Influence of an optical strain rate controlled tensile testing method on mechanical properties of sheet metals

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Abstract. Precise material characterization is a key factor not only for representative finite-element-analysis (FEA) in production technology, but also for product development in general. Hereby, the tensile test is of particular importance, as it can be used to determine the most relevant material parameters. These are used to ensure a better process and tool design but therefore material behavior has to be determined to a high level of precision [1]. Especially in the field of metal forming, strain rate sensitive material properties like work hardening, yield point or tensile strength need to be measured at constant strain rate to provide coherent data for material models in numerical forming simulations [2]. Current testing procedures control the strain rate with a feedback control, in which various measuring systems can be used. From this comes the necessity to investigate the influence of a strain rate controlled tensile testing procedure compared to a conventional crosshead-displacement controlled one. Thus, in the scope of this study, an optical strain rate controlled (OSRC) tensile test procedure with a digital image correlation (DIC) system, and a universal testing machine (UTM) was developed. The resulting mechanical properties and the evolution of the strain rate during the test of the steel DP600 (CR330Y590T-DH) and DC05 (CR4) were analyzed at a nominal strain rate of 0.4 %/s. In addition, the results obtained from displacement strain rate controlled (DSRC) tensile tests were compared. The results demonstrate that OSRC testing method enables the measurement of mechanical material properties at a higher level of precision in terms of constant strain rate compared to DSRC procedure.

Introduction

One of the greatest challenges facing society in the 21st century is climate change and the scarcity of natural resources. In order to meet these challenges, the European Parliament is placing a stronger focus on material efficiency in the area of production, for example with the Eco-Design Directive [3]. The aim is not only to improve product and process design in terms of greater resource efficiency, but also to enable the development of lightweight structures. In the mobility sector in particular, a reduction in weight leads to a reduction in environmentally harmful carbon dioxide emissions.

The usage of FEA is state of the art in both product and process development in order to make rapid and resource-efficient progress. To do so, precise material data as an input for such simulations is a key factor to get reliable results. Such material data is gained from characterization tests with standardized specimens like the tensile test in accordance with ISO 6892-1. In the field of sheet metal forming, for example, the hardening behavior can be determined in this way up to the uniform elongation. Due to the strain rate sensitivity most metals exhibit, it is crucial to measure material data at a constant strain rate to receive coherent data for material cards in numerical simulations [2]. Strain rate is calculated with the gauge length L_0 and the speed of the moving part v(t) as follows:

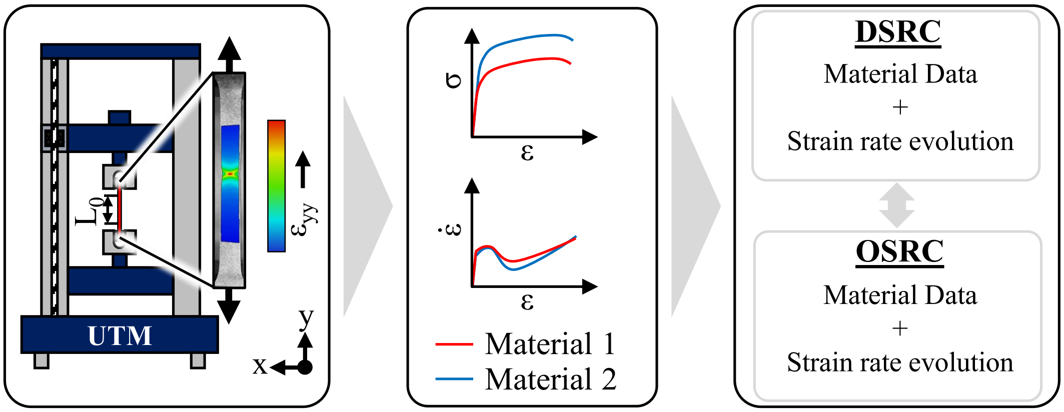
$$\dot{\varepsilon}(t) = \frac{d\varepsilon}{dt} = \frac{v(t)}{L_0}\,. \tag{1}$$

Peters et al. showed that forming operations like deep drawing show a temporal and spatial distribution of strain rates over the sheet metal, hence strain rate sensitivity should be considered in forming simulations [4]. Closed loop strain rate controlled characterization tests are available with tactile and optical extensometers. These extensometers allow an in-situ strain measurement on the specimen, which is fed back to the testing machine to control the crosshead speed. This achieves a constant strain rate throughout the whole test for the used gauge length. Bartholomew et al. developed already in the early 1950s a machine, to carry out optical controlled constant strain rate tensile tests [5]. To analyze the material behavior under biaxial load, Suttner and Merklein developed an optical strain rate controlled hydraulic bulge test with a 3D-DIC system [6]. Hereby it is not only possible to conduct experiments with a constant strain rate, but also to perform strain rate jumps during bulging. However, the influence of the test procedure on the determination of mechanical parameters from the tensile test with optical controlled strain rate has not yet been comprehensively investigated.

Objective and Methodology

The objective of this research is the experimental investigation of the influence the OSRC tensile testing procedure has on the determination of mechanical properties of sheet metals in comparison to a DSRC procedure. Therefore, different tensile tests with specimen geometries according with ISO 6892-1 A80 were conducted. To investigate the influence of different material strengths, the tests were carried out with the deep drawing grade steel DC05 and the higher strength dual phase steel DP600. Both steels were tested at a nominal sheet thickness of 1.2 mm.

Fig. 1 shows the applied methodology. To validate the new developed characterization method, at first the process is analyzed with respect to the strain rate evolutions regarding accuracy and repeatability for which the standard deviation and the root mean square error (RMSE) as key figures are used. For the influence on the determination of the mechanical properties, strain rate sensitive properties like yield (YS) and tensile strength (TS), anisotropy (lankford-coefficient), hardening exponent (n) and uniform and fracture elongation values (UE and FS) are evaluated for the rolling direction, diagonal direction and transversal direction and contrasted in conclusion.



Tensile testing Evaluation Comparison

Fig. 1. Methodology

Experimental Setup

A UTM (ZwickRoell GmbH & Co. KG Z100) with a maximum force of 100 kN and a maximum crosshead speed of 600 mm/min was used to conduct quasi static flat tensile tests with a nominal strain rate of 0.4 %/s. The strain measurement for the live control and the post processing was done with a ARAMIS 12M SRX 3D-DIC system from Carl Zeiss GOM Metrology GmbH. The schematic setup of the optical closed loop control is depicted in Fig. 2. The adaptive feedback control consists of the 3D-DIC system, which provides an analog live signal, with an acquisition rate of 50 Hz in the range between 0 V and 10 V, of the gauge length to the electronic control unit (testControll II) of the UTM. Here, the signal is utilized to adapt the crosshead speed for a constant strain rate over the gauge length. For the evaluation, the software GOM Correlate Pro 2022 was used.

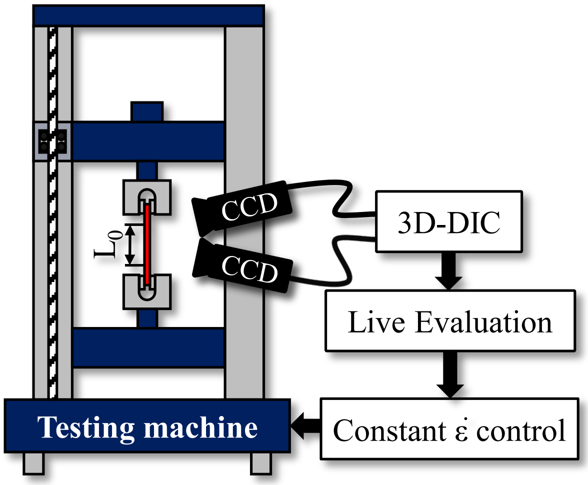


Fig. 2. Schematic setup of the applied DIC-OSRC with an UTM

To decrease the user impact and to increase the repeatability of the testing results, an automatic CAD-fitting was applied. Thereby, the centerpoint of the gauge length L_0 can be determined and used for the position of the virtual extensometer, which is needed for the OSRC method and the subsequent evaluation. In Fig. 3 is the fitting process with the different coordinate systems and the resulting coordinate system, used for controlling and evaluation, shown.

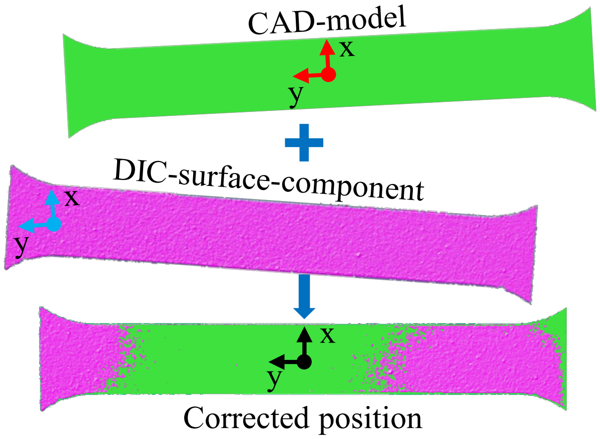


Fig. 3. Positioning of the coordinate system via CAD-fitting

Based on that, the so received corrected position and centerpoint, the virtual extensometer for controlling the test and the area for strain averaging are automatically aligned. Fig. 4 shows the placement of the area along L_0 and the different extensometers with gauge lengths of 80 mm, 40 mm and 20 mm. With the gauge lengths, the impact of the control mode can be analysed with respect to the diffuse necking of the specimen after reaching the uniform elongation. For all OSRC trials in this scope, the extensometer with a length of 80 mm was used.

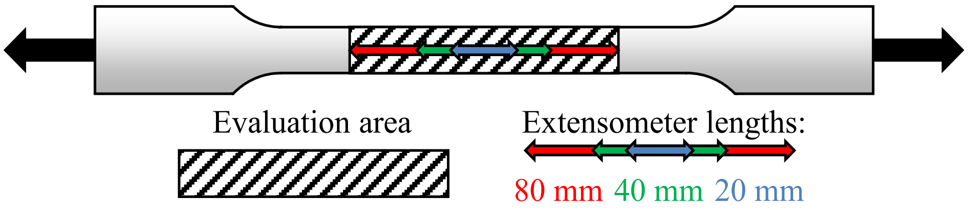


Fig. 4 Areas on tensile specimen used for controlling and evaluation

Results

Fig. 5 shows the areal strain rate evolutions for both investigated steels and methods in rolling direction (RD). The strain rate of the conventional approach with the DSRC reaches nearly the nominal value of 0.4 %/s but decreases directly afterwards. After a decrease of the strain rate to 0.31 %/s respectively 0.32 %/s, both strain rates rise to maximum of about 0.62 %/s respectively 0.68 %/s. Banerjee et al. observed a similar strain rate evolution during DSRC tensile testing [7]. The not-constant progression of the strain rate is based on not considered factors like machine stiffness, specimen gripping and the associated influence of the specimen heads. These factors do not affect the OSRC method, due to the 3D-DIC in-situ strain measurement on the specimen surface. Therefore, the progress of the strain rate obtained by OSRC experiments is constant at 0.4%/s over the whole test with minimal fluctuations until the fracture of the specimen.

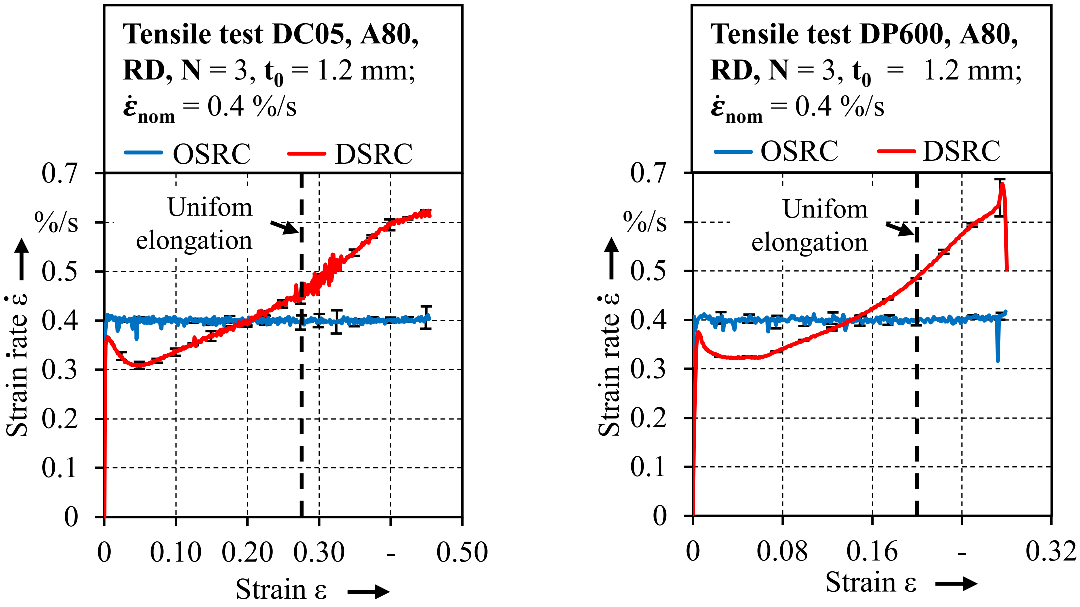


Fig. 5. Strain rate evolutions for DC05 and DP600 with different control modes

Tab. 1 summarises the parameters of the strain rate curves. The averaged values of the strain rates of the DSRC tests are 0.369 %/s for DC05 and 0.428 %/s for DP600. With the OSRC test, the averaged values meet the nominal value of 0.4 %/s with a very high accuracy which is displayed by the low RMSE of $2.4 \cdot 10^{-5}$ %/s and $5.6 \cdot 10^{-5}$ %/s with a maximum deviation each of 0.037 %/s respectively 0.084 %/s. The OSRC method provides a significant increase in the precision of constant strain rate testing over the entire trial.

Tab. 1. Strain rate values for OSRC and DSRC tensile tests

	Method	**Nominal strain rate [%/s]**	**Measured averaged strain rate [%/s]**	**RMSE [%/s]**	**Max. Absolute deviation [%/s]**
DC05 (RD)	DSRC	0.4	0.369 ± 0.004	0.012	0.224
	OSRC	0.4	0.399 ± 0.006	$2.4\cdot10^{-5}$	0.037
DP600 (RD)	DSRC	0.4	0.428 ± 0.004	0.011	0.278
	OSRC	0.4	0.400 ± 0.007	$5.6\cdot10^{-5}$	0.084

Fig. 6 shows the strain rate distribution over a tensile specimen during elongation until fracture. To make the distribution visible, three different lengths of extensometers are used like demonstrated in Fig. 4. Due to diffuse necking both steels exhibit, strain localization and thus, strain rate localization occurs. This leads to significant increase of strain rate in the region of necking.

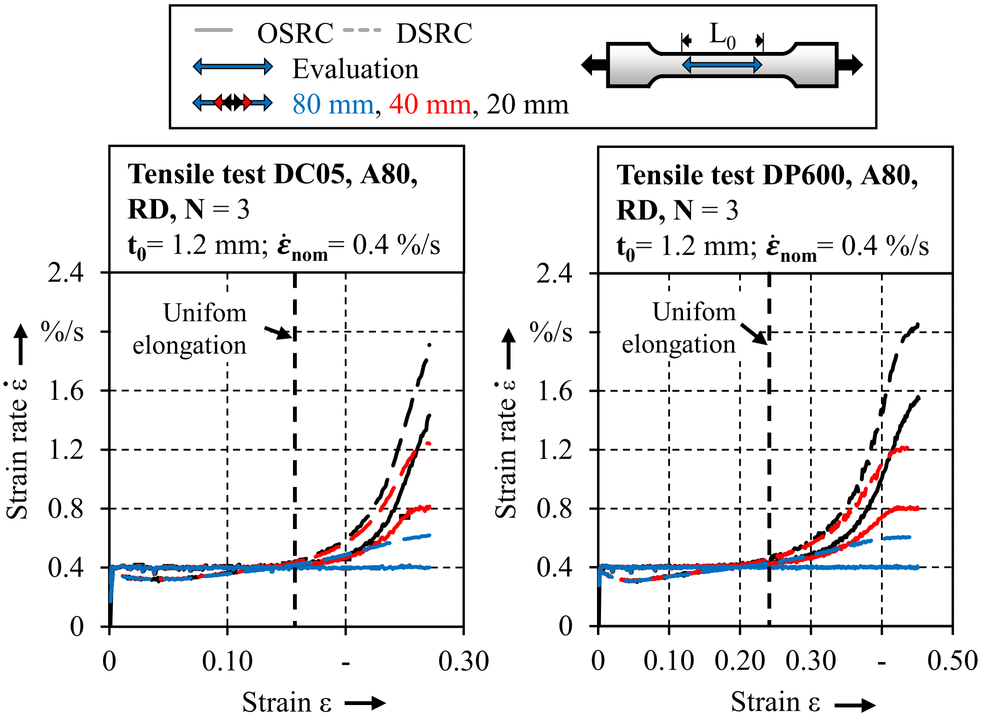


Fig. 6. Comparison of different extensometer lengths for OSRC and DSRC

The influence of the OSRC testing on the UTM crosshead speed is shown in Fig. 7. The crosshead speed for the DSRC trial is constant as depicted in equation 1. With a clamping length of 120 mm, which is the parallel span of the specimen and a nominal strain rate of 0.4 %/s, the crosshead speed results in 28.8 mm/min. The influence of the OSRC testing on the crosshead speed is shown in Fig. 7. Vice versa to the strain rate evolution, the crosshead speed of the OSRC trial is in the beginning above the speed of the DSRC trial. The crosshead speed then decreases nearly linear to a value of about 18 mm/min to the specimen fracture.

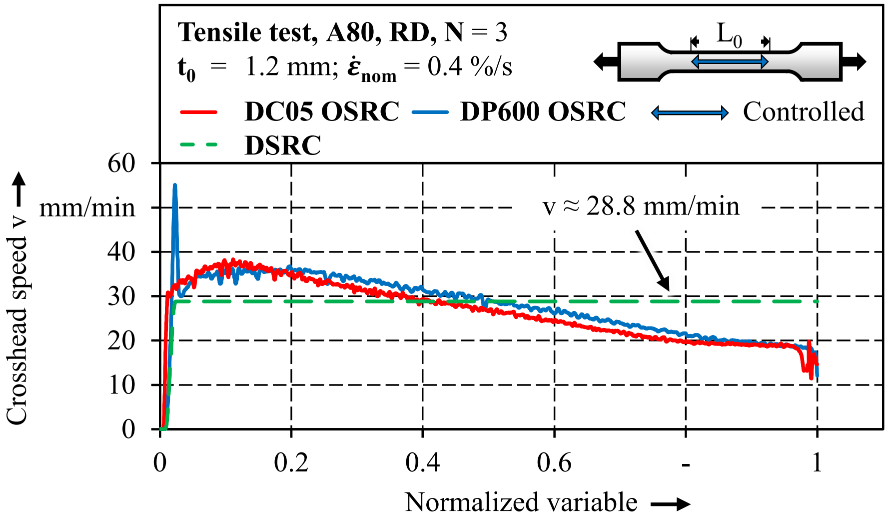


Fig. 7. Crosshead speeds for different testing methods

In the following part, the influence of the testing method on the determination of the mechanical properties is presented. Fig. 8 displays the comparison of different mechanical values for DC05 obtained in DSRC and OSRC experiments. For most parameters, the difference is negligible small or not measurable. Only for the strain hardening exponent n in 45° and 90° to the rolling direction, an impact of the testing method was observed. Here, the measured value for n in diagonal (DD) and transversal direction (TD) is 0.253 respectively 0.257 for DSRC and 0.247 respectively 0.250 for OSRC. The small standard deviations in the determination of the yield and tensile stress for both methods indicates a high repeatability. Only for the ultimate elongation (UE), the experiments with the OSRC trial provides a higher standard deviation for all testing directions compared to DSRC.

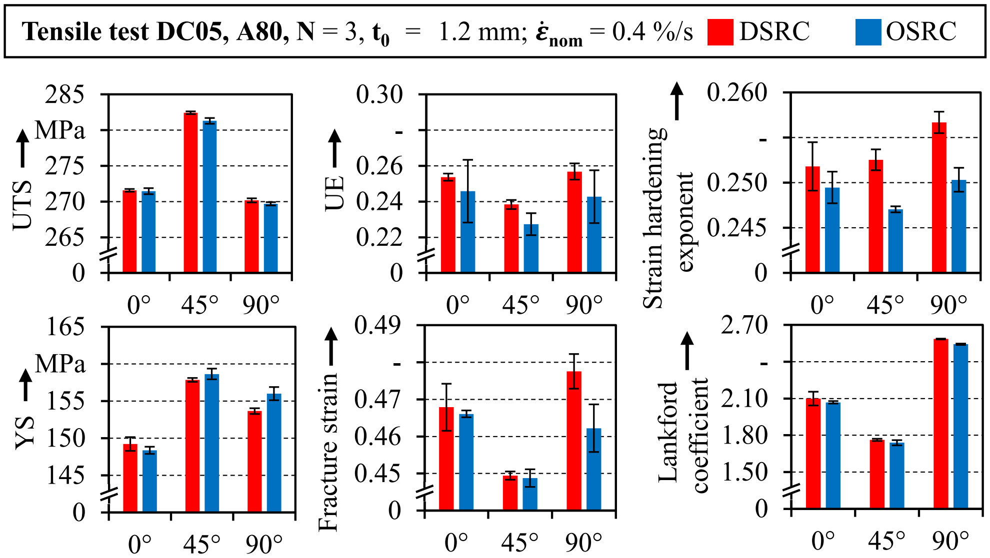


Fig. 8. Overview of strain rate sensitive material properties of DC05 obtained from DSRC and OSRC tensile tests

The difference in the measurement of the strain hardening exponent which is present for DC05 could not be observed for DP600 as Fig. 9 indicates. Here, for all values, no significant impact of the testing method could be demonstrated. Due to the lower strain rate sensitivity of DP600 in comparison to DC05, no influence can be measured. Additionally, the quasi-static strain rate of

0.004 1/s and the associated relatively low deviation from the nominal strain rate, even in DSRC tests, makes the identification of a distinction difficult.

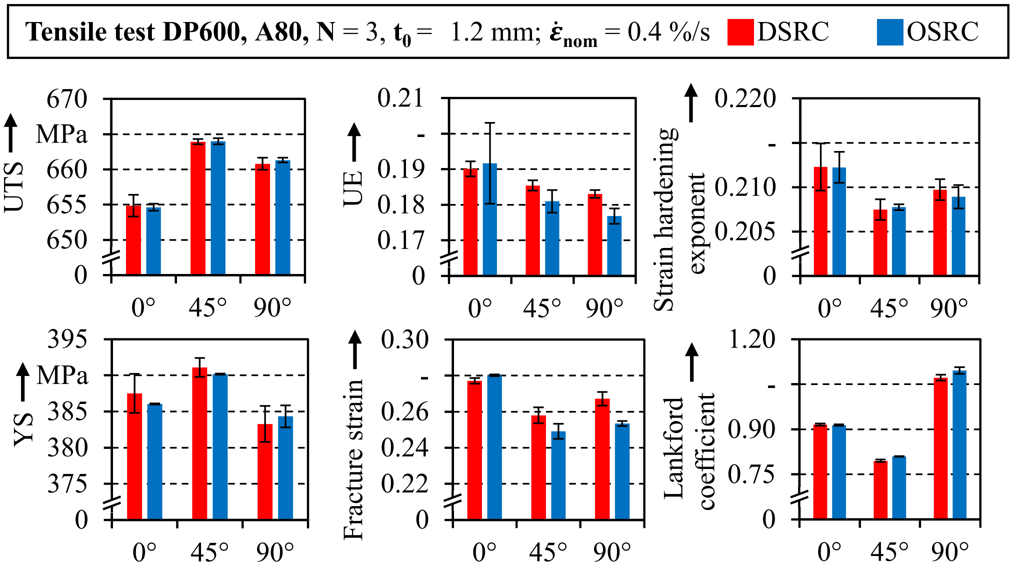


Fig. 9. Overview of strain rate sensitive material properties of DP600 obtained from DSRC and OSRC tensile tests

Summary and Outlook

To increase the prediction quality of numerical simulations and consequently improve tool and part design, precise material data is crucial. A current issue in state of the art characterization procedures is either non-constant strain rates or the unknown impact of constant strain rate testing on the determination of material properties. This research presented a novel and versatile method for a 3D-DIC strain rate controlled tensile test, to provide constant strain rate testing. The method is independent from the testing machine and the specimen-geometry, such that influences like machine stiffness are negligible and do not affect the strain rate anymore. DSRC and OSRC tensile test where conducted and the resulting properties compared. Hereby, the standard gauge length of A80 tensile test specimen geometry of 80 mm was used as input for controlling the strain rate. A significant increase in the constancy and precision of the strain rate was observed for quasi-static testing at 0.4 %/s. The RMSE of the strain rate during tensile testing could be improved from 0.012 %/s for DC05 respectively 0.011 %/s for DP600 to $2.4 \cdot 10^{-5}$ %/s respectively $5.6 \cdot 10^{-5}$ %/s. Also the maximum deviation to the nominal strain rate was reduced from 0.224 %/s to 0.037 %/s respectively 0.278 %/s to 0.084 %/s. Due to the low strain rate sensitivity at room temperature of steels in general and the investigated materials DC05 and DP600, nearly no influence on the measurement of the mechanical properties could be observed [8]. However, in future work the OSRC with a 3D-DIC system can be applied for characterization tests at elevated temperatures, where strain rate sensitivity is more pronounced for most metals. Because of the increase of strain rate in the region of necking, an adaptive and tailored strain rate control system, which controls the strain rate in these regions, provides the potential to improve the determination of material data up to higher strains.

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