Influence of Temperature on the Forming Limits of High Strength Steels

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ABSTRACT

High strength steels (HSS) appear as a good alternative to common steels to reduce the weight of vehicles, thus reducing fuel consumption. However, its application in industry is still limited. Despite the excellent mechanical behavior towards its lower weight, manufacturing such materials suffers from limitations, especially with regard to formability. The literature shows the springback as the most common problem. Among the parameters that can be studied to minimize this problem, the temperature appears to be, according to the literature, one that most influences positively to minimize the springback. However, the consequence of the temperature increase in the forming limits of materials is not completely understood. This study proposes to understand the consequences of the use of temperature rise technique in the forming limits of high strength steels. Two different steels were studied (HSLA 350/450 and DP 350/450). To evaluate the formability, Nakazima method were used (practical) and the thickness gradient criterion (finite element method). The practical and computational results were compared in order to validate the mathematical model. Four different temperature ranges were analyzed. In general, it was found that 400°C has a negative impact on the forming limits of both steels. Temperatures above 400°C showed adverse behavior during the computational experiments.

Key Words: Forming limits curves. High strength steel. Forming sheets in high temperatures. Computer simulation.

1. INTRODUCTION

The challenges in the industrial application of high strength steels refer primarily to conformability, joining of sheets, tool life and springback. In relation to the latter is pointed out in the literature as the problem more committed to mass production of structural components using these materials. The difficulty in predicting and controlling the springback may imply the need for project adjustments on the geometry of the tool, adjustment of process parameters and control of the forming temperature during production [1]-[2]. Regarding the influence of temperature on the springback of metals subjected to forming operations, the literature indicates that the relationship between the factors is that the higher the temperature used in the operations, the lower the problems of the springback effect [3]-[6].

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In contrast, the effect of the temperature increase within the forming limits of metals is not completely understood. While for certain materials and certain ranges of temperature increase occurs in the forming limits, in other cases damages are found with respect to conformability [7]-[11].

The need to predict failures were identified in stampings critical applications. In order to check the forming limits of materials, [12] introduced the concept of Forming Limit Diagram (FLC), defined on the axles of minor and major principal strains in the sheet plane. The forming limit of a sheet metal is defined as the state in which a localized thinning (necking) on the sheet starts during forming, essentially leading to a break. The two principal strains (ε_1 e ε_2) measures in various component points in the imminence of failure result in a curve (Forming Limit Curve – FLC) separating the failure conditions and does not fail. The concept of FLC was extended to the domain of deformations of between states of deep drawing and biaxial stretch.

Reference [13] proposed determine through a single testing method, both the deformation of the deep drawing as biaxial stretch, comparing their results with those obtained by other methods known simulation tests, like Bulge and Erichsen. With a single tooling it is possible to reproduce the states of uniaxial and biaxial deformation through the deformation imposed by a semispherical punch in rectangular metal sheets which vary in width and are fixed by a die and blank holder.

The first simulation work of forming metal sheet dating back to the 30s [14]. However, it was in recent decades, through simulation based on the finite element method, the numerical simulation has gained ground as a very useful tool in component designs obtained by forming. In sheet metal stamping, numerical analysis has contributed a lot to reduce time and cost of development tools. In the case of numerical tests to predict forming limits, as Nakazima test, one of the challenges is to develop a computer routine that is able to predict the onset of necking. Developed by [15], the Thickness Gradient Criterion (TGC) correlates each of the elements of the finite element mesh with each of its neighbors. When the thickness ratio between two elements reaches a critical gradient (0.92), it is considered that necking occurred.

The present study investigates the effects of four temperature levels within the forming limits of two high strength steels. The Nakazima method was performed experimentally and numerically modeled using the finite element software Abaqus. The TGC was used to predict the onset of necking in the mathematical model.

2. MATERIALS AND METHOD

2.1. Materials

Two high strength steels have been used in practical and computational experiments, being a conventional high strength steel (HSLA 350/450) and an advanced high strength steel (DP 350/600). The chemical composition and mechanical properties are showed in Table 1 and Table 2.

Table 1: Chemical composition of the steels used.

Material	C	Si	Mn
HSLA 350/450	0.14	0.40	2.10
DP 350/600	0.08	0.03	0.60

Table 2: Mechanicals properties of the steels used.

Material	Thickness (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Uniform Stretch (%)	Total Stretch (%)	Modulus of Elasticity (GPa)
HSLA 350/450	1.4	356	449	14.8	20.8	206
DP 350/600	1.5	395	620	14.9	20.0	206

For both steels tensile tests were performed at four different temperatures. The aim was to obtain data that would be able to describe the mechanical behavior of the materials at such temperatures. These data were used to feed the computational models constructed for this study. The tests were conducted at uniform temperature, at the temperature levels shown in Table 3.

Table 3: Temperature levels studied.

30°C
400°C
600°C
800°C

2.2. Practical experiments (Nakazima method)

The FLC were obtained from the use of the tooling shown in Figure 1. For practical experiments, only two temperature levels were studied: Room temperature and 400°C. A set of eight specimens (Figure 2) was tested for each of the two temperatures, totaling 32 test specimens (two different steels). For evaluation of the forming limit, square meshes impressions were carried out (4 mm by 4 mm) on the samples, using scratching technique. The electrochemical printing technique was discarded due to degradation of the mesh suffer at high temperatures. The parameters blank holder force and strain rate were set at 120 bar and 1.107 mm/s, respectively.

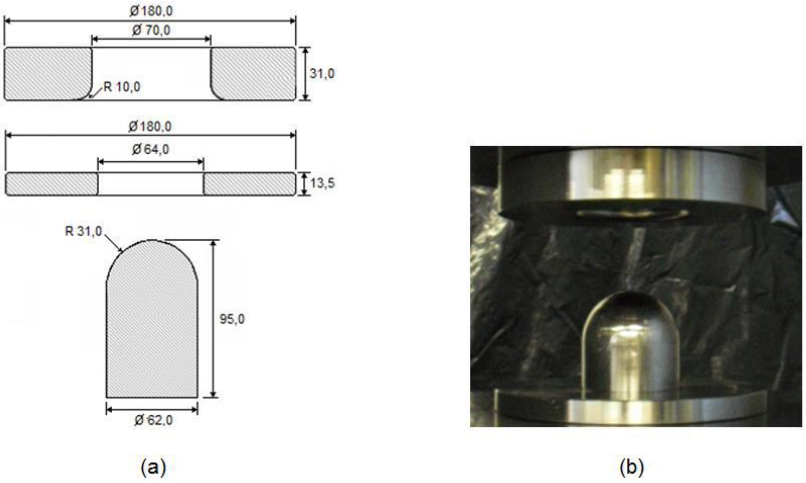


Figure 1: Tooling designed for implementation of Nakazima Tests.

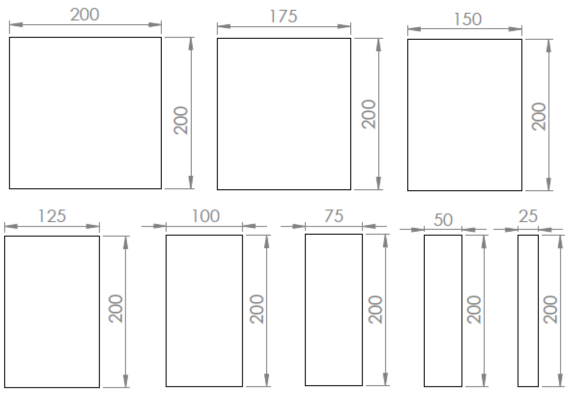


Figure 2: Specimens for implementation of Nakazima Tests (dimensions represented in mm).

All quads were measured, on each of specimens generated, that apparently had significant deformation imposed by the punch, as in the example of Figure 3.

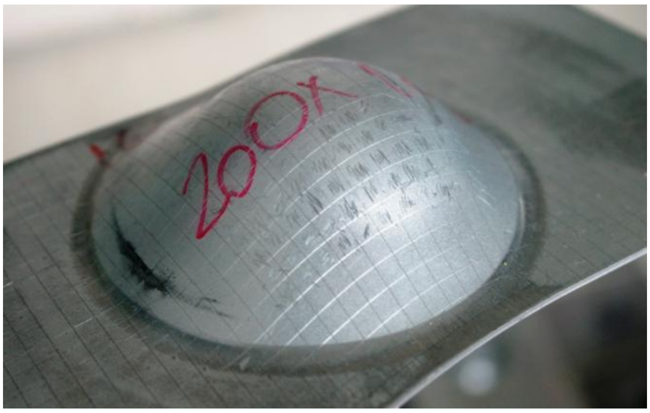


Figure 3: Detail region measured in a sample.

2.3. Numerical experiments (TGC)

Through Abaqus software, the tests to obtain the FLC was investigated with an approximate three-dimensional mode (Figure 4)l. The bodies that make up the model of the stamping tool (die, punch and blank holder) were considered as non-deformable rigid bodies. The metal sheet is the only deformable body, using the S4R shell element constituting the finite element mesh.

The thicknesses of the sheets measured experimentally were detailed in the model. To define the mechanical properties of materials were used to stress-strain curves for each temperature defined for the study. In this model, the four levels were checked (30°C, 400°C, 600°C and 800°C). The flow criterion used was von-Mises.

Taking advantage of the axisymmetric relationship of the problem, only a quarter of the sheets were tested in order to reduce computational time. The parameters used in the practical experiments, as blank holder force and strain rate were reproduced in the simulations.

To predict the forming limit strains from the simulation, this work follows the thickness gradient criterion. A localized neck is recognized by the presence of a critical local thickness gradient in the sheet metal during forming. This kind of the localized neck is independent of the strain path, rate of forming and the type of sheet metal (i.e. the material properties) being formed. At the onset of a visible local neck the existence of the critical local thickness critical gradient is occurred. During the deformation, a thickness gradient develops in the sheet which is expressed in

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

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

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

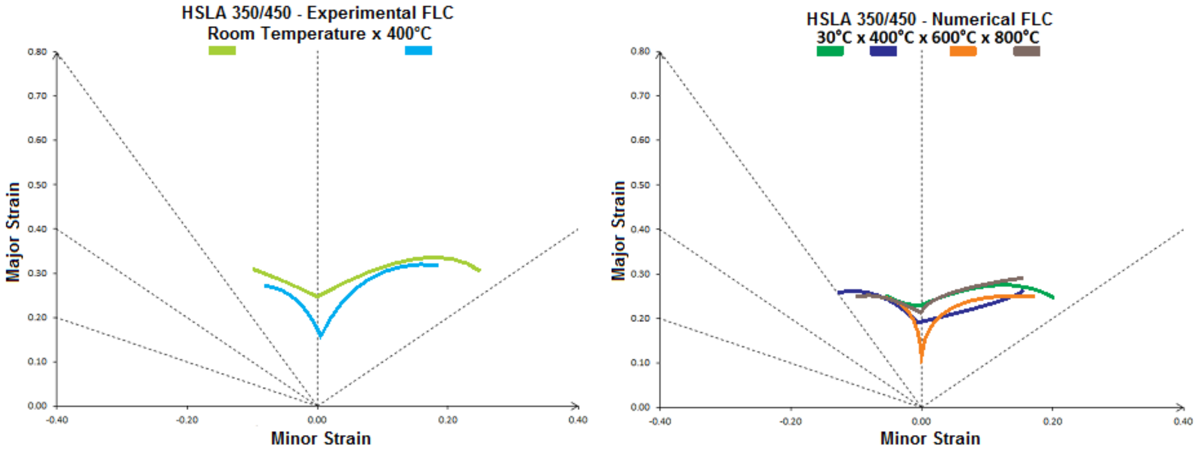
The R_{critical} is experimentally estimated as 0.92. If $R_{\text{thickness gradient}}$ is less than 0.92, the component is considered as necked [15].

3. RESULTS AND DISCUSSION

3.1. FLC of HSLA 350/450

For HSLA 350/440 steel, according to experimental tests (Figure 4a), a significant decrease in the forming limit supported by the material when subjected to plane strain state was demonstrated (about 34%) when tested at temperature 400°C compared with tests at room temperature. In contrast, the other two strain states analyzed, the decrease observed in boundaries was small (less than 8% for an approximately 4% to the other), and may possibly be a difference to be disregarded if taken into account the possible measurements errors.

When the four numeric curves are compared (Figure 4b), note that the decrease in forming limits at the biaxial strain state to 400°C and 600°C, compared with the curve of the tested material numerically at 30°C . In the plane strain state, this same trend is observed with the addition of a sharp drop in the curve representing the test at 600°C. In uniaxial strain state, the four curves are presented much closer. The curve for the experiment at 800°C approaches in all aspects of the FLC to 30°C.



(a) (b)

Figure 4: Experimental and numerical FLC for the HSLA 350/450 steel.

3.2. FLC of DP 350/600

According to experimental tests (Figure 5a), a decrease occur in the FLC of the DP 350/600 when at temperature 400°C compared with tests at room temperature. In the three strain states, decreases are similar, in the order of 6% to 14%.

When the numerical FLC's are compared (Figure 5b), the biggest difference in the biaxial strain state between the curves is just over 5%. In uniaxial strain state, the second highest limit is it the FLC at 600°C (about 22% below the FLC at 30°C), followed by the FLC at 800°C (about 24% lower) and 400°C, with about 29% below the curve at 30°C. For the plane strain state, the two highest temperature curves taken exceed the FLC at 30°C, and at 400°C the curve shows a limit of about 15% less than 30°C.

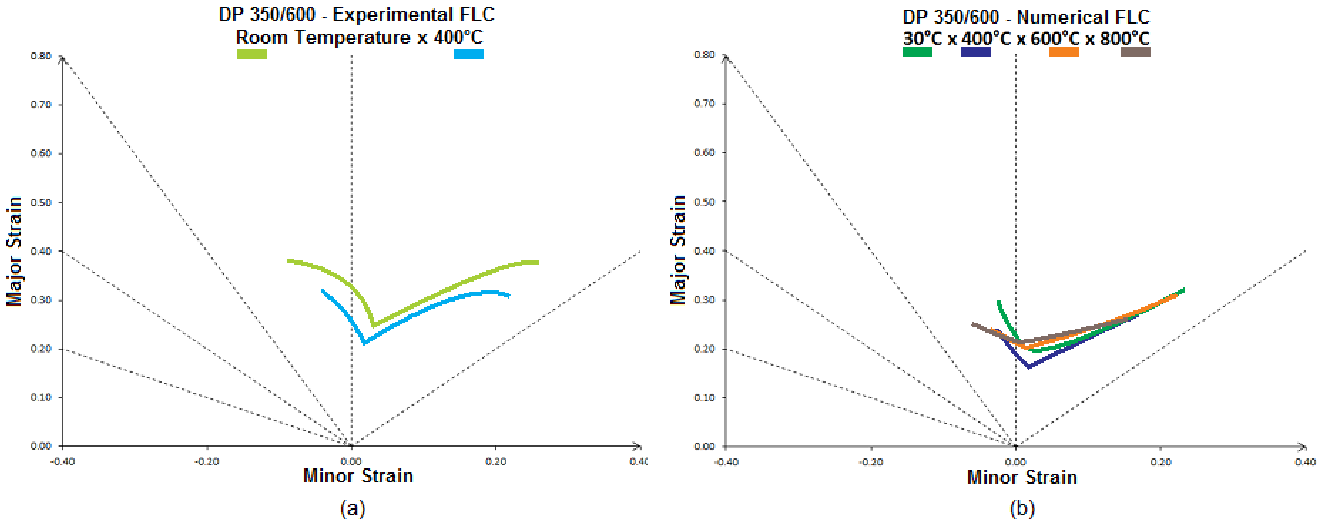


Figure 5: Experimental and numerical FLC for the DP 350/600 steel.

4. CONCLUSIONS

- Practical experiments for obtaining forming limits (Nakazima method) showed that the impact of the increase in temperature is negative with respect to the forming limits in the case of the two steels studied, checked for both temperature levels.

- The computational model built and the thickness gradient method predicted curves forming limit lower than those built with the practical experiment. For both steels the proportion of this reduction was equivalent. This fact is due, probably, to the difficulty to predict the necking during practical experiments.

- The computer model built and the method used for necking prediction proved equivalent to reality in response to high temperature employed. That is, for the computational model, the impact of temperature 400°C is also negative.

- The other two temperatures studied using the numerical method showed adverse performance compared to 400°C. Instead of this, the impact of temperature increase to higher levels is not always negative. In the case of HSLA 350/450, the FLC at 800°C proved to be very close to the FLC at room temperature, while 600°C is very approached to FLC at 400°C. In the case of the DP 350/600, both curves to higher temperature levels were significantly above the FLC constructed with the use of the 400°C temperature.

- It is suspected, however, that for higher temperature levels than those achieved in practical experiments, forming limits of both studied steels can be kept without loss.

- In the case of suspicion above is true, it is likely that there are great temperature levels for each steel, in terms of reduction of springback without significant loss of conformation limits.

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