Applicability of miniature tensile test in the automotive sector

P Konopík, P Farahnak, M Rund, J Džugan, and S Rzepa
1COMTES FHT a.s., Dobřany, Czech Republic, EU
2AGH University of Science and Technology, Kraków, Poland, EU
E-mail: pavel.konopik@comtesfht.cz

Abstract. The aim of this paper is to show the applicability of miniature tensile test (M-TT) for local properties determination on steel sheets for drawing and forming which are mostly used in automotive industry. Knowledge of local mechanical properties is a key factor for parts quality assurance. A comparison of the tensile test results from standard sized and miniature sized geometry has been done to assess the M-TT reliability. Various mechanical properties, such as the ultimate tensile and yield strengths the elongation, and reductions in area will be obtained. Moreover, thanks to advanced measurement techniques like digital image correlation with high resolution, strain hardening parameters and plastic strain ratio can be evaluated as well. Finally, flow stress curves are calibrated by inverse analysis in Abaqus FEM software.

1 Introduction
The tensile properties of materials, such as the ultimate tensile strength, yield strength, elongation and cross-sectional area, are very important factors for engineering design. In automotive industry, a group of cold-rolled steels for drawing and cold forming (DC01 – DC06) is widely used [1]. These steel grades have excellent formability, which facilitates cold forming operations, and are ideal for deep drawing. They are used for bending and deep drawing forming processes for applications where strength, rigidity and ductility are required.

There are guaranteed mechanical properties of delivered sheet which can be easily determined using standard tensile test. However, for the quality and reliability assessment of the final manufactured part, local properties can be crucial. The most critical are often sharp bending locations with small radiuses where residual formability and elongation can be near to the material limit.

On the other hand, due to lower friction than expected during cold forming, some areas can be deformed less than expected and thus, these locations could have lower strength. In comparison with [2], the recently-developed miniature tensile test (M-TT) is an excellent tool for local properties determination [3] or, in all cases, where only a limited amount of material is available [4-5].

The aim of this paper is to show the applicability of miniature tensile test for local properties determination on steel sheets for drawing and forming. For this purpose, standard and miniature tensile tests (M-TT) were performed in 3 orientations: 0°, 45° and 90°. Moreover, for thickness influence evaluation, miniaturized specimens were machined with several different thicknesses and material model using Abaqus FEM software will be created.
2 Testing method, M-TT

For local properties determination, miniature test pieces had to be used. The recently-developed miniature-tensile test (M-TT) technique was chosen for this purpose. The shape of the M-TT test pieces was initially derived from the small punch test (SPT). Small punch test specimens are discs 8 mm in diameter and 0.5 mm in thickness. SPT is used for determining the mechanical properties of in-service components because it only requires a very small amount of material. However, its drawback comes when interpreting the test readings, which must be converted by means of empirically-derived correlations to ordinary mechanical properties, such as yield and ultimate strength [6].

On the contrary, M-TT stress-strain curves are identical to standard ones [7], provided that several conditions are met. M-TT only requires small amounts of experimental material, and therefore enables local mechanical properties to be measured. To obtain consistent data, the test piece thickness must be $\geq 10 \times$ grain size [8]. When standard conditions [7] are met, such as accuracy of the measurement of force and extension and the required strain rate, M-TT data are identical to standard test data within a broad range of metals and their strength levels [9][10]. The initial test piece design (Figure 1a) was modified (Figure 1b) for current investigated material DC01. A modified M-TT specimen has a thickness of 0.5 mm and parallel length of 4.5 mm. M-TT is carried out using a special test device with high load cell sensitivity. Its linear motor runs smoothly at very slow speeds to fulfill all criteria given by the standard [7]. The test piece is clamped in special flat grips which have been developed for this purpose. The axial extension is captured with a high-speed CCD camera integrated into the system Mercury RT or ARAMIS™ that relies on digital image correlation (DIC). As the force and extension data are captured accurately, the record need not be specially processed and the evaluation can follow the standard procedure [7].

![Figure 1.](image)

Figure 1. Geometry of an M-TT test piece; (a) initial design, (b) modified geometry for testing ductile steel sheets

3 Experiment

The uniaxial tensile tests are performed on the specimen geometries with different thicknesses 0.2, 0.5 and 1.5 mm to investigate material behavior. Specimens were taken from DC01 steel sheet in three directions: longitudinal direction 0°, diagonal direction 45° and transverse direction 90°, related to the rolling direction.

Electro-mechanical testing system Mayes is used to conduct the uniaxial tests and Aramis™ system with 12 megapixel is utilized to monitor 2D strain fields with high resolution. Figure 2a illustrates the experimental setup and data acquisition rate is set at 100 Hz in testing system for clear visualizing the tensile behavior. It is noticeable that for all experiments initial lengths of extensometers are chosen 4 mm. Figure 2b represents engineering stress-strain curves of tensile tests for all considered specimens geometries in rolling direction (RD).
Figure 2. (a) Experimental setup, (b) engineering stress- strain curves for different thicknesses

4 Tensile test results

Tensile tests were evaluated based on the standard [7]. The measurement for the plastic strain ratio determination was performed with the use of continuous strain measurement by DIC system ARAMIS. Subsequently, r-values (i.e. plastic strain ratio) for the plastic strain range of 2-10 % were evaluated according to the standard [11].

Results of averaged values from three tests per conditions are shown in Table 1, where YS is Yield strength, UTS is Ultimate tensile strength, \( A_g \) is plastic extension at maximum force, A is plastic elongation of the gauge length after fracture (GL for standard geometry was 50 mm and for M-TT 4 mm), Z is maximum change in cross-sectional area and \( r_{2,10} \) is plastic strain ratio evaluated in the range of 2-10 % plastic deformation.

| Specimen              | YS  | UTS | \( A_g \) | A   | Z   | \( r_{2,10} \) |
|-----------------------|-----|-----|-----------|-----|-----|-----------------|
| Standard \(_0^\circ\_1,5\) | 195 | 309 | 25.4      | 44.6| 70.3| 2.11            |
| M-TT \(_45^\circ\_0,2\) | 176 | 272 | 16.8      | 31.7| 50.8| 1.21            |
| M-TT \(_45^\circ\_0,5\) | 184 | 315 | 22.3      | 44.4| 77.7| 1.22            |
| M-TT \(_90^\circ\_0,2\) | 150 | 231 | 17.9      | 36  | 53.7| 2.16            |
| M-TT \(_90^\circ\_0,5\) | 166 | 298 | 23.9      | 54  | 87.2| 2.28            |
| M-TT \(_90^\circ\_1,5\) | 170 | 287 | 26        | 59.8| 84.2| 2.31            |
| Standard \(_90^\circ\_1,5\) | 196 | 304 | 24.2      | 48.1| 71.4| 2.45            |

The evaluation of strain hardening parameters was carried out based on Hollomons equation (1):
\[ \sigma = K \varepsilon^n \]  

where \( \sigma \) is the stress, \( K \) is the strength index or strength coefficient, \( \varepsilon \) is the plastic strain and \( n \) is the strain hardening exponent. In equation (1), the power law relationship between the stress and the amount of plastic strain is used. The fitting range considered for the Hollomons law parameters is between 2-10% of the plastic strain. Results are summarized in Figure 3.

**Figure 3.** (a) Strain hardening exponent, (b) Strength coefficient

5 Abaqus FEM simulation

Abaqus FEM software is utilized for numerical simulation with conventional plasticity \([12]\) based on von Mises material model. Flow curves are calibrated through inverse analysis by comparing experimental and numerical force-displacement curves and are depicted in Figure 4. For all simulations, 3D elements are used (C3D8R according to Abaqus element library) and mesh size is chosen 0.06 mm between the extensometer points and 0.15 mm for surrounding area. Moreover, 5 elements are assigned along the thickness. As it can be seen in Figure 4a, 4b and 4c, numerical simulations are in close agreement with experimental data measured in rolling direction. For measuring Lankford ratios, Gauge sections are defined in transversal direction as well as axial direction. Three experiments are performed on specimens in rolling, diagonal and transverse directions. GOM Aramis\textsuperscript{TM} captures 2D displacement fields during deformation, e.g., axial and transversal extensometers, provides engineering surface strains which are then transformed into true values. Finally, thickness strain is measured based on incompressibility condition. Lankford ratio (plastic strain ratio) can be calculated from average slope of the true plastic width \( (\varepsilon_{w}^p) \) and thickness \( (\varepsilon_{rh}^p) \) strain based on equation (2) for the specific range of equivalent plastic strain \( (\varepsilon_{p}) \) and are indicated in figure 4d.

\[ r = \frac{d\varepsilon_{w}^p}{d\varepsilon_{rh}^p} \quad \text{while} \quad 0.1 \leq \varepsilon_{p} \leq 0.2 \]  

(2)
Figure 4. Engineering stress-strain curves for different thicknesses (a). for thickness 0.2 mm, (b). for thickness 0.5 mm, (c). for thickness 1.5 mm, (d). Lankford ratios

6 Results discussion
Overall, the agreement ranged from acceptable results to excellent results. The biggest differences were seen in the stress-strain curves obtained from M-TT 0.2 mm in thickness for all rolling directions, where the most significant deviation was measured in respect of UTS and corresponding C values. This can have several causes. Firstly, machining and handling of a specimen 0.2 mm thick is challenging and surface finish could possibly have a big influence. Furthermore, the specimens were taken from the middle part of the sheet where the material can be softer than material near to the surface.

However, this study indicated that values of plastic strain ratio are not dependent on specimen thickness. Trends obtained here for this parameter are in agreement with those published in [13-15].

7 Conclusions
The paper presented here successfully shows the possibility of metal sheet characterization for forming processes with the use of miniaturized tensile specimens. Generally, very good agreement was found for all considered parameters and conditions between the results attained with the use of standard and M-TT specimens. FEM simulation in Abaqus software demonstrated that data obtained from M-TT can be easily used as input data for all software requiring reliable stress – strain data and thus, local properties can be taken into count for part quality assurance.
Acknowledgements
This paper was created by project No: TH02010544, financed by the TA ČR and project No.: LO1412 - Development of West-Bohemian Centre of Materials and Metallurgy, financed by the MEYES of the Czech Republic.

References
[1] ArcelorMittal, Extract from the product catalogue, 2018, [online] https://automotive.arcelormittal.com/saturnus/sheets/ArcelorMittal%20Automotive%20product%20offer%20EN.pdf
[2] Janoušek J and Balda M 2014 Strain gage measurements for accurate yield point determination, Applied Mechanics and Materials 486, pp. 123-128
[3] Jirková J, Rubešová K, Konopík P and Opatová K 2018 Effect of the Parameters of Semi-Solid Processing on the Elimination of Sharp-Edged Primary Chromium Carbides from Tool Steel, Metals - Open Access Metallurgy Journal 8(9):713
[4] Dzugan J, Prochazka R and Konopik P 2017 Low cycle fatigue tests with the use of miniaturized test specimens, ASME Pressure Vessels and Piping Conference, Location: Waikoloa, HI, Date: JUL 16-20, 2017, Article Number: UNSP V01AT01A072
[5] Dzugan J, Prochazka R and Konopik P 2015 Micro-Tensile Test Technique Development and Application to Mechanical Property Determination, 6th ASTM International Symposium on Small Specimen Test Techniques Location: Houston, Date: JAN 29-31, 2014, Volume: 1576, Pages: 12-30
[6] Dobes F and Dymacek P 2016 Fracture-based correlation of uniaxial and small punch creep data Theoretical and Applied Fracture Mechanics, Part: A, 86, 34-38, DOI: 10.1016/j.tafmec.2016.08.020
[7] ISO 6892-1:2016: Metallic materials -- Tensile testing -- Part 1: Method of test at room temperature, 2016
[8] Kumar K, Madhusoodanan K and Rupani, B. B. 2006 Miniature Specimen Technique as an NDT Tool for Estimation of Service Life of Operating Pressure Equipment., International Conference & Exhibition on Pressure Vessel and Piping, Chennai, India, 7-9 February 2006; 92-102
[9] Rund M, Procházka R, Konopik P, Džugan J and Folgar H 2015 Investigation of Sample-size Influence on Tensile Test Results at Different Strain Rate. Procedia Engineering, 114, 410-415, https://doi.org/10.1016/j.proeng.2015.08.086
[10] Prochazka R, Dzugan J, Konopik P and Rund M 2018 Investigation of high-strength stainless steel using small specimen test techniques - tensile and fatigue properties, 7th International Conference on Mechanics and Materials in Design (M2D), Albufeira, Portugal, 11-15 June 2017; Eds. Gomes, J.F.S.; Meguid, S.A.; INEGI/FEUP: 2017; Paper ref. 6841, 343-354
[11] ISO 10113:2006: Metallic materials Sheet and strip determination of plastic strain ratio
[12] Farahnak P, Azinpour E, Belinha J and Cesar de Sa J 2016 The numerical non-linear analysis of elasto-plastic materials using the radial point interpolation method International book of Material Modelling: Applications, Challenges and Research ISBN: 978-1-53612-161-2.
[13] Gavrus A and Francillette H 2011 An Anisotropic Behaviour Analysis of AA2024 Aluminium Alloy Undergoing Large Plastic Deformations Aluminium Alloys, Theory and Applications, ISBN 978-953-307-244-9.
[14] Ramos G, Stout M, Bolmaro R E, Signorelli J W and Turner P 2010 Study of a drawing-quality sheet steel. I: Stress/strain behaviors and Lankford coefficients by experiments and micromechanical simulations, International Journal of Solids and Structures Volume 47, Issue 17, 15 Pages 2285-2293.
[15] Huh J, Huh H, Lee C S 2013 Effect of strain rate on plastic anisotropy of advanced high strength steel sheets, International Journal of Plasticity, Volume: 44, Pages: 23-46, 2013, DOI: 10.1016/j.ijplas.2012.11.012