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# Application of micro-tensile test for material characterization of mild steel DC01

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**Abstract:** During recent years, material characterization based on miniature tensile specimens has been investigated extensively. The Small Punch Test (SPT) is often used for determination of tensile properties but alternative miniature tensile specimen geometries have been suggested due to the limitations of the SPT specimen geometry. However, compared to SPT, the Micro-Tensile Test (M-TT) has a significant advantage since it does not need previous established correlations and enables direct results conversion into standard terms. In this paper, the applicability of the M-TT is investigated for material characterization including Lankford coefficients, hardening laws and stress-strain curves. For this purpose, mild steel DC01 M-TT samples were extracted from sheet in Rolling, Transverse and Diagonal Directions. Moreover, M-TT samples were machined to achieve different thicknesses for indicating thickness effects on strain path.

**Keywords:** Small Punch Test; Micro-Tensile Test; digital image correlation (DIC); Lankford coefficients; DC01 steel

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## 1. Introduction

A substantial effort is currently devoted to the development of small specimens and corresponding test techniques from which useful information can be derived. A number of techniques have been developed to extract mechanical properties from sub-sized specimens [1-4]. These include specimens that are either miniaturized versions of their full-scale counterparts or specifically designed discs or coupon specimens of small dimensions. One of the most used methods is the Small Punch Test (SPT). SPT is widely used, but its application is traditionally bound with necessity of known correlation parameters valid for a specific material only and thus it is impossible to use it on a blind material [5]. Recently, there are assumptions to used trained neural networks for SPT evaluation [6] but again, neural networks can be trained for some material group but they are not generally valid.

Based on the SPT disc, which is typically 8 mm in diameter and 0.5 mm in thickness, a new specimen geometry for developing the testing procedure was suggested [7]. The target was to run a real tensile test, free of any necessary correlations, on specimens using the same material volume as SPT. After initial finite element modelling (FEM) calculations, a specimen with a thickness of 0.5 mm, width of 1.5 mm and parallel length of 3 mm was suggested. The newly proposed specimen size was very small in comparison to standard size or sub-size specimens and thus the new testing procedure was named the Micro-Tensile Test (M-TT).

The specimen did not fit into any kind of testing fixtures and thus the next step was to develop a new set of testing fixtures. Initially, a very simple test set up was used for the first M-TT trials and an actuator LVDT was used for strain measurement. The first results were very promising, since the stress levels obtained at M-TT were very close to those obtained for standard size specimens. A further step was then improvement of the strain measurement. Due to the miniature specimen size, it was not possible to attach a standard extensometer directly on the test piece. Alternatively, the extensometer was attached to the grips. At this stage, it was just slightly improved crosshead measurement. The obtained curves were very similar to the curves obtained for standard size samples, except the yielding part of the curve.

In the last stage of the testing procedure was the development of the strain measurement for M-TT, where Digital Image Correlation (DIC) system ARAMIS was used. The principle of the DIC method is based on the recognition of change in the sequence of images. A stochastic pattern is applied on the surface of the specimen prior to testing. The test itself is recorded by one (2D in-plane deflection measurement) or two (3D) cameras. Under the applied load, the specimen is deformed and so is the applied pattern. Comparing the images, changes in the pattern are registered and displacements and strains are calculated. Systems based on this method enable 3D strains measurements of either testing samples or real components to be recorded. Distribution of major or minor strain can be depicted in color maps (see Figure 1) but for M-TT, DIC was used as a very precise video extensometer.

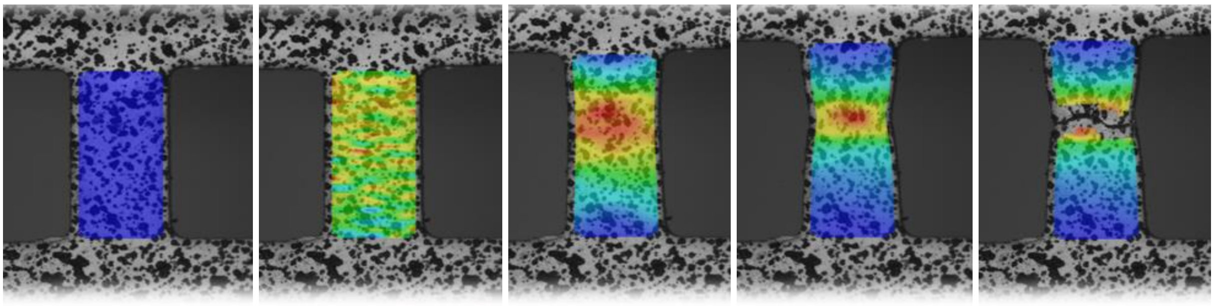


**Figure 1.** Color map of major strain of M-TT sample.

Tests were carried out on several various materials with a wide range of tensile properties. Namely, Al-alloy, Ni-alloy, Titanium Gr. 5, and several steels were compared while tested on standard size specimens and with the use of M-TT. Standard size samples were cylindrical with diameters ranging from 5 to 10mm. The resulting curves of these tests were almost identical and there can be found excellent agreement for all materials investigated between standard size specimens and M-TTs for a whole range of strength levels from about 250MPa up to 1250MPa [8].

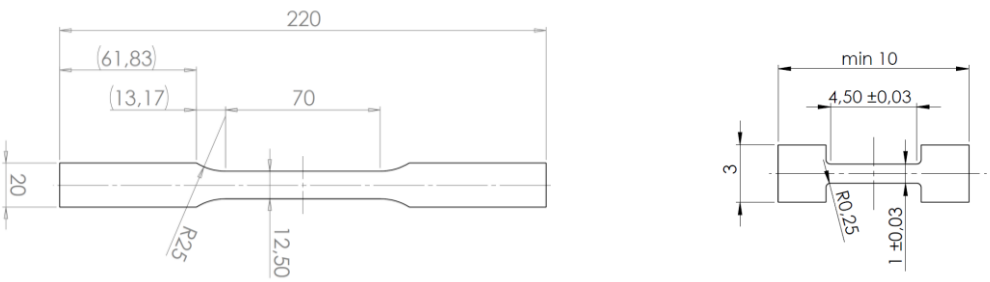
Nowadays, M-TT is used for a wide range of applications (in addition to the standard tensile properties already mentioned):

- Local mechanical properties of steel weld [9]
- Tensile properties for high temperature (hot M-TT) [10]
- Strain rate sensitivity [11]
- High and low cycle fatigue [12–14]

In this paper, the application of M-TT for determination of Lankford coefficients and strain hardening determination is investigated. These parameters are crucial as input data for any reliable material model represent the material behaviour in the course of the processing. To demonstrate usability of the M-TT for the above mentioned purpose, metal sheet DC01was chosen as a very well known and widely used material for metal sheet forming. Metal sheets exhibit certain peculiarities in comparison to bulk materials, due to their crystallographic structure and the characteristics of the rolling process where sheet metals usually exhibit a certain degree of mechanical properties anisotropy. The properties variation has to be described together with strain hardening for precise material behaviour description. 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. During the sampling from components with very complex shapes, the M-TT specimen can be expected to obtain lower thickness than is initially used in sheet. Therefore, M-TT was machined to achieve different thicknesses for indicating thickness effects on strain path.

## 2. Standard and M-TT tests

Tensile tests were performed on flat samples made of DC01steel sheet according to standards [15,16]. The original sheet thickness was 1.5 mm. Standard size specimens with a thickness of 1.5 mm and the geometry according to Figure 2a were milled as a stock of 10 specimens. M-TT specimens, with the geometry according to Figure 2b and thicknesses of 0.2 mm and 0.5 mm, were machined from the middle part of the sheet by spark eroding of the specimen silhouette and grinding to the final thickness. M-TTs specimens with a thickness 1.5 mm were not grinded at all.




(**a**) (**b**)

**Figure 2.** Tensile test specimen geometry: (**a**) Standard geometry; (**b**) M-TT geometry.

Standard specimen orientations were considered for both specimen geometries: longitudinal direction 0°, diagonal direction 45° and transverse direction 90°, related to the rolling direction. Testing was carried out with the use of the MTS servo-hydraulic testing system with the capacity of 25 kN for standard sized specimens. M-TT specimens were tested on a small size testing system with a linear drive with the load capacity of 5 kN. All tests were executed at room temperature and the strain measurement was achieved with the use of a Mercury RT Digital Image Correlation system (DIC). Three specimens per condition were tested for all considered cases. Quasi-static tensile tests were carried out for both specimen 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. Specimen designation consists of specimen geometry (Standard or M-TT), specimen orientation and the specimen thickness in mm. Representative tensile curves obtained for all tested conditions are shown in Figures 3-5.

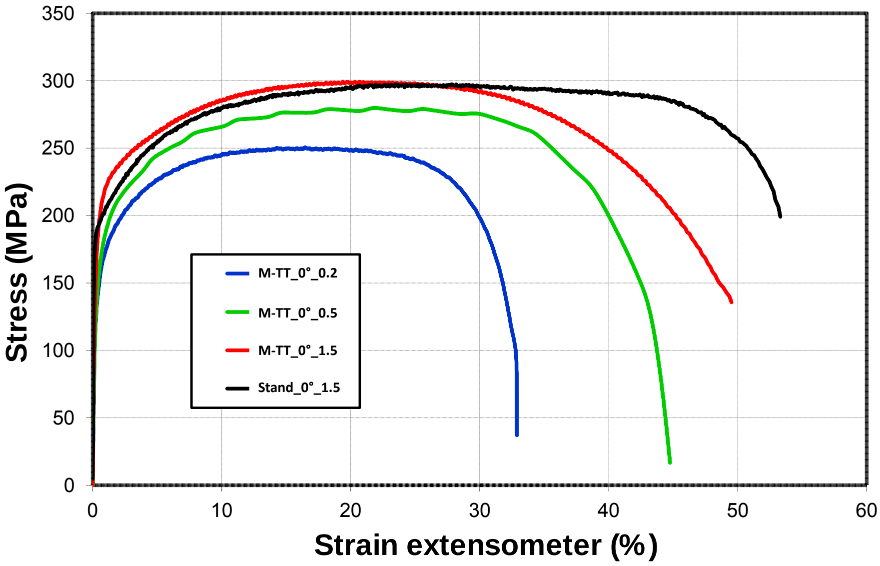



**Figure 3.** Tensile curves of both specimen geometries in longitudinal direction.

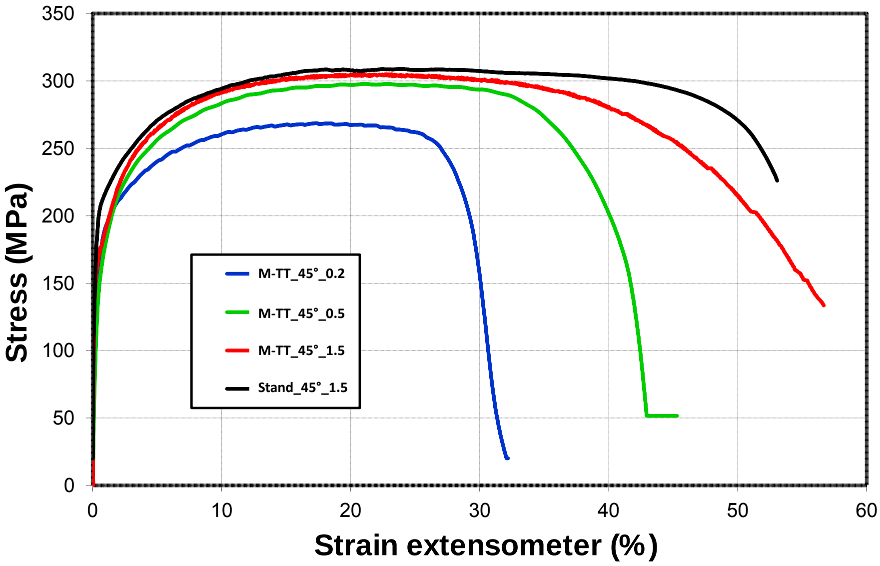



**Figure 4.** Tensile curves of both specimen geometries in diagonal orientation.

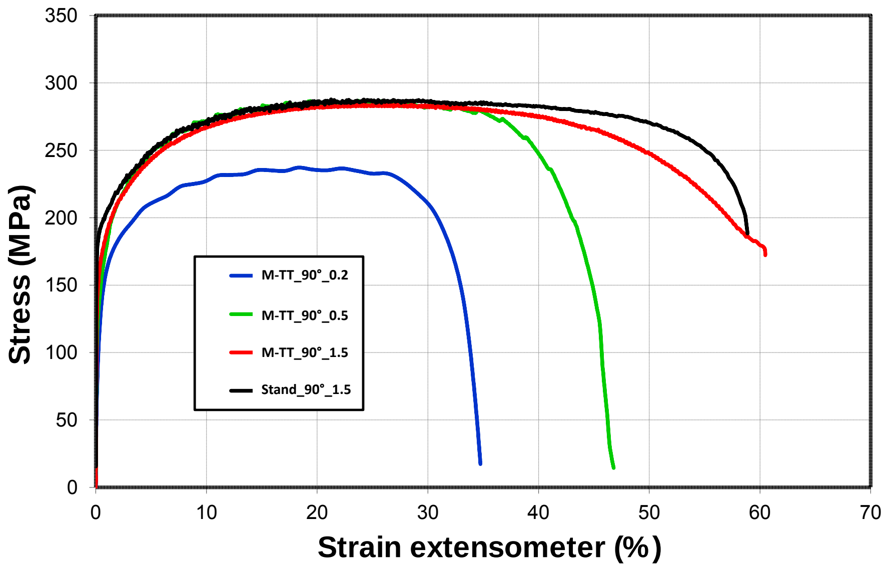


**Figure 5.** Tensile curves of both specimen geometries in transversal orientation.

## 3. Evaluation and Results

### *3.1. Tensile test*

Tensile tests were evaluated based on ISO 6892-1 standard [15]. 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 permanent elongation of the gauge length after fracture (GL for standard geometry was 50 mm and for M-TT 4 mm) and Z is maximum change in cross-sectional area.

**Table 1.** Summary of tensile tests results.

| Specimen | YS MPa | UTS MPa | $A_g$ % | A % | Z % |
|---|---|---|---|---|---|
| M-TT_0°_0.2 | 151.4 | 238.8 | 15.8 | 34.8 | 58.4 |
| M-TT_0°_0.5 | 179.8 | 283.7 | 17.9 | 50.2 | 78.2 |
| M-TT_0°_1.5 | 182.0 | 292.1 | 20.9 | 56.6 | 81.6 |
| Standard_0°_1.5 | 189.3 | 297.2 | 24.2 | 42.1 | 65.7 |
| M-TT_45°_0.2 | 172.2 | 269.7 | 16.8 | 32.0 | 51.8 |
| M-TT_45°_0.5 | 178.6 | 302.8 | 21.2 | 41.9 | 72.6 |
| M-TT_45°_1.5 | 192.1 | 303.5 | 21.7 | 58.2 | 85.6 |
| Standard_45°_1.5 | 199.8 | 310.8 | 23.2 | 42.3 | 41.8 |
| M-TT_90°_0.2 | 147.5 | 228.4 | 17.9 | 36.4 | 54.8 |
| M-TT_90°_0.5 | 161.1 | 287.0 | 22.8 | 50.9 | 81.5 |
| M-TT_90°_1.5 | 166.9 | 284.1 | 26.0 | 60.4 | 85.9 |
| Standard_90°_1.5 | 190.2 | 292.7 | 23.0 | 45.4 | 66.7 |

*3.2. Strain hardening*

The evaluation of strain hardening parameters was carried out based on Hollomons equation 1:

$$\sigma = C.\varepsilon^{n}. \qquad (1)$$

Where 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-$A_g$ percent of the plastic strain. The example of the evaluation is shown in Figure 6. Results are summarized in Figures 7-8.

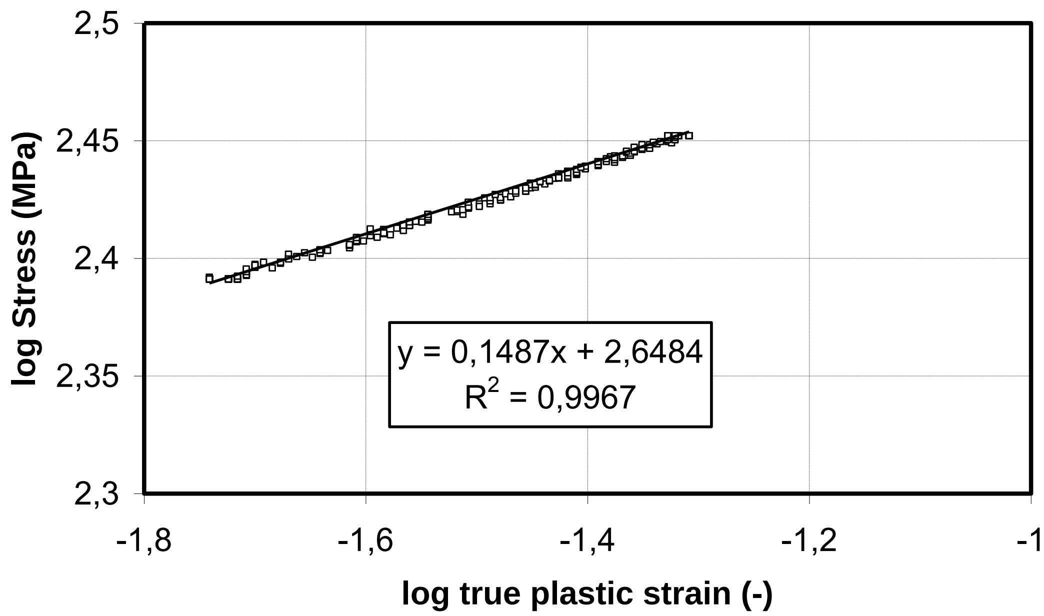



**Figure 6.** Example of Hollomons law parameters fitting.

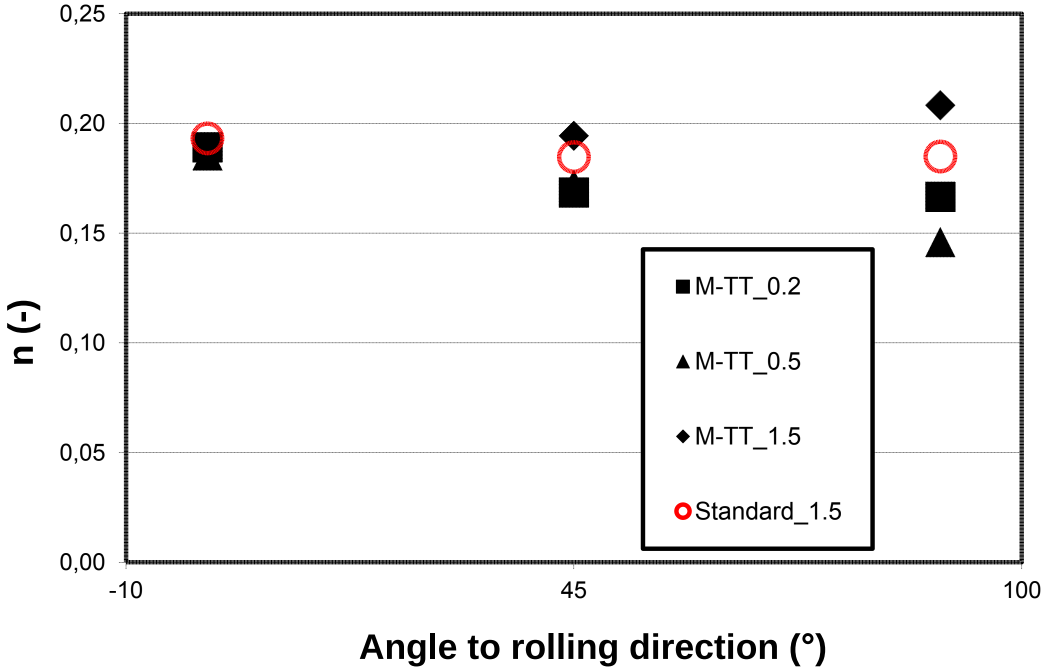



**Figure 7.** Strain hardening exponent.

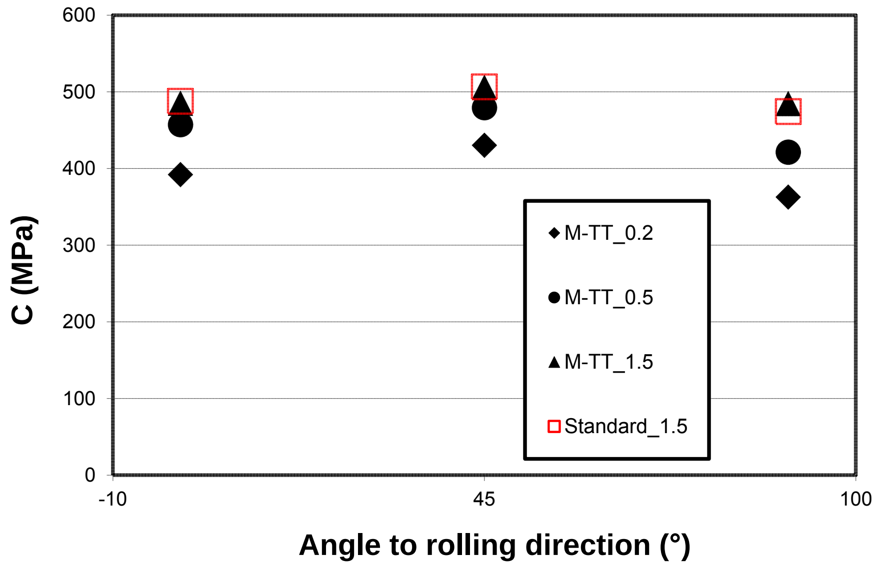



**Figure 8.** Strength coefficient.

*3.3. Plastic strain ratio - Lankford coefficients*

Lankford coefficients are one of the key parameters in the metal sheet forming process [17-21]. The measurement for the plastic strain ratio determination was performed 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:

$$r = \frac{-m_r}{1 + m_r} \quad (2)$$

Where $m_r$ is determined from the linear regression fit between the lower limit (2%plastic strain) and the upper limit ($A_g$ value) through the origin [16].

Longitudinal ($\varepsilon_l$) and transverse ($\varepsilon_b$) true plastic strains are calculated according to equations 3 and 4:

$$\varepsilon_l = ln\left[\frac{L_e - \Delta L}{L_e} - \frac{F}{S_0 . m_E}\right] \quad (3)$$

$$\varepsilon_b = ln\left[\frac{b_0 - \Delta b + \frac{b_0 . \upsilon . F}{S_0 . m_E}}{b_0}\right] \quad (4)$$

Where:

| | | |
|---|---|---|
| $L_e$ | Extensometer gauge length | mm |
| $b_0$ | Original gauge width | mm |
| $\Delta L$ | Instantaneous elongation/ extension of the measurement base | mm |
| $\Delta b$ | Instantaneous width elongation | mm |
| $F$ | Force | N |
| $S_0$ | Original cross-section area | $mm^2$ |
| $\upsilon$ | Poisson constant | - |
| $m_E$ | Young modulus | MPa |

Results are summarized in Figure 9.

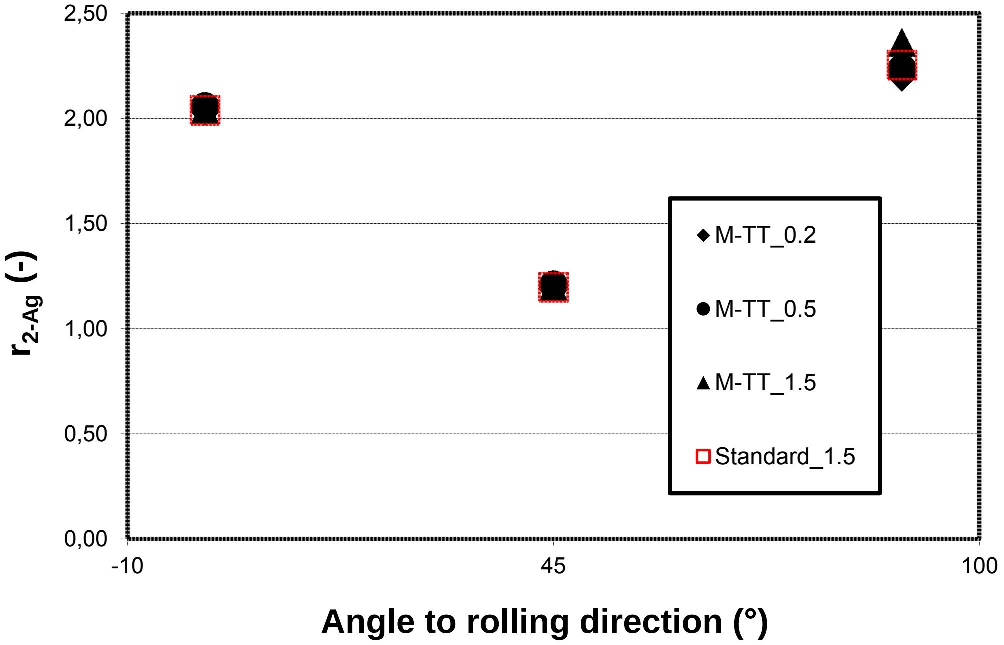



**Figure 9.** Plastic strain ratio for considered orientations.

## 4. Discussion

The results of the M-TT specimens were compared with standard size specimens for 0°, 45° and 90° sampling orientations. The investigation was performed at room temperature. The following parameters were compared: tensile technological parameters (YS, UTS, Ag, A, Z), strain hardening and plastic strain ratio. 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, where the most significant deviation was measured in respect of UTS and corresponding C values. This can have several causes. Firstly, machining and handling with 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. On the other hand, excellent results were obtained for plastic strain ration for all tested M-TT thicknesses and all directions. Trends obtained here for this parameter are in agreement with those published in [18-20].

Except for the previously mentioned 0.2 mm M-TT specimens, assessment of strain hardening coefficients points out excellent agreement within a few MPa between *C* coefficients of standard sized specimens and M-TT specimens for 0.5 mm and 1.5 mm and angle direction 0 and 45°. For M-TT 0.5 mm and 90° direction, the deviation is about 50 MPa. This point was scrutinized, but there was not found to be any error in the measurement of evaluation and thus it was kept among the results population and was not discarded. In the case of the *n* parameter, a difference of about 0.03 can be found for the transverse direction, while the values in the other directions agree very well.

## 5. Conclusions

The paper presented here successfully shows 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. Slight discrepancies between results from M-TT and standard size specimens can be assigned to sampling location of the M-TT specimens in the middle of the sheet thickness, where small material behavior deviation from near surface properties can be expected. Further investigations are planned to assess the influence of the M-TT specimen localization within the sheet thickness.

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