LARGE STRAIN FLOW CURVE IDENTIFICATION FOR SHEET METAL: PROCESS-INFORMED METHOD SELECTION

S. Coppieters[1*], M. Jäckel[2], N. Miyake[3], C. Kraus[2], H. Traphöner[4], T. Kuwabara[3], E. A. Tekkaya[4]

[1] Department of Materials Engineering, KU Leuven, Belgium
[2] Fraunhofer Institute for Machine Tools and Forming Technology IWU, Germany
[3] Division of Advanced Mechanical Systems Engineering, Institute of Engineering Tokyo University of Agriculture and Technology, Japan
[4] Institute of Forming Technology and Lightweight Construction (IUL), TU Dortmund University, Germany

ABSTRACT: Sheet metal forming and joining processes can be optimized with the aid of numerical simulations provided that an accurate large strain flow curve is available. Several experimental techniques can be used to determine the large strain flow curve. These material tests are typically dominated by a certain stress state and yield different results depending on the degree of plastic anisotropy. In this paper, a first order numerical stress state analysis of the forming process is used to select the most appropriate material test for determining the large strain flow curve. Flow curves of DC04 obtained through the homogeneous stack compression test, the strain-rate controlled hydraulic bulge test, the post-necking tensile experiment and the in-plane torsion test are compared. Finally, the proposed procedure is applied to a joining by forming process and the results are experimentally validated.

KEYWORDS: Large strain flow curve identification, sheet metal, strain hardening

1 INTRODUCTION

The predictive accuracy of finite element simulations for forming and joining by forming of sheet metal largely depends on the adopted material model. Many of these processes generate severe plastic deformation of the sheet metal. For example, during joining by forming of sheet metal (e.g. clinching) a multitude of stress states is generated accompanied with large plastic straining of the material. From a simulation point of view, however, plastic anisotropy of the sheet metal can be safely ignored for predicting the metal flow [1]. Indeed, the metal flow is strongly constrained by the joining tools preventing plastic anisotropy to manifest itself at the length scale of the joint. As such, joining by forming is usually simulated assuming a von Mises material solely requiring a large strain flow curve to account for strain hardening. Obviously, standard tensile tests are of limited usefulness because necking limits uniform deformation. Several experimental techniques have been developed [2,3,4,5] to determine the large strain flow curve of sheet metal. In this regard, there are two issues. Firstly, these material tests are typically dominated by a certain stress state and yield different results depending on the degree of plastic anisotropy, see Fig. 1. Secondly, due to the small dimensions of the forming tools (e.g. punch or rivet) compared to the nominal sheet thickness, joining by forming processes of sheet metal must be regarded as a bulk forming problem in which the through-thickness stress cannot be ignored. The crux of the problem here is that the plastic material behavior of sheet metal is conventionally determined using material tests, which are confined to homogeneous plane stress conditions in the plane of the sheet.

Sheet metal itself often exhibits plastic anisotropy. As such, when adopting the von Mises criterion for simulating joining by forming, it is crucial to identify the flow curve using a material test, which generates a stress state resembling the dominating stress state. The aim of this paper is to present a generic methodology to identify the dominating stress state in joining by forming processes, which can be used

* KU Leuven, Ghent Technology Campus, Gebroeders De Smetstraat 1, 9000 Ghent, Belgium.

to select the most appropriate material test to identify the large strain flow curve.

2 Large strain flow curve identification

In this section, four material tests are used to determine the large strain flow curve of DC04 sheet with a nominal thickness of 1 mm and an average r-value of $r_{avg}=1.64$. A quasi-static tensile test in Rolling Direction (RD) was conducted on a standard tensile machine with a load capacity of 10 kN. The pre-necking strain hardening (labelled *Tensile Test (RD)*) is shown in Figure 1. Additionally, the tensile machine was equipped with a stereo Digital Image Correlation (DIC) system to measure the full-field displacements fields within the diffuse neck during a quasi-static Post-Necking Tensile Experiment (PNTE). The energy method was used to inversely identify the post-necking hardening parameter p [2] using 121 load steps. The dashed red curve shown in Figure 2 is the resulting PNTE-flow curve. Fig. 2 shows the reconstructed equivalent von Mises strain and stress, respectively. It has been shown that the energy method [1] extends the validity of the standard tensile test and generally enhances the fitting quality of phenomenological hardening laws in the post-necking regime.

The Stack Compression Test (SCT) [3] was carried out on a electro-mechanical press with a maximum press force of 100 kN using 4 disks. Lubrication was applied to minimize the effect of friction. The orange circles in Fig. 1 show the experimentally acquired flow curve using the SCT. The hydraulic bulge test (HBT) [4] enables to probe large plastic strains under quasi-balanced biaxial tension. The thickness plastic strain and the radius of curvature at the top of the bulged specimen were measured using a stereo DIC system. The blue solid curve in Fig. 1 shows the flow curve measured using the strain-controlled HBT.

Finally, the in-plane torsion test with groove [5] was successfully conducted up to an equivalent plastic strain of approximately 1.2. The onset of wrinkling at higher strains has limited the flow curve determination for the DC04 in 1 mm.

From Fig. 1 it can be seen that initial yielding corresponds to a von Mises material. Beyond a reference plastic strain of 0.05, however, the flow curve strongly depends on the adopted material test indicating the occurrence of differential work hardening which is a typical observation for low carbon steel sheet with an average r-value $r_{avg} > 1.5$ [6]. From the equivalence of work hardening in terms of plastic work it can be shown that the HBT-flow curve can be converted to an uniaxial stress-plastic strain curve in the RD [4]. The concept of work conjugate shows that the converted HBT-flow curve correspondence with the PNTE-flow curve. The latter is recently also observed by Hakoyama et al.[7]. As such, it can be stated that the post-necking strain hardening rate identified by the HBT and the PNTE is in good agreement. Moreover, it can be inferred from Fig. 1 that the IPTT yields a post-necking strain hardening behaviour that is in good agreement with the PNTE. The IPTT enables to probe the largest plastic equivalent strain (approximately 1.2).

The most remarkable observation in the post-necking regime is that the SCT-flow curve exhibits significantly more strain hardening than observed in the other experiments. In terms of stress state, the SCT is equivalent to the HBT provided that symmetry between biaxial compression and tension can be assumed. As such, the discrepancy between the flow curves obtained through the HBT and the SCT suggests that the hydrostatic stress component affects the flow stress. The latter observation will be scrutinized in more detail in future work.

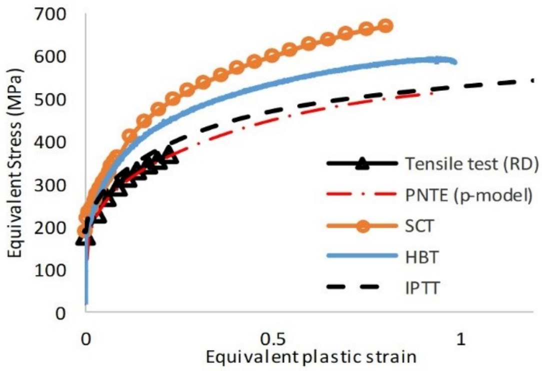

Fig. 1 Large strain flow curves (DC04)

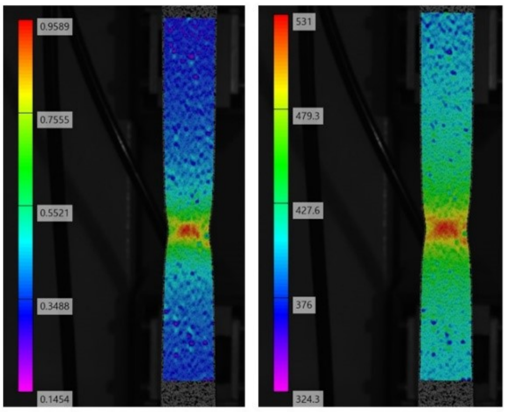

Fig. 2. PNTE: reconstructed equivalent von Mises strain (left) and stress [MPa] (right).

3 Process-informed method selection

3.1 Stress-state analysis

If the material exhibits plastic anisotropy, it seems important to calibrate the von Mises yield criterion to a stress state which dominates the joining process. The latter procedure can be regarded as stress state fitting, and, consequently, selection of a proper material test requires a stress state analysis. Since the deformation is expected to be complex, numerical simulation is used for the stress state analysis. A 3D stress state can be unambiguously described by the Lode angle ξ and the triaxiality η [8]. Figure 3 shows the (ω-η)-diagram, where the stress metric ω is defined as $\omega=1-\xi^2$. For shear-dominated stress states ω equals 1, while for axisymmetric stress states ω equals 0. The solid black curve shown in the (ω-η)-diagram is the so-called *plane stress path* directly derived from the plane stress von Mises yield locus. The *plane stress path* can be divided in three regions associated with the stress space quadrants. The orange and the blue curves correspond to the first and the third quadrant of the stress space, respectively. The black part of the plane stress path represents the second and the fourth quadrant of stress space.

Material points lying on the plane stress path (e.g. the orange bubble) exhibit a plane stress condition and can be probed using a sheet metal material test. Material points which deviate from the plane stress path (e.g. the red bubbles) are subjected to a 3D stress state. The size of the bubbles in the (ω-η)-diagram corresponds to the magnitude of the equivalent plastic strain in the considered material point. The position of the material tests can be theoretically shown in this diagram.

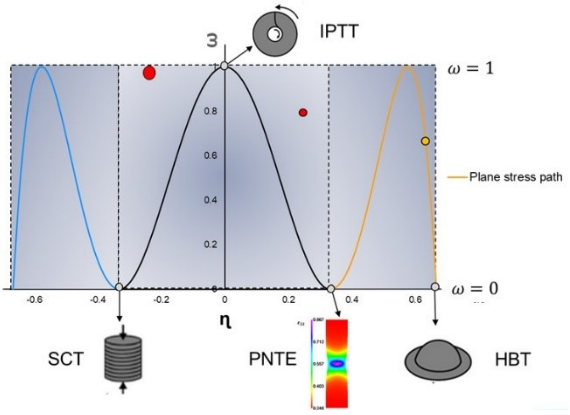

***Fig. 3**. Stress-state analysis: the* (ω-η)-diagram.

3.2 Process-informed method selection

The (ω-η)-diagram enables to analyse the stress states and plastic strains occurring in metal forming processes. The complexity of the deformation history, however, requires an additional metric to extract the dominating stress state. Figure 4 shows the initial indentation of the punch during clinch forming. The associated stress states in the upper sheet are plotted in the (ω-η)-diagram shown in Fig. 5. It can be inferred that the stress states corresponding to large plastic deformation cluster around ω=0. Indeed, the upper sheet is sheared between the punch and the die shoulder. Below the punch, the upper sheet is subjected to biaxial tension, albeit at significantly a lower plastic deformation. In this case, it is clear that the majority of the stress states is shear-dominated. When the joining process proceeds, however, the material state becomes more complicated.

In order to objectify the assessment of the dominating stress state, the consumption of plastic work can be considered. The left panel of Fig. 5 shows the plastic work (% of total consumed plastic work in the process) associated with the different stress states (by binning the stress metric ω). In such a way, it can be inferred that almost 50% of the plastic work relates to shear-dominated stress states. The latter information can guide the selection of the most appropriate material test for flow curve identification. Indeed, for this particular forming stage shown in Fig. 4, the IPTT would be preferred to identify the flow curve.

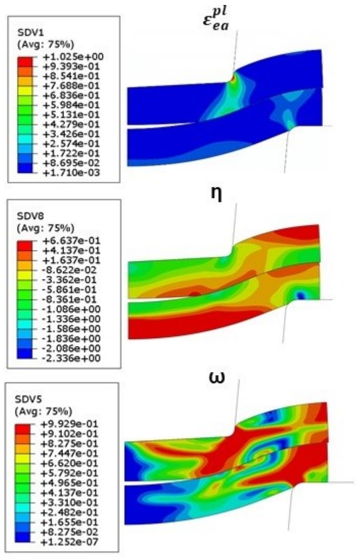

***Fig. 4**. Clinch forming: Stage I. Equivalent Plastic Strain (Upper), Triaxiality (Middle), Stress metric ω (Lower).*

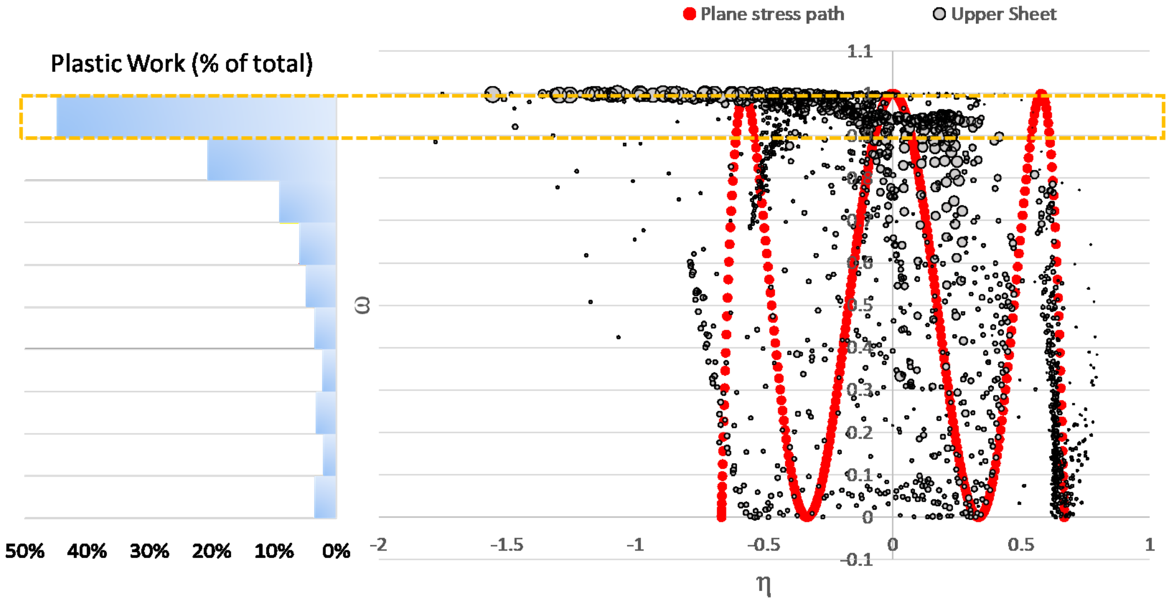

Fig. 5*. Stress state analysis clinch forming Stage I: Upper Sheet.*

4 Experimental validation

In this section, the aim is to validate the process-informed method selection presented in the previous section for clinch forming of similar sheet metal. The methodology is applied to clinch forming of two DC04 sheets with a nominal thickness of 1 mm.

4.1 Stress-state analysis

Figure 6 shows the equivalent plastic strain, the triaxiality η and the stress metric ω at the end of the joining process. The (ω-η)-diagrams associated with the upper and lower sheet are shown in Fig. 7 and 8, respectively. It can be seen that similar stress states occur in the upper and the lower sheet. Obviously, joining dissimilar materials will likely result in different (ω-η)-diagrams for the upper and the lower sheet. The latter would lead to the selection of different material tests for upper and lower sheet.

Assessment of the consumption of plastic work shows that more than 20% of the plastic work is associated with a pure axisymmetric stress state. Indeed, the stress states cluster around (η=-1.5, ω=0). Due to the punch indentation, the upper sheet consumes more shear-dominated plastic work than the lower sheet. Nevertheless, the dominating stress state in terms of plastic work in both sheets is axisymmetric in nature. As such, the stress state analysis suggests that, both sheets are preferably characterized using a material test, which induces an axisymmetric stress state (assuming symmetry between tension and compression) with η ≈ -1.5 and an equivalent plastic strain in the order of 2. Obviously, there is no sheet metal test available satisfying the latter conditions. From the considered material test in section 2, the SCT is the only axisymmetric test enabling to probe large plastic strains under a negative triaxialty (η=-1\3). As such, from the stress state analysis, it is expected that the SCT yields the most accurate result for simulating clinching forming of similar materials.

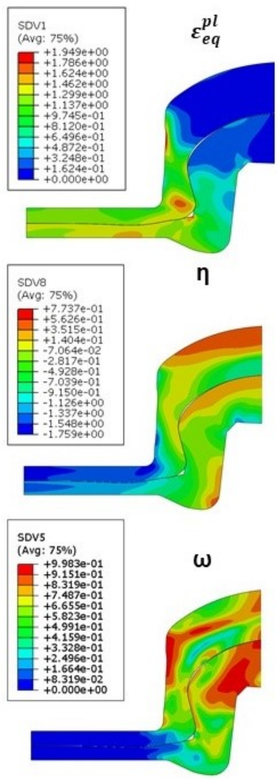

Fig. 6*. Clinch forming: Stage IV. Equivalent Plastic Strain (Upper), Triaxiality (Middle), Stress metric ω (Lower).*

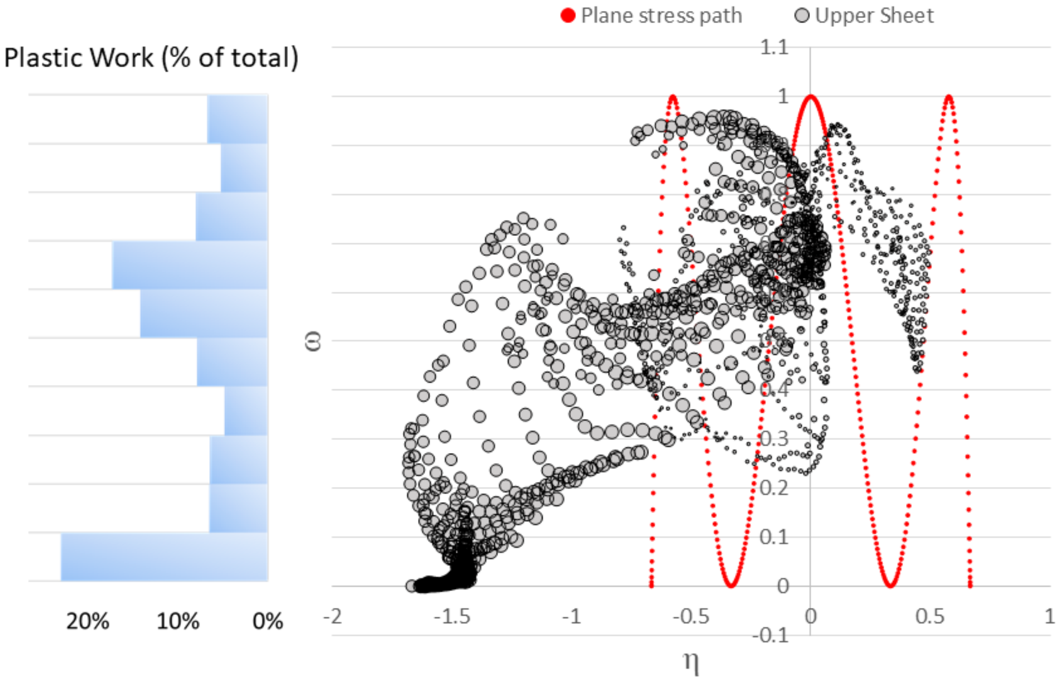

Fig. 7. *Stress state analysis clinching forming stage IV: Upper sheet.*

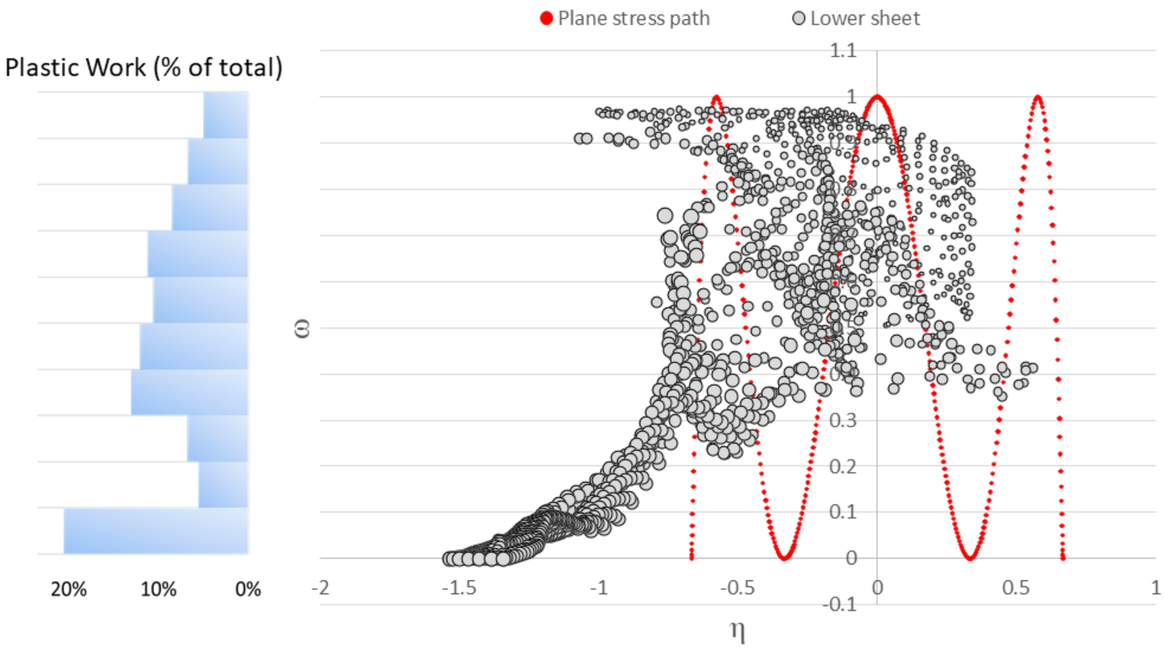

Fig. 8. *Stress state analysis clinching forming stage IV: Lower sheet.*

4.2 Metal flow

The flow curves shown in Fig. 1 are used to simulate clinch forming of two DC04 sheets. It is well-known that the strength of a clinched joint strongly depends on geometrical characteristics such as the interlock and neck thickness. Fig. 9 shows the numerically predicted contours of the cross-section along with the experimentally measured contours. It can be inferred that the predicted metal flow is not very sensitive with respect to the adopted strain hardening. This is not surprising since the metal flow is strongly constrained by the forming tools consisting here of a punch and a closed die.

4.3 Process graph

Besides the geometrical characteristics, the material state (stress and strain) after forming is important to accurately predict the strength of the joint. Unfortunately, the material state cannot be experimentally validated via full-field measurements as deformation is confined to the inside of the die. An indirect measurement of the material state can be obtained via the so-called process graph: punch force versus stroke. Since the process graph is a global response, it merely enables to validate material state predicted by the numerical simulation in an average sense. Fig. 10 shows the experimentally measured process graph during clinch joining. It can be inferred that the SCT very accurately reproduces the process graph. This observation supports the stress state analysis in section 3. The HBT, PNTE and IPTT-flow curves highly under estimate the joining force required indicating that the final material state is incorrect.

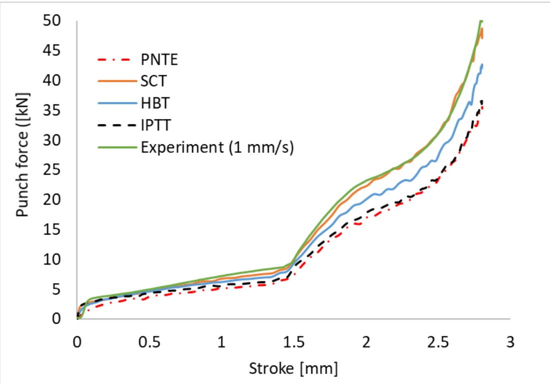

***Fig. 10.** Predicted and experimentally measured process graph.*

5 CONCLUSIONS

This paper deals with a process-informed methodology for selecting the most appropriate material test for identifying the large strain flow curve of sheet metal. It is proposed to perform a first order simulation used to feed the stress state analysis. The dominating stress state is assigned based on the consumption of plastic work. Finally, the result from the stress state analysis is used to select the most appropriate material test. The methodology is applied and validated to the problem of clinching forming.

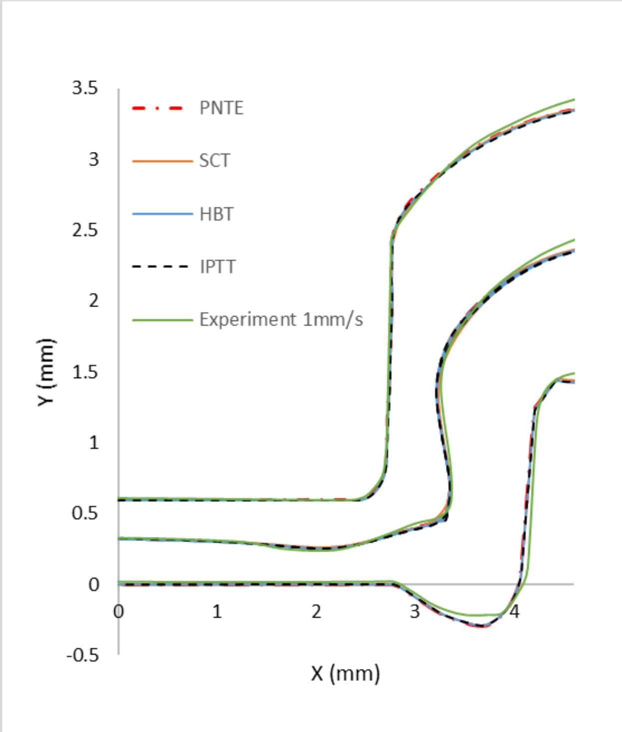

***Fig. 9.** Predicted and experimentally measured cross-section.*

6 ACKNOWLEDGEMENT

The presented results are part of the CORNET research project " Standardization of Flow Curve Determination for Joining by Forming" coordinated by European Research Association for Sheet Metal Working funded by the program for "Industrial Research" (IGF) of the Federal Ministry of Economics and Technology Germany and the Belgian government agency “Flanders Innovation & Entrepreneurship” (VLAIO).

REFERENCES

[1] Coppieters, S.: *Experimental and numerical study of clinched connection*, PhD thesis, KU Leuven, 2012.

[2] Coppieters S., Kuwabara T.: *Identification of post-Necking hardening phenomena in ductile sheet metal*. Exp. Mech. 54:1355-1371, 2014.

[3] Steglich D., Tian X., Bohlen J., Kuwabara T.: *Mechanical testing of thin sheet magnesium alloys in biaxial tension and uniaxial compression*. Exp. Mech. 54:1447-1258, 2014.

[4] ISO 16808:2014 : *Metallic materials –Sheet and strip – Determination of biaxial stress-strain curve of bulge test with optical measuring systems*

[5] Traphöner, H., Clausmeyer, T., Tekkaya, A. E.: *Material Characterization for Plane and Curved Sheets Using the In-Plane Torsion Test – An Overview*. Journal of Materials Processing Technology 257, pp. 278-287, 2018.

[6] Sekiguchi, C., Saito, M., Kuwabara, T.: *Measurement and analysis of the differential work hardening of ultra-low carbon steels.* Key Eng. Mater. 651-653: 552-557, 2015.

[7] Hakoyama T., Coppieters, S., Kuwabara, T.: *Effect of strain rate on determining post-necking work hardening of a low-carbon sheet steel.* NUMIFORM 2019, June 23-27, New Hampshire.

[8] Bai Y., Wierzbicki, T.: *A new model of metal plasticity and fracture with pressure and Lode dependence*. Int. J. Plas. 24:1071-1096, 2008.