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Application of Thermography during Tensile Testing of Butt Welded Joints

This paper presents experimental results of comparative tensile tests of butt welded joints (P295GH) by the use of thermography and standard methods. During tensile testing the deformation of base and weld material is occurring. The occurrence of plastic deformation is accompanied by the temperature increase in the zone where plastic deformation is present. Test specimens were tested on electro mechanical tensile testing machine with the application of the control strain. These tests have shown the potentiality for the application of non-contact thermography during deformation of the material where the possibility for the estimation of stress conditions and prediction damage in welded structures and materials exists.

Keywords: *thermography, butt welded joints, tensile test, contactless testing, thermograms.*

1. INTRODUCTION

Welded structures are widely used in industry, since many products are made by welding [1]. The primary function of welded joint is to achieve inseparable connection between two elements in welded structure, then to sustain and/or transfer the required loads to the rest of the construction, and often to ensure hermetic connection.

There are many standard methods of welded joints' characteristics testing. Some of them are destructive, and some are nondestructive (NDT), but all have certain limitations in applications. The advantage of NDT testing is its application to the final product, without its destruction. In addition to standard testing, new methods such as thermography are used, especially in contactless testing of complex structures [2-4]. The thermography is based on the detection of the heat radiated by the body, which is under some stress. Infrared radiation of the body is converted into a visible image-thermogram. The zones with different temperatures can be distinguished on thermograms, enabling the detection of zones where plastic strain occurred.

The aim of this study is to examine the behavior of butt welded joints of steel P295GH, under the influence of tension stress, and to determine differences in the behavior of specimens samples obtained from welded joints in relation to the basic materials. Another objective of testing is to verify in laboratory conditions thermography as a method of contactless testing, which can be used for diagnosis and monitoring of stress conditions of complex metal structures in exploitation conditions. For this purpose, tensile testing and thermographic measurements are performed simultaneously. Results are displayed side by side, in order to make a comparative analysis.

2. MATERIALS

Welded joint is a structural unit consisting of the base material and weld metal. In the melting welding process in the presence of filler metal, weld metal emerges as the result of solidification of liquid mixture of filler metal and basic material. Weld metal is characterized by different chemical composition, microstructure and physical-mechanical characteristics in relation with the base material. Weld metal contains particles as inclusions, gas pores, and a number of different defects, whose presence is undesirable because they are the weak points in the weld metal structure.

Basic material with some structural changes below the solidus line, obtained during the welding process, is called the heat affected zone (HAZ) [1]. In relation with the basic material heat affected zone (HAZ) is characterized by changes in mechanical properties, such as the increase of hardness and decrease of ductility characteristics, especially for steels disposed to create brittle structures. Those changes depend of the type and thickness of base material, welding process, filler material, the type of welded joint, heat input, cooling rate, heat treatment and other relevant parameters.

From all above mentioned, it is obvious that the weld is a heterogeneous entity, whose behavior in the relevant conditions depends on many parameters.

The basic material in the experiments is non-alloy steel P295GH (EN 10028-2) with specified elevated temperature properties, widely used in pressure vessel production. These materials have relatively good weldability, especially at smaller thicknesses of the basic material. The structure of this steel is ferritic-pearlitic.

If the same basic materials are welded, filler material is selected according to the type of basic material, the selected welding process and functionality of the structure. Welding process used is MAG (Metal Active Gas), or 135, according to ISO 4063, and protective gas M21 (82 % Ar + 18 % CO_2), according to EN ISO 14175. As filler material electrode wire G3Si1 (EN 1668) was used, with the diameter of 0.8 mm, which

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gives better mechanical properties than the base materials.

3. A BRIEF REVIEW OF USED METHODS

Thermography is one of the recent NDT, non-contact methods, which is used to determine the local variance of temperature on a considerable object. Thermography has application in many branches of human activity: technology, medicine, biology, etc. [3-19].

The occurrence of a local temperature increase of the body exposed to static or dynamic load is caused by the heat release during the internal deformation process [2].

Analysis of the behavior of welded joints under the influence of tension stress was based on standard tensile tests. Thermography continuously recorded temperature changes on examined specimen. It enables possible prediction of the critical places for appearance of cracks and the definition of criteria for determining the maximum temperature changes in the specimen in zones where plastic deformations most probably do not appear.

Thermography has become one of the most significant methods in preventive maintenance of power plants, heating systems plants, gasification systems and so on. There are no sufficient data in the literature about the application of thermography in determination of stress condition in complex mechanical facilities exposed to dynamic or static loads in situ. It is known [2-5], that the radiation that reaches the camera sensor can determine the temperature distribution of the observed object and connect it with the plastic deformations. For proper interpretation of the recorded thermogram, it is necessary to know the properties of the object surface, the temperature of surrounding objects, the distance between the camera and the observed object, ambient temperature and relative humidity. In complex conditions of exploitation this is very difficult to implement. It is therefore necessary to make the initial tests in the laboratory on test specimen taken from the most significant parts of the examined structure [5-10].

In the study of thermomechanical and structural characteristics, conventional metallographic examination was performed, in order to determine the micro- and macrostructure of the tested sample. Hardness testing and radiographic testing in range of 100 % (EN 12517), for quality level “B” (EN 5817) were also performed.

4. EXPERIMENT

The experimental setup for specimen’s tensile features testing is shown in Figure 1, and the specimen after the testing in Figure 2. Dimensions of specimen, before and after the experiment, are presented in Figure 3.

Test specimens were prepared according to standard procedure. The survey was conducted in a number of test specimens.

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.

A surface of testing specimen had a low emissivity and acted as a mirror, which made measurements difficult. The welded specimens had surface zones with various optical and thermal emissivity, which depend of surface orientation, temperature, wavelengths. Various techniques were applied to solve low or uneven emissivity problems. Among them, covering the inspected surface with a high emissivity flat paint ($\varepsilon \sim 0.9$) is the most common one for imaging applications [14,18,19]. In order to improve emissive properties, the tested specimens were coated by grey, base metal, paint with emissivity $\varepsilon = 0.94$.

Infrared camera Therma CAM SC640, FLIR Systems, was used for the thermograms recordings [4]. The camera resolution is 640 × 480 pixels. Camera was positioned at a distance of 0.5 m from the surface of the sample. The sensitivity of the camera is 60 mK at 30 °C, the field of view is 24° × 18°, minimum focus distance is 0.3 m, the spatial resolution is 0.65 mrad, recording frequency 30 Hz, the electronic 1 – 8 × zoom continuously. The detector type is a Focal Plane Array, non-cooled microbolometer 640 × 480 pixels.

Figure 1. Tension test and thermography equipment

Figure 2. Specimen after the test

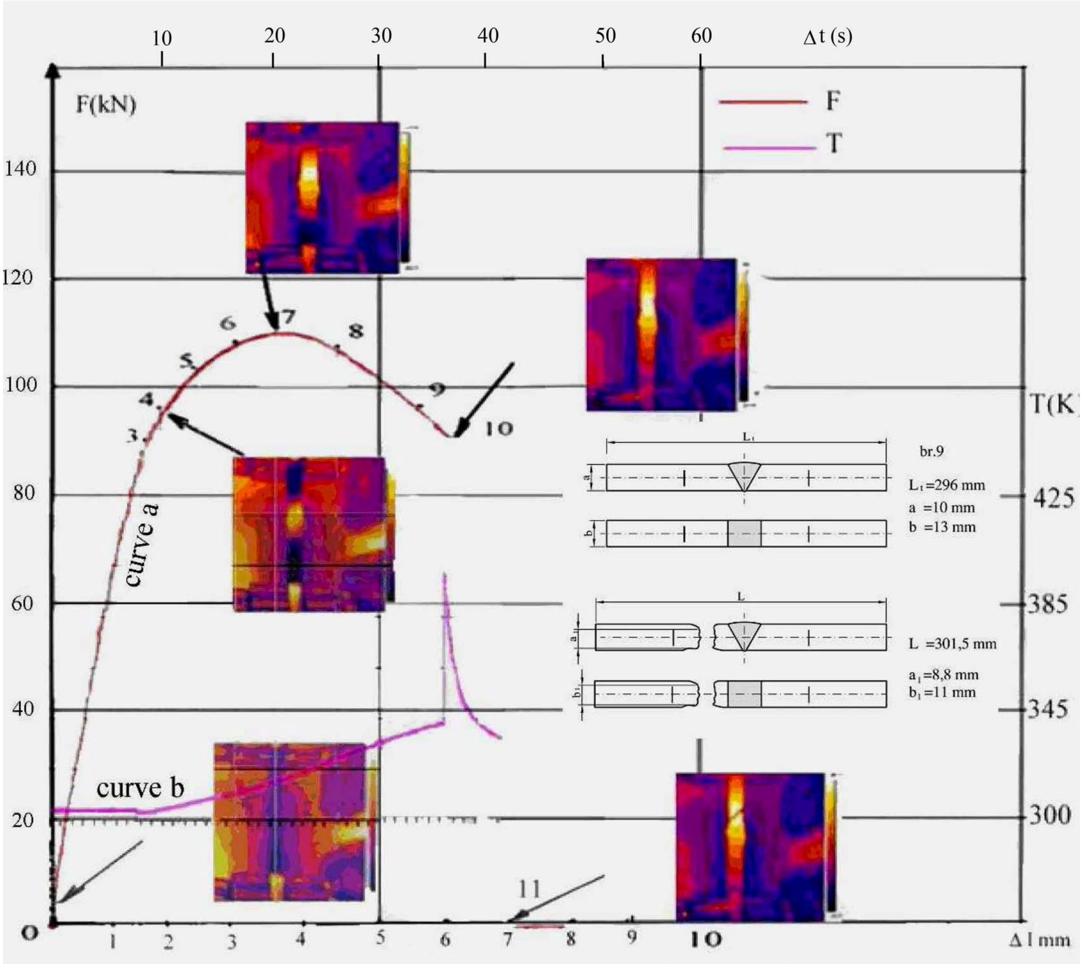


Figure. 3. Diagrams of force vs. extension and temperature changes vs. time with thermograms in specific points for the P295GH specimen

The spectral range of camera is 7.5 to 13 μm, and the temperature range is – 40 °C to + 1.500 °C, divided into three intervals, or optionally can operate up to + 2000 °C, with a precision of ± 2 °C. High quality thermograms, obtained by the camera ThermaCAM SC640 can be processed by specially developed software in versions customized for monitoring systems (ThermaCAM Reporter) and in versions suggested for diagnostics and research (ThermaCAM Researcher). The main purpose of this program is to process thermogram in real time. Besides, the program can process thermogram after the experiment as well.

The Therma CAM Researcher software can measure temperature at spots, on lines and in selected areas of various shapes and dimensions, and shows isotherms using the gradation of grey or the palette of various colors and shades. The camera is provided with the automatic correction of emissivity and atmospheric transmission based on the distance, ambient temperature and relative humidity. It simultaneously makes video and thermographic recordings or tracks.

5. RESULTS AND ANALYSIS

The test results are presented in Figure 3: diagram force – extension (curve a), and maximum temperature changes during the testing (curve b). Some characteristic points are illustrated with corresponding thermograms: the beginning of elastic deformation (start of experiment), the beginning of plastic deformation, reaching maximum force, the homogeneous plastic deformation and finally fracture of the specimen. Temperature measurements in different measurement lines are also presented (Fig. 4). Measurement lines are placed on the specimen's characteristic zones: basic materials (BM), heat affected zone (HAZ) and weld metal (WM).

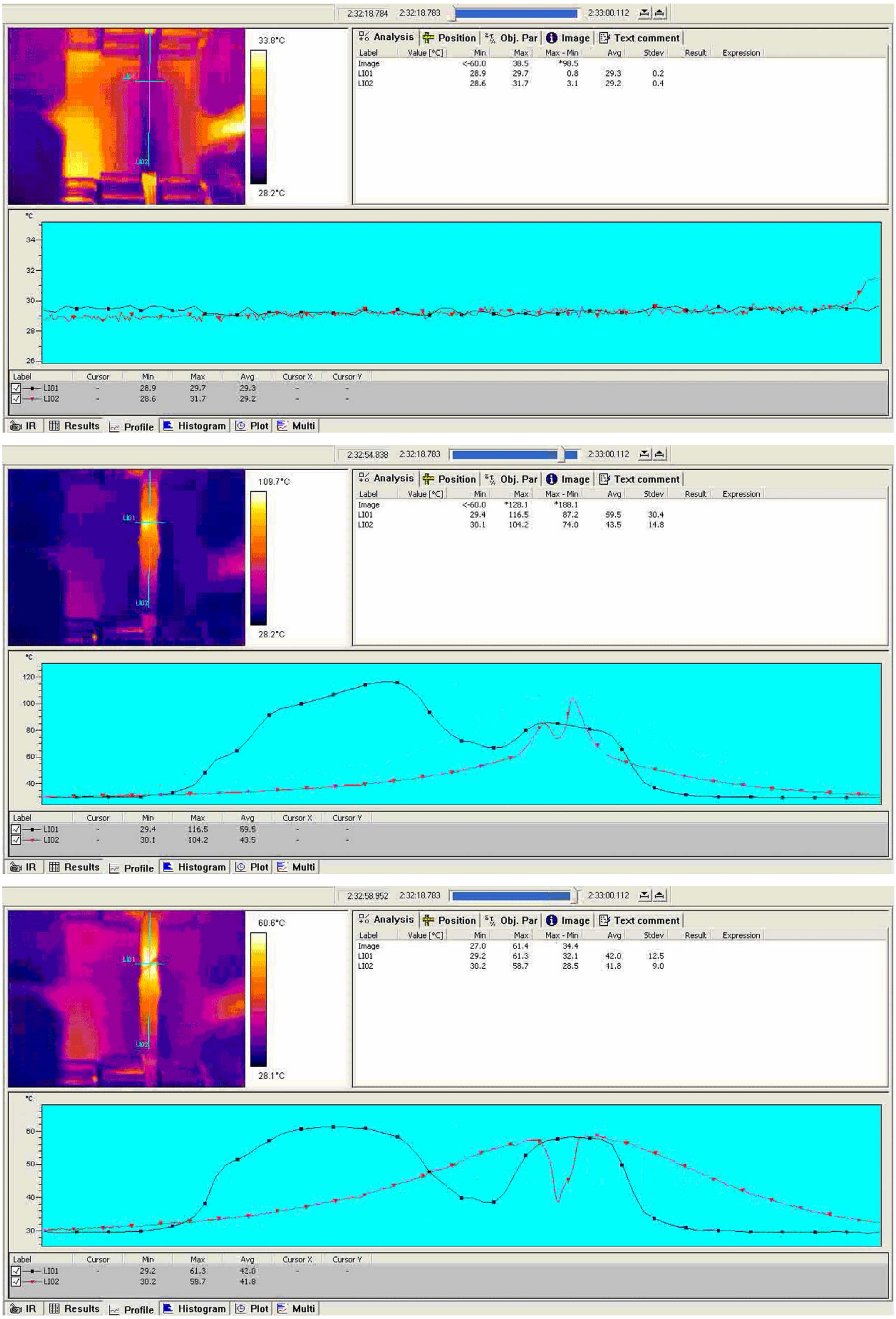
The period of the first 10 seconds of testing, the zone of elastic deformation (Fig. 3, curve a) followed by a small change in temperature $\Delta T \approx 1$ K. Thermograms on the images are recorded at the time indicated on diagram (Fig. 3).

They confirm that the temperature of the sample is increased in that interval at the root of the welded joint. It indicates that the highest stress is reached in that zone. The character of the force – extension (curve a, Fig. 3) corresponds to ductile materials with approximately equal share of homogeneous and inhomogeneous elongation.

The homogeneous elongation is elongation before the maximum force, and inhomogeneous elongation is elongation between the maximum force and fracture.

In the test specimen characteristic yield stress point is not present, probably due to inhomogeneity of the welded structure.

Measurement values for the selected characteristic temperature: room temperature (302 K, t = 0), maximum (point 9, T = 418.8 K, t = 36 s) and fracture of specimen (t = 40 s) are shown in Figure 4.



Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev	Result	Expression
Image		<-60.0	38.5	*98.5				
LI01		28.9	29.7	0.8	29.3	0.2		
LI02		28.6	31.7	3.1	29.2	0.4		

Label	Cursor	Min	Max	Avg	Cursor X	Cursor Y
☑ LI01	-	28.9	29.7	29.3	-	-
☑ LI02	-	28.6	31.7	29.2	-	-

Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev	Result	Expression
Image		<-60.0	*128.1	*188.1				
LI01		29.4	116.5	87.2	59.5	30.4		
LI02		30.1	104.2	74.0	43.5	14.8		

Label	Cursor	Min	Max	Avg	Cursor X	Cursor Y
☑ LI01	-	29.4	116.5	59.5	-	-
☑ LI02	-	30.1	104.2	43.5	-	-

Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev	Result	Expression
Image		27.0	61.4	34.4				
LI01		29.2	61.3	32.1	42.0	12.5		
LI02		30.2	58.7	28.5	41.8	9.0		

Label	Cursor	Min	Max	Avg	Cursor X	Cursor Y
☑ LI01	-	29.2	61.3	42.0	-	-
☑ LI02	-	30.2	58.7	41.8	-	-

Figure 4. Thermograms and measured temperature values on the specimen surface at: (a) *t* = 0 s, (b) *t* = 36 s and (c) *t* = 40 s

Measurement lines are placed in the middle of the specimen vertically and horizontally at the point where the break occurred.

Monitoring of temperature over time in marked positions allows detection of initial changes in temperature, and indicates that there are conditions for the appearance and growth of cracks under impact load.

Thermography has confirmed the expectations that the initial changes occur in the HAZ (Fig. 4).

Macro section of welded joint, is presented in Figure 5.

In macrograph, Fig. 5, of welded joints macro defects (not welded places, cracks and inclusions) are not perceived.

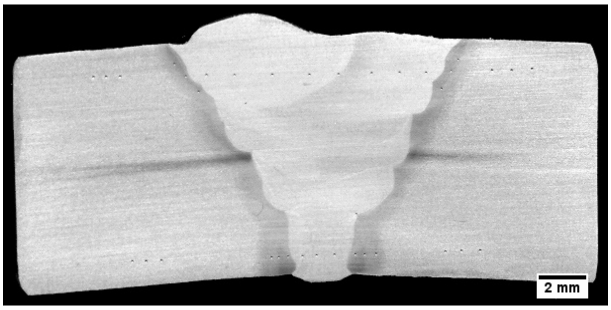


Figure 5. Cross-section of welded joint

According to the local increase in temperature, the initial plastic deformation was noticed in the root of the welded joint. The possible reason for this is the fact that at unsymmetrical welds this zone is exposed to highest stress. In combination with the presence of brittle structures and/or possible micro-defects, welding zone is the critical zone for the appearance of the exceeding local limits of plasticity, and the appearance of initial cracks.

In paper [18], the specimens for experiment are made by structural steel S355J2G3 (EN 10025) while in this one, the used material is P295GH (EN 10028-2), which is often useful in thermoenergetic equipment production, particularly for pressure vessels that work at elevated temperature. These materials are different in chemical composition, mechanical properties, behavior on elevated temperatures, weldability, etc.

Thermograms, with those two experiments, show that times of experiment's duration are unequal, as the increasing temperature of specimens, too.

Metallographic testing of welded sample was made as well, with the aim to determine macro and microstructure of sample, presence of defects and occurrence of characteristic zones of welded joint (Fig. 5).

6. CONCLUSION

The experiments and results of thermography application, simultaneously with the conventional methods results, of welded joints tensile properties testing are presented. The main aim of testing was to relate the temperature changes of the spacemen, continuously recorded by thermography, with force – extension diagram. As a conclusion, it can be pointed out that the obtained results confirm that the thermography is very useful for early diagnostics of the complex structures in the exploitation or service conditions. Also, on the basis of temperature field, detected from surface of metal structures or structure elements subjected to static or dynamic overloading, the zones corresponding to different deformation conditions, can be estimated.

Therefore, this technology enables conducting stress analysis and estimation of plastic deformation limits within a shorter period than in other nondestructive and non-contact method. During the tensile test, the thermography gives visible data of temperature changes on the surface of specimen. This proves that the variations in temperature captured by the IR camera are strongly correlated to the loads actually applied to the specimen.

Results of welded steel joint tests show that the selected welding technology is realized with required quality (overmatching), because the fracture of specimen occurred outside the weld metal. Experimental results show that welded joint values of yield and tensile strength are similar to those of base material, except the loss of marked yield point. The temperature rise began at the root of welded joint, but specimen broke outside weld metal, as it is required at the correctly performed "overmatching" welding technology.

Infrared thermography has proven to be an invaluable tool in solving a wide range of scientific questions and problems related to the reliable assessment of the structure integrity and lifetime.

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ПРИМЕНА ТЕРМОГРАФИЈЕ ТОКОМ ИСПИТИВАЊА ЗАТЕЗАЊЕМ СУЧЕОНО ЗАВАРЕНИХ СПОЈЕВА

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У раду су приказани експериментални резултати упоредног испитивања карактеристика сучеоно заварених спојева (P295GH) термографијом и затезањем на механичкој кидалици. Током затезних испитивања долази до пораста напона у материјалу завареног споја и појаве деформисања основног материјала и материјала шава. Појава пластичне деформације у материјалу је праћена порастом температуре у зони у којој се одвија пластично деформисање. На основу расподеле температуре на испитиваном узорку, може се донети закључак о присуству пластичних деформација у посматраним зонама. Епрувете су испитане на електромеханичкој кидалици уз примену контроле деформација. Резултати испитивања применом обе методе су приказани паралелно. Ова испитивања су показала предности примене термографије у бесконтактним испитивањима за брзо доношење закључака о деформационом процесу на конструкцијама и могућности предикције зона у којима је појава оштећења највероватнија.