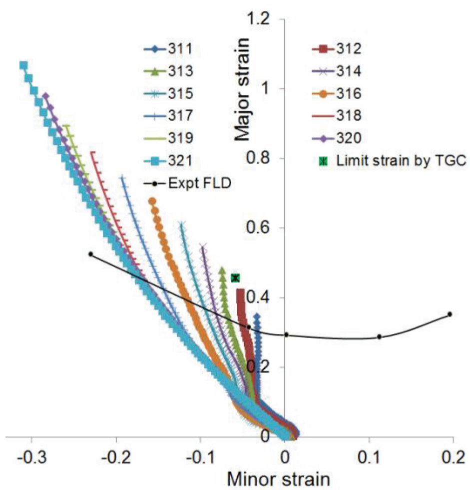

FIGURE 3. Strain paths for HE

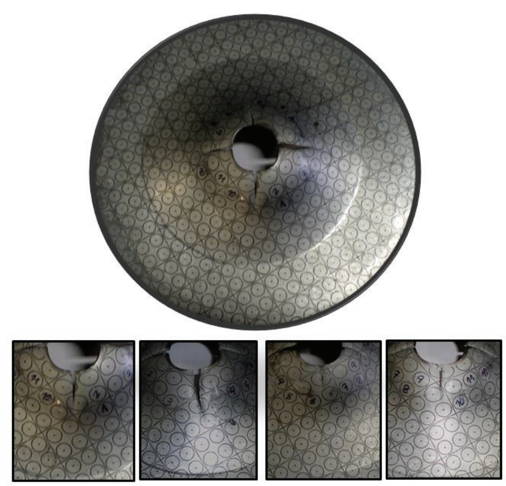

FIGURE 4. Deformed circles on HE sample

The experimental forming limit curve for CPW800 is shown in Figure 3 along with the predicted strain paths of 11elements from inner circumference (i.e., element number 321) towards the outer (element number 311) along the crack. It can be seen that element 321 i.e., on inner circumference have almost uniaxial deformation and as move along the crack towards outer circumference the strain path changes towards near plane strain. This can be experimentally seen in Figure 4.

The deformed quarter geometry is shown in Figure 5 with sheet thickness legend. The limit strain from the quarter deformed specimen was predicted using TGC and plotted which can be found in Figure 3 (legend: limit strain by TGC). The limit strain predicted by this criterion over predicted compared to the experimental FLD. This limit strain also shows that the necking is happened between uniaxial and plane strain deformation. However the material first splits on inner circumference and then move towards the outer circumference. As said the material first fails in uniaxial deformation mode due to dominant circumferential strain. Whereas the used criterion to predict the limit strain provides the limit strain near to plane strain. This is because this criterion is based on thickness at neck. This discrepancy was further clarified in Figure 6. It is observed that the thickness at the tip of the crack is higher than the adjacent next few elements and further gets thicker towards the outer circumference as also found in experiments. This may be the reason that used criterion to predict limit strain is off. According to NADDRG [13] the sheet thickness value of the material at failure in pure uniaxial deformation and plane strain deformation are same. If it is assumed that the thickness strain at failure in uniaxial deformation is less than plane strain then thickness of the material in uniaxial deformation will be greater than in plane strain and vice-versa. The hole expansion case examined in this study observed that the thickness is bigger in uniaxial direction than plane strain. The point of minimum thickness was assumed to be near to plane strain.

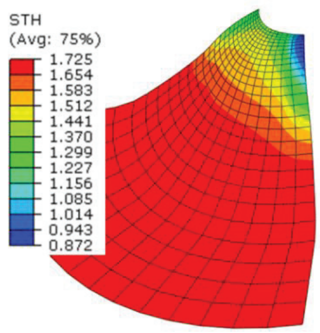

FIGURE 5. Simulated quarter geometry

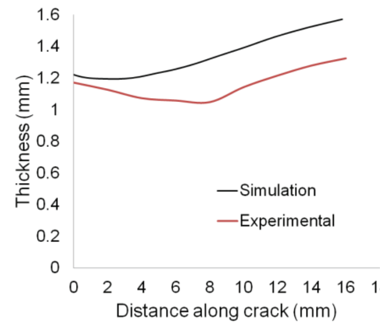

FIGURE 6. Thickness distribution from inner circumference towards outer circumference along the neck

CONCLUSION

The forming and formability of multiphase sheet CPW800 steel was studied in this paper through hole expansion process. Further the numerical simulation for hole expansion was performed. The limit strain was predicted by applying thickness gradient criterion. This limit strain was then compared with the conventional forming limit diagram of the considered material. It was observed that the limit strains predicted by TGC over predicts FLD and near to plane strain. This criterion is dependent on the thickness of the material. However observed minimum thickness was not found at the crack location and thus the discrepancy may have occurred. 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. The point of minimum thickness was assumed to be near to plane strain.

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