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Scientific paper
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Comparative testing of metal and welded joints by thermography and classical methods

The paper shows the results obtained in the simultaneously testing of steel spaceman's and welded joints using conventional methods and thermography. The main aim of testing was to relate the temperature changes of the specimen, continuously recorded by thermography, with stress – extension diagram. It is shown that the temperature changes on the specimen surface provide possibility to predict the critical stresses and to define the criteria for allowed maximum specimen temperature changes during elastic and elastoplastic strains, important for material caracterisation, diagnosis and monitoring of complex metal structures with welded joints by thermography.

Key words: *thermography, welded joints, tension, material caracterization*

1. INTRODUCTION

With regard to the exploitation safety of the metal and welded structures, the most important are the characteristics, which describe the appearance and growth of the fatigue cracks under the impact of the static and dynamic loads. Welded joint, like complex and heterogeneous structure, presents a critical point in welded structures. The conventional testing methods of the metal structures and welded joints are well known [Harwood, 1991]. The properties, obtainned by tension tests describe the global mechanical behavior of the materials, especially welded joints.

Thermography is a method which provides the analysis of thermoelastic stress [Maldague,1993; Flir, 2006], based on the measurement of infrared radiation, emitted by the component surface [Luong, 1998; Radovanović 2005; Man-Yong, 2006], which is exposed to dynamic or static, linear elastic or plastic strain and its conversion into visible image, thermogram [Bremond, 2000; Meola, 2005; Meola, 2004; Castanedo, 2005]. Recently infrared thermography has been applied successfully to study the early fatigue behavior of welded steel specimens in laboratory conditions [Ummenhofer. 2009]. This nondestructive test typically requires a sensitive infrared camera capable of detecting temperatures changes less than 0.05 mK.

In order to calculate the temperature of the monitored object from the radiation reaching the camera sensor and link it with stresses and early fatigue, it is necessary to know emissivity of the object surface, temperature of the surrounding objects, camera distance from the tested object, thermal losses, air temperature and relative humidity [Maldague, 1993]. Because of that, it is very difficult to apply infrared thermography for large objects inspection in the exploitation conditions.

Benefits of applying thermography as a non-destructive technique for inspection, monitoring and maintenance surveys of complex structures, operating in the real conditions of the static and dynamic loads, would be better used, if calibration diagrams for construction materials and welded joints exist [Kutin, 2009; Song, 2004; Avdelidis, 2005].

Thermography is a usfull NDT technique for the caracterization of corrosion in metallic materials, especially in welded joints, too [Hermanson1 1998; Lui, 2012].

This paper presents some results relating to making data base of thermographic tests in laboratory condition, on diferent construction steels and different thechniques welded joints. The experiemnt and calibration diagrams for: C45E, DX55D and S 355J2G3 steel welded spacemen are presented.

Thermography stands among the different NDT&E techniques, as an attractive tool for fast inspection of large surfaces exposed to different conditions [Crupi, 2010; Guo, 2011]

2. EXPERIMENTAL PROCEDURE

Experimental setup for steel specimen's tensile test is illustrated on the fig. 1. The testing of specimens was carried out on the electromechanical testing machine, with displacement and the tension control at room temperature. The tension speed was 10 mm/min. The extension was registered using double extensometer. The precision of extensometer measurement is ±0,001 mm. Tensile testing and

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thermographic measurements were performed simultaneously.

The steels C45E and DX55D are very often used for production of the structures exposed to static and dynamic loads and low temperature action, due to which, in addition to the sufficient strength, its must also have good toughness or ductility. Elements with circular and square cross-section are often integral parts of the structures. For this reason, a series of spacemen C45E with a circular section and DX55D with square section have been investigated.

Welded samples were joined using standard MAG (Metal Active Gas) welding process, designated as 135 according to ISO 4063. Shielding gas (M21) composed of 82% Ar and 18% CO_2 (EN 14175) and filler metal W3Si1 (EN 1668) were applied. Samples were investigated by radiography (EN 12517) for joint quality level B (EN 25817). Some tested specimens were removed from the lug assembly of the dredger anchor steel-wire rope Sch Rs 1760/5x32, made of S 355J2G3 steel.

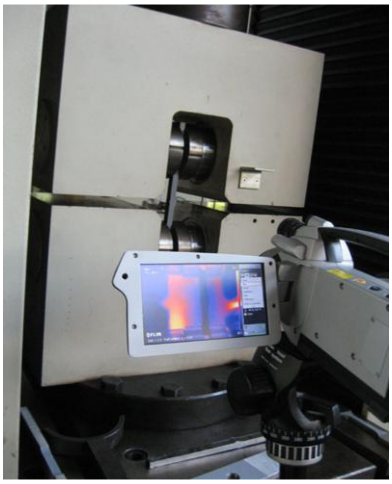


Figure 1 - Thermographic and tensile test equipment

Tensile test of steel spacemen is defined using EN 10002-1 standard. Tests of butt welded joints at room temperature, including the shape and dimensions of the specimens, as well as the testing procedure itself, are defined using EN 895 standard.

The samples have been coated using gray paint with known uniform emissivity, in order to improve their emissive properties.

Therma CAM SC640 Infrared camera, FLIR Systems, has been used for recording thermogram. The camera resolution is 640 x 480 pixels. It was positioned on the distance of 0.5m related to the sample surface. Camera sensitivity is 60mK at 30°C, field of view is 24°x18°, minimum focus distance is 0.3m, spatial resolution is 0.65 mrad, recording frequency is 30 Hz and electronic zoom is 1-8x continuously. Detector type is Focal Plane Array, non-cooled microbolometer 640 x 480 pixels [http://www1.flir.com/l/5392/2012-01-03/34OXW]. Camera spectral range is 7.5 to 13μm, whereas the temperature range is from -40°C to +1,500°C, with precision of ±2°C, ±2.

During tests, thermographic camera detected the temperature changes on spacemen surface and made the continuous track. The thermograms, as track sequences, were selected in characteristic time, which was chosen on the stress VS extension curve: force impact start, (elastic strain start), plastic strain start (Yield stress), point where is reached of maximum force, (end of homogeneous plastic strain), up to the final specimen fracture and finally after crack.

For real-time and static image analysis the associated software is used, because it contains powerful measurement and analysis functions for extensive temperature analysis, including isotherms, line profiles, area histograms, image subtraction capability and many more [http://www1.flir. com/ l/5392/2012-01-03/34OXW].

3. RESULTS AND DISCUSSIONS

The testing results are shown simultaneously in order to comprehend the possibilities based on the comparative analysis and to define the criterion for applying the thermography in predictions material behavior during inspection, monitoring and maintenance surveys of complex structures operating in the real conditions of the static and dynamic loads.

3.1. C45E steel spacemen

Detailed analysis of C45E steel spacemen is made to deeply understand the results of simultaneous tests. The geometry and dimensions of spacemen made of C45 E steel are shown in figure 2 and figure3 (upper right corner).

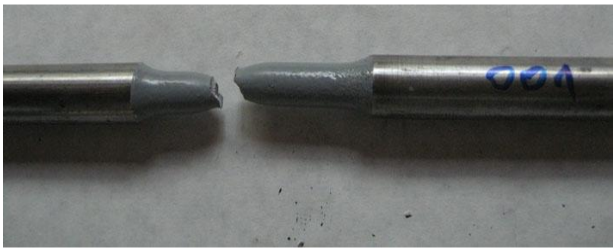


Figure 2 - Photo of specimen after tensile test

The temperature changes VS time (green line), stress VS extension curves (red lines) and some thermograms for tested spacemen are shown on the fig 3. for this specimen.

The diagrams (figure 3) show tensile test results for C45E steel spacemen. In 10th second after test beginning occurs elastically stretching. Temperature curve, a green colored diagram, is almost constant. It varies in the interval 302 ± 0.2 K. The appearance of plastic deformation and the formation of the neck are characterized by appearance of temperature changes with a constant gradient to 18 second and gradient with different slope between 18 and 33 seconds. The total change of the temperature during this interval is ΔT = 23K. In the 34th second, after elongation of 12.5%, spacemen crack occurs. Immediately prior to cracking, temperature rapidly increases to 346K, which gives the total increment of ΔT = 44K. Cooling begins immediately after cracking and after 4 seconds the temperature fall to 316K.

With regard to the testing of steel spacemen, the chart character corresponds to ductile material.

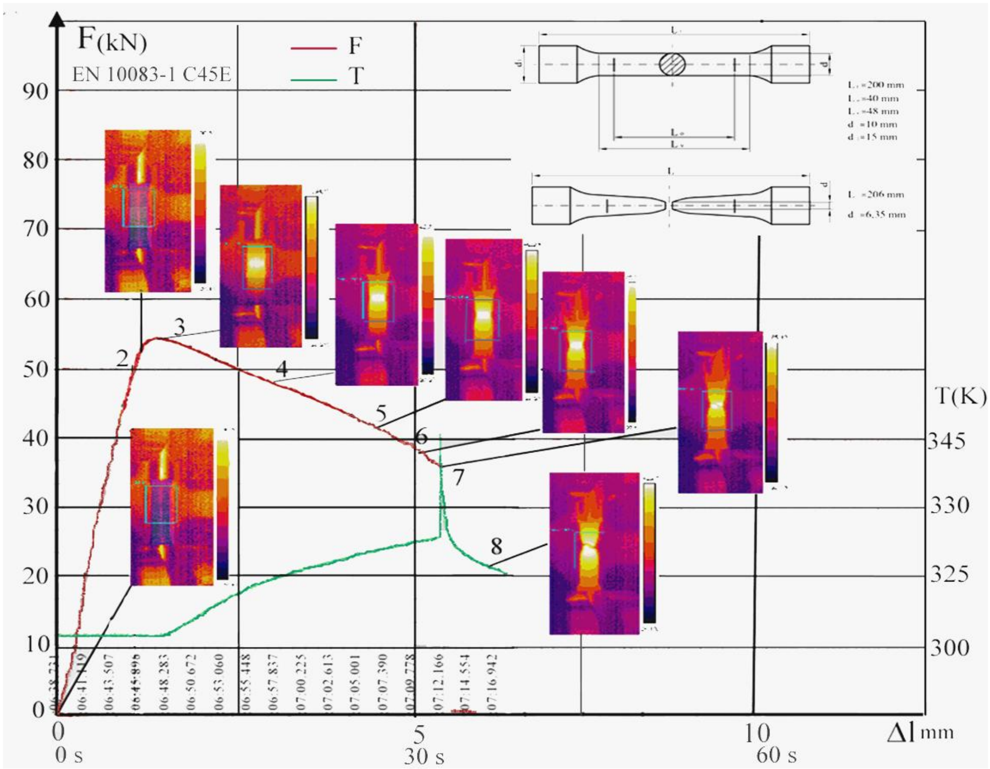
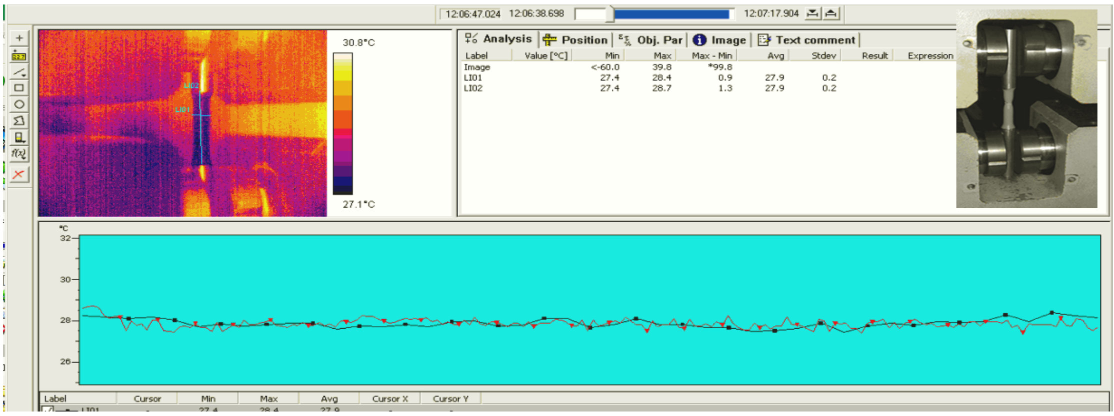


Figure 3 - Diagrams of stress VS extension and temperature changes VS time with thermograms in specific points for specimen C45E.

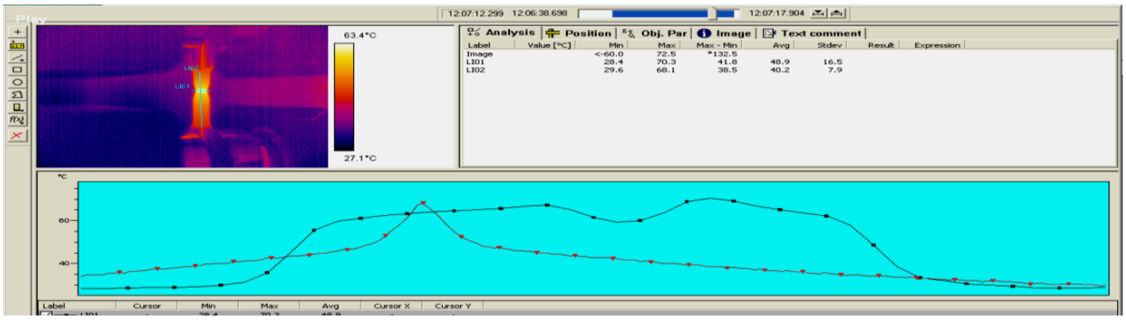
Therma CAM Researcher software makes possible to analyze the temperature in the 640 x 480 point of specimen surface. In the order to analyze temperature variations, two measuring lines were positioned in the middle of the recorded thermograms, L01 vertically and L02 horizontally. The results are presented on fig.4. The upper right corner field indicates minimum, average and maximum temperatures at the moment of recording and photo of spacemen after crack. Figure 4 (position 1) shows the temperature at the beginning of test, figure 4 (position 7) immediately prior to the final cracking, when the highest temperature was detected. Figure 4 (position 8) shows temperature distribution along lines in the moment when the cooling was began.

The thermograms and the measuring lines on them, illustrate plastic deformations and enable to determine the narrowing cross-section and forming the bar neck. Fig.3 (upper right corner) shows the dimensions of spacemen cross section before and after stretching. Initial diameter of 10mm was reduced to 6.35 mm (diameter of the neck is about 63.5% of the initial diameter). Horizontal measuring line on the thermogram of spacemen (blue line) is settled to include all the pixels on the test surface. Figure 4 (position 1) refers to the start conditions. Increased temperature was registered on the line part passing above spacemen surface (that line part includes 14, from a total 22 measuring segments, that is 64% of the total line length). These results are in excellent agreement with dimension measurements. The temperature monitoring during the test in all marked positions provide the detection of the initial temperature variation, indicating where are conditions for initiation of crack under the load impact. Table 1 contains the temperature changes during test. The sudden rising of temperature occurs immediately before cracking.

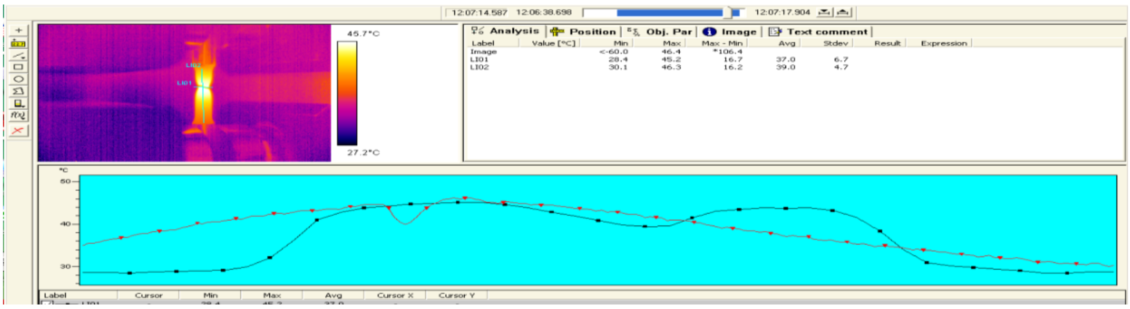
The crack tip stretching was investigated by scanning electron microscope. Figure 5 illustrates the ductile fracture, record by scanning electron microscopy (SEM), after the tensile test. With regard to the testing of steel spacemen, the chart character corresponds to the ductile, too.



(position 1)



(position 7)



(position 8)

Figure 4 - Thermograms and measured temperature values for specimen surface on lines L01 and L02

Table 1 - Temperature variation during tensile test

t (hh:mm:ss:xxx)	Tmax(K)	t (hh:mm:ss:xxx)	Tmax(K)	t (hh:mm:ss:xxx)	Tmax(K)
12:06:38.764	302,093	12:06:54.254	310,666	12:07:12.198	323,324
12:06:38.797	302,306	12:06:54.287	310,643	12:07:12.233	323,410
12:06:38.830	302,286	12:06:54.320	310,844	12:07:12.265	323,467
12:06:38.863	302,133	12:06:54.354	310,757	12:07:12.299	345,605
12:06:38.897	302,123	12:06:54.387	310,789	12:07:12.331	344,608
12:06:38.930	302,351	12:06:54.420	310,807	12:07:12.364	340,061
12:06:38.963	302,365	12:06:54.453	310,857	12:07:12.398	336,823
12:06:38.996	302,281	12:06:54.486	310,881	12:07:12.431	334,471
12:06:39.029	302,286	12:06:54.520	311,026	12:07:12.464	332,722
……………	………..	………………	………..	………………	………......

12:06:44.071	302,177	12:06:58.533	314,859	12:07:17.572	316,161
12:06:44.105	302,148	12:06:58.567	314,969	12:07:17.606	316,118
12:06:44.138	302,232	12:06:58.600	314,908	12:07:17.639	316,061
12:06:44.171	302,222	12:06:58.633	314,939	12:07:17.672	316,053
12:06:44.204	302,148	12:06:58.666	315,031	12:07:17.705	316,061
12:06:44.237	302,148	12:06:58.699	315,022	12:07:17.738	316,022
………………	……….	……………	………..	………………..	………......

3.2. DX55D steel spacemen

During tensil testing of DX55D steel spacemen, almost 30mm elongation of spacemen is occurred (figure 3). The experiment lasted about 3 minutes, almost 180s. Thermo camera recorded the images 30 times per seconds; so that the diagram of temperature changes is obtained with 5500 measurements (each thermogram gives one measurement value).

Figure 3 shows diagrams of stress VS extension and maximal temperature VS time on the surface of the sample. Some characteristic points are illustrated with belonging thermograms: the beginning of elastic deformation, then the beginning of plastic deformation, reaching maximum force, the homogeneous plastic deformation to final fracture of spacemen.

Analysis of results presented in fig. 3 shows that in the first 10s the force reaches 42 kN. Temperature of the sample has not changed and elastic deformation occurred with spacemen. Total elongation is 2mm. The increase in force of only a few kN leads to the appearance of plastic deformation. Max tensile force is about 47kN. In the time from 12s to 146s temperature increases from 305K to 342K with a constant gradient, and spacemen total elongation is 24mm. Then, rapidly increase the temperature occurs. 170s after beginning the spacemen elongation reaches 29mm. At the same time the spacemen neck is formatted. In 170s sudden jump in temperature and spacemen crack occur. After that, the temperature decreases. Diagrams: stress VS extension and maximal temperature VS time; show that the spacemen material DX55D is ductile.

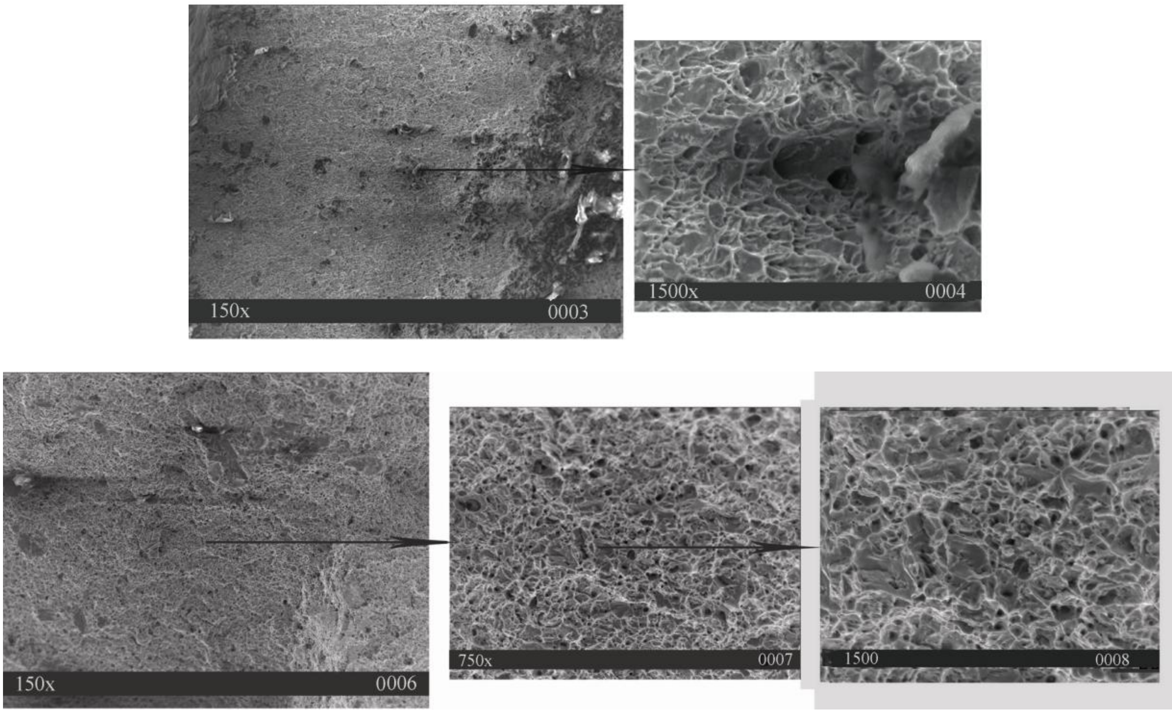


Figure 5 - SEM photo of ductile fracture

3.3. Welded butt joint specimen

Figure 4 illustrates the diagram of maximum temperature along the surface of welded spacemen versus time. The total time of load impact was 41,130s. If the temperature diagram is compared with the stress VS extension diagram of the welded butt joint specimen, it is seen that the significant temperature change hasn’t occurred up to the moment which is marked as the position 3 (around 8s from the start of force impact). In that period the temperature has varied around 303,7K. The temperature increase has occurred in the point 4. Stress VS extension diagram of the specimen indicates that material leaves the elastic zone and is entering the zone of elastoplastic strains. The temperature change is some ten degrees. The additional temperature gradient occurs in the point 6 (around 20th s). Temperature is increasing faster. The spacemen crack occurs in the point 10. At the moment immediate prior to specimen crack, the temperature increased around 100K. The cooling occurs after crack (point 11 on diagram).

With regard to the testing of welded joint, the curve character corresponds to the ductile material with approximate participation of homogeneous and non-homogeneous extension in the ratio of 1/2:1/2. The homogeneous extension exists up to the maximum force, whereas the non-homogeneous extension began up to the rupture, i.e. from the moment when the neck is created on the specimen.

The loss of yield stress phenomenon appearance for the specimens of butt welded joint is a consequence of non-homogeneity. The welded joint consists of seam metal, zone of heat affected and basic material. The various microstructures are present in the welded joint as a consequence of different chemical composition and thermal treatment. When the load attains the level when plastic strain should occur (in this case the basic material has the least strength) the appearance of non-linearity occurs.

Crack initiation is a highly localized event which is strongly affected by the random distribution of material properties and defects that exist at the micro structural level. The temperature monitoring during thermografic test provide the detection of the initial temperature changes, indicating where are conditions for appearance and growth of cracks under the load impact.

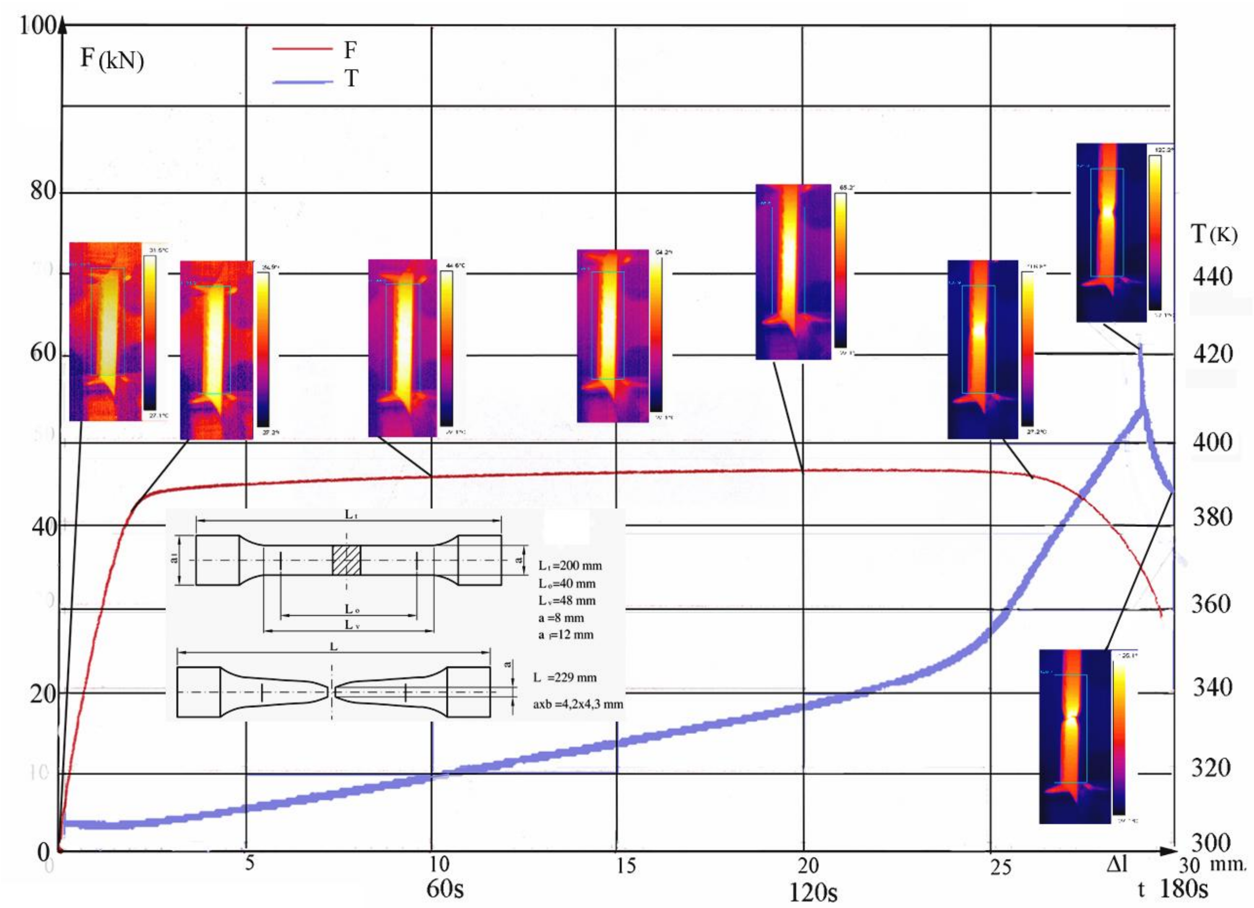


Figure 6 - Diagrams of stress VS extension and temperature changes VS time with thermograms in specific points for specimen DX55D

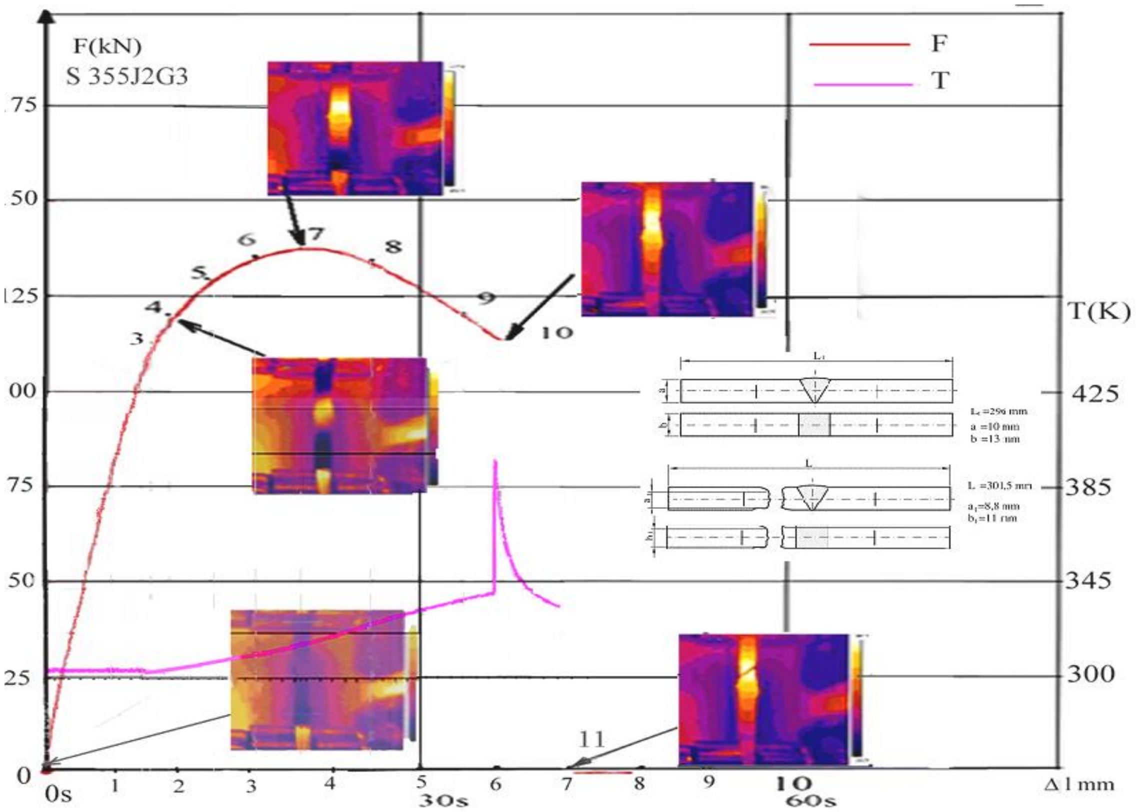


Figure 7 - Diagram of stress VS extension and diagram of temperature – time for butt joint specimen

4. CONCLUSION

The experiments and results of thermography application, simultaneously with the conventional methods, for testing the tensile properties of metal spacemen and welded joints are presented. The main aim of testing was to relate the temperature changes of the spacemen, continuously recorded by thermography, with stress – extension diagram. As a conclusion can be pointed out that:

The obtained results confirm that it is very useful to use thermography for early diagnostics of the complex structures in the exploitation or service conditions.

- This technology enables conducting stress analysis and estimation of fatigue limits in a nondestructive and non-contact method within a shorter period. The tensile test allowed obtaining visible data of surface stress distribution using thermography.

- This proves that the variations in temperature captured by the IR camera were strongly correlated to the loads actually applied to the specimens.

- The results, considered in this paper, show that its can be used for someone quickly make a conclusion on whether the temperature increase, sign that critical zone appeared in that place.

- Thermography provides simple and fast location of the defects in the material which could be the spots of the potential cracks initiation and growth.

- Infrared thermography has proven to be an invaluable tool to solve a wide range of scientific questions and problems related to the material caracterization and the reliable assessment of the structure integrity and life time.

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IZVOD

UPOREDNO ISPITIVANJE METALNIH UZORAKA I ZAVARENIH SPOJEVA TERMOGRAFIJOM I KLASIČNIM METODAMA

U radu su prikazani rezultati dobijeni simultanim ispitivanjem čeličnih uzoraka i zavarenih spojeva standardnim metodama i termografijom. Glavni cilj istraživanja je bio da se povežu temperaturne promene uzorka, snimljene termografijom, sa parametrima dijagrama napon – izduženje. Dobijeni rezultati su pokazali da temperaturne promene na površini uzorka, snimljene termografijom, omogućavaju da se predvidi kritični napon i da se definiše kriterijum maksimalno dozvoljene temperaturne promene tokom elastičnih i elastoplastičnih naprezanja, što je veoma značajno za karakterizaciju materijala, dijagnostiku i monitoring složenih metalnih konstrukcija sa zavarenim spojevima.

Ključne reči: *termografija, zavareni spojevi, naprezanje, karakterizacija materijala*

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