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Numerical Analysis of the Small Punch Test for Different Theoretical Materials

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1. Introduction

The Small Punch Test (SPT) estimates the mechanical properties of metallic materials using small specimens [1,2]. The small dimensions of the specimen are noteworthy to the nuclear industry to evaluate the mechanical properties after-irradiation in a nuclear reactor [3]. Various parameters can affect the results, like the friction between the punch and specimen, the equipment geometry (punch diameter, fillet radius), and specimen thickness [4]. The effects of these parameters can be estimated using numerical models. One way to model the plastic behavior is using the power-law expression, Eq. 1, also known as the Hollomon equation [5]. Where σ is the tensile true stress, ε is the tensile true plastic strain, K is the strength coefficient, and n is the strain hardening exponent. This paper evaluates the curves obtained for different theoretical materials, varying the values of K and n. Furthermore, the study of the mesh and the friction effect was done to choose the best values to use in the materials simulations.

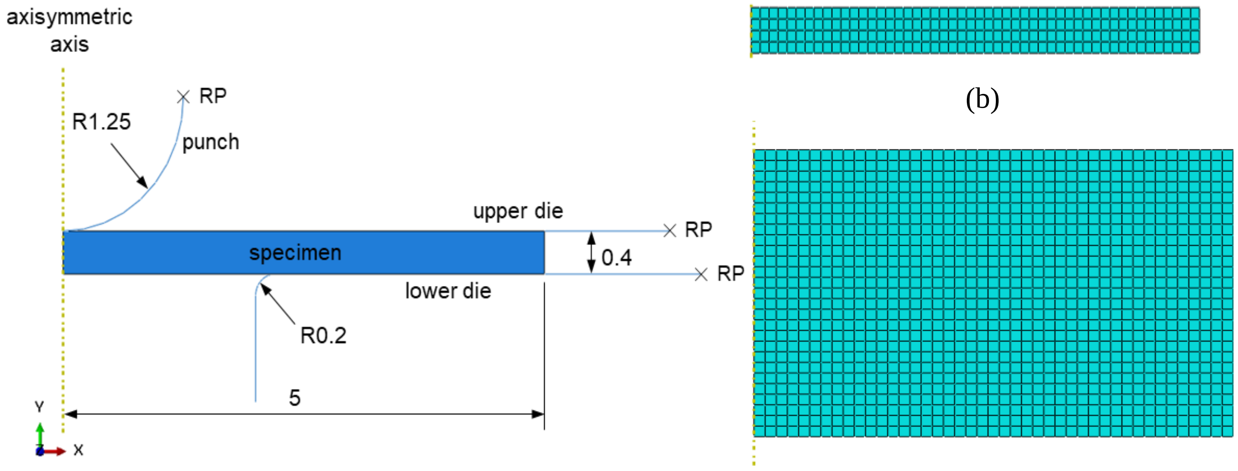
$$\sigma = K(\varepsilon)^n \tag{1}$$

2. Methodology

The numerical analyzes were executed on Abaqus (2020). The geometry was based on literature [6], Fig. 1(a). The elastic properties used were Young's modulus equal to 200 GPa and Poisson's ratio equal to 0.3 (typical values for steel). Then, the elasto-plastic behavior was modeled using points of the σ vs. ε curve. These curves were obtained using Eq. 1, calculating the σ value for some strain values between $\varepsilon = 0$ and $\varepsilon = 1$ mm/mm for different combinations of K and n. The models were axisymmetric, and the mesh was done in Abaqus (2020) using elements QUAD, Fig. 1(b), and Fig.1(c). The punch and dies are modeled as an analytical rigid body, and the contact between these parts and the specimens was modeled using "hard" contact as normal behavior. Furthermore, penalty contact uses the friction coefficient to model the tangential behavior [7]. The lower and upper dies were fixed, and a displacement, 2 mm, was added on Y-direction. These boundary conditions were applied on the reference point (RP), Fig. 1(a).

Refining the mesh can improve the quality of the results, because of that six different elements sizes were used: 0.100 (Fig. 1(b)), 0.075, 0.050, 0.025, 0.015 (Fig. 1(c)) and 0.010 mm. For these analyses, the material properties were K = 500 MPa and n = 0.1, and the contact was frictionless (friction coefficient = 0). After that, the chosen mesh size was 0.015 x 0.015 mm, as shown in the results and discussion part.

The second analysis evaluated the effect of friction on the result, with the same plastic properties, using four different friction coefficients: 0 (frictionless), 0.1, 0.2, and 0.5. Lastly, the most important analysis is to compare among them the curves obtained in simulation with different materials. This analysis was done using nine different σ vs. ε curves combining three values of K (100, 500, and 1000 MPa) and three values of n (0.01, 0.10, and 0.50), using a friction coefficient equal to 0.1.



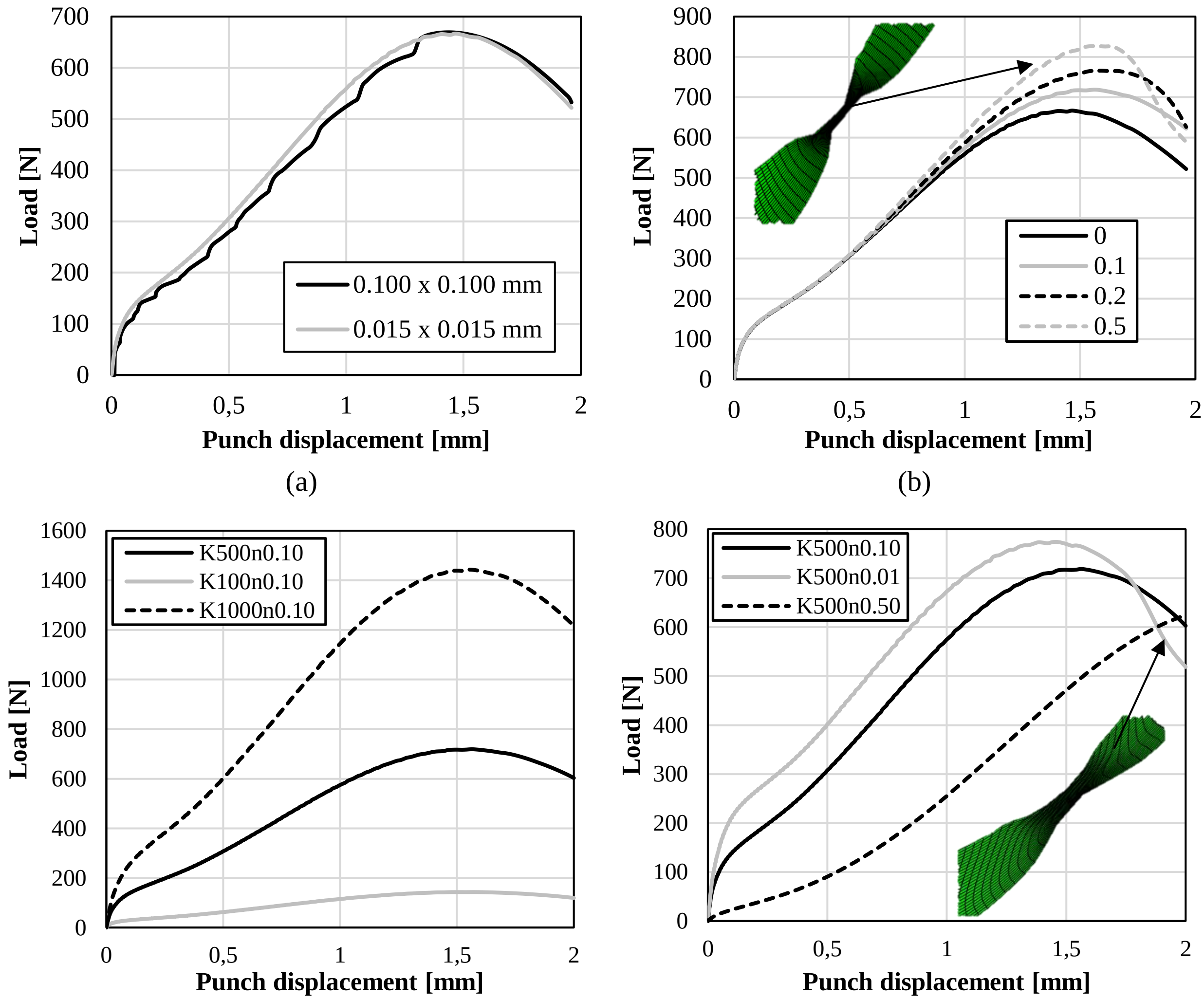
(a) (c)

Figure 1: (a) geometry with dimensions in mm; (b) mesh with elements size 0.1 x 0.1 mm; (c) part of the mesh with elements size 0.015 x 0.015 mm.

3. Results and Discussion

Using a coarse mesh, 0.1 x 0.1 mm, the results are not smooth, Fig. 2(a). Refining the mesh improves the curve, Fig. 2(a), but the simulation time increases. The simulation time using the coarser mesh (0.1 x 0.1 mm) was approximately 45 seconds, whereas, for the most refined mesh (0.01 x 0.01 mm) was one hour. The simulation with a satisfactory result, Fig. 2(a), and a simulation time of 17 minutes employed an element size of 0.015 x 0.015 mm. Using this element size, the friction coefficient was increased. Fig. 2(b) shows these results. In this case, the higher the coefficient, the higher the loads, as expected. However, the simulation using the friction coefficient 0.2 and 0.5 an instability occurs, Fig. 2(b), and this caused the load decreases earlier. Simulating this frictionless contact is not phenomenological, so the best option is using the 0.1.

Fig. 2(c) shows the results changing only K with $n = 0.10$. The K multiples ε, Eq. (1), so the materials with high K the load is higher, this means the material is more resistant, the same occurs in the tensile test. The evaluation varying the n is more complex, Fig. 2(d). The material behavior for $n = 0$ is perfectly plastic, without strain hardening. In this case, independently of the strain, the stress will be equal to K. Increasing n increases the strain hardening, but the relation is not direct as the K analysis. Separating this evaluation into two parts can be interesting. First, observing the beginning of the curves, the conclusion was that the lower the strain hardening, the higher the loads. As the K value is the same, the yield stress is higher for $n = 0.01$, so the loads are larger. Then, the maximum point of the curve was analyzed. For the 0.01 simulation, the load starts to decrease before the others, and plastic instability happened, Fig. 2(d). That means the plastic instability resistance is low, causing problems for the low strain hardening materials. For $n = 0.5$, the load increasing caused by the strain hardening compensates the decrease in resistant area. So, the higher the n lower is the force at the beginning, and it takes longer to decrease the load. Comparing an experimental result to these curves can be interesting to discover the K and n values for the tested material.



(a) (b)

(c) (d)

Figure 2: load vs. punch displacement curves varying: (a) the element size; (b) the friction coefficient; (c) the strain hardening exponent; (d) the strength coefficient.

4. Conclusions

Evaluating the mesh is necessary to verify an element size that guarantees the efficacy of the results without excessively increasing the simulation time. The study of the fiction effect was done using this element size. Based on the results, an appropriate friction coefficient was chosen. Those two analyses were essential for the development of models for the study of theoretical materials. The evaluation of the curves for different materials was necessary to understand the effect of the *K* and *n* parameters of the power-law equation used to model the plastic behavior of the materials. The curve shape is not affected by the *K* parameter. Increasing the *K* increases the load for all punch displacement. Alternatively, by maintaining the *K* and varying the *n* parameters, the curve shape changes. The higher the strain hardening the lower is the force at the curve beginning, and the faster the maximum point is reached. Finally, using more *K* and *n* combinations may be possible to estimate these parameters for several materials. In this case, the experimental curve can be compared to the numerical curves. This comparison may be interesting since the *n* describes the strain hardening, and for low values, the plastic instability is facilitated.

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