Accurate plane strain compression test validation

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Abstract. Large strain characterization of sheet metals has become increasingly important with the generalization of advanced high strength steels, for which the tensile test provides data over a very reduced strain range. Among the numerous alternative characterization tests, the plane strain compression test (PSCT) requires a small amount of material and classical testing machine and acquisition. PSCT was mainly used for hot forming characterization, but recently it has been proved sufficiently accurate for application in cold metal forming. This work provides an in-depth validation of the PSCT by means of the finite element method. When converting the PSCT force-displacement curve into a stress-strain curve (flow curve), several analytical corrections are applied. Several sets of such corrections terms were proposed in the literature, some of which are consistently used by all authors, while others being only used in some papers. The FE simulation of the test was used in order to validate these correction terms and their hypotheses. The originality of the approach is the design of a sequence of test configurations which allow for the individual validation of each and every one of the correction terms concerning the effect of several test parameters. The FE simulations showed that the analytical exploitation of the PSCT provides a very good accuracy. They helped identifying the most suitable correction terms to consider.

1. Introduction

Accurate stress-strain curves of sheet metal are required for realistic simulations, for example in the automotive industry. According to the ISO 6892-1 standard, stress-strain curves are traditionally built from the uniaxial tensile test. However, this test cannot provide data at strains beyond uniform elongation within the ISO norm specifications. Therefore, it is necessary to find other alternative methods to obtain an accurate flow curve. Over the past decades, many alternative methods have been developed. Some of the more commonly used in the literature are: bulge test, simple shear test, stack compression test, in-plane torsion test, and plane strain compression test. Only the hydraulic bulge test gave rise to an ISO standard. Most of these experiments require dedicated testing devices, sometimes dedicated testing machines, and image correlation-based acquisition. The plane strain compression test is an exception to this rule, since it makes use of a simple test device and a universal tension-compression machine and standard force-displacement acquisition. From this point of view, it is thus very appealing for industrial application, especially as it requires small amounts of sample material. While it was traditionally applied in the context hot rolling applications, several authors seem to
indicate that the test is sufficiently accurate for the flow curve determination in cold forming conditions [1][2].

In the plane strain compression test (PSCT), a rectangular sample is compressed between two rectangular dies, wider than the part, and extend the part in the direction of its length, as illustrated in Figure 1. The displacement of one of the tools is imposed and the force is measured from which a stress-strain curve under the plane strain stress state is derived. The friction between the tool and the workpiece is reduced using lubricants made of different materials such as graphite, glass, polymer (Teflon), oil, which are chosen mainly according to the temperature of the test. Several drawbacks were summarized in the literature [3]: lateral misalignment of the tool, stress concentration at tool edge, heterogeneous distribution of deformations and friction. Lateral tool misalignment reduces the area of the workpiece in contact with the tool and affects the measured force. The concentration of stresses on the edges of the tool can cause crack initiation at relatively low tool penetration. And the distribution of stresses in the part is heterogeneous, which poses problems of interpretation of the results of the plane strain compression test. To improve the reliability of the plane compression test, Becker and Pöhlandt [1] used a tool with a radius and proposed an analytical method for the determination of the effective tool width. However, friction cannot be entirely eliminated in the test. Thus, the correction of friction has been studied by several researchers, who applied Tresca's law and Coulomb's law or a combination of the two [4] to the friction between the tool and the test piece. These studies provide friction correction equations for each case. Finally, optimization of the specimen geometry was also proposed [5].

The purpose of this paper is to validate the various correction terms proposed in the literature for the PSCT flow curve calculation, by means of finite element simulations. The research methodology adopted in this work is described in Section 2. Section 3 summarizes the main results of the study, which are further discussed in Section 4.

![Figure 1. Schematic description of the PSCT test configuration a) before and b) after test and main notations [6].](image)

2. Research methodology

An analytical analysis of the results of the plane strain compression test is required to extract the material’s flow curve from the PSCT. Several correction terms are involved in these calculations, whose validation is insufficient in the literature. Therefore, an efficient and reliable verification method is necessary. To validate these corrections, FE simulation with the Forge® software was used. Such simulations allow for individual and combined analyzes of the impact of these corrections.

The method proposed is summarized in Figure 2:

- First, a material law is chosen, corresponding to a cold formed steel sheet. Here, a C35 steel material was considered; its properties were selected from the Forge® software database.
- Then PSCT simulations are performed under different conditions. The applied force as a function of tool movement is recorded. The geometry of the test is defined by the sheet thickness (2 mm), tool width (6 mm), sample width (40 mm).
Finally, stress-strain curves are calculated by applying the PSCT analytical formulas to the FE-based force-displacement recordings. These curves can be used to compare with the curve generated by the constitutive equation, which serves as reference. The analytical analysis equations used in this work were taken from [2].

![Figure 2. Research methodology used for the numerical validation of the PSCT.](image)

This approach allows one to rigorously compare the result of the PSCT procedure to a rigorously known reference. Moreover, simulation further allows one to decompose the problem in sub-problems in order to decouple the different correction terms. Consequently, several 2D and 3D test configurations were simulated, as schematically shown in Figure 3. Two-dimensional simulations did not need to be compensated for the sample width variation while frictionless simulations avoid the influence of friction, and the small length configuration is not affected by shear side effect. Simulation configurations were designed to emphasize only one single effect (width variation; friction; shear…) and thus validate individually each correction term, which would be impossible experimentally. The tools were described as rigid, analytical surfaces, while the material was considered elasto-plastic and meshed with triangular / tetrahedral elements. According to a convergence study, a fine element size of 25µm was used for all simulations. This was important in particular for a correct estimation of the contact area. Given the large strains, remeshing was used in order to maintain a good mesh quality. It was verified that strain rate and heat transfer during the process do not have any influence on the obtained force-displacement curves.

![Figure 3. Simulated PSCT configurations within the validation procedure: reference configuration (l>w); small length configuration (l<w); and misalignment configuration.](image)
3. Simulation results

The small length configuration was used in order to explore the corrections related to friction correction and to the yield surface model employed in the analytical calculation of the flow stress. Indeed, in this configuration the shape of the sample geometry remains perfectly rectangular thus involving less approximations.

Figure 4 shows predicted flow curves using 2D PSCT simulations with the small length configuration. Various friction models were used for the correction. The figure clearly shows that the friction correction improves the accuracy of the flow stress calculation, in particular at large strains. In turn, these simulations showed an equivalent accuracy for all the friction models tested: Coulomb friction, Tresca friction and combined friction. This may explain why recent publications [2] still use a friction correction based on the Coulomb friction model, although this model is not acceptable for this test on physical grounds.

The same analysis using the reference configuration, with a sample longer than the tool width, led to the same conclusions. With the reference configuration, the accuracy of the free boundary condition at the die exit surfaces was questions by several authors. Becker and Pöhland [1] proposed a so-called shear correction to address this problem. Figure 5 shows that this shear correction does not improve flow curve calculation, provided that a von Mises yield surface is used in the analytical calculation of the flow stress. In contrast, the usage of Tresca’s yield surface as was done in [1] significantly overestimates the flow stress; this may explain why these authors found the shear correction useful, as its effect is a decrease in the flow stress.

A classical correction term [2-5] aims to take into consideration the increase of the sample width $b$, which induces an increase in the contact surface between dies and sample, thus affecting the calculation of the average normal stress. The simulation of the width increase required a full 3D simulation. The correction term makes use of the maximum sample width measured at the end of the experiment. As it is made clear in Figure 6, this correction term compensates with very good accuracy the influence of the width increase on the flow curve calculation, although the corresponding error is not very large. In the last two simulations the friction was set to zero in order to avoid superposition of several errors. Nevertheless, the same conclusions were also obtained with similar simulations where small to moderate friction was considered. Also, the three different friction correction terms were again confronted to each other using 3D simulations of the PSCT. The same conclusions are drawn as in two dimensions: the friction correction is necessary, the three proposed correction terms are accurate and there is almost no difference between their predictions.
Finally, the influence of an accidental tool misalignment was investigated with 2D simulations. No correction term was proposed, but the influence of a misalignment imposed in the simulations on the resulting flow curve was determined. Figure 8 plots the errors between flow curve with misalignment and the input flow curve. These results show that the error is negligible for tool misalignments inferior to 0.2 mm. However, for a tool misalignment of 0.5 mm the error becomes very significant,
approaching 10%. It is thus recommended to carefully consider the tool alignment when building PSCT devices.

Figure 8. Predicted flow curves from the 2D PSCT simulations; influence of tool misalignment.

4. Discussion and conclusions
The plane strain compression test provides an economical means for flow curve determination of sheet metals at large strains. The analytical calculation of the flow curve from force-displacement measurements involves a number of corrections to compensate for edge effects, friction effects etc. While it is very difficult or even impossible to validate these correction terms independently with respect to experimental data, the numerical simulation of the test provides a rigorous means for validation, in particular when several test configurations are used. In this work, several analytical correction factors were analysed. These are the effect of the plasticity surface, shear-type edge effect, effect of friction and effect of the specimen width correction. The investigation conforms that for materials without plastic anisotropy, the von Mises yield surface should be preferred to Tresca’s. In this case, the so-called shear correction of the edge effects does not improve the results and should be avoided. In turn, the classical compensation terms for the specimen width increase and the friction influence proved both necessary and accurate. In particular, the performed simulations could not show any difference between the correction terms using Coulomb and Tresca friction laws. Some of these conclusions could be further explored with more detailed simulations.

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