Possibility of using thermography and digital image correlation for determination of stress and strain distribution in deformation zone

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MOGUĆNOST PRIMJENE TERMOGRAFIJE I DIGITALNE KORELACIJE SLIKE KOD ODREĐIVANJA RASPODJELE NAPREZANJA I DEFORMACIJE U ZONI DEFORMACIJE

POSSIBILITY OF USING THERMOGRAPHY AND DIGITAL IMAGE CORRELATION FOR DETERMINATION OF STRESS AND STRAIN DISTRIBUTION IN DEFORMATION ZONE

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Abstract

Determining the strain flow and stress distribution in metallic materials during their deformation represents a significant challenge for researchers. The foil strain gage gave the possibility to test the actual stress in the deformation zone. Their application at higher deformations has proven to be limited, and does not give information on the entire deformation zone. With the development of digital technology, methods of digital image correlation (DIC) and thermography were developed. Their applications in researches today are more frequent, and are commonly being used for studying deformation of metals. The aim of this study was to determine the possibility of applying DIC method parallel with thermography to monitor the stresses distribution in deformation zone during the static tensile testing. The possibility of measuring with both methods on the same side of the sample, and the impact of markers required for DIC on the thermographic measurements, were tested. It has been proven that it is possible to use both methods on the same side of the sample without affecting one on the other. It was also found that by application of these two methods it is possible to observe the stresses distribution in the deformation zone.

Keywords: *deformation zone, thermography, digital image correlation, stress distribution*

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1. INTRODUCTION

Advances in technology increased demands on the quality of metallic and non-metallic materials during their application. For metal materials such as steels, the aim is to reduce the total mass of finished products by improving the mechanical properties without decreasing the application of the product. In the case of the constructions, modeling is first used to ensure that used metals will withstand certain loads. In order to successfully set up different models it is necessary to have complete information on the mechanical properties of the metal, behavior of his deformation and strains during deformation [1-3].

The biggest challenge to researchers is the study of the deformation zone and strain distribution within her. There are various methods to research the plasticity of materials [3-6]. The conventional methods of testing of mechanical properties do not give a complete picture of strain distribution within the deformation zone. In order to determine the amount of stress and deformation in some point of the deformation zone, strain gauges are commonly being used. They have proved to be very suitable for measuring the amount of strain in certain parts of the structure. Thus, scientists were able to measure the actual amounts of strain on different shapes and loads onto a tested piece [7,8]. However, setting strain gauges requires a large number of actions, a large number of samples and a large amount of information to be analyzed. Sometimes there is a need for repeating the experiment, such in case when strain gauge falls from specimen before the end of measurement.

Strain gauges give accurate results, which can be extrapolated to the whole piece, but only if we are sure that there is a homogeneous distribution of strain and stress. If this is not the case, it is possible to use multiple strain gauges, but there is still a limited number of measuring points, and this is limited by the surface of the strain gauges. The strain gauges have restraints when there are large amounts of deformation.

With the development of technologies, new methods for investigation of deformation zone are developed, such as a method of digital image correlation and thermography. These two methods are becoming more and more used during testing of different metal materials and in clarifying some phenomenon's that occur during the plastic deformation of the metal.

1.1. Thermography in metal testing

Thermography is based on the measurement of the temperature of the observed object in the infrared spectrum of radiation. It is well known that all the bodies up to 500 °C emit all of their thermal energy in the infrared spectrum. It is also a known fact that during deformation, due to the plastic work, there is an increase in the temperature of the deformed body [9,10]. In this way, by using an infrared camera as a basic tool for thermography, it is possible to detect and measure these temperature changes. Analyzing these temperature changes the information's on changes that occur in the deformation zone can be obtained. Method of thermography is a non-contact method and has no effect on the deformation zone during the testing. The basic conditions that must be fulfilled are to remove all surrounding disturbances that could affect the measured value.

The most influential parameter on thermography is the emissivity factor, it represents the ratio of the total energy of the real body radiation to the total energy of the ideal black body radiation at the same temperature [11,12]. The emissivity factor depends on the material, surface condition of the observed body, and the temperature at which the body is located. In order to obtain a uniform and known factor of emissivity, scientists usually apply a thin coat of coating on the surface of the sample [13]. Thermography has found its application in different branches of metallurgy, from testing in operating conditions up to laboratory testing of plastic deformation. Studies [9,10,14,15] have demonstrated that thermography can detect the beginning of plastic flow, regardless does the material have expressed or not the limit of proportionality. Thermography has proven that during the elastic deformation of metals there is a certain drop in temperature [16,17]. This is related to the thermoelastic effect that occurs in metals, and in our earlier studies it was associated with a change in volume that occurs during the elastic deformation of the steel [16]. Furthermore, thermographic tests allow measuring very small temperature changes such as the Lüders bands [10,18] and even to predict the localization of deformation and place of fracture on samples.

1.2. Digital image correlation in metal testing

Along with thermography, nowadays the method of digital image correlation (DIC) is been increasingly used for materials investigation. This method enables to determine the material flow in the deformation zone simply by measuring the changes in the position of markers that are placed on the surface of the samples [19-21]. To achieve a good contrast between markers and background, researchers commonly use white primer coating on the surface of the samples, and then they apply markers of different shapes and sizes using black paint.

Second basic requirement for a good deformation analysis using DIC is that the deformation process is recorded by an optical camera using the sufficiently high resolution, and at known time intervals. The camera must be in the optical plane with the observed sample to avoid distortion of recorded images and thus error in analysis of the measurement [19]. By recording of deformation during the plastic deformation, for example during static tensile testing, it is possible by subsequent analysis to determine the amount of deformation at each particular moment of the test.

Just like thermography, DIC is a contactless method that has no influence on the deformation of the tested samples. Available software packages provide a very accurate and relatively fast analysis of the recorded deformations, thus measuring actual displacements and determining deformation fields on the surface of the samples at different stress schemes [20,21]. The application of DIC is found in testing of different phenomenon’s during metal plastic deformation. Values obtained by this method researchers often use for modeling the material behavior during deformation.

By applying the methods of thermography and digital image correlation, it is possible to obtain new information's on material flow and development of deformation zone during plastic deformation of metals. However in studies researchers usually use one of mentioned methods, or in case of using both of them, they are not carried out on the same surfaces of sample. In order to be able to link the measured values of temperature with the strain and stress distribution in the deformation zone, it is necessary to measure the accurate values of deformations and temperature changes in the same points. Therefore, it is of great importance to conduct parallel research by using digital image correlation and the thermographic method on the same surface of the samples. Only then it is possible to obtain information about the exact temperature and deformation distribution at each point of the deformation zone.

The aim of this study is to determine the possibility of simultaneous application of the DIC method and thermography for observing the distribution of stresses in the deformation zone. Also, the influence of different surface preparation of samples, in relation to the commonly used one, will be determined.

2. EXPERIMENTAL PROCEDURE

For thermographic testing was used an infrared camera (VarioCAM® M82910 Jenoptik) with an uncooled microbolometer. This infrared camera has a sensitivity of 80mK, with possibility of recording up to 50 frames per second. The analysis of thermographic tests was carried out using Irbis 3 Professional software package. Deformation of samples was continuously captured using the Samsung DCR-SR-77E digital camera with CCD sensor, and the subsequent analysis was performed using MatchID 2D program for digital image correlation analysis. All studies were conducted on low-carbon steel St52-2N, the chemical composition of tested steel is given in table 1. To achieve deformation samples were stretched using Zwick 50kN universal tensile testing machine. Used samples had a rectangular cross-section with gauge length of 45x20x3 mm.

Tab. 1: Chemical composition of tested steels / wt %

Element	C	Mn	Si	Al	N
composition	0,13	0,77	0,18	0,02	-

As the one of the aims of this research was to investigate the possibility of parallel implementation of DIC and thermographic method on the same surface of the sample, first the impact of differences of sample preparation on the accuracy of the methods used should be investigated. To test these two 150x150 mm steel tiles were prepared. Both tiles were coated with a black matt coating with known emissivity factor of 0.95. This coating was selected for the needs of the thermographic method. By applying the coating it results in a uniform emissivity of samples surface. After black coating dried, white random markers for the digital image correlation were applied on one tile. Both tiles were kept under constant laboratory conditions for a period of 2 hours to equalize them to the ambient temperature. The contact thermometer was used to measure the exact temperature of the tiles and after that they were recorded with an infrared camera. The influence of markers on thermographic measurements was subsequently analyzed using Irbis3 Professional software package. The results of this test and image of tiles with and without markers are given in the results and discussion section.

Samples for static tensile tests were prepared in the same way by applying black coating and white markers. After drying they were subjected to uniaxial static tensile load, until the fracture. The whole process of deformation is simultaneously captured by an infrared camera and a digital optical camera. Subsequent analysis of recorded videos and thermograms was performed using MatchID 2D and Irbis3 Professional software packages for the analysis of digital image correlation and thermography.

3. RESULTS AND DISCUSSION

Before the recording and analysis of samples deformation during uniaxial tensile stretching, the impact of the sample preparation for subsequent analysis of thermographic measurement and digital image correlation was investigated. The appearance of the tiles with and without white markers is given in Fig. 1.

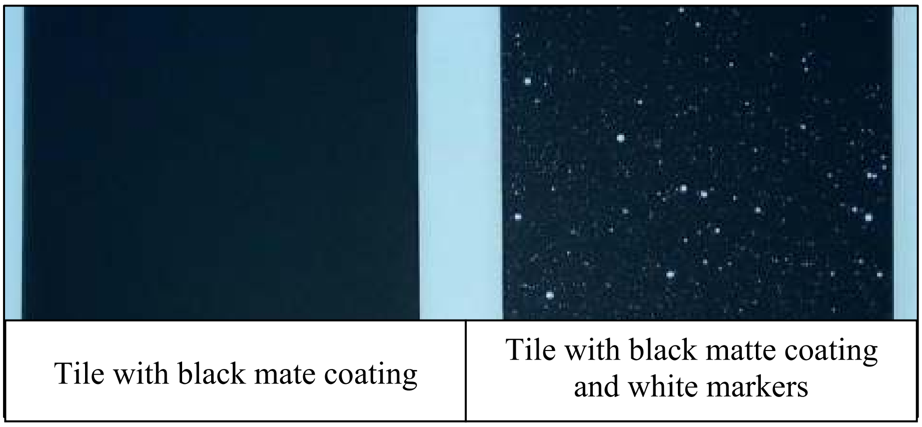


Fig. 1: Tile with and without white markers

Clearly, it is possible in this way to apply random white markers that have a great contrast to the background. In both cases a thermographic analysis of the recorded temperature distribution was performed to determine the effect of white markers on temperature distribution, Fig. 2

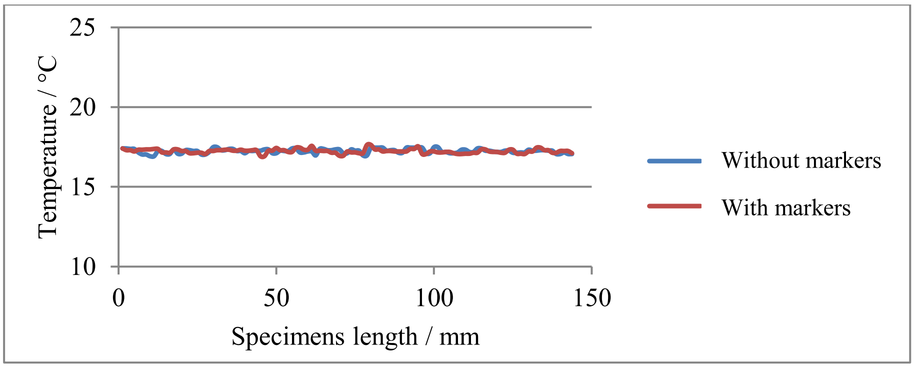


Fig. 2: Measured temperature values with and without white markers

The temperature distribution over the width of the tested tile with only the black coating is shown on Fig. 2 by the blue line, and the red line represents the temperature readings at the same conditions on other tile that has random white markers. From the temperature distribution in Fig. 2, it can be seen that white markers have no significant influence on the accuracy of thermographic measurements of the temperature distribution. The deviations in the temperature measurement are not higher than the usual noise that occurs during thermographic measurements. Also, DIC analysis has shown that it is possible to achieve correlation in the case when white markers are used on a black surface. This proved that the samples can be prepared in this way, and samples for static tensile tests were prepared in the same way. The results of the static tensile test are shown in the form of the force-elongation diagram, Fig. 3. The results of the thermographic and the digital image correlation analysis are given on Fig. 4.

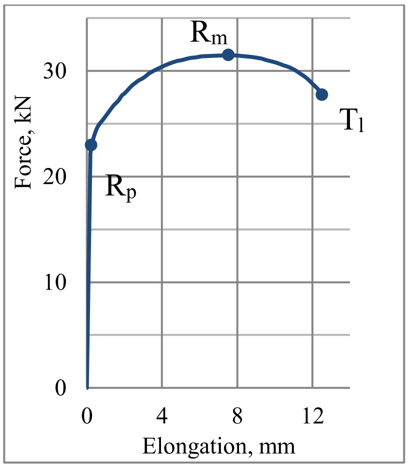


Fig. 3: Diagram obtained by static tensile test

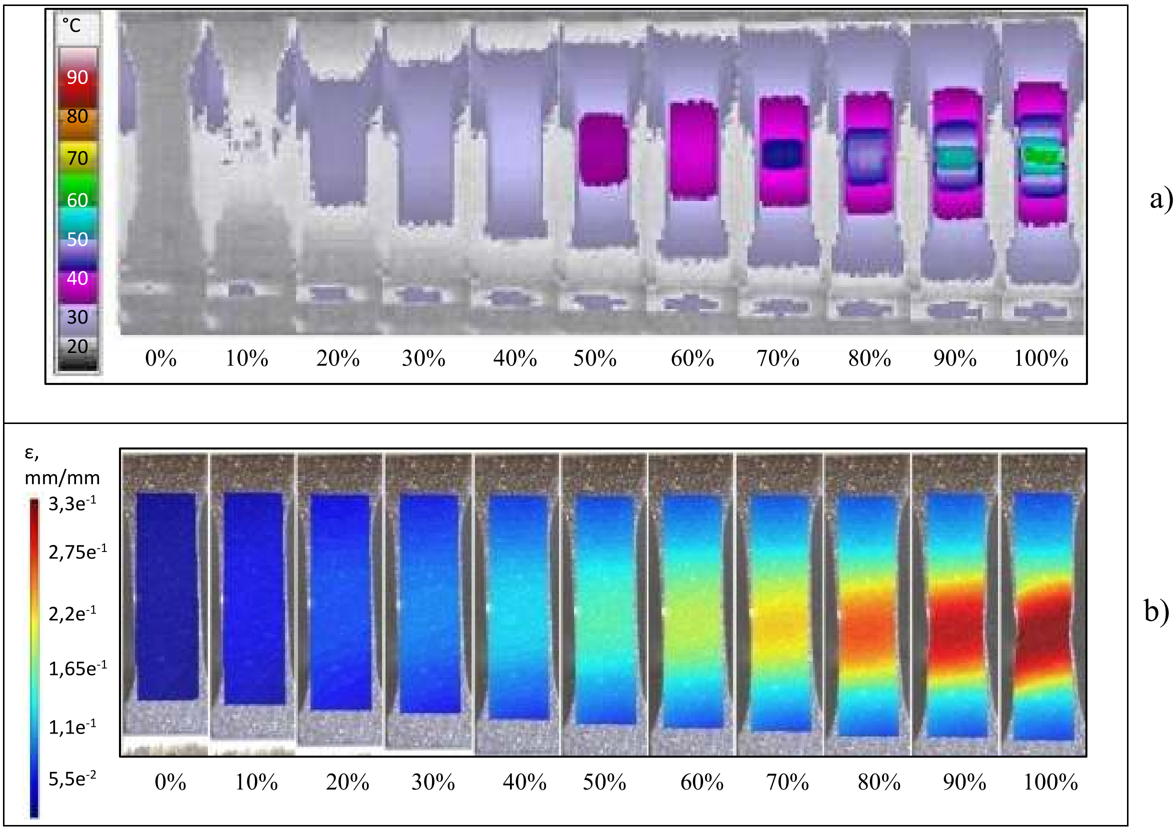


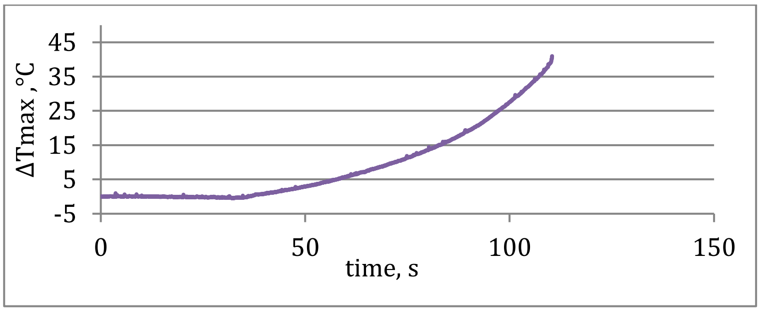
Fig. 4: Results of parallel thermography and DIC method during the testing

a) Temperature change for every 10 % of total deformation

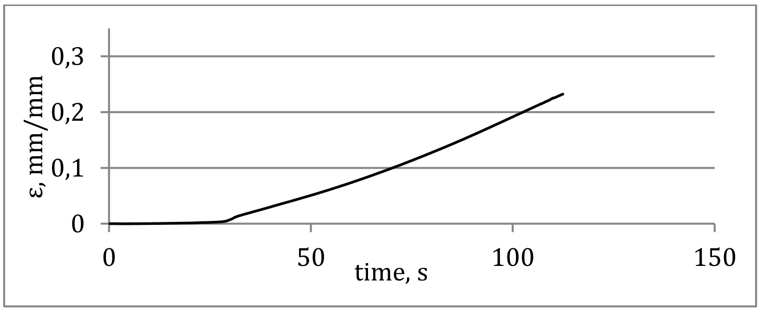
b) Deformation maps for every 10 % of total deformation

Static tensile test gave the basic mechanical properties of the steel, and on the diagram, Fig. 1, the point of proportionality limit (R_p), tensile strength (R_m) and the fracture point (T_1) are indicated. It can be seen that tested steel does not have expressed point of proportionality limit, and the resulting deformation at fracture was $\varepsilon = 0.17$ mm/mm with the average tensile strength of 530 MPa.

During the plastic deformation of steel, all from the beginning of the plastic flow of steel, Fig 3 point R_p, up until the fracture of the samples, Fig 3 point T_1, analyzes were carried out of thermographic measurement and digital image correlation. Using methods of DIC and thermography the values of deformation and temperature distribution in the deformation zone were obtained, in the whole period of deformation. On Fig. 4 a) there are shown the thermograms of recorded temperature changes that occurred due to the deformation. Compared to the deformation maps in the same points, obtained by the DIC analysis, Fig. 4 b), it can be seen that the temperature changes are following the deformation, which was to be expected. It can be seen that during deformation, strains and temperature changes are localized in the central part of the samples. After reaching tensile strength, R_m Fig. 3, the deformation now continues in the narrow part of the neck, and this is followed by the temperature increase in same part of the sample, Fig. 4. By the quantitative analysis of the measured values using DIC and thermography, diagrams of maximum temperature and deformation changes over the entire gauge length of samples were obtained, Fig. 5.



a)



b)

Fig. 5: Comparison of the obtained results with DIC and thermography

a) Maximum temperature change during stretching of samples
b) Deformation during stretching of samples

Fig. 5 displays the diagrams in actual measured values of temperature change and strain during stretching of the same sample. It is noted that although the tested steel did not have a clearly expressed yielding point, by using thermography and DIC one can determine the beginning of the plastic flow of the tested steel simply and with ease. On diagrams of temperature and deformation changes, this point is clearly visible. In the case of temperature distribution, this is the point at which the first positive temperature change occurs, and this occurs in our research near 29th second of the experiment. Up to this point there was recorded a slight decrease in temperature, down to -0.45 °C. This is related to a thermoelastic effect occurring during elastic deformation [15,16]. Up until that point DIC method does not show any significant change in deformation, Fig. 5b). At the point when the first positive change in temperature is detected by thermal camera, DIC method also shows a significant jump in the change of strain. Thereafter, the strain increases during the entire stretching period, which is equally followed with the temperature increase, Fig. 5b) and Fig. 5a), all up to the point of the specimen fracture, point T_1 on Fig. 3.

On the diagram of temperature change, Fig. 5a), when the tensile strength of the steel is reached (Fig. 3, point R_m), it is noted that the curve of temperature increase changes its inclination. Until now it has not been established that this phenomenon was further explored. The deformation change also has a certain change in slope curves, but much less pronounced, Fig. 5. It is possible that in the point of tensile strength there really is a momentarily change in the inclination of both curves, since at this point there is localization of deformation and formation of the neck, however this we cannot claim with certainty. Firstly, because the curves of temperature change and deformation are not linear, they already have a certain slope in their growth, and this requires additional research.

4. CONCLUSION

The conducted studies have shown that parallel DIC and thermography can be performed on the same surface of the test sample. The white markers did not have any negative influence on the results of thermographic analysis.

By the parallel performing of thermographic analysis and digital image correlation it is possible to obtain new and accurate information about temperature and deformation changes in any point of the deformation zone. In this way it is possible to get a clearer picture of the material flow. By knowing the exact amount of deformation, it is possible to look at the temperature change as distribution of stress in deformation zone, all because the temperature change is the direct result of changes in stress and strain.

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