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Functionality Study of an Optical Measurement Concept for Local Force Signal Determination in High Strain Rate Tensile Tests

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Abstract. Many mechanical material properties show a dependence on the strain rate, e.g. yield stress or elongation at fracture. The quantitative description of the material behavior under dynamic loading is of major importance for the evaluation of crash safety. This is carried out using numerical methods and requires characteristic values for the materials used. For the standardized determination of dynamic characteristic values in sheet metal materials, tensile tests performed according to the guideline from [1]. A particular challenge in dynamic tensile tests is the force measurement during the test. For this purpose, strain gauges are attached on each specimen, wired to the measuring equipment and calibrated. This is a common way to determine a force signal that is as low in vibration and as free of bending moments as possible. The preparation effort for the used strain gauges are enormous. For these reasons, an optical method to determine the force by strain measurement using DIC is presented.
The experiments are carried out on a high speed tensile testing system. In combioantion with a 3D DIC high speed system for optical strain measurement. The elastic deformation of the specimen in the dynamometric section is measured using strain gauges and the optical method. The measured signals are then compared to validate the presented method. The investigations are conducted using the dual phase steel material HCT590X and the aluminum material EN AW-6014 T4. Strain rates of up to 240 s^{-1} are investigated.

Introduction

Dynamic Material Characterization. In many technical applications and processes, material is deformed under conditions that imply high strain rates, e.g. in manufacturing processes or crash loads in the automotive or aerospace sector. In this regard, the used materials properties depend on the strain rate. The yield stress or the elongation at fracture may be influenced by the strain rate. In the case of metallic materials, this is due to their microstructure, which in turn depends on the chemical composition and the process chain [2]. In order to be able to adequately dimension components and structures for a crash situation, knowledge of the material properties under dynamic loading is essential. Numerical methods are used for this purpose in the product development process. The material models implemented in the simulation must be able to characterize the flow behavior of the materials at quasi-static as well as at high strain rates. The material properties required for this are usually determined on the basis of tensile tests. Therefore, the guidelines in [1] contain a procedure for determining dynamic material parameters for crash simulation. A specific challenge in highly dynamic tensile tests is the force measurement due to occurring vibrations during the test. The further away the force is measured from the point of failure (e.g. load cell of the test facility), the greater the vibrations in the measurement signal. For this reason, strain gauges are attached to the tensile specimens and used for force measurement. In Fig. 1 the geometry of a tensile test specimen can be seen in accordance with [3].

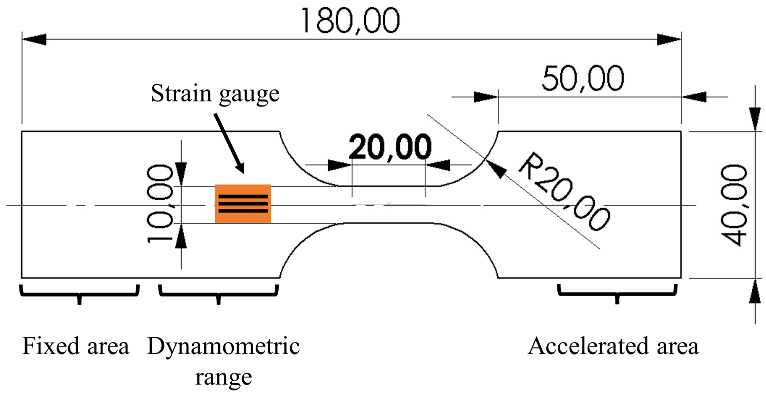


Fig. 1: Specimen for tensile tests at high strain rates according to [3]

It shows the area of the specimen that is fixed in the test system and the accelerated area of the specimen. Also, a dynamometric area is shown where a solely elastic deformation occurs during the whole test. The strain gauges must be applied in this area. For this purpose, the specimen surface is cleaned and surface prepared in such a way that the strain gauge can be bonded with liquid adhesive. The strain gauges must be attached on both sides and connected in a measuring bridge in such a way that any bending moments occurring in the tensile specimen during the test can be recorded and taken into account in the signal processing. Before each test, the applied strain gauges must be wired to the signal amplifier and calibrated under preload in the elastic range of the specimen. This procedure enables the determination of low-vibration and accurate measurement results, but is very time-consuming.

Digital Image Correlation (DIC). 3D digital image correlation is an optical, non-contact measurement technique used to determine displacements and full-field strain of an object during deformation [4]. In this measuring concept the deformed object is recorded by two high resolution digital cameras. A stochastically distributed high contrast pattern is applied to the object before the test. This pattern, normally done with spray paint, needs to deform with the object. After image recording, the obtained pictures are processed in a computer. The initial processing creates a unit of overlapping unique correlation areas across the imaging area, so called micro facets. After calculating the facets, they can be tracked by the software in each captured image with an accuracy of a few pixels. As each facet has been tracked through the entire image set, the software creates a set of 3D coordinates for the imaging area. Using this coordinate system the 3D shape, 3D displacement, and full-field strains can be measured [5]. DIC can also be applied with only one camera in 2D. Thus, the calibration is more easily performed and the experimental effort is lower. However, in this case only in a single plane and no 3D deformations can be measured and evaluated. In this paper, the commercial 3D image correlation system GOM ARAMIS is used for measuring the deformation in the tensile test specimen. In [6] the concrete concept of this DIC system is explained.

DIC for Strain Measurement. Due to its simplicity and ease of application the DIC method has been widely applied for different technical situations, such as studies of measuring strain phenomena occuring during quasistatic tension experiments of sheet metal material [7]. A comprehensive investigation and verification examples for strain and strain-rate determination of DIC systems can be referenced in [8]. However, the DIC method combined with high-speed photography has not been widely used in tensile tests with high strain rates. In [9] the DIC method was used in combination with high speed imaging systems for 2D and 3D deformation measurements. However, the uniaxial tension experiments were carried out only with quasistatic loadings. In [10], 2D digital speckle photography has been applied in the study of dynamic material behavior in a microscopic scale. The investigations of [11] used 2D DIC methods together with high-speed photography to study strain localization in tensile specimens out of a dual-phase steel at high strain rates. In [12], the local strain

of stainless steel tensile specimens was measured by 2D DIC method in a Hopkinson bar setup with strain rates up to 3000 s^{-1}. 3D full field strain measurement in high strain rate tensile Split Hopkinson Bar experiments were conducted in [13]. In this study, the plastic deformation of tensile specimens made of copper material was investigated. The strains recorded by strain gauge in the plastic specimen region agreed well with the strains measured by DIC. However, relatively large strains were recorded, for which a coarse stochastic pattern with a high frame rate can be used. Furthermore, the signal obtained deviates from the strain gauge signal due to plastic deformation outside of the strain gauge section caused by the specimens fixture in the testing system.
The aim of this study is to develop a measurement concept based on a 3D DIC method in combination with high-speed photography, which is able to detect minimal elastic deformations in high strain rate tensile tests in the dynamometric range of tensile specimens. The measured values are to be compared with conventional local strain measurement with strain gauges in order to consider replacing them with the presented method.

Experimental

Materials. The investigations in this study were carried out on a dual phase steel HCT590X with a sheet thickness t = 1.5 mm and a minimum yield strength of 330 MPa as well as a minimum elongation A_{80} of 20 % [14]. Furthermore, the aluminum alloy EN AW-6014 in temper T4 and sheet thickness t = 2.0 mm was investigated, which has a yield strength of about 130 MPa and a minimum elongation A_{80} of 23 % [15].

High Strain Rate Tensile Tests and DIC. The high strain rate tensile tests are carried out on an Instron VHS 65/80-20 high speed tensile testing system, which can be seen in Fig. 2, left side. It can apply a maximum test force of 80 kN with a maximum speed of 20 m/s.

Testing system
Instron VHS 65/80-20
Max. force
80 kN
Max. testing speed
20 m/s
Max. displacemet (piston)
300 mm

DIC system
GOM ARAMIS 3D Highspeed System
Max. frame rate
1,100,000 fps
Max. resolution
1024 x 1024 pixel
Photosensitivity
ISO 64.000

Fig. 2: High speed tensile testing system Instron VHS 65/80-20 and GOM ARAMIS 3D high speed system

For the optical non-contact strain measurement a GOM ARAMIS 3D high speed system is used (Fig. 2, right side). It consists of two Photron FASTCAM Nova S12 high speed cameras with a maximum resolution of 1024 x 1024 pixel at a frame rate of 12,800 fps and a maximum frame rate of 1,100,000 fps with a reduced resolution. The captured images are processed with a GOM ARAMIS software in order to enable a full field 3D strain measurement of the specimen. A 3D strain measurement is necessary, as this is the only way to identify the deformation in the depth direction and thus the bending moments of the specimen during the test, which is conventionally done by applying the strain gauges on both sides of the specimen.
The tensile specimen investigated were wire eroded according to the geometry shown in Fig 1. Subsequently, the samples were cleaned and strain gauges of the type SGD-3/120-LY41 were applied in the dynamometric area on both sides. The strain gauges are connected in a measuring bridge in such a way that the output signal corresponds to the strain of the specimen in the loading direction with the bending component already compensated. The technical specifications of the strain gauges can be found in [16]. Above the applied strain gauge, the dynamometric area of the tensile specimens is provided with a fine stochastic speckle pattern in order to be able to record the elastic strains

occurring there in the micrometer scale. The DIC system is calibrated to a measuring volume of 30 x 25 x 15 mm. The entire experimental setup and prepared specimen can be seen in Fig. 3.

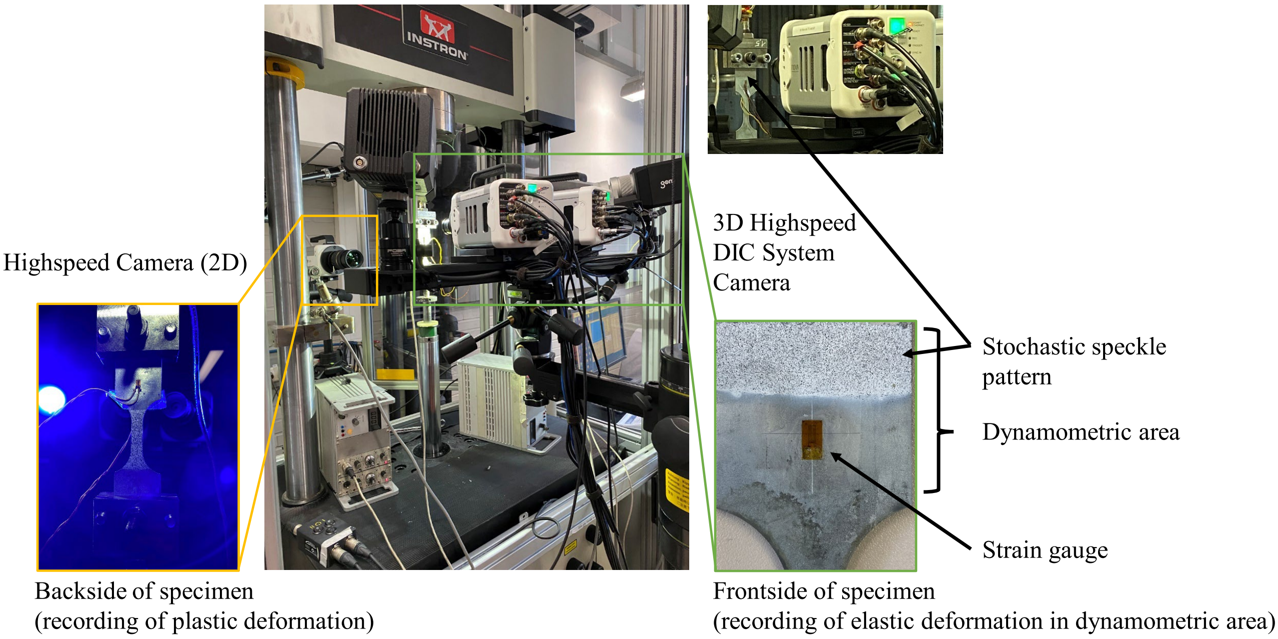


Fig. 3: Test setup and prepared specimen for high strain rate tensile tests

From one side, the specimen is recorded with the 3D high speed DIC system in the elastic strain region, see bottom right. In order to sufficiently illuminate the specimen for the highest possible frame rate, two external spotlights were used in addition to the two lights of the DIC system. On the other side of the specimen, an additional 2D high-speed camera is installed. It records the measurement area of the specimen with plastic deformation, which is assumed to be planar. At this point, the specimen was also provided with a stochastic pattern. This makes it possible to evaluate the plastic strain of the specimen using 2D DIC, see bottom left. However, in order to proof the functionality of the presented method only the recording of strain in the elastic dynamometer area is evaluated for force determination in comparison with the applied strain gauges.

Regarding the testing procedure, the specimen is first mounted in the testing system and loaded with a force in the elastic range of the specimen. The strain gauge is then calibrated in alignment with the load cell of the test system. Furthermore, an image is taken in the 3D DIC system and the strain in the area of the stochastic pattern is evaluated. This strain value is also correlated with the calibrated strain gauge and the load cell, resulting in a conversion factor by which the subsequent strain signal of the DIC system must be multiplied in order to compare it with the force values of the strain gauge.

Signal Analysis. After the test, the images are evaluated in the GOM ARAMIS software. An exemplary evaluation of the specimen can be seen in Fig. 4. With the help of a generated surface component on the specimen, the strain in the tensile direction (Y-direction) in the elastic region of the specimen can be evaluated. The strain signal is then multiplied by the previously determined conversion factor to compare it with the strain gauge force signal. The original signals, determined by DIC, can be seen in Fig. 5 and following. Due to dynamic effects during the impact load application, oscillations occur in the optical signal. Following [1], the signal was smoothed with a filter. For this purpose, a part of the original signal was extracted between the beginning of the yield point of the material (steep curve increase) and the break of the specimen (steep curve decrease). The points of extraction of the signal are marked with red bars in Fig. 5.

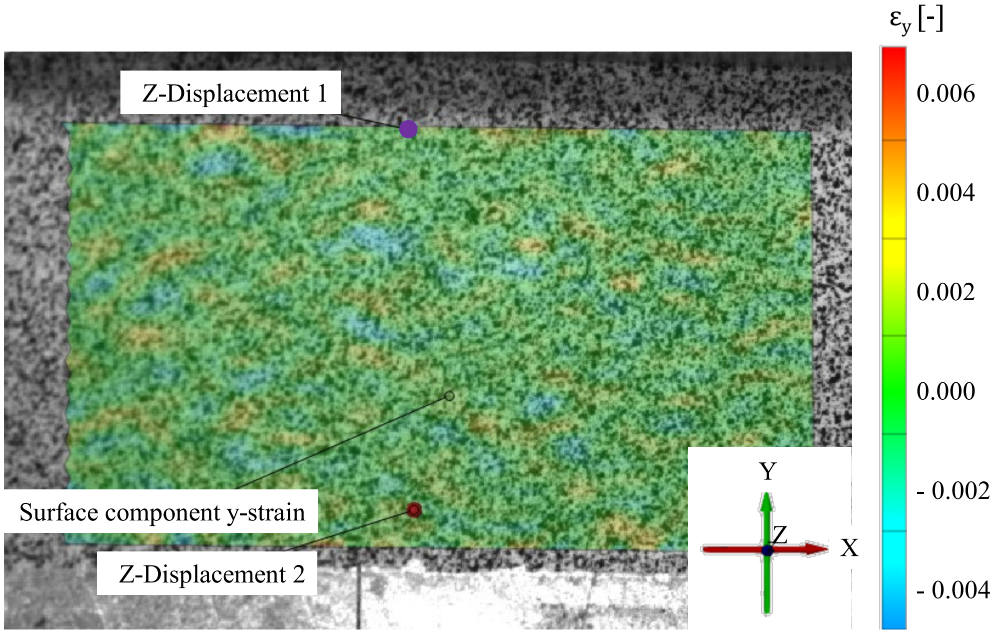


Fig. 4: Evaluation of strain in the dynamometric area of the specimen using DIC software

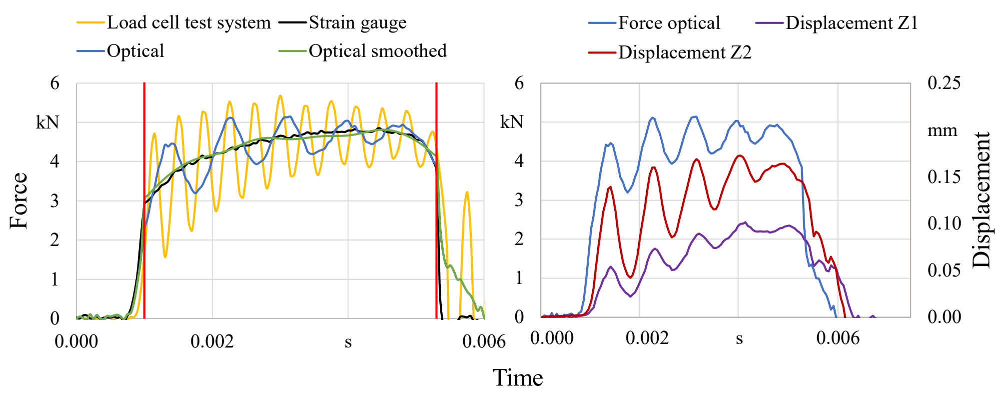
For smoothing the oscillatory signal, approximation with a low degree polynomial is recommended in [1]. In this study, MATLAB software was used for this purpose, applying a 2nd degree Savitzky-Golay filter [17]. The generalized moving average smoothing filter by Savitzky-Golay is derived from least squares fitting of a lower order polynomial to a number of consecutive points and is well suited for signal processing in technical applications [18].

Experimental design. In this study, the influence of different test parameters on the results of the developed measurement concept is investigated. First, high rate tensile tests with specimens from the steel and aluminum material at a strain rate of 100 s^{-1} and a frame rate of 20,000 fps are examined to investigate the influence of the material on the measurement result. Afterwards, the frame rate is increased up to 50,000 fps in order to resolve the measurement signal more finely and achieve a more accurate evaluation. After that, the test speed is increased and the tensile specimens are tested at a strain rate of 240 s^{-1}. The influence of the strain rate on the applicability of the methodology will be investigated.

Results and Discussion

The characteristic force-time curves from high strain rate tensile tests on the aluminium sheet material EN AW-6014 T4, determined using different measurement methods, are shown in Fig. 5. The strain rate used was 100 s^{-1} at a frame rate of 20,000 fps. The force-time signal measured using the load cell (yellow curve) of the test system is superimposed by strong oscillations due to dynamic effects caused by the impulsive force application. Resulting from the local measurement directly on the specimen, the signal of the strain gauge (black curve) shows no significant oscillations. The original signal measured with the developed optical measurement method (blue curve) shows very good agreement with the strain gauge signal up to the yield point of the specimen and during the specimen failure at the end. However, in between these areas (marked by red bars) the signal also shows oscillations. Due to the also local measurement on the specimen, it can be assumed that the oscillations result from a spatial movement of the specimen during the test. An extended examination in the GOM ARAMIS software demonstrated a movement of the specimen in the depth direction (Z-direction). For this purpose, the Z-displacement of two points (Fig. 4) in the measuring range of the specimen was evaluated, see Fig. 5 right. In this, it can be seen that the specimen performs an oscillating motion in the Z-direction. The oscillation in the Z-direction influences the measuring signal in the Y-direction, due to varying distance and angle to the cameras. This can be seen from the almost in-phase oscillations in the signals. The difference between the Z-displacement in the measuring points 1 and

2 results from their different distances to the specimens fixture in the test system. The original signal was smoothed with a filter as already described and can be seen as a green curve in the diagram. The smoothed curve shows very good agreement with the strain gauge signal.



Material
EN AW-6014 T4; t = 2.0 mm; 0°
Strain rate
100 s^{-1}
Frame rate
20000 Hz
Specimen geometry
SEP1230

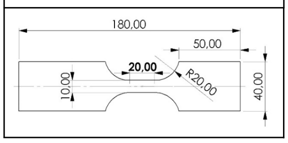
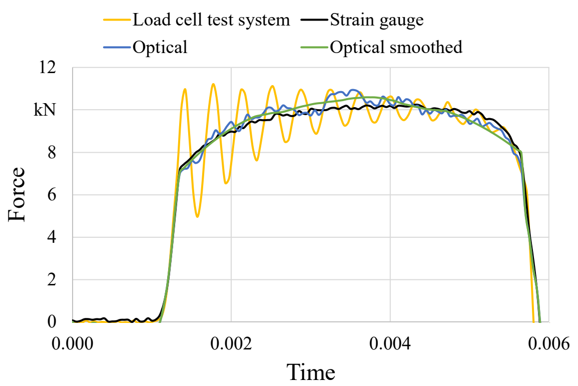


Fig. 5: Force-time curves from high strain rate tensile tests in EN AW-6014 T4 material for different measurement methods (left) and correlation of the optically measured force-time curve and the local specimen displacement in Z-direction (right)

The characteristic force-time curves from high strain rate tensile tests on the steel sheet material HCT590X, determined using different measurement methods, are shown in Fig. 6. Here as well, the strain rate used was 100 s^{-1} at a frame rate of 20,000 fps. Again, the signal of the load cell of the test system shows strong oscillations, whereas the force signal of the strain gauge is low in oscillations. The force signal of the optical measurement method again agrees very well in the rise and fall of the curve with the signal of the strain gauge. Compared to the aluminium, however, no regular oscillations can be detected. The signal oscillates discontinuously with an exaggeration in the force maximum. Thus, the smoothed signal matches the curve of the strain gauge signal mostly well, but overestimates it in the area of the force maximum and then drops early.



Material
HCT590X; t = 1.5 mm; 0°
Strain rate
100 s^{-1}
Frame rate
20000 Hz
Specimen geometry
SEP1230

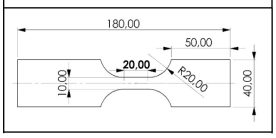
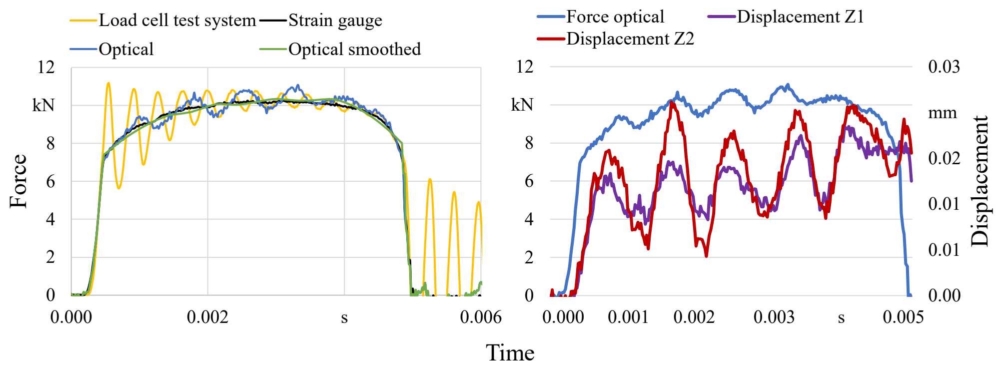


Fig. 6: Force-time curves from high strain rate tensile tests in HCT590X for different measurement methods

In order to increase the measurement accuracy and to be able to better investigate occurring dynamic effects in the signal, the frame rate of the 3D DIC system for the experiments was increased to 50,000 fps using the same strain rate of 100 s^{-1}. The measurement results can be seen in Fig. 7, left side. Similar to the force-time curves of the aluminium specimens, the signal of the optical measuring method shows a regular oscillation over the entire test. Also for this experiment, the Z-displacements of the specimen were evaluated and are shown in the right diagram from Fig. 7. In this, an oscillatory motion of the specimen in the Z-direction can be seen, which is approximately in phase with the force signal of the optical measurement method. However, the vibration amplitude is significantly lower than for the aluminium specimens, probably due to the higher stiffness of the steel material. However, it can be seen in the left diagram from Fig. 7 that the smoothed signal agrees very well with the signal from the strain gauge. This may result from the better detection of the sample deformation due to the higher frame rate used in this experiment.



Material
HCT590X; t = 1.5 mm; 0°
Strain rate
100 s^{-1}
Frame rate
50000 Hz
Specimen geometry
SEP1230

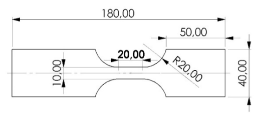
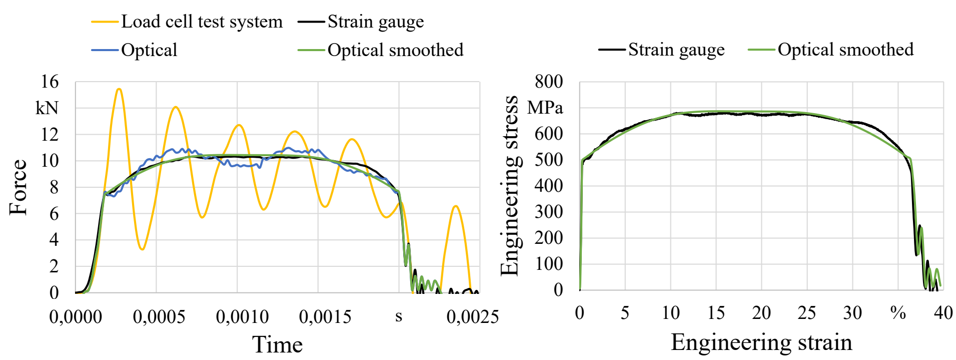


Fig. 7: Force-time curves from high strain rate tensile tests in HCT590X material for different measurement methods (left) and correlation of the optically measured force-time curve and the local specimen displacement in Z-direction (right)

To investigate the influence of higher strain rates on the applicability of the developed measurement methodology, the strain rate was increased up to 240 s^{-1} and specimens made of HCT590X were tested. The frame rate remained unchanged at 50,000 fps. The measurement results are shown in Fig. 8. The oscillations in the load cell signal of the test system are significantly higher than at 100 s^{-1}, since the dynamic effects are amplified at a higher strain rate. The signal of the strain gauge is still low in vibration. Even with the increased strain rate, the force signal of the optical measurement method agrees very well in the rise and fall of the curve with the signal of the strain gauge. In addition, a regular oscillation can also be seen in the optically measured force signal. However, the filtered signal agrees well with the signal of the strain gauge.



Material			
HCT590X; t = 1.5 mm; 0°			
Strain rate			
240 s^{-1}			
Frame rate			
50000 Hz			
Specimen geometry			
SEP1230			
Strain gauge		Optical	
UTS	681 MPa	UTS	687 MPa
YS	495 MPa	YS	501 MPa

Fig. 8: Force-time curves (left) and stress-strain curves (right) from high strain rate tensile tests in HCT590X for different measurement methods at a strain rate of 240 s^{-1}

Furthermore, an engineering stress – engineering strain curve generated from the test data is shown in the diagram on the right. This shows the signals determined by the conventional approach with strain gauges and the optical method. The close agreement between the curves, especially in the area of yield strength and ultimate tensile strength, confirms the functionality of the method. The mechanical characteristic values of the test were determined and deviate only slightly from each other. The ultimate tensile strength determined with strain gage is 0.9 % below the value of the optical method and the yield strength is 1.2 %.

Summary

In this study an optical measurement concept based on a 3D DIC method in combination with high-speed photography was presented, which is able to detect minimal elastic deformations in high strain rate tensile tests in the dynamometric range of tensile specimens. The aim was to check whether the signal quality is as valid as that of strain gauges used for conventional local force measurement in tensile tests. The results of the investigation have shown that the optical measurement method shows good agreement with the strain gauge signal up to the yield point of the specimen and during the specimen failure at the end. However, in between these areas the signal shows oscillations. After applying common filtering methods, the signal matches with the strain gauge signals, which provides the general proof of functionality of the method. The advantage of the measurement concept is the enormous savings in test effort, since the application and wiring of the strain gauges would be avoided. Limitations of the methodology might arise at higher strain rates, since a sufficient frame rate is required for an adequate resolution of the signal. A higher frame rate can be achieved through improved camera technology. For this purpose, larger camera lenses can be used and a finer speckle pattern can be applied to the specimen. In addition, the specimen must be sufficiently illuminated, possibly by several external spotlights.

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