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# An evaluation of the mechanical properties of 13MnSiCr7 steel by digital image correlation

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**Abstract**

In this paper, the possibility of replacing tensile extensometers with a non-contacting device for measuring elongation has been analyzed. An example of a non-contacting device is a Digital Image Correlation System (DIC). Such systems are widely used in various areas, for example, biology or modern engineering. DIC systems have several advantages that seem to be promising for testing modern materials. The most important is the fact that there is no physical contact between the sample and the DIC and therefore no additional force is applied during the experiment. On the other hand, a lack of contact with the sample can cause large measurement inaccuracies. Another advantage would be that a DIC can measure strain on the whole surface of the sample in all directions, instead of measuring part of the surface in one direction like in other extensometers. Because of these abilities, the environment impact on test bench (DIC + load device), and differences between conducted experiment with normalized tensile test needed to be investigated. The testing machine was replaced by a DIC system cooperating with a tension-compression module. The proposed method was used to monitor and record the images to determine the basic properties of 13MnSiCr7 grade steel. Twelve tests were performed. The analysis was done by comparing the values of mechanical properties obtained in a static tensile test, such as yield strength, tensile strength, Young's modulus, elongation of the material; with the values of these properties determined experimentally. For each sample, stress-strain curves were evaluated. To check if the results were correct, a Q-Dixon test was performed in each case, confidence intervals were also calculated. Finally, the obtained properties were compared with those from the standard tensile test acquired from the manufacturer's material card.

**Keywords:** Static Tensile Test, Digital Image Correlation, Young's modulus, yield strength, tensile strength, 13MnSiCr7

## 1. Introduction

In tensile testing, the commonly used sensors for measuring specimen strain are various extensometers (Jastrzębski et al., 1986). While this type of instrumentation allows for high accuracy measurements, it has some drawbacks. Extensometers require the blades of the gauge to be in contact with the surface of the specimen, and that is why an additional force is applied to the specimen (Śmierzchalski & Radke, 2012). If the blades are misaligned or the surface of the tested sample is smooth, blade slippage and measurement interference will occur (Kocańda, 1978). Furthermore, contact strain measurement methods are highly susceptible to the temperature of the test object. Melt flow and softening of the material can also cause blade slippage. At extremely high temperatures, high strain rates, or cyclic deformations, even damage of the extensometer can occur (Dumoulin et al., 2020).

In addition to the technical difficulties associated with the use of extensometers, it should also be noted that these types of sensors only measure the range between extensometer's blade. They do not record what is happening with the sample outside of the tested range (Dumoulin et al., 2020).

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Non-contact strain measurement methods are an alternative to this type of measurement. An example of this type of solution are DIC systems. This technique has been known since 1983 (Sutton et al., 1983), and is based on recording and comparing a series of digital images of the surface of the tested object taken during the experiment with each other. The algorithm measures the change of distance between characteristic points on the surface of the sample, which allows determining the deformation of the tested material. DIC offers the advantage of being able to image objects of any size and of measuring strain along the entire length of the surface, so any deformation of the specimen is recorded, even outside the measurement area of standard extensometers. Since this is a non-contact technique, there is no additional force applied to the specimen, and it eliminates the need for precise mounting of sensors on the specimen's surface, thus simplifying the testing methodology. A great advantage is also the potential to present the results in the form of visualization of the strain map on the tested surface (Schmidt, 2020).

The aim of the study was to check the possibility of the implementation a Digital Image Correlation system to determine the material properties. Researchers have suggested a practical use of DIC systems with equipment such as a Kammrath–Weiss tension-compression module, a strength testing device, or a Gleeble 3800 metallurgical process simulator. The possibility of replacing extensometers with a DIC system in typical, well-known testing procedures was checked.

## 2. Research methodology

### 2.1. Investigated material

The research consisted in determining the mechanical properties of 13MnSiCr7 steel (the chemical composition of which is given in Table 1 and comparing them with the analogous values provided by the steel manufacturer. This steel was chosen because it was well described in the literature, and researchers have experience with 13MnSiCr7 from previous investigations. As the main aim of this work is to determine the differences between standardized experiments and those with another test bench (DIC + load device), it is important to use well-described steel.

The material was supplied in the form of sheet cuttings, from which specimens with the dimensions and shape given in Figure 1 were manufactured.

**Table 1.** Chemical composition of investigated steel (in mass percent)

| Element | Percentage [%] |
|---|---|
| C | 0.1200 |
| Mn | 1.7100 |
| Si | 0.5700 |
| P | 0.0120 |
| S | 0.0100 |
| Cr | 0.6400 |
| Mo | 0.0120 |
| Ni | 0.0700 |
| V | 0.0840 |
| Nb | 0.0560 |
| Ti | 0.0017 |
| Al | 0.0260 |
| B | 0.0010 |
| N | 0.0107 |

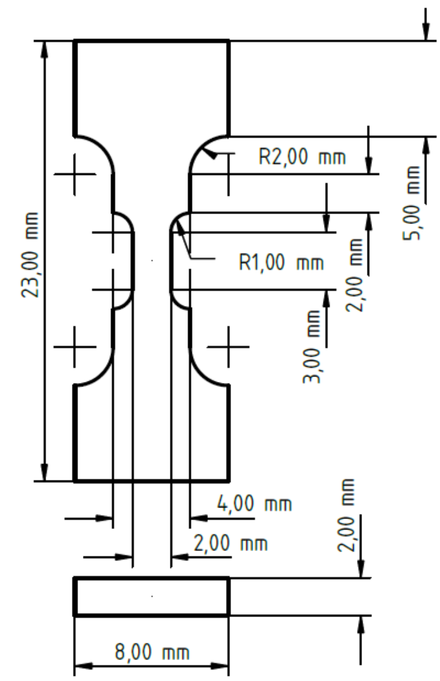


**Fig. 1.** Technical sketch of the sample for the tensile test

### 2.2. Research methodology

The loading device for the specimen was a tensile-compression module, while a DIC system was used to record the dimensional change.

#### 2.2.1. Tension/compression module

The Kammrath–Weiss tension/compression module is a device mainly dedicated to scanning electron microscopy (SEM) applications. The length of the test objects should vary between 20 mm and 60 mm, and should not be thicker than 5 mm. The device has a mechanical drive built on the basis of right and left screws. The module is equipped with a linear displacement gauge. This indicator covers a total displacement range of up to 45 mm, with a resolution of 100 nm. In addition, the extensive software enables conducting static and dynamic tests and observing surface changes under controlled mechanical load, crack growth, delimitation phenomena or slip plane formation. The device is presented in Figure 2.

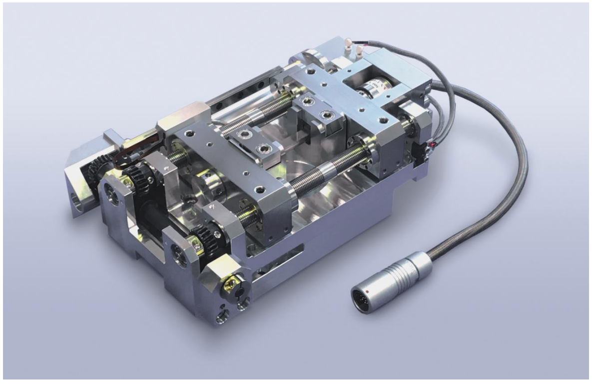

**Fig. 2.** Tension/compression Module from Kammrath–Weiss (pik-instruments.pl)

#### 2.2.2. Digital image correlation system

DIC is used to measure strain based on recording and comparing a series of digital images with each other. Before taking measurements, it is necessary to mark the test surface with a speckle structure using a well-contrasting paint (Marcinczak, 2019). The sample during the experiment with the applied speckle structure is illustrated in Figure 3. In this figure, a strain distribution map is also presented. Thus, it is possible to observe sample behavior during an experiment under *in-situ* conditions.

The data obtained from the DIC system was verified by comparing it with the data provided by the manufacturer (Steeltec, 2016). To make the comparison meaningful, it was decided to perform 12 tests. Stress (Kammrath–Weiss module) and strain (DIC system) measurements were synchronized in time. The tests were conducted at room temperature. The tool velocity was set at 30 μm/s, and the tests were carried out until material failure. From the obtained data, the tensile strength, Young's modulus, yield strength, and relative elongation of the material were determined according to a normalized procedure (European Standard EN ISO 6892-1:2019).

## 3. Test results

As mentioned before, the main advantage of the DIC system is the ability to generate a live visualization of the strain map directly on the surface of the object. Figure 4 illustrates how the strain distribution in the specimen altered during the experiment. The following paragraphs present the results of the experiments performed. The first two photos showed that there is no strain change in the range of the linear elastic region. According to Hooke's law, the strain in this region is elastic and reversible, therefore in the first two images of the sample surface, no changes are observed. Changes start to be visible at images 3–5, the strain change can be observed, and it is possible to predict where the sample will break. These points are above yield strength, where strain change is not reversible, something clearly visible on the curve and on the sample images.

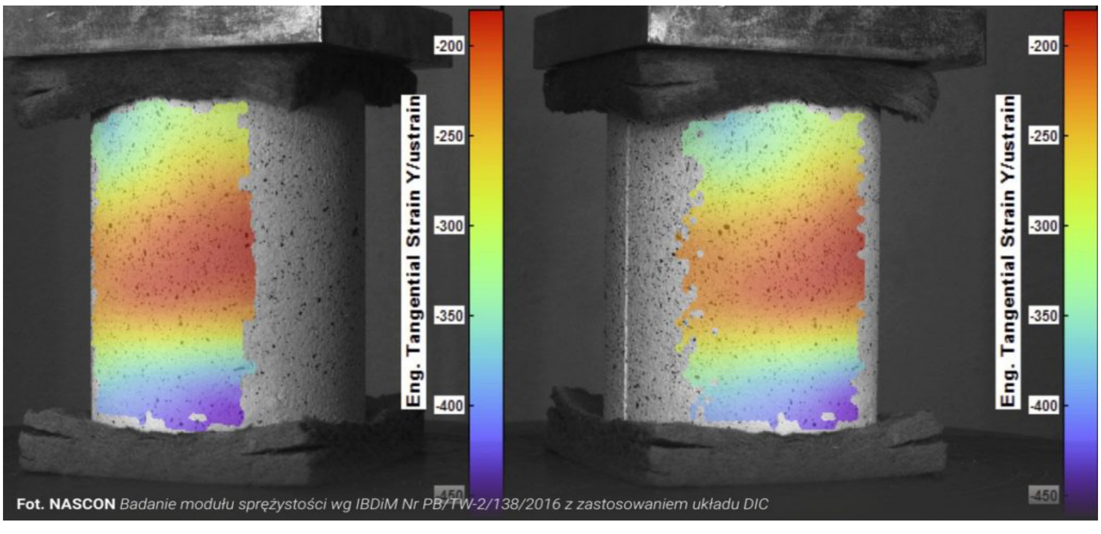


**Fig. 3.** View of the specimen with a strain distribution

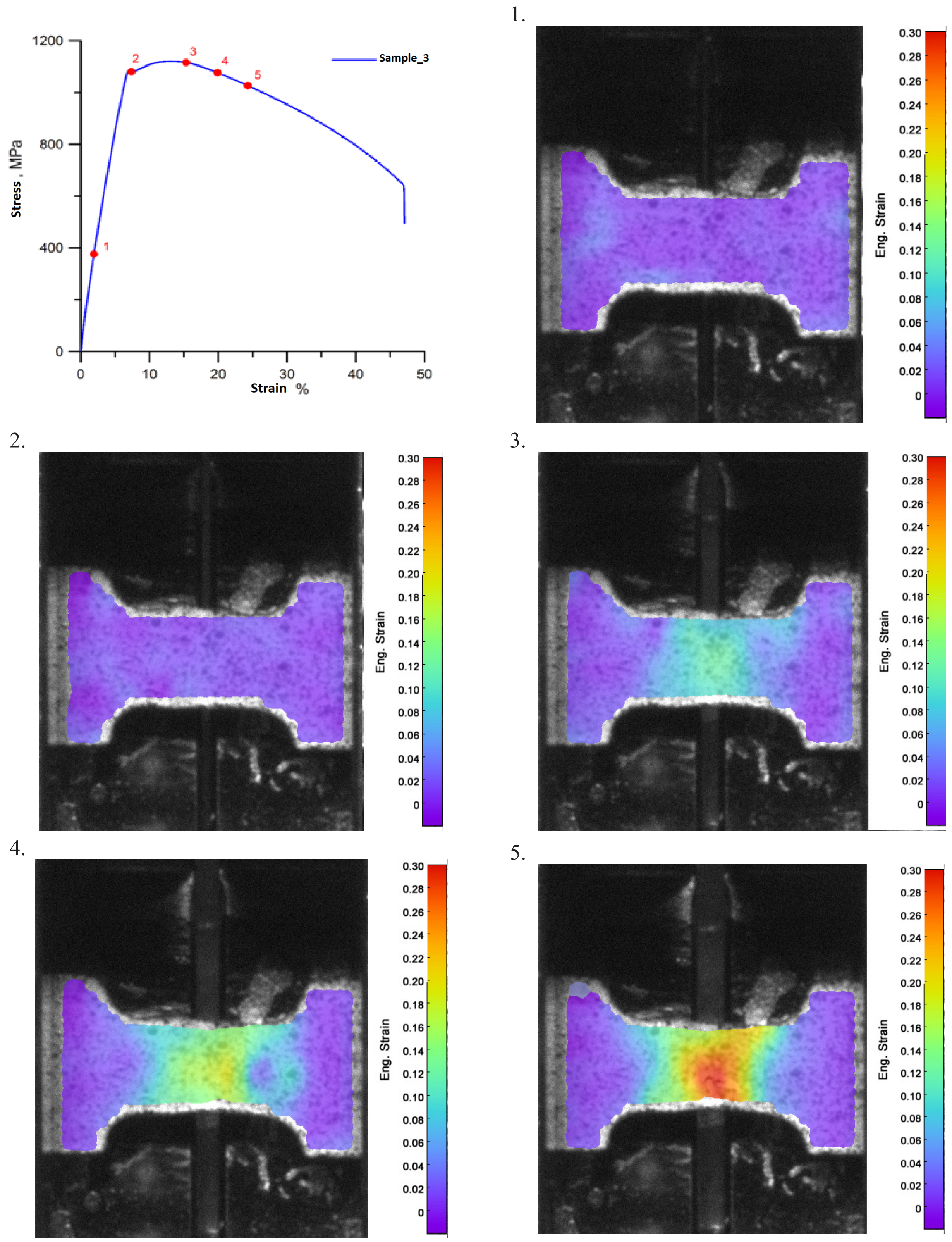


**Fig. 4.** The strain distribution of the test specimen in successive stages of the test

### 3.1. Yield strength of the investigated material

The stress-strain diagrams are shown in Figure 5, while the detailed results are given in Table 2. Preliminary analysis showed that the obtained test results can be divided into two categories. With a clear yield point for samples 1–4 and without a clear yield point for samples 5–12, in which a conventional yield point was determined. This situation proves that specimens 1–4 were made of material delivered in a different state than specimens 5–12, this issue requires further investigation, but for the purpose of this paper, it was decided to omit specimens 1–4. The examination of the second group of samples showed that sample no. 10 was significantly different from the other results. In order to check whether the sample was subject to significant error, the Q-Dixon test (Kręglewski, 2018) was conducted, establishing the level of significance $\alpha = 0.05$. For the tested value, the parameter $Q = 0.508$; was found to be greater than the critical value $Q_{kr} = 0.468$. Therefore, it was decided to reject the obtained result $Y_{0.2}$ for sample 10, as subject to significant error. Several reasons for this error are possible: a significant mistake made by the investigator, or this particular specimen might have made from another material. The remaining results were averaged to obtain the yield strength of the material equal to $Y_{0.2} = 636$ MPa. The confidence interval was also calculated for this measurement and it equaled 85.8 MPa.

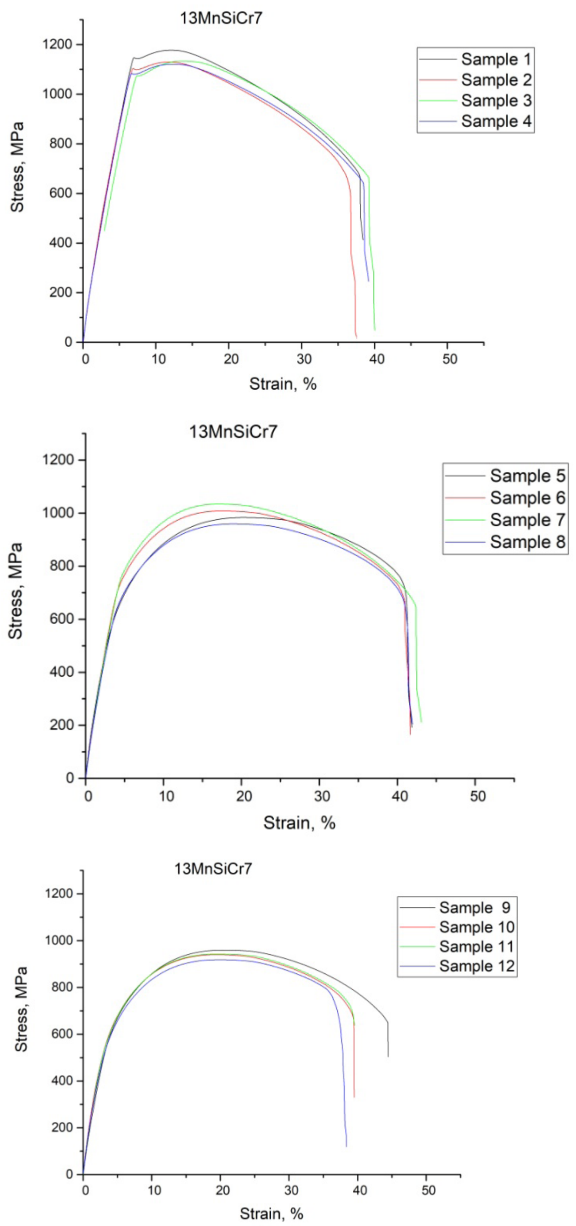


**Fig. 5.** Stress-strain curves

**Table 2.** Yield strength of 13MnSiCr7 steel for individual samples

| Sample | *YS* [MPa] | $Y_{0.2}$ [MPa] |
|---|---|---|
| 1 | 1148 | – |
| 2 | 1104 | – |
| 3 | 1074 | – |
| 4 | 1084 | – |
| 5 | – | 721 |
| 6 | – | 764 |
| 7 | – | 645 |
| 8 | – | 624 |
| 9 | – | 564 |
| 10 | – | 353 |
| 11 | – | 570 |
| 12 | – | 562 |

### 3.2. Young's modulus of the tested material

Young's modulus was determined by analyzing specimens 5, 6, 7, 8, 9, 11, 12 according to the relationship described in standard (European Standard EN ISO 6892-1:2019). The results are presented in Table 3. For the results, the confidence interval of the samples was calculated. The averaged Young's modulus was equal to $E = 230.18$ GPa, and confidence interval was equal to 20.4 GPa.

**Table 3.** Young's modulus of 13MnSiCr7 steel

| Sample | *E* [GPa] |
|---|---|
| 5 | 252.58 |
| 6 | 222.92 |
| 7 | 230.26 |
| 8 | 224.01 |
| 9 | 303.14 |
| 11 | 247.80 |
| 12 | 256.82 |

### 3.3. Relative elongation of the test material

Relative elongation of the material for the analyzed samples is presented in Table 4. Results were then averaged to obtain $A = 6.76\%$ and confidence interval was 0.25%.

**Table 4.** Relative elongation of 13MnSiCr7 steel

| Sample | *A* [%] |
|---|---|
| 5 | 6.78 |
| 6 | 6.74 |
| 7 | 7.03 |
| 8 | 6.80 |
| 9 | 7.43 |
| 11 | 6.42 |
| 12 | 6.10 |

### 3.4. Tensile strength of the test material

The tensile strength of 13MnSiCr7 steel was determined by finding the extremes of functions for stress-strain curves determined for the analyzed samples (Fig. 5). The results are summarized in Table 5. The values were then averaged to obtain the tensile strengths:

$$UTS = 972 \text{ MPa}$$

with a confidence interval of 36,56 MPa.

**Table 5.** Tensile strength of 13MnSiCr7 steel specimens

| Sample | *UTS* [MPa] |
|---|---|
| 5 | 984 |
| 6 | 1008 |
| 7 | 1035 |
| 8 | 959 |
| 9 | 959 |
| 11 | 943 |
| 12 | 919 |

## 4. Discussion

The values of the mechanical properties of 13MnSiCr7 grade steel obtained in the course of experiments were compared with the corresponding values provided by the manufacturer (Steeltec, 2016). The results of the comparison are presented in Table 6.

**Table 6.** Comparison of the mechanical properties of 13MnSiCr7 steel determined experimentally and specified by the manufacturer

| Property | Experimentally determined | Specified by the manufacturer | Difference |
|---|---|---|---|
| *YS* | 636.00 MPa | 750.00 MPa | 15.00% |
| *UTS* | 972.00 MPa | 980.00 MPa | 0.78% |
| *A* | 6.76% | 6.00% | 13.00% |

Several factors contribute to the resulting differences between the mechanical properties specified by the manufacturer and the values determined experimentally:
- Due to local non-metallic inclusions and elemental concentrations, it is impossible to obtain two identical melts; moreover, samples taken from different locations in the ingot may have different properties.
- The geometry of the samples deviated from standardized guidelines.
- The speed rate of the tool was not in accordance with the speed recommended by the standard.
- The standards do not consider a DIC system as a data acquisition device.

The comparison showed more than 10% differences between the experimentally determined values and those given in the material data sheet for yield strength and elongation, substantiating the fact that these properties are strongly correlated to changes in specimen length. Unlike tensile testing using an in-sample extensometer, the DIC system analyzes the entire length of the specimen.

The above summary shows that the difference between the experimentally determined properties and the manufacturer's characteristics only for tensile strength falls within the relative scatter range established by the Ministry of Economy, Labour and Social Policy (Rozporządzenie Ministra…, 2004). Elongation and Yield Strength falls within the accepted range.

## 5. Conclusions

The study found that:
- The proposed static tensile test kit, the Tension/Compression module working with a DIC system can provide more data about the strain concentration in the test object than the classical tensile test. It creates strain distribution maps on the test surface and the measurement range covers the whole sample.
- The mechanical property values obtained are not equal to those provided by the manufacturer.
- Only the percentage difference between the tensile strength obtained experimentally and the tensile strength obtained by the manufacturer meets the conditions for class 1 accuracy of testing machines (Rozporządzenie Ministra…, 2004). This parameter is not strictly correlated with strain value. Such a situation proves that there are differences between the strain measurement methodology in the experiment and the normalized methodology used by the manufacturer. Corrections will be necessary to ensure that the results obtained from the system can be compared with data from other extensometers.

The DIC system provides a wealth of useful information about the mechanical properties of materials under investigation, including the visualization of strain maps, observation of strain at distances omitted by other sensors, and its design allows it to be used with a variety of devices.

Further work on the issue is planned. In particular, an analysis of the behavior of the DIC system in experiments performed on a testing machine is considered and, at a later stage, the possibility of using the device for experiments involving a Gleeble 3800 metallurgical process simulator.

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