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NUMERICAL STUDY ON HOLE EXPANSION TESTS OF METAL SHEETS

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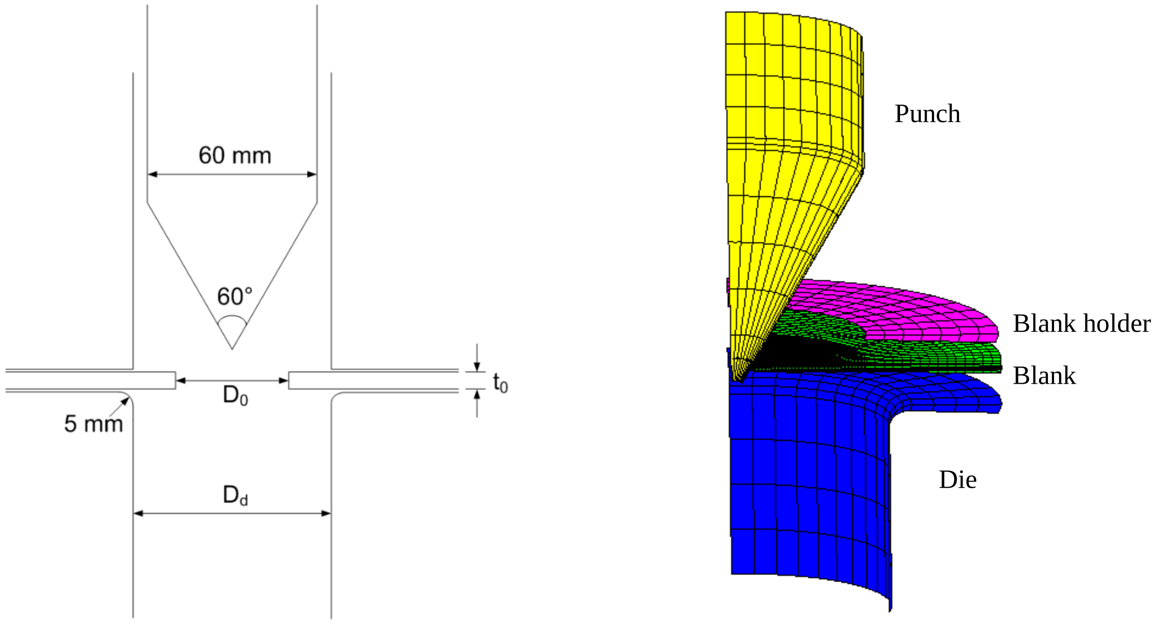
Abstract *In this work, a numerical analysis of the hole expansion test is presented. This analysis focuses on the impact that certain geometric and material features have on the strain path and maximum values achieved for the principal strains, during the test. The features analysed are the die diameter, the sheet thickness and the material hardening behaviour. In order to study the impact of each feature individually, a reference study case was defined, which strictly follows the ISO 16630 standard, to serve as a basis of comparison. Then, other study cases were created from the reference one, by changing each feature in study. The results show that a uniaxial tension strain path is observed at the outer edge of the blank hole, which is not significantly changed with the variation of the features under study.*

1. INTRODUCTION

Advanced high-strength steels (AHSS) have been increasingly used in the automotive industry due to their good strength-to-weight ratio. However, metal forming of AHSS sheets can lead to cracking at the edge of a flange, submitted to tensile stress states. In order to evaluate the occurrence of edge cracking during flanging, the hole expansion test is commonly used. This test consists in the expansion of a circular hole by the action of a conical punch. The minimum displacement of the punch required to cause the occurrence of a crack is measured. The hole expansion test is generally performed according to the ISO 16630 standard, which defines a blank hole diameter of 10 mm, for a sheet thickness between 1.2 mm and 6 mm, a die opening diameter larger than 40 mm and a conical (60º) punch [1]. Nevertheless, there are studies in literature that propose deviations to some geometrical features. Paul [2] conducted an experimental hole expansion test, in which a forming tool geometry that followed the ISO 16630 standard is used, but with a sheet thickness of 0.8 mm, which is under the thickness range defined in the standard. Chen et al. [3] applied the hole expansion test to various high-strength steels, assuming various sheet thicknesses, some of which under the range defined in the standard. Uthaisangsuk et al. [4], [5] applied the hole expansion test assuming blank hole diameters of 10 mm and 15 mm, the latter being a deviation from the standard. In this work, a numerical study is carried out to evaluate the impact of certain geometric and material features of the hole expansion test on the strain path and maximum values achieved for the principal strain. The geometric features studied are the die diameter and sheet thickness. In order to study the effect of material parameters, sheet materials with different hardening behaviours are compared.

2. NUMERICAL MODEL AND PROCEDURE

The mechanical and numerical simulation models of the hole expansion test are represented in Figure 1. For this test, the blank is a circular sheet with a diameter of 120 mm, on which the blank holder applies a constant force of 50 kN. The punch is conical, with a tip-angle of 60º, and the die has a corner radius of 5 mm. The diameter of the die (D_d), as well as the sheet thickness (t_0) are variables in this work; the blank hole diameter D_0 is set equal to 10 mm, as defined in ISO 16630 standard. Due to material and geometry symmetries, only one fourth of the blank is simulated, considering a finite element mesh of 13860, 8-node hexahedral solid elements.



(a) (b)

Figure 1. Hole expansion test: (a) mechanical model; (b) numerical simulation model.

The numerical simulations were carried out with the in-house finite element code DD3IMP, developed and optimized for simulating sheet metal forming processes [6]. The forming tool geometry was modelled using Nagata patches [7]. The contact with friction is described by Coulomb's law, with a friction coefficient of 0.1. The material is considered isotropic. The constitutive model adopted in this study assumes (i) the isotropic elastic behaviour described by the generalised Hooke's law, with E = 210 GPa and ν = 0.30, and (ii) the plastic behaviour is described by the von Mises yield criterion combined with the Swift isotropic hardening law. The Swift hardening law is expressed by:

$$Y = C\left[\left(Y_0/C\right)^{(1/n)} + \bar{\varepsilon}^{\mathrm{p}}\right]^n, \tag{1}$$

where Y is the flow stress, $\bar{\varepsilon}^{p}$ is the equivalent plastic strain and C, Y_0 and n are material parameters.
For each study case, the evolution of the major and minor in-plane principal strain (ε_1, ε_2) with the punch displacement (Δl) is evaluated. The measurement of the punch displacement starts from the position in which the punch establishes contact with the blank. The major principal strain values are measured at the outer edge of the blank hole, which is the edge opposite to the contact area between the sheet and the punch (see red line in Figure 2).

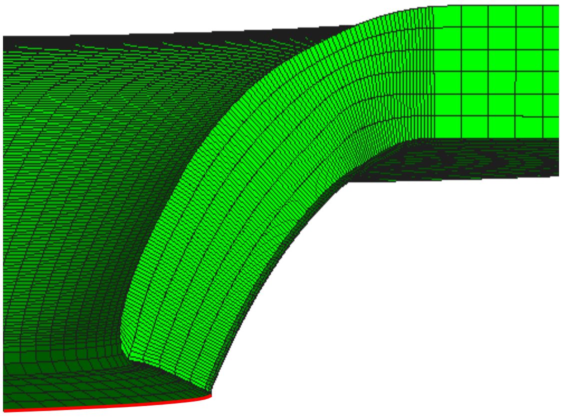


Figure 2. Detailed view of the deformed sheet after hole expansion. The values of the major and minor in-plane principal strains are measured at the outer edge of the blank hole (in red).

3. CASE STUDIES

The first case study is in full conformity with the ISO 16630 standard, considering a blank hole diameter D_0 = 10 mm, initial sheet thickness t_0 = 2 mm and a die diameter D_d = 70 mm. The blank has a hardening behaviour typical of an S460MC high-strength low-alloy steel, and its constitutive parameters are presented in Table 1.

Y_0 [MPa]	C [MPa]	n
519.19	804	0.083

Table 1. Swift hardening law parameters of the S460MC steel.

Figures 3 a) and b) represent the evolution of the major principal strain and strain path during the test, respectively. A uniaxial tension strain path occurs at the outer edge of the blank hole during deformation; this also occurs in the remaining case studies.

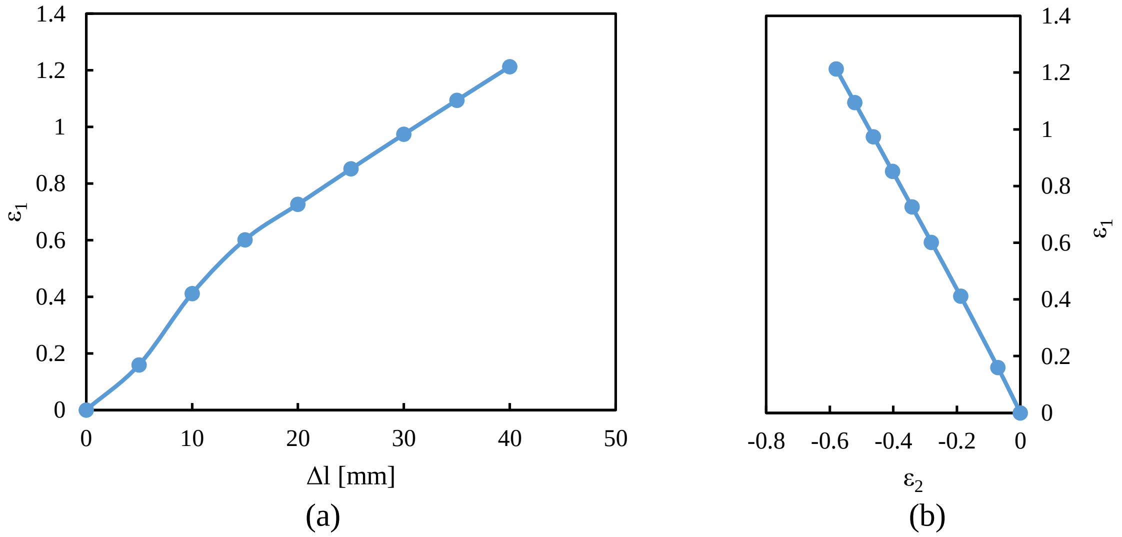


Figure 3. (a) Major principal strain *vs.* punch displacement; (b) strain path evolution.

Taking this case study as reference, three additional case studies were considered, each focusing on the influence of one of the following geometrical and material features: (i) die diameter; (ii) sheet thickness and (iii) material hardening behaviour.

3.1. Die Diameter

In the case of the die diameter, the ISO 16630 standard is quite flexible, allowing for any diameter above 40 mm. Three additional numerical simulations were performed, with die diameters equal to 40 mm, 60 mm and 80 mm. The results are presented in Figure 4.

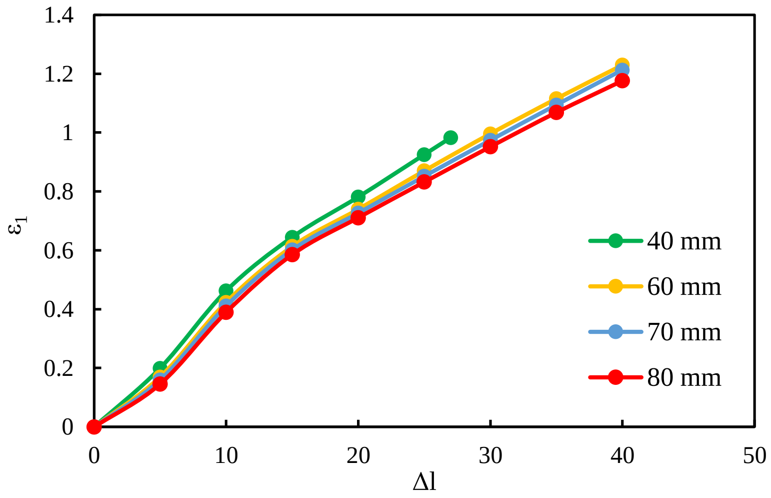


Figure 4. Influence of the die diameter on the major principal strain values achieved during the hole expansion test.

Figure 4 shows that smaller die diameters lead to higher values for the major principal strain, although the relative difference is minimal. These results also demonstrate that care must be taken to guarantee that the clearance between the punch and the die is greater than the sheet thickness. For example, the 40 mm study case only allowed for a punch displacement of 27 mm because, at that point, the punch starts crushing the sheet against the die, which invalidates the test.

3.2. Blank Thickness

According to the ISO 16630 standard, the hole expansion test is used for blanks with thickness values ranging between 1.2 mm and 6 mm. Figure 5 shows the evolution of the major principal strain during the hole expansion test, for blank thicknesses equal to 2 mm, 4 mm and 6 mm. The evolutions of the major principal strain are similar whatever the thickness value, namely between 4 mm and 6 mm blank thickness.

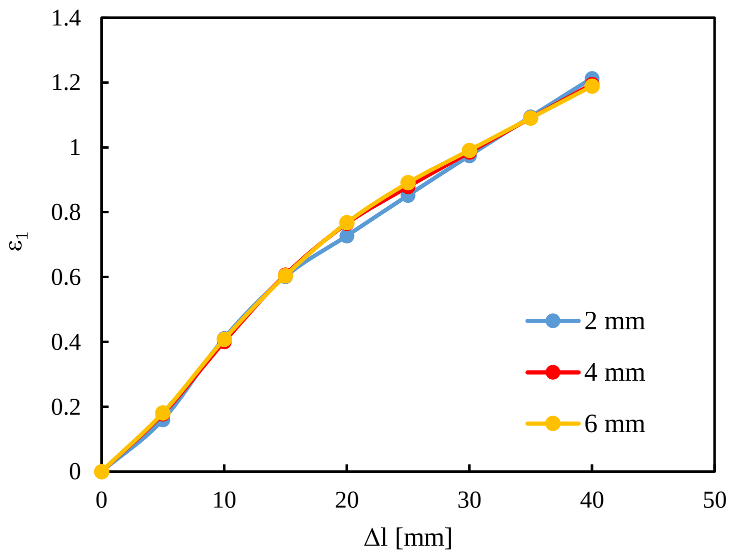


Figure 5. Influence of the blank thickness on the major principal strain values achieved during the hole expansion test.

3.3. Hardening Behaviour

In order to study the effect of hardening behaviour in the results of the hole expansion test, an additional material was considered. The hardening behaviour considered for this material is typical of a mild steel, and its constitutive parameters are presented in Table 2. Figure 6 presents a comparison of the stress-strain curves obtained for both S460MC and mild steel, and Figure 7 shows the evolutions of the maximum principal strain results during the hole expansion test. It is clear from these results that hardening behaviour has a very small impact on the values of maximum principal strain achieved during this test.

Y_0 [MPa]	C [MPa]	n
150	564	0.25

Table 2. Swift law parameters of a material with hardening behaviour typical of a mild steel.

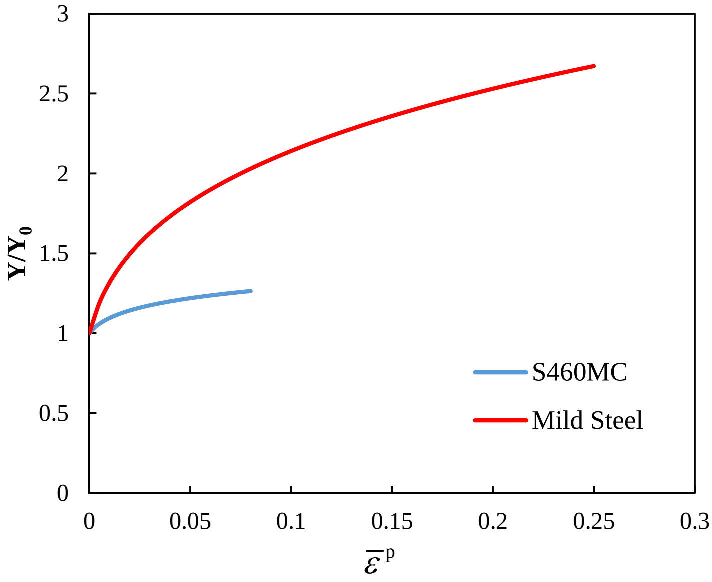


Figure 6. Hardening curves of S460MC and Mild Steel materials.

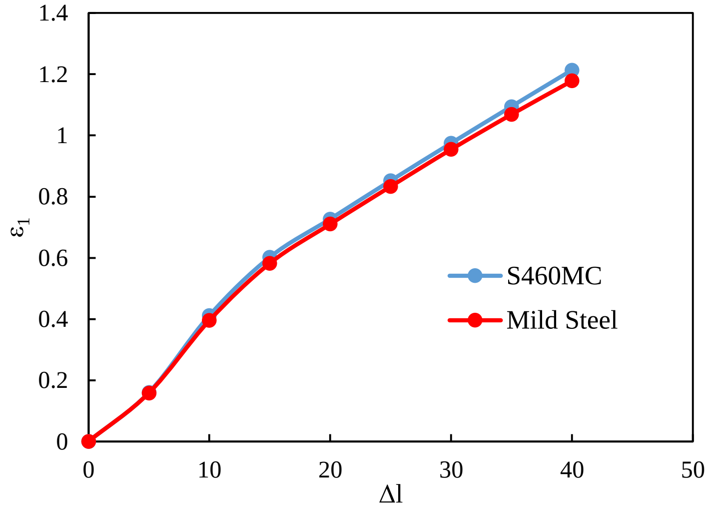


Figure 7. Influence of the hardening behaviour on the major principal strain values during the hole expansion test.

4. CONCLUSION

In this work, a numerical study was performed on the impact of geometric features and material properties, on the strain path and maximum values achieved for the principal plastic strain during a hole expansion test. The features tested are the die diameter and sheet thickness, as well as material hardening behaviour. In regard to the die diameter, one must ensure that it allows for sufficient clearance between die and punch; otherwise, the die diameter has low impact on the results achieved. The thickness value and the hardening behaviour were also found to have little impact on the results obtained. Also, a uniaxial tension strain path is observed at the outer edge of the blank hole, which is not significantly changed with the variation of the features under study.

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