LASER SPOT THERMOGRAPHY OF WELDED JOINTS

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Summary

The paper investigates the application of active thermography for nondestructive testing of welded joints. Two measurements techniques are considered: laser spot thermography and vibrothermography. Experiments were performed on a welded carbon steel plate with welding defects. Laser spot thermography was used to reveal welding defects and vibrothermography was used to provide reference results. Both methods proved to be very effective and their results were found comparable. In addition, the paper presents a semi-automatic image processing algorithm used to facilitate laser spot thermography tests. The algorithm combines multiple thermographic sequences captured during the test and allows for automated damage features extraction. The algorithm allows to significantly reduce the post processing time and gives a clear information on the damage state of a material. The paper discusses the operational principles and measurement setup of both nondestructive testing methods.

Keywords: laser spot thermography, vibrothermography, damage detection, welded joints

TERMOGRAFIA LASEROWA POŁĄCZEŃ SPAWANYCH

Streszczenie

Artykuł omawia zastosowanie aktywnej termografii w badaniu połączeń spawanych. Rozważane są dwie metody diagnostyczne: termografia laserowa oraz wibrotermografia. Badania eksperymentalne przeprowadzono na spawanej płycie ze stali węglowej z uszkodzeniami spawalniczymi. Badania nieniszczące przeprowadzono na próbce metodą termografii laserowej a następnie metodą wibrotermografii w celu otrzymania wyników porównawczych. Obydwie metody okazały się skuteczne w omawianym zastosowaniu a otrzymane wyniki porównywalne ze sobą. Dodatkowo w artykule przedstawiono półautomatyczny algorytm przetwarzania obrazów termowizyjnych w badaniu termografii laserowej. Zasada działania algorytmu opiera się na automatycznym łączeniu sekwencji termowizyjnych zarejestrowanych w trakcie pomiaru oraz na automatycznym wykrywaniu cech obrazu związanych z uszkodzeniami struktury materiału. Wykorzystanie zaproponowanego algorytmu pozwoliło na znaczne zredukowanie czasu potrzebnego na obróbkę wyników badań termografii laserowej i pozwoliło na uzyskanie bardziej jednoznacznej informacji o występujących uszkodzeniach. Artykuł omawia zasadę działania oraz szczegóły techniczne obu rozpatrywanych metod diagnostycznych.

Słowa kluczowe: termografia, badania nieniszczące, termografia laserowa, wibrotermografia, detekcja uszkodzeń, NDT

1. INTRODUCTION

Nondestructive testing (NDT) of welded joints is of major importance in many fields of engineering. Welding has found applications in numerous structures such as: hull constructions, steam boilers, pressure vessels, pipelines or machinery components. Many of those structures require constant maintenance and monitoring. There are many NDT techniques that can be used for this purpose including visual inspection, magnetic particle inspection, liquid (dye) penetrant testing, radiography, air or water pressure testing, ultrasound and active thermography [1].

In recent years, active thermography is gaining increasing interest in nondestructive testing applications [2]. This is due to several factors including the wider availability of affordable thermographic cameras, noncontact nature of the measurement, full field evaluation, short measurement time and simple test setup. Thanks these advantages the family of thermographic nondestructive testing (TNDT) methods found applications in many fields including: aerospace, automotive, civil engineering or renewable energy among others [3-4]. Recently TNDT has been also applied to welded joints [5-8].

Like all nondestructive testing methods, thermography has its limitations. One of the most difficult tasks is quantitative evaluation of the results. Evaluation of damage features from a captured thermographic sequence could absorb large amount of time. Moreover, proper evaluation and interpretation of the results can be achieved only by qualified personnel with long term experience with this type of measurements. Therefore, the overall cost of a measurement can be high. This cost can be significantly reduced by developing more effective and automated postprocessing techniques. This area is currently one of the main tasks in development of modern NDT systems.

This paper presents the application and comparison of vibrothermography and laser thermography methods. The tests were performed on a welded steel plate with welding defects. The paper is organized in the following way: in paragraph 2 vibrothermography and laser thermography techniques are described. Paragraph 3 gives the details of welded carbon steel sample, on which the test were conducted. Paragraph 4 presents the results of laser spot thermography test. The new post processing algorithm for semi-automated defect detection is also presented. Paragraph 5 presents the results obtained with vibrothermography and compares them with those obtained from laser spot thermography. Summary of the result and conclusions are given in paragraph 6.

2. MEASUREMENT TECHNIQUES

Thermographic nondestructive testing (TNDT) is based on the analysis of dynamic temperature distribution on a surface of tested object. The family of active TNDT testing techniques can be classified into two sub categories according to the applied excitation source [9]. The first group of comprises the methods utilizing external excitation; flash lamps, infrared lamps or lasers. The second group comprises methods utilizing internal vibration excitation and inductive heating sources [10]. The methods from both groups, including pulsed thermography, lock-in thermography and vibrothermography, has been successfully applied in nondestructive testing applications [11, 12].

Laser spot thermography is a TNDT method based on external thermal excitation provided by a high power laser source. Measurement is based on the analysis of changes in surface temperature distribution in close neighborhood of the exciting laser spot [13, 14]. Figure 1 shows the experimental setup of laser thermography test system. The setup consists of four major components, namely: a laser source, a laser controller, an infrared camera, and a computer for data acquisition and storage.

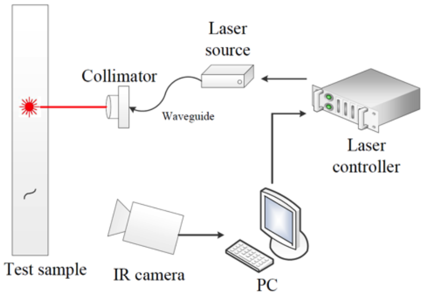

Fig. 1. Laser spot thermography test setup

Figure 2 shows the basic principle of laser spot thermography measurement sequence. Testing of the structure is performed in a point-by-point manner. A short pulse of laser light is sequentially heating the surface of the sample in a number of points - p_1 to p_n as shown in Figure 2. Thermographic camera is synchronized with the laser source to record a sequence of thermal images comprising the heating and cooling phase of the material in the vicinity of each point. Precise positioning of the laser beam and of the infrared camera can be provided by a two axial or three axial Cartesian positioning system or an optical scanning system. Due to the local nature of the thermal excitation method, image is obtained from a relatively small area. This allows for a significant increase in the image resolution in comparison with the classical active thermographic techniques. In case of homogenous thermally isotropic materials temperature distribution around the excitation point is continuous and symmetric and can be easily calculated theoretically. The lack of symmetry and temperature profile discontinuity might be a result of the presence of defects such as cracks or voids. Therefore the analysis of temperature profile and time history in the vicinity of the excitation laser spot is used to identify damage. It has been already shown that laser spot thermography can be used to detect defects formed in metallic structures due to material fatigue [15-17].

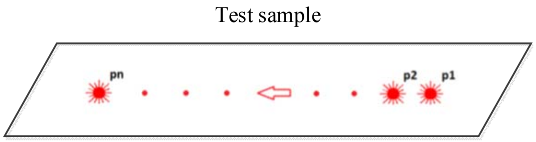

Fig. 2. Measurement sequence in laser spot thermography

Vibrothermography is also an active TNDT method based on the local heat generation. In this case, however, the heat is generated selectively at the locations of material discontinuities as a consequence of the externally generated elastic waves. Typically elastic waves in the ultrasonic frequency range from 15 to 70 kHz are used for excitation. Elastic waves propagating in the material interact with defects such as cracks or delaminations. Due to this interaction the mechanical energy is dissipated into heat mainly due to friction. Generated heat propagates to the surface, where it may be detected by an infrared camera [18]. The experimental setup for vibrothermography is shown in Figure 3. The setup consists of four major components, namely: an ultrasonic wave source, an infrared camera, a control unit and a computer with dedicated data processing software.

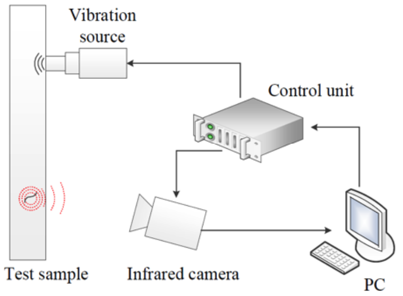

Fig. 3. Vibrotermography test setup

The most important advantages of vibrothermography are: very short measurement time, usually no longer than few seconds, and relatively simple image processing algorithms, mainly based on the image subtraction methods. Vibrothermography has been applied in many fields including the aircraft engine blades inspection [19] and identification of loose rivets on the fuselage and wing panels of a fighter jet [20] among others.

The application of both TNDT techniques for welding defects characterization has been performed and the results were compared in the context of this work.

3. TESTED SPECIMEN

The study has been performed on a welded carbon steel sample with the overall dimensions of 200×100×10 mm. Welding defects of known type and size were generated in the weld during the manufacturing stage. Two welding defects were confirmed in a post manufacturing ultrasonic inspection using the Sonatest Sitescan 230 system and a 4 MHz probe. Two welding defects were identified, namely: a 19 mm long lack of root fusion located 58mm from the longer edge of the sample (Figure 4a) and 21 mm long root crack located 18 mm from the longer edge of the sample (Figure 4b).

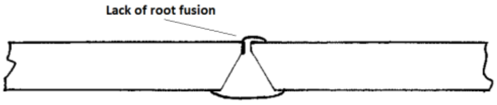

Fig. 4a. Cross section of the lack of root fusion

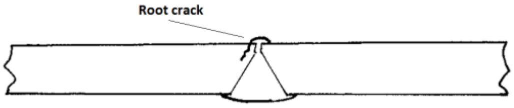

Fig. 4b. Cross section of the root crack

Prior to thermographic testing the sample was coated with black paint, in order to obtain uniform surface emissivity.

4. LASER SPOT THERMOGRAPHY BASED TESTING

Laser spot thermography experiments were conducted on an in-house laboratory laser test system at AGH University (Figure 5). The test system includes: a photon detector infrared camera (1) diode laser source with maximal power of 120W and 805, 5 nm wavelength (3) mounted on 3 axis Cartesian positioning manipulator (2).

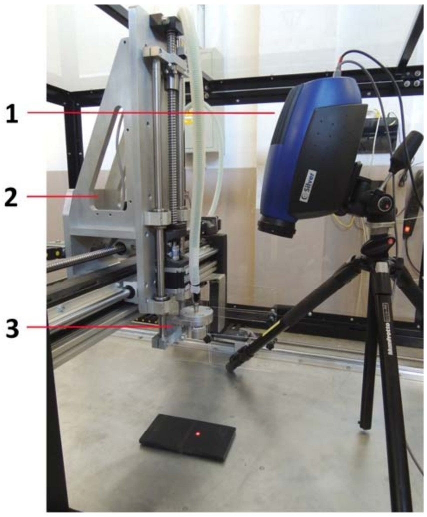

Fig. 5. Laser spot thermography test system

During laser spot thermography testing the steel sample was exposed to repetitive laser irradiation of the following parameters: pulse power – 30 W, pulse duration – 0.1 s. Laser spot diameter was 9 mm. That gives the intensity level of 47.2 W/cm^2 which is below the ablation threshold for this material equal to 100 W/cm^2 for 0.1 s laser pulse [21]. Single pulse of the applied laser radiation resulted in almost 10 °C local temperature increase on the surface of the plate. Irregularity of temperature distribution above the excitation point caused by the crack is clearly visible on thermographic image in Figure 6. The associated temperature time history plot for laser spot area (blue curve) and non-defected area (green curve) is shown in Figure 7.

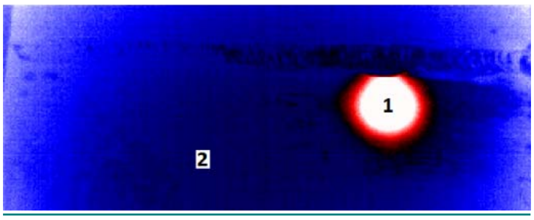

Fig. 6. Single laser spot excitation

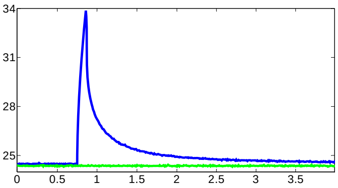

Fig. 7. Temperature time graph for the point inside the laser spot area (blue curve) and point away from the excitation area (green curve)

Figure 8 shows the temperature distribution across the weld (blue line) with its first spatial derivative (green line) for a single excitation point. The derivative (i.e. the thermal gradient) has a peak value in the location of the crack. This is due to a significantly lower thermal conductivity across the cracked area with respect to the sound material. In other words, the crack acts as thermal barrier that alters the temperature distribution around the excitation point. This fact is used to identify cracks in laser spot thermography tests.

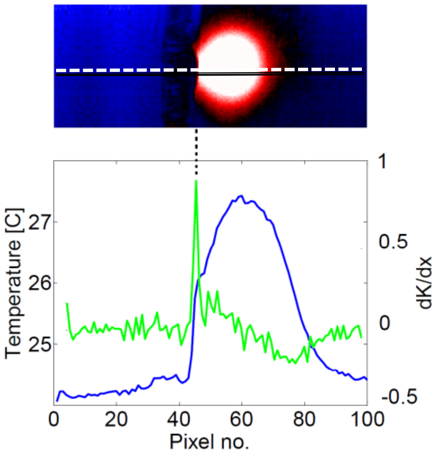

Fig. 8. Temperature distribution across the weld (blue curve) and first spatial derivative of temperature distribution (green curve)

It has been verified experimentally that laser spot thermography can detect surface cracks with good accuracy. The defects can be, however, identified only in the close vicinity of the laser spot, where temperature gradient is high. Thermographic sequences captured for each laser beam location have to be evaluated separately, which makes this method relatively slow, for materials with low thermal conductivity. A possible way to overcome this problem, and speed up the experiment, is to change the image acquisition sequence. Thermographic sequences can be captured in a sequence different from the one shown in Figure 2 i.e. measuring consecutively at points p_1 to p_n. Excitation at a point alters the temperature distribution only in the close vicinity of that point. Therefore one can modify the measurement sequence to have multiple passes of the positioning system for a single line. Each time, every n-th point can be measured, considering that the points are distant enough and measurement at one point does not influence the measurement in the consecutive point. The parameter n will depend on the spatial density of the points and thermal properties of the tested material.

Thermographic image sequences acquired for each excitation point have to be integrated into a single sequence in order to evaluate the diagnostic information for the whole area of interest. Figure 9 shows a block diagram of an automated post processing algorithm that has been developed for this purpose.

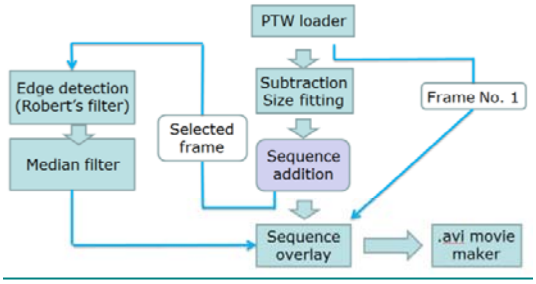

Fig. 9. Block diagram of the proposed thermal image processing algorithm for laser spot thermography

The first step of the procedure is an automatic subroutine for loading all constituent thermal image sequences. Then the preliminary post processing is done including the background temperature level subtraction and frame size fitting. All constituent sequences from a given test sequence are then added and averaged. The result of this processing step for the analyzed sample is shown in Figure 10. The image was created from 21 thermal image sequences captured for the consecutive excitation points. The outline of the root crack can be already identified in the central right part of the picture but the lack of root fusion defect is not visible. In the next step of the algorithm, the user has to select a representative image frame from the cooling phase and an automated edge detection procedure is conducted. Detected edges, representing surface cracks, are overlaid on the first image frame for better visualization and damage localization. In the last step of the procedure the results, in a form of thermographic sequence with overlaid damage, can be exported to a video file for presentation.

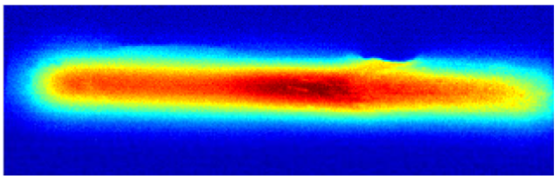

Fig. 10. Result of sequence addition procedure

Figure 11 presents the final result obtained for the analyzed weld sample with use of the laser spot thermography and the proposed thermal image processing algorithm. As can be seen, the application of edge detection algorithm resulted in identification of two areas (red lines in Figure 11) related to damages in the weld (see Figure 4a and 4b).

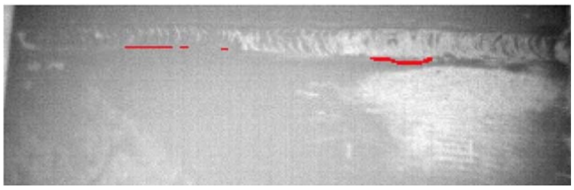

Fig. 11. Result of laser spot thermography test obtained with the proposed thermal image processing algorithm

5. VIBROTHERMOGRAPHY BASED TESTING

Vibrothermography was applied to verify the presence and location of the weld defects in the test sample. Experiment was performed on a vibrothermographic test system developed at AGH University as shown in Figure 12. The test system complies with the general setup shown in Figure 3 and comprises: (1) the positioning press system, (2) the photon detector infrared camera *FLIR SILVER 420M*, (3) the power amplifier and (4) the 35 kHz ultrasonic vibration source (4). The vibration source was a typical ultrasonic welding setup consisting of a converter, a booster and a sonotrode. The thermal camera allows for high speed image capturing at 150 frames per second with the noise equivalent temperature difference (NETD) at 20mK. This is especially important for testing of materials with high thermal diffusivity such as steel or aluminum. The pneumatic press system guarantees the constant and controllable contact force between the sonotrode and test sample.

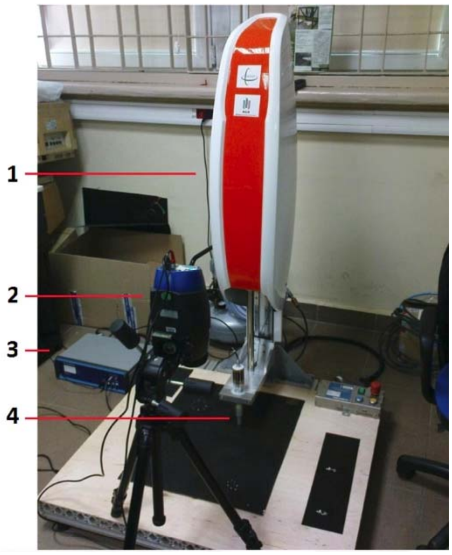

Fig. 12. Vibrothermography based test system

The measurement on the weld specimen was performed using the following settings: the frequency of excitation was equal to 35kHz and the ultrasonic source was operating at 500W of input electrical power, exciting the sample for 500 ms. Thermographic image sequence acquired during the test was processed in the *MONIT SHM ThermoAnalysis* software package [22]. The result of vibrothermographic test is shown in Figure 13. Captured thermal image sequence was only processes by subtracting the background temperature distribution acquired prior to the activation of ultrasonic excitation. This allows to analyze the temperature increase due do the applied excitation. The presence and locations of both welding defects: the root crack (1) and the lack of root fusion (2) were clearly identified.

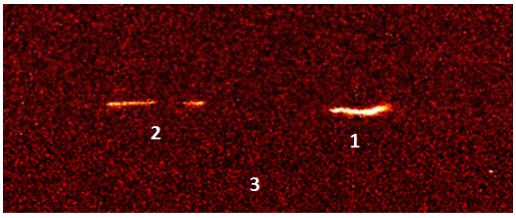

Fig. 13. Result of the vibrothermographic test processed in the ThermoAnalysis software

Figure 14 shows a temperature time history plot obtained from the identified defect area (1) and from the sound area (3). The applied 500 ms ultrasonic excitation burst resulted in a 1.2 °C temperature increase, which was an easily detectable with the infrared camera.

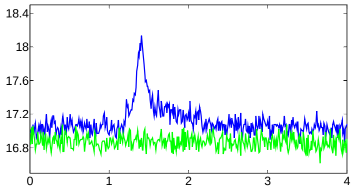

Fig. 14. Temperature time history plot obtained during vibrothermographic test. Blue curve represents the damaged area (1), green curve represents sound area (3)

6. RESULTS AND CONCLUSIONS

Figure 15 shows the comparison of both thermal imaging modalities that were used for inspecting the weld sample. The top image in Figure 15 was obtained from the vibrothermographic test (bright areas indicate the locations of damages), while the bottom image was obtained from laser spot thermography test and the proposed thermal image processing technique (red curves indicate the locations of damages). As can be seen both results are in very good agreement, and comply with the results of post manufacturing ultrasonic inspection.

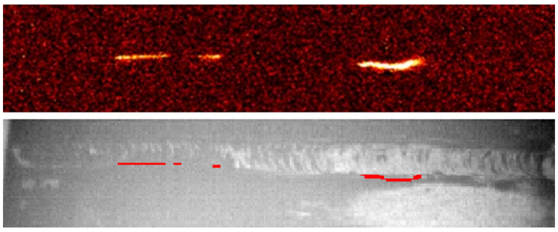

Fig. 15. Comparison of damage detection results obtained with two thermographic techniques: (a) using vibrothermography (bright areas indicate damage locations) and (b) using laser spot thermography (red lines indicate damage locations)

The paper presented the application of two different thermographic nondestructive testing techniques to characterize damage in a welded carbon steel sample. Obtained results confirmed the feasibility of applying both methods to detect surface cracks in welded joints. Both considered methods offer time-efficient full-field damage inspection capability. Laser spot thermography can be automated to a great extent by using programmable Cartesian positioning system to reposition the excitation laser spot on the sample to take single measurements. The individual measurements can be subsequently merged and post processed with the proposed thermal image processing algorithm to obtain a highly automated damage detection system. The local nature of individual measurements gives the possibility to obtain better spatial resolution by reducing the field of view of infrared camera. Vibrothermography is a fast full-field technique that does not require advanced thermal image processing. It is a dark field technique where the damage itself becomes the heat source. The interpretation of results in both methods is straightforward. Identified damaged areas are overlaid on the image of the test sample to provide easy localization and size estimation.

Further investigations are scheduled to speed up laser spot thermography testing and improve the processing algorithms to allow for inspection of thermally anisotropic materials as composites.

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