Mini-tensile specimen application for sheets characterization

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Abstract. There are many cases when there is a shortage of the experimental material for detailed analysis and then small size specimens techniques becomes essential. The current paper deals with investigations of mini-tensile tests (MTT) application to metal sheets characterization. In the case of metal sheets assessment the most common are tensile tests for Lankford parameters and strain hardening determination. As most of the processes are not quasi-static and constant strain rate processes, thus assessment of strain rate hardening is also crucial part of the characterization. Previously developed and verified testing procedure of M-TTs for bulk materials is applied here for steel sheet made of DC01 characterization. Tests under quasi-static and dynamic loading conditions are carried out in order to describe above mentioned properties at room temperature. Accurate strain measurement is carried out with digital image correlation systems and results obtained with M-TTs are going to be confronted with standard size specimens’ results.

1 Introduction

Metal sheet forming is multifarious process producing components with very complex shapes within very narrow tolerance bounds. In order to achieve desired component shapes, detailed FEM analyses are carried out in order to assure the proposed production process stability and components good quality. Critical component of the FEM simulation are input material characteristics that together with appropriate material model represent the material behaviour in the course of the processing. Metal sheets exhibit certain peculiarities in comparison to bulk materials, due to crystallographic structure and the characteristics of the rolling process sheet metals usually exhibit a certain degree of mechanical properties anisotropy. The properties variation has to be described together with, strain hardening and strain rate sensitivity for precise material behaviour description. There are standard procedures available for these parameters determination that have been used for a many years yet. The current paper shows possibility of determination of all considered properties with the use of miniaturized tensile specimens.

The performance of mini-tensile tests (MTT) for bulk materials characterisation has been successfully shown in [1-6]. The advantage of MTT are very low requirements on the experimental material volume and possibility of local properties determination, even from real components for the local properties determination. Moreover M-TT can be effectively applied for FEM models verification, e.g. by evaluation of local ductility of sheet in the processed component that can be confronted with FEM model prediction for the same location. Additionally, as the forming processes are usually not performed at constant strain rates over whole component, the strain rate sensitivity has to be covered over a wide range of strain rates, from the slowest up to dynamic ones. M-TT allows effectively asses even high strain rate properties with most of the usual testing machines. This is achieved thanks to its small gauge length (3mm) allowing reaching strain rates in
the order of several hundreds on testing systems with the actuator velocity of about 1 m/s, which is not some extremely sophisticated and thus expensive high strain rate testing machine. Determination of anisotropy, strain-hardening and strain rate sensitivity is presented in this paper for DC01 sheet of thickness 1.5 mm. Strain during all tests are measured with the use of digital image correlation system. Standard size specimens are used for anisotropy and strain hardening determination under a quasi-static loading conditions, where they are compared with MTT results. Strain rate dependency of the parameters consider here are further determined with MTT only.

2 Tensile tests
Tensile tests were performed on flat samples made of steel sheet DC01. The original sheet thickness was 1.5 mm. Standard size specimens with thickness of 1.5 mm and the geometry according to figure 1 were milled as a stock of 10 specimens. M-TT specimens with the geometry according to figure 2 were machined from the middle part of the sheet thickness by spark eroding of the specimen silhouette and grinding to the final thickness. Standard specimens’ orientations were considered for both specimen geometries: longitudinal in rolling direction the 45° and 90°from rolling direction. Testing was carried out with the use of servo-hydraulic testing system MTS with capacity of 25 kN and the actuator velocity up to 1.1 m/s for standard sized specimens. MTT specimens were tested on small size testing system with linear drive with the load capacity of 5kN and maximum actuator velocity of 0.3 m/s. All tests were executed at room temperature and the strain measurement was done with the use of ARAMIS Digital Image Correlation system (DIC). Three specimens per condition were tested for all considered cases.

Figure 1. Standard tensile test specimen geometry. Figure 2. M-TT Specimen geometry.

Quasi-static tensile test were carried out for both specimens geometries and all sampling directions for comparison of the results obtained from standard size and M-TT specimens. On the basis of these tests strain hardening and plastic strain ratio were subsequently evaluated. The strain rate sensitivity determination was determined with the M-TT specimens only. Specimens designation consists of specimen geometry (MTT), specimen orientation and the strain rate. In the case of standard tensile specimens only two latter mentioned parameters are used for designation. Tensile curves obtained for all tested conditions are shown in figure 3-figure 5 and tensile tests results are summarized in table 1, where averaged values from three tests per conditions are shown.
Figure 3. Tensile curves of both specimen geometries in longitudinal direction.

Figure 4. Tensile curves of both specimen geometries 45° orientation.

Figure 5. Tensile curves of both specimen geometries 90° orientation.

Table 1. Summary of tensile tests results.

| Sample geometry | ε (s⁻¹) | Angle (°) | YS (MPa) | UTS (MPa) | A50 (%) |
|-----------------|---------|-----------|----------|-----------|---------|
| Standard        | 0,001   | 0         | 189,3    | 297,2     | 42,1    |
| MTT             | 0,001   | 0         | 197,4    | 304,4     | 46,7    |
| MTT             | 0,01    | 0         | 219,8    | 316,9     | 42,8    |
| MTT             | 0,1     | 0         | 229,9    | 326,0     | 45,9    |
| Standard        | 0,001   | 45        | 199,8    | 310,8     | 42,3    |
| MTT             | 0,001   | 45        | 199,9    | 312,8     | 43,2    |
| MTT             | 0,01    | 45        | 217,4    | 324,6     | 42,6    |
| MTT             | 0,1     | 45        | 226,9    | 334,2     | 45,6    |
| Standard        | 0,001   | 90        | 190,2    | 292,7     | 45,4    |
| MTT             | 0,001   | 90        | 185,8    | 292,2     | 43,8    |
| MTT             | 0,01    | 90        | 211,5    | 314,8     | 48,0    |
| MTT             | 0,1     | 90        | 220,5    | 321,8     | 45,9    |

Where:
- ε Strain rate (s⁻¹)
- YS Yield strength (MPa)
- UTS Ultimate strength (MPa)
- A50 Elongation for initial length 50mm
3 Strain hardening

The evaluation of strain hardening parameters was carried out based on Hollomon's equation (1) where the power law relationship between the stress and the amount of plastic strain is used.

$$\sigma = C \cdot \varepsilon^n$$  \hspace{1cm} (1)

The fitting range considered for the Hollomon's law parameters is between 2-5% of the plastic strain. The example of the evaluation is shown in figure 6. Results are summarized in the figure 7-figure 9.

![Figure 6. Example of Hollomon's law parameters fitting.](image)

![Figure 7. Strain hardening parameters - longitudinal.](image)

![Figure 8. Strain hardening parameters - 45° orientation.](image)

![Figure 9. Strain hardening parameters - 90° orientation.](image)

4 Strain rate sensitivity

The strain rate sensitivity of yield stress and ultimate tensile strength was determined within the range of 0.001 up to 0.1 s\(^{-1}\) for all considered specimens orientations with the use of MTT only. The evaluated strain rate sensitivity of yield stress and ultimate tensile stress are summarized for specific specimen orientations in figure 10-figure 12.
5 Plastic strain ratio
The plastic strain ratio is one of the key parameters in the metal sheet forming [7-11]. The measurement for the plastic strain ratio determination was done with the use of continuous strain measurement by DIC system ARAMIS. The plastic strain ratio was determined from the measured data with the use of equation (2), where \( m_r \) is determined from the linear regression fit between the lower limit (2% plastic strain) and the upper limit (5% plastic strain) through the origin [12].

\[
r' = \frac{-m_r}{1 + m_r} \tag{2}
\]

![Figure 13. Example of plastic strain determination.](image)

Longitudinal (\( \varepsilon_L \)) and transversal (\( \varepsilon_B \)) true plastic strains are calculated according to equations (3) and (4) [12].

\[
\varepsilon_L = \ln \left[ \frac{l_0 - \Delta L}{l_0} - \frac{F}{S_0 m_L} \right] \tag{3}
\]
\[ \varepsilon_b = \ln \left( \frac{b_0 - \Delta b + \frac{b_0 \cdot v \cdot F}{S_0 \cdot m_E}}{b_0} \right) \]  

where:
- \( L_e \) Extensometer gauge length \( \text{mm} \)
- \( b_0 \) Original gauge width \( \text{mm} \)
- \( \Delta L \) Instantaneous elongation/extension of the measurement base \( \text{mm} \)
- \( \Delta b \) Instantaneous width elongation \( \text{mm} \)
- \( F \) Force \( \text{N} \)
- \( S_0 \) Original cross-section area \( \text{mm}^2 \)
- \( \nu \) Poisson constant
- \( m_E \) Young modulus \( \text{MPa} \)

**Figure 14.** Plastic strain ratio for considered orientations.

### 6 Conclusions
The paper presented here is dealing with mechanical characteristics determination of sheet materials. Namely strain hardening, strain rate sensitivity and plastic strain ratio for 1.5 mm thick steel sheet made of DC01 were assessed. The properties assessment was done on the basis of the miniaturized tensile tests and standard tests. Results of the MTT specimens are compared with standard size specimens for longitudinal, 45° and 90° sampling orientations. The assessment was done at room temperature. In the case of the strain rate sensitivity MTT specimens were used only.

Obtained tensile tests parameters exhibit excellent agreement between values measured with MTT and standard size specimens for all considered sampling directions. This finding confirms previous results in [1-6].

Strain hardening coefficients assessment points out excellent agreement within a few MPa between C coefficients of MTT and standard sized specimens for all considered sampling directions. In the case of the \( n \) parameter, difference of about 0.02 can be found for the longitudinal direction, while the other directions values agree together very well.

The strain rate sensitivity was evaluated with the application of MTT specimens only. Clear consistent trends were achieved for all three directions investigated. The strain rate sensitivity of the ultimate tensile strength was similar for all considered directions. The trend in the case of yield stress is not uniform across the directions investigated. The longitudinal and 90° directions exhibit very similar strain rate hardening behaviour, while the 45° direction yields slightly lower strain rate hardening, however differences are rather small.

Determination of the plastic strain ratio with the use of both specimens geometries points very good agreement between MTT and standard samples for longitudinal and 90° directions. Trends obtained here for this parameter are in agreement with those published in [8-10]. Slightly bigger discrepancy can be found for 45° direction. Investigation of the plastic strain ratio dependency on strain rate shows its increase with increasing velocity as can be expected. The measurement with
MTT specimens for 90° orientation and strain rate 0.01 s\(^{-1}\) yields rather outlying value. This point was scrutinized, but there was not found any error in the measurement of evaluation and thus it was kept among the results population and was not discarded.

The paper presented here successfully shows possibility of the metal sheet characterisation for forming processes with the use of miniaturize tensile specimens. Generally, very good agreement was found for all considered parameters and conditions between the results attained with the use of standard specimens and MTT. Slight discrepancies between results from MTT and standard size specimens can be assigned to sampling location of the MTT specimens in the middle of the sheet thickness, where small material behaviour deviation from near surface properties can be expected. Further investigations are planned to assess the influence of the MTT specimen localisation within the sheet thickness.

Miniaturized tensile specimens offer very powerful tool for local properties assessment that can be used either for material basic characterisation or as input data for FEM simulations.

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