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Abstract. The adoption of advanced high-strength steels is growing in the automotive industry due to their good strength-to-weight ratio. However, the frictional contact conditions differ from the ones arising in mild steels due to the high values of contact pressure. The objective of this study is the detailed numerical analysis of the frictional contact conditions in the hole expansion test. The Coulomb friction law is adopted in the finite element model, using different values for the (constant) friction coefficient, as well as a pressure dependent friction coefficient. The increase of the friction coefficient leads to an increase of the punch force and a slight decrease of the hole expansion. The results show that increasing the friction coefficient postpones the onset of necking, but the localization does not change.

1. Introduction

The hole expansion test is commonly adopted to study the formability of metallic sheets, allowing the study of fracture occurrence in stretch-flanging areas [1]. The accurate prediction of thinning and localization of fracture by numerical simulation requires an accurate modelling of the plastic deformation behavior, namely the anisotropic yield function [2]. However, some authors suggest that the friction model may also play a role because of its interaction with the material flow, since the strain distribution in the hole expansion test is not uniform [1]. Thus, despite the lubrication of the contact interfaces between the blank and the tools, friction can be an important factor in the finite element analysis, which is usually modeled by the Coulomb friction law. The adoption of advanced high-strength steels leads to large contact pressure values [3], which can also contribute to a higher influence of this process parameter.

Traditionally, the friction coefficient is assumed constant in the numerical simulation. However, some experimental studies show that the friction coefficient is affected by several interface properties [4]. Accordingly, some models have been developed considering a variable friction coefficient, typically considering the influence of the contact pressure [5]. Besides, the dependence of the friction coefficient on the contact pressure can be experimentally evaluated using the strip drawing test. The objective of the present study is the detailed numerical analysis of the frictional contact conditions in the hole expansion test, specifically the influence of the friction coefficient on the fracture prediction (location and instant).

The hole expansion test is briefly described in the section 2, comprising both the experimental setup and the finite element model developed. Different values for the (constant) friction coefficient, as well as a law describing the dependency of the friction coefficient on the contact pressure is presented and compared. Section 3 contains the results and discussion, where the effect of the friction coefficient on the punch force and hole diameter is evaluated. All numerical simulations are performed considering solid finite elements and the modelling of the boundary conditions imposed by the draw-bead geometry adopted in the experimental test.

2. Hole expansion test

The geometry of the tools used to perform the hole expansion test is presented in Figure 1. The specimen is obtained from a dual phase steel (DP980) sheet (1.2 mm thickness), which is trimmed into a circular blank with a diameter of 215 mm, presenting a central hole with a diameter of 30 mm. The interface between the blank and the punch head was lubricated with Vaseline and 0.3 mm thick Teflon sheet, while no lubricant was applied to the interfaces between the blank and the upper/lower die. The periphery of the blank is clamped using a draw-bead (see detail in Figure 1) and the blank-holding force is approximately 800 kN [1].

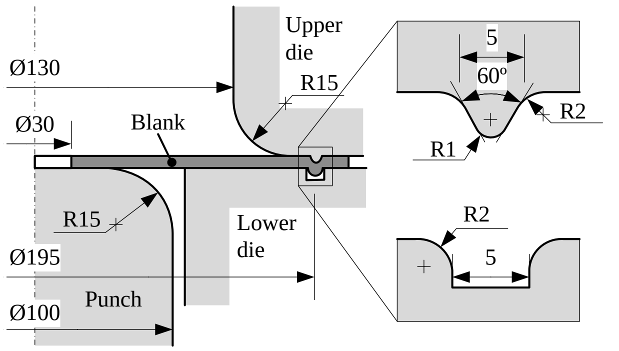

Figure 1. Schematic illustration of the tools geometry and specimen used in the hole expansion test. All dimensions are in millimeter.

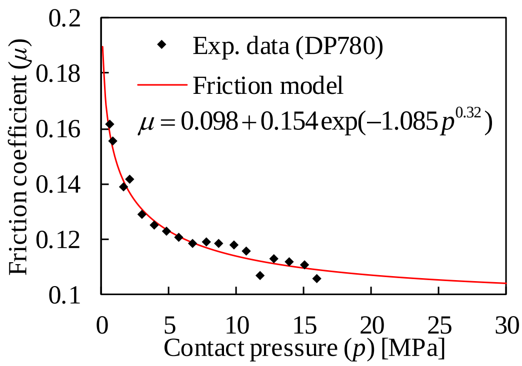

Figure 2. Evolution of the friction coefficient with the contact pressure. Comparison between the experimental values [5] and the friction model.

2.1. Finite element model

The finite element simulations were performed with the in-house finite element code DD3IMP [6], assuming that the forming tools are rigid [7]. The study is focused on the influence of the friction conditions at the interface between the blank and the punch. The classical Coulomb friction law is adopted considering different values for the constant friction coefficient as well as a model considering a pressure-dependent friction coefficient. Figure 2 presents experimental values obtained for a different dual phase steel (DP780) using the strip drawing tests [5], which are used to fit the pressure-dependent model for the friction coefficient. The friction coefficient μ=0.15 is adopted for the interfaces between the blank and the upper/lower dies. The presence of the Teflon sheet between the blank and the punch head is considered in a new model. The Teflon is assumed elastoplastic with E=600 MPa and ν=0.3 in the elastic domain and modelled by $\sigma=46.8(0.014+\varepsilon^{p})^{0.43}$ in the plastic domain. No sliding between the blank and the Teflon sheet is considered, while a null friction coefficient value is assumed between the Teflon and the punch.

The plastic behavior of the dual phase steel DP980 is described by the isotropic work hardening (Swift law) and the yield criterion (Hill'48). Figure 3 presents the comparison between the available experimental data and the constitutive models adopted. The stress–strain curve obtained from the uniaxial tensile test is used to fit the parameters of the Swift law, which are presented in Figure 3 (a). The experimental r-values, measured at every 15º from the rolling direction (RD), are used to fit the anisotropy parameters of the Hill'48 yield criterion, which are listed in Figure 3 (b). Only one-quarter model is simulated, allowing to perform the discretization of the blank with 64.800 hexahedral finite elements (3 layers through the thickness).

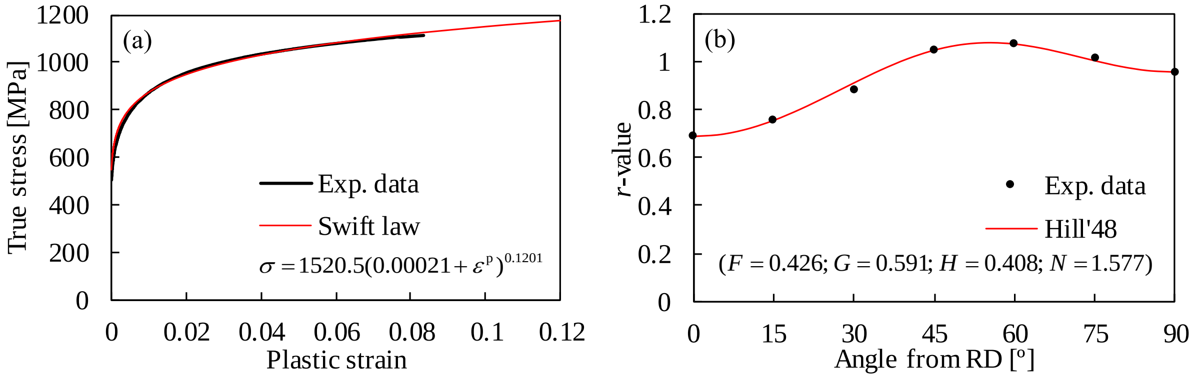

Figure 3. Mechanical behavior of the dual phase steel DP980. Comparison between the experimental data and the numerical model: (a) true stress–plastic strain curve from the uniaxial tensile test in the RD; (b) distribution of the anisotropy coefficient (r-value) in the plane of the sheet.

3. Results and discussion

The predicted punch force evolution is presented in Figure 4, comparing different values of (constant) friction coefficient and the pressure dependent friction coefficient described by the model shown in Figure 2. The influence of including a layer of Teflon between the punch and the blank (frictionless contact) is negligible. On the other hand, the effect of the friction coefficient on the punch force increases with the punch displacement, as highlighted in Figure 4. The predicted contact pressure distribution on the blank (punch head area) is shown in Figure 5 for two different values of punch displacement. Since the contact pressure is relatively high from the beginning (>30 MPa) and the saturated friction coefficient given by the pressure dependent friction model is about 0.1 (see Figure 2), the punch force evolution is identical to the one obtained with a constant friction coefficient μ=0.10 (see Figure 4).

The evolution of the hole diameter with the punch displacements (exponential growth) is presented in Figure 6 (a), while the shape of the hole at 15 mm of punch displacement is shown in Figure 6 (b). The frictionless condition provides the highest hole diameter because the blank is free to slip over the punch head (absence of restraining friction forces). The geometry of the hole is dictated by the material anisotropic behavior. Since the hoop stress is approximately constant in the hole edge and the material yield stress is lower near the diagonal direction, the hole diameter is slightly larger around the diagonal direction. The compressive stress applied on the Teflon sheet induces a significant reduction of the thickness, which leads to a reduction of the blank deformation for the same value of punch displacement and consequent reduction of the hole expansion (see Figure 6 (b)).

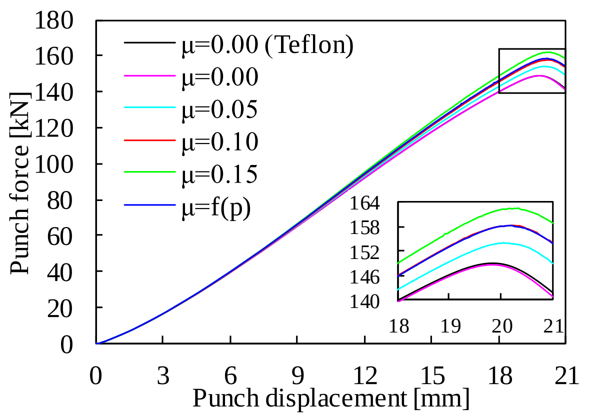

Figure 4. Influence of the friction coefficient between the punch and the blank on the punch force evolution.

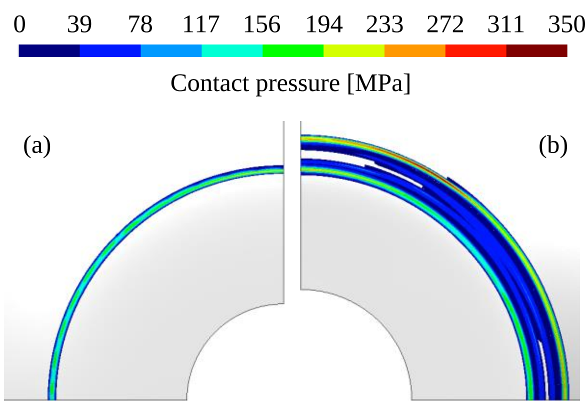

Figure 5. Distribution of the contact pressure on the blank, predicted for two values of punch displacement: (a) 5 mm; (b) 15 mm.

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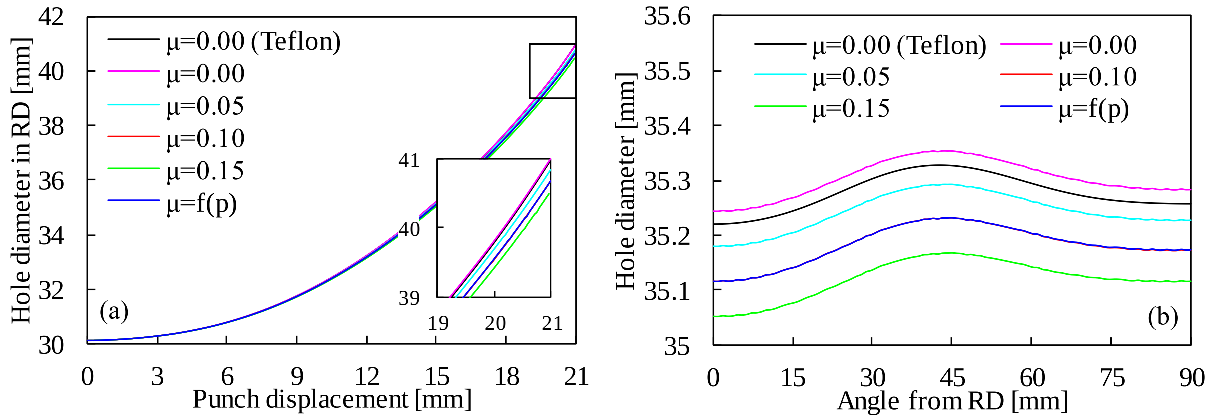

Figure 6. Influence of the friction coefficient between the punch and the blank on the predicted hole diameter: (a) evolution of the hole diameter (measured in the RD) with the punch displacement; (b) distribution of the hole diameter along the circumferential direction for 15 mm of punch displacement.

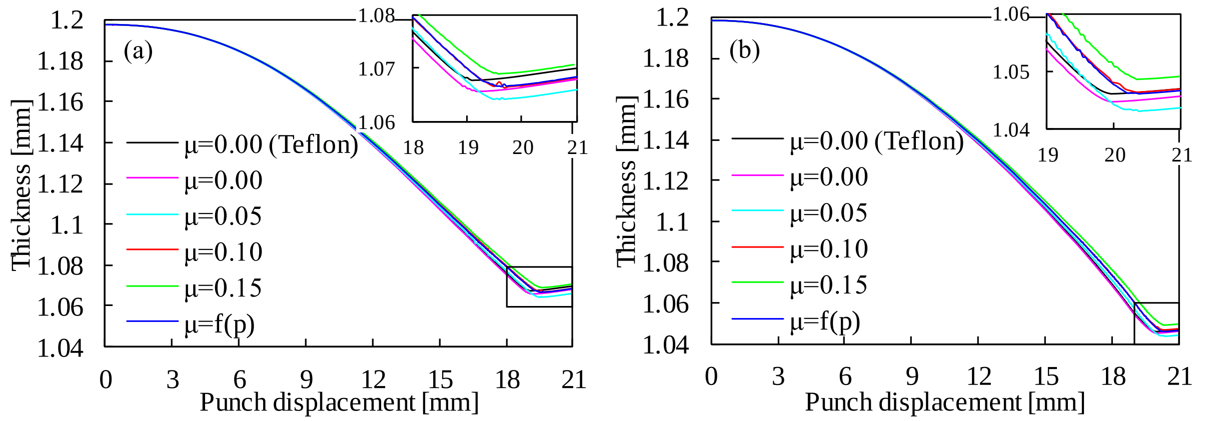

Figure 7. Influence of the friction coefficient between the punch and the blank on the predicted thickness evolution in the hole edge: (a) evaluated in the RD; (b) evaluated in the TD.

The evolution of the blank thickness with the punch displacement is presented in Figure 7, evaluated in two points of the hole edge, namely in RD and transverse direction (TD). The thickness reduction is similar for both points, being more pronounced under frictionless contact conditions. The slight increase of the predicted thickness after 20 mm of punch displacement is a consequence of the localized necking that occurs near the diagonal direction (DD). The thickness distribution at 2 mm from the hole edge is presented in Figure 8 for two values of punch displacement. Since the strain path close the hole is between uniaxial tension and plane strain, the minimum thickness arises near the DD due to the low value of yield stress. For 15 mm of punch displacement, the influence of the friction coefficient on the thickness is roughly a shift of the curve (Figure 8 (a)), i.e. increasing the friction coefficient leads to a reduction of the thickness strain.

The thickness distribution evaluated in the three different directions (RD, DD and TD) is presented in Figure 9, considering two distinct values of friction coefficient. The predicted thickness is significantly lower along the DD, while it presents similar distributions along RD and TD. This difference between directions increases with the punch displacement. Since the contact between the punch and the blank occurs only in the punch corner (see Figure 5), the inclusion of friction in the numerical model leads to a global decrease of the thickness strain in the flat region of the blank, as highlighted in Figure 9.

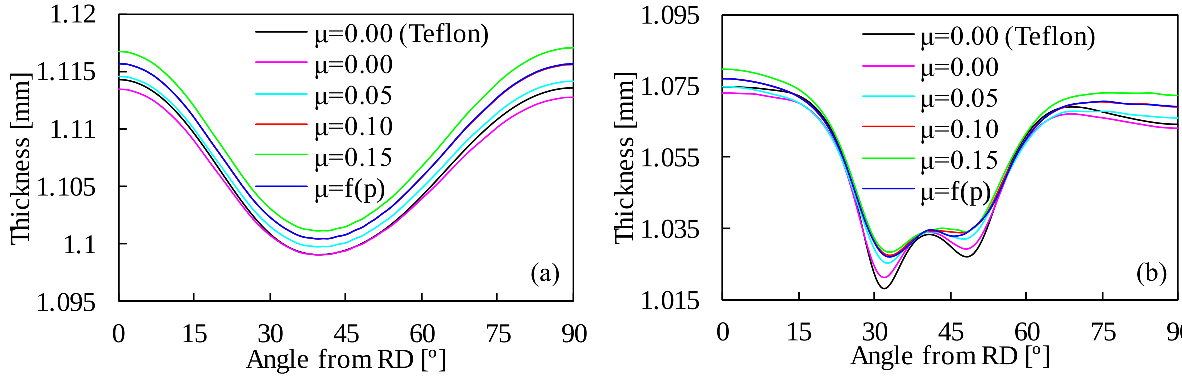

Figure 8. Influence of the friction coefficient between the punch and the blank on the predicted thickness distribution at 2 mm from the hole edge for: (a) 15 mm of punch displacement; (b) 19 mm of punch displacement.

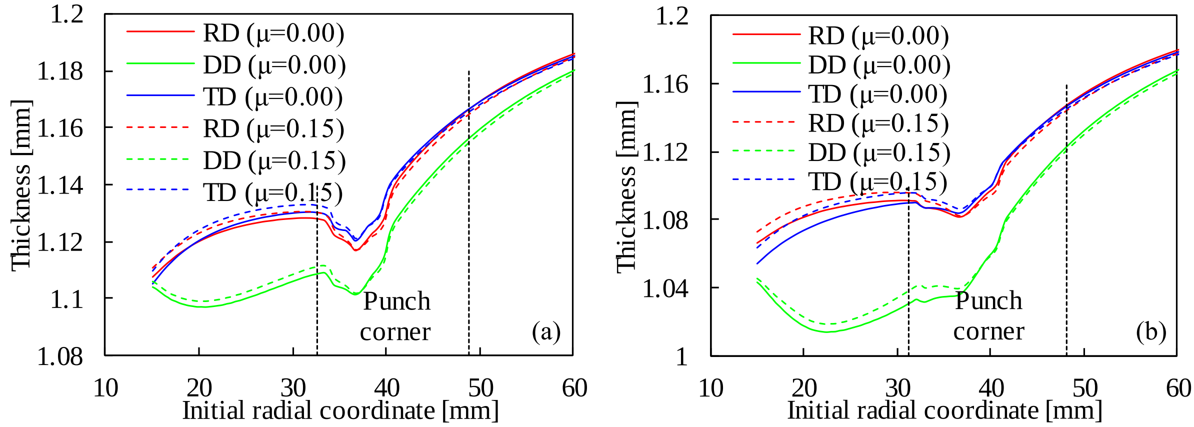

Figure 9. Influence of the friction coefficient between the punch and the blank on the predicted thickness distribution in three different directions for: (a) 15 mm of punch displacement; (b) 19 mm of punch displacement.

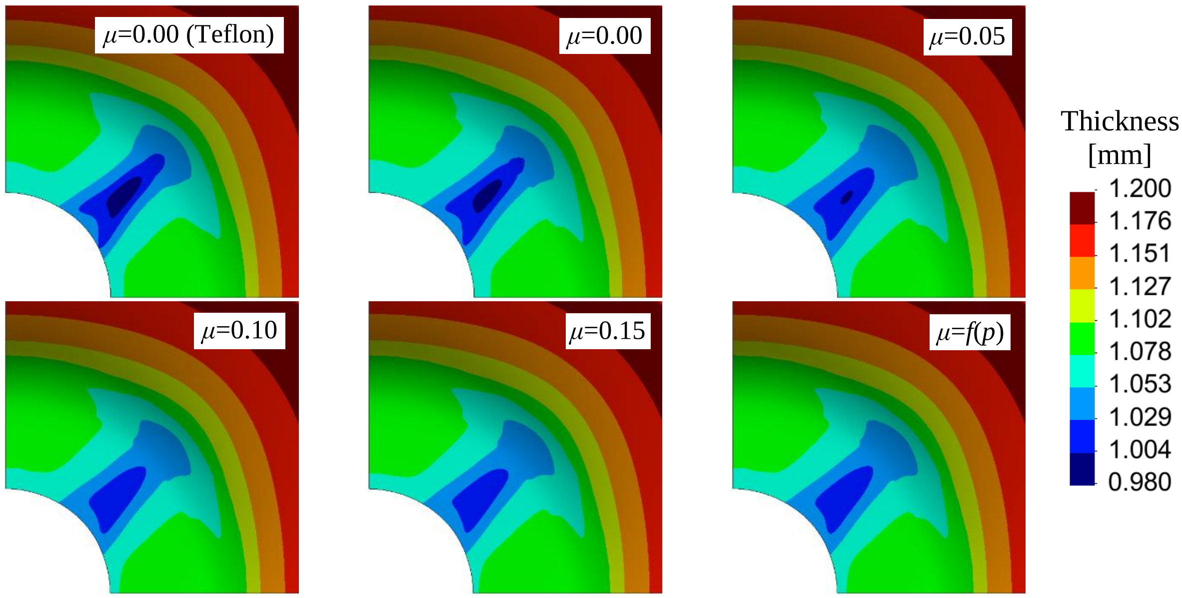

Figure 10. Influence of the friction coefficient between the punch and the blank on the thickness distribution predicted for 19 mm of punch displacement.

Figure 10 presents the blank thickness distribution, predicted at 19 mm of punch displacement, comparing different values of friction coefficient. The onset of necking occurs always in the same localization (close to the DD and ~13 mm from the hole edge). Nevertheless, the instant for which it arises depends on the friction coefficient, i.e. the inclusion of friction postpones the onset of necking. Indeed, the two local minimum values of thickness evaluated at 2 mm from the hole edge (see Figure 8 (b)) are a consequence of the localized necking in the flat region of the blank.

4. Conclusions

This paper presents a numerical study of the frictional contact conditions, between the blank and the punch head, on the hole expansion test. The dual phase steel DP980 is adopted in the finite element simulation, which is modeled by an elastoplastic constitutive model (isotropic Swift law and Hill'48 yield criterion), while the forming tools are assumed rigid. Regarding the friction behavior, the Coulomb friction law is adopted, comprising both constant values of friction coefficient and the pressure dependent friction coefficient. Since high-strength steels lead to large values of contact pressure, the numerical prediction obtained with the pressure-dependent friction coefficient is identical to the one considering a constant friction coefficient (evaluated at large contact pressure). Both the punch force and the hole diameter evolutions are only slightly affected by the friction coefficient. Increasing the friction coefficient in the numerical model leads to a global decrease of the thickness strain in the flat region of the blank, which postpones the onset of necking. Nevertheless, its localization is independent of the friction coefficient adopted, occurring close to the diagonal direction.

Acknowledgments

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