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Testing the Tensile Features of Steel Specimens by Thermography and Conventional Methods

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The paper shows the results obtained in the simultaneous testing of DX55D steel specimens using conventional methods and thermography. The main aim of the testing was to relate the temperature changes of the specimens, continuously recorded by thermography, with the stress – extension diagram. It enables to predict reaching the critical stresses which cause the appearance of fractures and to define the criteria for determining the maximum sample temperature alteration in the field of elastic and elastic-plastic strains.

Key words: **thermography, fracture mechaniques, critical stress, tension, steel.**

Introduction

THERMOGRPHY is a method which provides the analysis of thermo-elastic stress, based on the measurement of infrared radiation emitted by the component surface exposed to dynamic or static, linear elastic or plastic strain and its conversion into a visible image, thermogram [1,2]. The surfaces emitting various amounts of infrared radiation can be differentiated on the thermogram by various colors or brightness levels, whereas the surfaces emitting the equal heat amounts have the same color (isothermal surfaces). Thermography is today used in engineering, medicine, criminology, biology, etc. [1-16] as an alternative or a complement to conventional inspection technologies.

The industrial application beginning of IR thermography is related to the year of 1965, when the first equipment with cooled detectors was manufactured, whereas the first model with microbolometer was introduced in 1997 [1, 2]. The image quality has been improved and the direct input of correction factors into the camera has been provided due to necessary compensations. The advanced infrared array detector technology and high speed digital processing have been combined to improve dramatically the applicability of the thermoelastic stress analysis [2, 3]. Thermography has become one of the most significant methods in the preventive maintenance of the facilities in many industrial building complexes.

The introduction of thermography, as a non-contact testing, inspection, monitoring and maintenance method of complex structures, operating in the real conditions of the dynamic load, requires extensive research [1, 2, 5, 7, 12, 14]. The assessment of heat dissipation on a structure under dynamic loading can give information on the damage mechanism involved [4, 8, 12, 14]. In order to calculate the temperature of the observed object from the radiation reaching the camera sensor and to link it with stresses and early fatigue, it is necessary to know the properties of the object surface, the temperature of the surrounding objects, the camera distance from the tested object, the air temperature and relative humidity [2].

Since it is very difficult to apply infrared thermography in the exploitation conditions, the first part of the tests was performed in the laboratory conditions on steel specimens.

The conventional methods of fracture mechanics were applied simultaneously with the thermography, on the samples of basic material and welded joints [1, 8]. Elements with square cross-sections are often integral parts of structures. For this reason, a series of Č.1212 (EN 10083-1 DX55D) specimens with square cross sections has been investigated. Tensile tests and fatigue tests have been carried out. In this article, the results of the tensile and thermography tests regarding the basic material will be presented. The fatigue behavior of materials under operating conditions is not identical to that determined under laboratory conditions with idealized specimens. The local fatigue strength in the component is influenced by stress concentrations, temperature, forming processes, residual stresses, load sequence effects, etc. The material homogeneity and even stress distribution on the cross-section are assumed during the experimental results discussion and numerical simulation.

The obtained results confirm that it is very useful to use thermography for early diagnostics of material behavior in laboratory conditions, because that is the base for application in tests and monitoring of complex structures in exploitation conditions.

Experiment

The experimental setup for testing the tensile features of specimens is illustrated in Fig.1a. Tensile testing and thermographic measurements were performed simultaneously.

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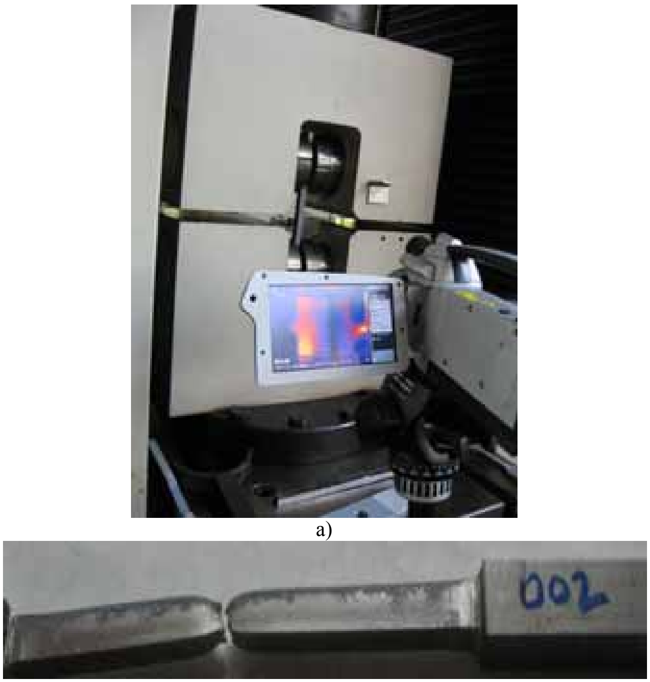
The testing of specimens was carried out on the electromechanical testing machine, with the displacement and the strain (extension) control at room temperature. The tension speed was 10 mm/min. The extension was registered using a double extensometer. The precision of the extensometer measurement is ±0.001 mm.

The DX55D steel is very often used for the production of structures exposed to dynamic load and low temperatures, due to which, in addition to the sufficient strength, it must also have good toughness or ductility. The more information about the experiment is in [9].



a)

b)

Figure 1. a)Tension test equipment and b) specimen after the test

The specimen geometry and dimensions are shown in Fig.2. The samples were coated using grey paint with known uniform emissivity in order to improve their emissive properties.

The therma CAM SC640 Infrared camera [2], FLIR Systems, has been used for recording thermograms. The camera resolution is 640 x 480 pixels. It was positioned at a distance of 0.5 m from the sample surface. The camera sensitivity is 60mK at 30°C, the field of view is 24°x18°, the minimum focus distance is 0.3 m, the spatial resolution is 0.65 mrad, the recording frequency is 30 Hz and the electronic zoom is 1-8x continuously. The detector type is a Focal Plane Array, non-cooled microbolometer of 640 x 480 pixels [2]. The spectral range of camera is 7.5 to 13µm, whereas the temperature range is from -40°C to +1,500°C, with a precision of ±2°C, ±2%. The camera is provided with the automatic correction of emissivity and atmospheric transmission based on the distance, atmospheric temperature and relative humidity. It simultaneously makes video and thermographic recordings or tracks.

The therma CAM Researcher software is capable of measuring temperature at spots, on lines and in selected areas of various shapes and dimensions, as well as of showing isotherms using the gradation of grey or the palette of various colors and shades.

Experimental results and discussion

The test results are shown simultaneously in order to comprehend the possibilities based on the comparative analysis and to define a criterion for applying the thermography in predicting material behavior.

The temperature changes (blue line), some thermograms and the stress-extension curve (black line) for one specimen are illustrated in Fig.2.

During the tensile testing of the DX55D steel specimen, the specimen elongation of almost 30mm occurred (Fig.2). The experiment lasted about 3 minutes, almost 180s. The thermo camera recorded the images 30 times per second, so that the diagram of temperature changes is obtained with 5500 measurements (each thermogram gives one measurement value).

Fig.2 shows the diagrams of stress vs. extension and maximum temperature vs. time on the surface of the sample. Some characteristic points are illustrated with corresponding thermograms: the beginning of elastic deformation, the beginning of plastic deformation, reaching maximum force, the homogeneous plastic deformation to the final fracture of the specimen.

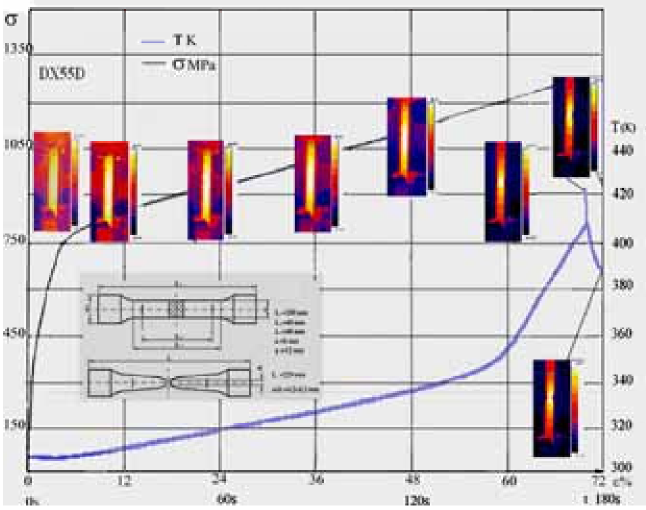


Figure 2. Diagrams of stress vs. extension and temperature changes vs. time with thermograms in specific points for the DX55D specimen

The analysis of the results presented in Fig.2 shows that in the first 10 seconds the force reaches 42 kN. The temperature of the sample was not changed and elastic deformation occurred within the specimen. The total elongation is 2 mm. The increase in force of only a few kN leads to the appearance of plastic deformation. The maximum tensile force is about 47kN. From 12s to 146s, the temperature increases from 305K to 342K with a constant gradient, and the specimen total elongation is 24 mm. Then a rapid increase in temperature occurs. 170 seconds after the beginning, the specimen elongation reaches 29 mm. At the same time, the specimen neck is formed. In 170th second a sudden jump in temperature occurs and the specimen cracks. After that, the temperature decreases. The diagrams stress vs. extension and maximum temperature vs. time show that the DX55D specimen material is ductile.

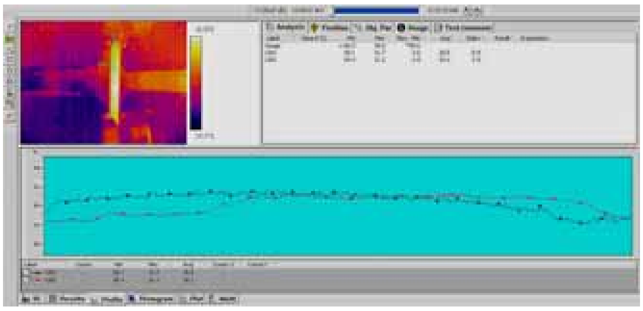
Table 1. Temperature values for some parts of the temperature changes vs. time diagram

t (hh:mm:ss:xxx)	*Tmax* (K)	*t* (hh:mm:ss:xxx)	*Tmax* (K)
12:09:07,495	304.931	12:10:09,755	317.483
12:09:07,528	304.878	12:10:09,788	317.466
12:09:07,563	304.907	12:10:09,821	317.427
12:09:07,595	304.907	12:10:09,855	317.423
12:09:07,628	304.892	12:10:09,888	317.444
12:09:07,661	304.849	12:10:09,920	317.462

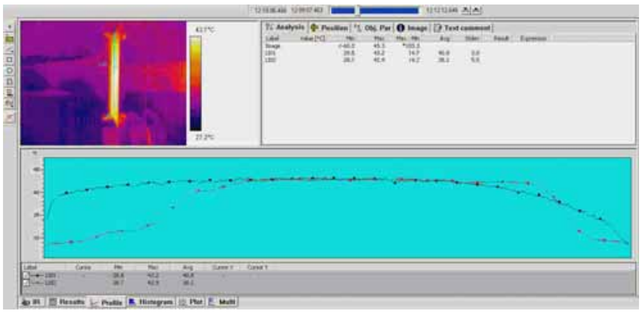
12:09:07,695	304.897	12:10:09,954	317.449
12:09:07,728	304.820	12:10:09,986	317.500
12:09:07,761	304.897	12:10:10,021	317.526
12:09:07,794	304.830	12:10:10,053	317.543
…………………	……….	…………………	……..
12:12:02,233	407.369	12:12:12,349	373.085
12:12:02,266	407.892	12:12:12,382	373.085
12:12:02,299	421.394	12:12:12,415	373.096
12:12:02,332	423.358	12:12:12,448	373.102
12:12:02,365	423.358	12:12:12,482	372.968
12:12:02,398	423.358	12:12:12,515	372.936
12:12:02,432	423.358	12:12:12,548	372.854
12:12:02,464	423.358	12:12:12,581	372.857
12:12:02,497	422.243	12:12:12,614	372.752
12:12:02,530	420.542	12:12:12,648	372.673

The therma CAM 640 has detected the temperature alteration and made a continuous track. Selected in time, the track sequences were chosen on the stress-extension curve as characteristic ones: load start, i.e. elastic strain start, then plastic strain start (Yield stress) point where the maximum force is reached, i.e. the end of homogenous plastic strain, up to the final specimen fracture and a thermogram after crack.

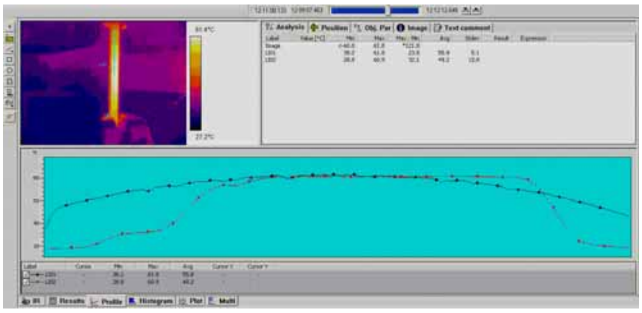
With the help of the Therma CAM Researcher software, the measuring lines were positioned in the middle of the specimen thermogram, L01 vertically and L02 horizontally at the spots where the fracture appeared (Fig.3) [2,3]. For a more precise analysis of the temperature variations on the tested specimen surface and its link to the mechanical properties, the detailed analysis has been conducted along the lines.



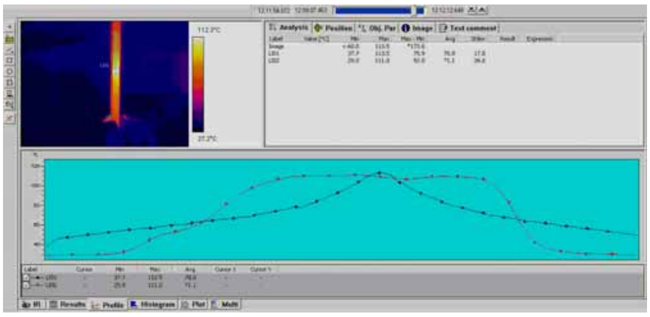
a) *t*=0s



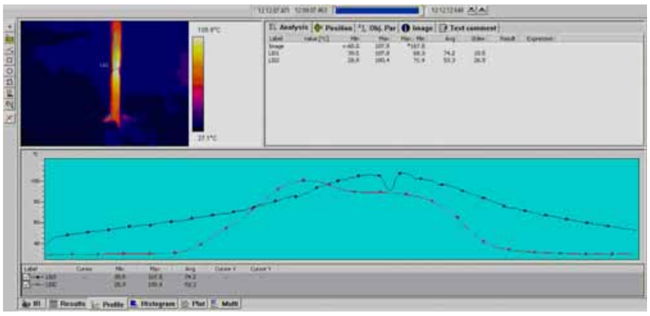
b) *t*=59s



c) *t*=119s



d) *t*=165s



e) *t*=180s

Figure 3. Thermograms and measured temperature values on the specimen surface

The upper right corner field indicates the minimum, average and maximum temperatures at the moment of recording. Fig. 3 (t=0s) shows the temperature at the beginning of the test, Fig. 3(t=165) shows the temperature immediately prior to the final crack, when its highest value has been detected. Fig. 3(t=180s) shows the temperature decrease after the crack.

The thermograms and the measuring lines on them, monitor plastic deformations and enable to determine the cross-section narrowing and the bar neck forming. Fig. 2 shows the dimensions of the specimen cross-section before and after stretching. The initial dimensions of 8x8mm were reduced to 4.2 x 4.3mm (the dimensions of the neck are about 52.5% of the initial one). The horizontal measuring line on the thermogram of the specimen (red line) is settled to include all the pixels on the surface of the bar. Fig. 4 (up to t=119s) shows that in the mention time there was no narrowing of the cross-section. Fig. 3 (after t=150s) shows the narrowing of the cross-section. The increased temperature is registered on the line segment that passes through the specimen (that part includes 11 out of a total of 19 measuring segments at the beginning, or 57%). On the other (peripheral) line segments, the temperature is about 302K which is the ambient temperature in the laboratory. These data are in good agreement with dimension measurements.

The temperature monitoring during the test by thermography, at all surface points, provides the detection of the initial temperature variation, indicating where the conditions for the crack initiation under the load impact are.

Conclusion

The experimental results for the tensile properties of steel specimens, considered in this paper, indicate the fact that the testing of metal structures requires new contactless methods, in addition to the conventional ones.

The tests using the methods of fracture mechanics were applied due to the safety assessment of metal structures. The conventional methods were applied simultaneously with the thermography. The obtained results confirm that it is very useful to use thermography for early diagnostics of complex metal structures in the exploitation or service conditions. It is of particular interest that this method allows not only qualitative test, such as finding flows, but also quantitative analysis of effects of flows on strength and durability of structural components.

The obtained results prove that infrared thermogarphy offers the possibility of nondestructive and in real time testing to observe the physical process of metal degradation and to detect the occurrence of energy dissipation. The results prove that the variations in temperature captured by the IR camera are strongly correlated to the loads actually applied to the specimens. Thermography can indicate very precisely (based on the surface temperature alteration) the appearance of elastoplastic strain zones as well as the initiation of cracks and their unstable propagation through material, without impairing the integrity of samples, components or an entire tested object.

Thermography provides simple and fast localization of existing defects in materials which could be spots of potential cracks.

Acknowledgments

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Ispitivanje zateznih osobina čelika termografijom i standardnim metodom

U radu su prikazani rezultati dobijeni istovremenim ispitivanjem čelične epruvete DX55D termografijom i standardnim metodama ispitivanja mehaničkih karakteristika materijala. Osnovni cilj ispitivanja je bio da se povežu promene temperature na površini epruvete, kontinuirano registrovani termografskim zapisom, sa dijagramom sila-istezanje. Ovo bi omogućilo procenu kritičnih naprezanja koji dovode do loma. Takođe omogućava definisanje kriterijuma za maksimalno dozvoljene temperaturne promene, koje pokazuju da je epruveta izložena elastičnim i elastoplastičnim deformacijama.

Ključne reči: **termografija, mehanika loma, kritično naprezanje, istezanje, čelik.**

Исследование натяжных свойств стали при помощи термографии и стандартным метода

В настоящей работе показаны результаты получены одновременным исследованием стальной пробирки DX55D при помощи термографии и стандартных методов механики излома. Основной целью исследования было связать измены температуры на поверхности пробирки, непрерывно регистрированы термографической записью, с графиком сил – расширения (вязкости). Этот процесс обеспечит оценку критических напряжений, которые приводят к излому. А тоже обеспечивает определение критерия для максимально и предельно выборочных измен температур, показывающих что пробирка находится под влиянием упругих и упруго-пластических деформаций.

Kly~evwe slova: **термография, механика излома, критическое напряжение, вязкость, сталь.**

Les essais sur les propriétés d'extension chez l'acier au moyen de la thermographie et la méthode classique

Les résultats des essais, obtenus par les recherches simultanées de l'éprouvette en acier DX55D à l'aide de la thermographie et les méthodes classiques de la mécanique de fracture, sont présentés dans ce papier. Le but principal de cet essai était de lier les changements de température sur la surface de l'éprouvette, enregistrés avec continuité par la thermographie, avec le diagramme force/extension. Cela permettrait l'estimation des tensions critiques qui produisent la fracture. Cela permet aussi la définition des critères pour les changements maximales permis de température qui démontrent que l'éprouvette est exposée aux déformations élastiques et déformations élastiques plastiques.

Mots clés: **thermographie, mécanique de fracture, contrainte critique, extension, acier.**