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DIAGNOSTICS OF WELDED JOINTS USING PASSIVE AND ACTIVE MAGNETIC METHODS

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Abstract

As the quality of welded joints transfers to the load carrying capacity of structures, welded joints naturally become the object of diagnostic tests. Welded joints are mainly tested in order to find out the places with structural or mechanical non-homogeneities. It is caused by the fact that the existence of welding imperfections significantly decreases mechanical properties of the welded joint and especially its fatigue strength.

The paper presents some results of diagnostic tests for welded joints of steel components carried out with the use of passive and active magnetic methods. Faults of the welded joint occurring within a tested object cause the phenomenon of magnetic anomalies existing over a tested surface and this phenomenon has been used to detect welding imperfections. A specially designed measurement matrix consisting of 768 one-axial miniature magnetic field sensors has been used to record the magnetic flux leakage. The paper includes a comparison of the effectiveness of diagnosing using the passive and active magnetic method. Moreover, it was shown that the magnetic diagnostics provides rapid inspection of quality of welded joints with no need for special preparation of joints for testing which is relevant for its practical applications and results in low costs of such tests.

Keywords: magnetic diagnostics, passive methods, active methods, welded joints

DIAGNOSTYKA POŁĄCZEŃ SPAWANYCH Z WYKORZYSTANIEM PASYWNYCH I AKTYWNYCH METOD MAGNETYCZNYCH

Streszczenie

Ponieważ jakość złączy spawanych przekłada się na możliwości przenoszenia obciążeń przez konstrukcje, połączenia spawane stają się w naturalny sposób obiektem badań diagnostycznych. Głównym celem badań połączeń spawanych jest wykrywanie miejsc, w których występuje niejednorodność strukturalna lub mechaniczna złącza. Taki cel badań wynika z faktu, że występowanie wad spawalniczych w decydującym stopniu pogarsza właściwości mechaniczne połączenia spawanego, a w szczególności jego wytrzymałość zmęczeniową.

W niniejszej pracy przedstawiono wyniki badań diagnostycznych połączeń spawanych stalowych elementów z wykorzystaniem pasywnych i aktywnych metod magnetycznych. Do wykrywania defektów połączenia spawanego wykorzystano zjawisko powstawania anomalii magnetycznych nad badaną powierzchnią wywołanych występowaniem wad spawalniczych w diagnozowanym elemencie. Zaburzenia strumienia magnetycznego były rejestrowane za pomocą specjalnie skonstruowanej matrycy pomiarowej składającej się z 768 jednoosiowych miniaturowych czujników pola magnetycznego. W pracy dokonano porównania skuteczności diagnozowania pasywną i aktywną metodą magnetyczną. Wykazano również, że diagnostyka magnetyczna umożliwia wykonanie szybkiej kontroli jakości połączeń spawanych bez konieczności specjalnego przygotowania połączeń do badań diagnostycznych, co ma duże znaczenie użytkowe i przekłada się bezpośrednio na niski koszt takich badań.

Słowa kluczowe: diagnostyka magnetyczna, metody pasywne, metody aktywne, połączenia spawane

1. INTRODUCTION

Welded joins are widely used to connect steel components. The common use of welded joints is caused by significant advantages of this method of joining represents as they can be made easy and fast and provide strong connections and possibilities for complete automation of component joining process.

Making welded joints is associated with melting, subsequent solidification, and also introducing heat energy (heat input) into the welded material which changes its structure in the Heat Affected Zone. Welding often leads to structural inhomogeneity (gas bubbles, metallic or non-metallic inclusions) and mechanical inhomogeneity (cracks and delaminations) of the joint. Hot cracks occur during crystallising of weld metal, and usually such cracks are formed in the middle line of the weld. The cold cracks happen at the final phase of the weld cooling or after some time when the welding was finished and they usually exist on the edge of the weld within heat affected zone. In addition to cracks resulting from welding processes, welded joints are exposed to the appearance of fatigue cracks resulting from the mechanical loads of the joint during operation [14]. As the quality of welded joints transfers to the load carrying capacity of structures, welded joints naturally become the object of diagnostic tests. Welded joints are mainly tested in order to find out the places with structural or mechanical inhomogeneities. It is caused by the fact that the existence of welding imperfections significantly decreases mechanical properties of the welded joint and especially its fatigue strength.

Contemporary technical diagnostics is focused most of all on the development of non-invasive methods which allow to determine the technical condition of diagnosed objects without any disassembling, turning off or even disturbing the functioning. Non-invasive diagnostic tests are based on assessment of quality of a tested object while preserving its original properties and without its destruction. Non-destructive methods of detecting heterogeneity in welded joints include primarily visual, penetrating, X-ray, and ultrasonic methods. The quality of welded joints for steel components may be also assessed using magnetic methods [1, 12].

Magnetic diagnostic methods may be divided into passive and active ones. The use of external magnetic field acting against a tested component is a common feature of active magnetic diagnostic methods and the evaluation of object's technical condition is made by analysing recorded magnetic parameters. The phenomenon of anomalies existing in distributions of magnetic field intensity components over a tested surface is used for magnetic detection of inhomogeneities within a tested object [8, 9]. The magnetic field flux passing through the material is dispersed in a place of inhomogeneity which produces magnetic flux leakage outside the tested object because on the edges of discontinuity the specific "magnetic poles" are created, which in turn generates magnetic field above this discontinuity (Fig. 1).

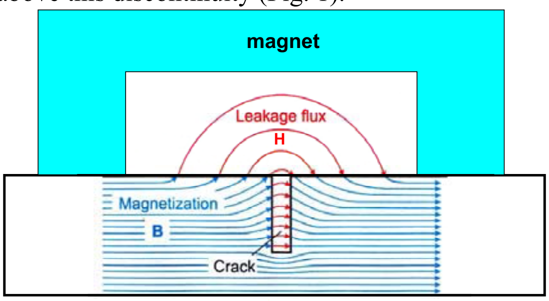

Fig. 1. Magnetic flux leakage at the location of a crack

Level of the magnetic flux leakage depends on the inhomogeneity localisation in the material and its orientation relative to the magnetic field flux passing through the material (Fig. 2). Magnetic flux leakage is the strongest in the case of transverse inhomogeneities located on the tested surface or at a small depth under this surface.

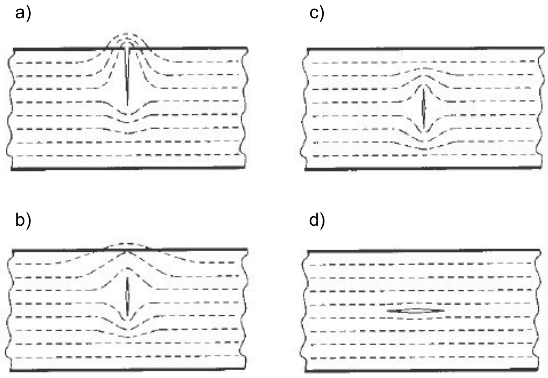

Fig. 2. Influence of material's inhomogeneity location and orientation on the magnetic flux leakage effect:
a) transverse surface discontinuity,
b) transverse subsurface discontinuity,
c) transverse internal discontinuity,
d) longitudinal internal discontinuity [10]

There are different ways used for detection of the magnetic flux leakage outside of tested element. In a magnetic particle method, the magnetic flux leakage is displayed by using ferromagnetic powder [11]. The disadvantage of such approach is caused by a need for accurate cleaning and preparing the tested surface which requires increased time and financial resources. In the magnetographic method magnetic flux leakage is recorded by means of a special tape that contains small magnetisable ferromagnetic particles. The magnetic tape contacts the surface of the tested component and if, due to the existence of inhomogeneity in the material, magnetic flux leakage occurs on the material surface, the tape will be magnetised. The image fixed on the tape can be read by a special head and displayed as a distribution of the magnetic field. In this way, the surface magnetic phenomena connected with the existence of inhomogeneities in the tested element can be identified [2, 4]. The magnetic flux leakage may be also measured by using magnetic field sensors. The measurements of magnetic field intensity above the surface of a tested element can detect local magnetic anomalies existing above the surface of material with structural or mechanical inhomogeneities.

Passive magnetic diagnostic methods deploy an analysis of the self-magnetic flux leakage distribution on the surface of the tested ferromagnetic material. The self-magnetic flux leakage is a magnetic field appearing on the surface of an element made of ferromagnetic material under the influence of the working loads or residual stress, and as a result of the inhomogeneities and discontinuities of the ferromagnetic material structure.

Local magnetic anomalies existing on ferromagnetic surface in the zones of stress concentration are produced by changed magnetic parameters of areas where the stresses are concentrated [5, 6]. On the other hand, inhomogeneities within ferromagnetic material structure cause the dispersion of the weak magnetic field flux, which is the magnetic field of the Earth, passing through the tested element. Existing self-magnetic flux leakages outside the tested element also cause the formation of local surface magnetic anomalies.

A method of metal magnetic memory (MMM method) may be distinguished among passive diagnostic methods [3, 16]. An interpretation of changes in values of derivative of a selected component of magnetic field intensity measured at the surface of the tested object has a principal meaning for the methodology was developed by Dubov and formulated in the ISO 24497 standard [17]. The analysis of changes in values of derivative of component of magnetic field intensity can be used to detect the zones of stress concentration and inhomogeneities in the tested object. The MMM method can be used for diagnostic tests of steel components and welded joints [7, 13]. The main difficulty using passive magnetic diagnostic methods is caused by the fact that the diagnostic process is based on the measurements of weak magnetic fields and the results of measurements are burdened with many external factors and internal material properties [15].

This paper presents results of diagnostic tests for welded joints of steel components using passive and active magnetic methods. The effect of magnetic anomalies appearing above the tested surface and caused by the presence of inhomogeneities within a tested component was used to detect the faults of a welded joint. The magnetic flux leakage was recorded by means of a specially designed measurement matrix consisting of 768 one-axial miniature magnetic field sensors. A comparison of the effectiveness of diagnosing using the passive and active magnetic method has been made. It was also proved that the magnetic diagnostics can be used for rapid examination of the quality of welded joints without any special preparations of joints for diagnostic tests, which is relevant for its practical applications and results in low costs of such tests.

2. TESTED OBJECTS

A few samples with dimensions of 125 x 100 x 6 mm (length x width x thickness) made of steel flat bar (steel ST3) by Energomontaż Północ Technika Spawalnicza i Laboratorium Sp. z o. o. were used for diagnostic tests of welded joints. The welded joints were made using different methods of welding:

a) 111 - MMA welding (Manual Arc Welding – welding with coated electrode);
b) 135 - MAG welding (Metal Active Gas – arc welding by metal electrode in chemical active gas shield);
c) 136 - MAG welding (Metal Active Gas – arc welding by powder wire in chemical active gas shield);
d) 141 – TIG welding (Tungsten Inert Gas – arc welding by non-melting electrode in inert gas shield);
e) 311 – Acetylene-oxygen welding (Gas).

The welded joints were made in two variants as the reference joints (properly made, without faults – reference samples) and faulty joints (with an introduced fault – slag, air, and non-ferromagnetic inclusions – faulty samples). Fig. 3 and 4 show exemplary reference samples of welded joints for diagnostic tests. For comparative purposes, a homogeneous sample was also made, without welded joints.

Fig. 3. The welded joint made by MAG method

Fig. 4. The welded joint made by TIG method

3. MEASUREMENT MATRIX

Magnetic flux leakage was recorded by the specially designed matrix consisting of 768 one-axial miniature sensors produced by Allegro MicroSystems with the measurement range between 0 and 5 Gauss, whose principle of operation is based on the Hall effect. The measurement matrix has the dimensions 125 x 110 mm and includes 256 three-dimensional measurement points (16 columns and 16 lines) (Fig. 5, 6). Each measurement point consists of three mutually perpendicular sensors measuring independently three orthogonal components of the magnetic field:

a) H_x – component perpendicular to the tested weld and tangential to the surface of the sample;
b) H_y – component vertical to the surface of the sample;
c) H_z – component parallel to the tested weld and tangential to the surface of the sample.

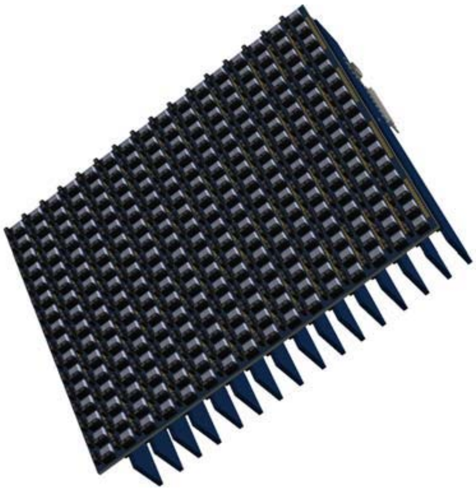

Fig. 5. A view of the front side of the measurement matrix

The matrix power consumption was limited. A sequential power supply switching for particular columns (48 sensors simultaneously) was applied. In order to reduce the impact of applied power switching for columns of sensors (multiplication) the signals from particular sensors were initially amplified in acoustic low-passing band filter limiting the signal band to 300 Hz. In the next step, the signal was amplified again after de-multiplication and before sending the measurement signals to A/C converter of the microcontroller. The raw measurement signals were amplified by 200 times in total.

An initial calibration of sensors was carried out before each measurement cycle because a spread of parameters of sensors was observed at testing. The matrix was calibrated by sending into the input of each sensor a specific value of reference voltage from the converter of Raspberry 3 controller to get the output level of 2.5 V at 1.0 mV accuracy corresponding to zero level of magnetic field intensity.

Selection of individual sensors, controlling the power supply, measurements of received signals, as well as their registration, were all performed using the Raspberry 3 microcomputer. A 7” touchscreen monitor was used to display preliminary test results (Fig. 7). The values of output voltages of magnetometers were recorded on the microSD memory card and then displayed on a colour scale.
Because the value of the sensor's output voltage, proportional to the intensity of the measured magnetic field, ranged from 0 to 5 V, the analysis was preceded by subtraction of 2.5 V from the sensor’s output signal. This preprocessing simplified the interpretation of the sensor's indications, because then the sensor’s zero output voltage signaled the absence of magnetic field.

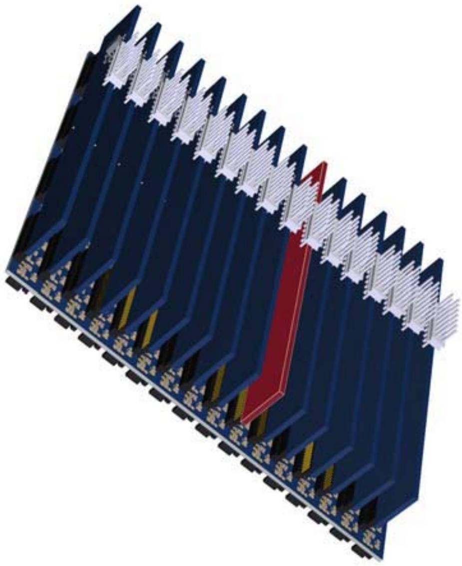

Fig. 6. A view of the back side of the measurement matrix

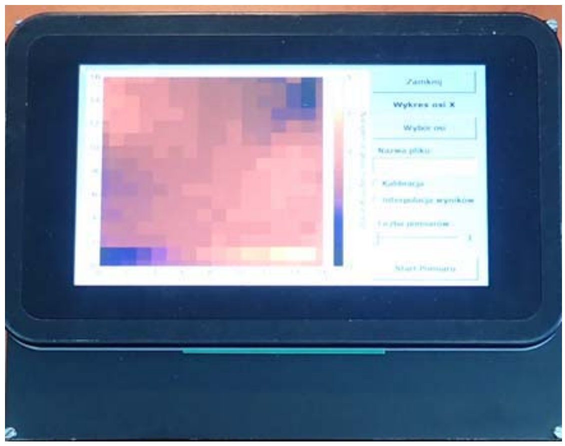

Fig. 7. The touchscreen monitor

4. DIAGNOSTIC TEST OF WELDED JOINTS USING THE PASSIVE MAGNETIC METHOD

In the first stage of the experiment the samples were tested using the passive magnetic method. Therefore, the tested elements were not subjected to the action of an external artificial magnetic field and only the Earth's magnetic field influenced the elements. Fig. 8 shows a set of measurement instruments used for testing.

Fig. 8. Measurement instruments used for passive magnetic tests

The samples were X-rayed before starting the magnetic tests. Exemplary X-ray images of samples are presented in Fig. 9 and 10.

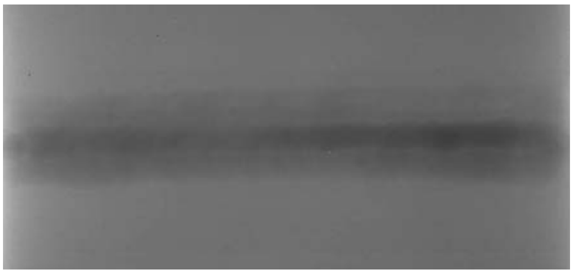

Fig. 9. X-ray image of the reference sample 136/02

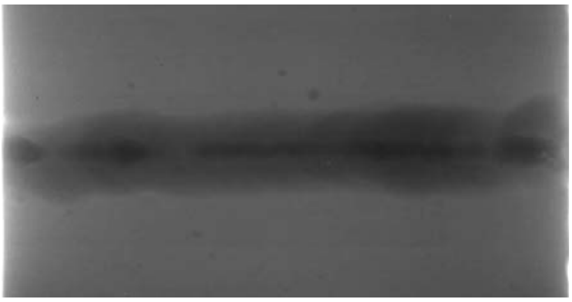

Fig. 10. X-ray image of the faulty sample 136/01

The measurement sensors were calibrated before starting each cycle of magnetic tests. The reference samples (without any faults) were tested three times. The results of measurements were averaged before recording on the memory card. In the next step, the magnetic field was measured in the same way on the surface of the faulty samples.

Fig. 11-14 show some exemplary magnetographs made at this stage of the experiment.

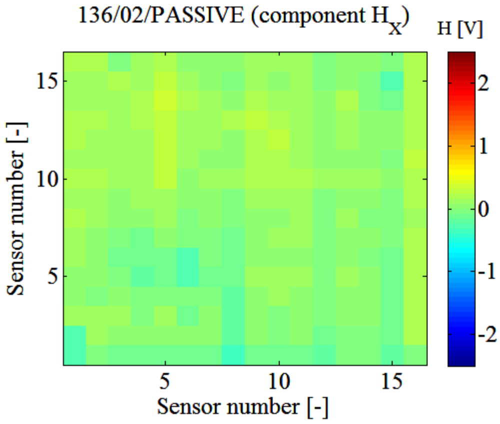

Fig. 11. Distribution of H_x component of the magnetic field on the surface of the reference sample 136/02

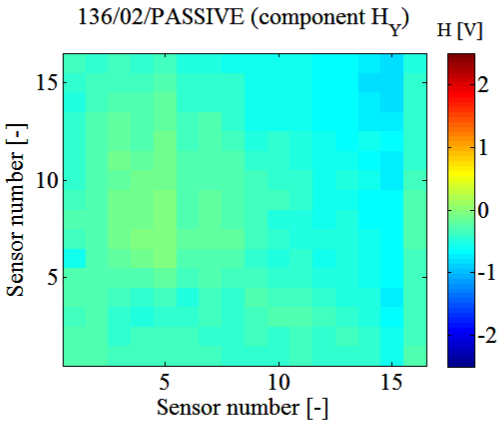

Fig. 12. Distribution of H_y component of the magnetic field on the surface of the reference sample 136/02

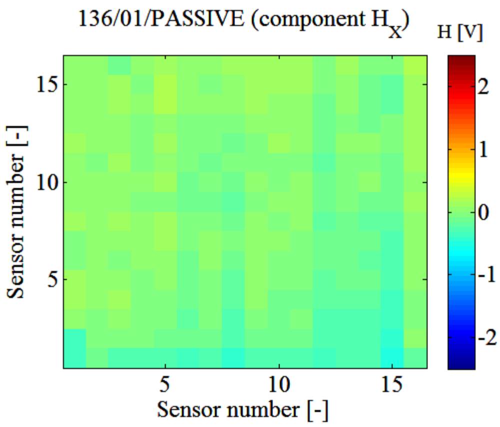

Fig. 13. Distribution of H_x component of the magnetic field on the surface of the faulty sample 136/01

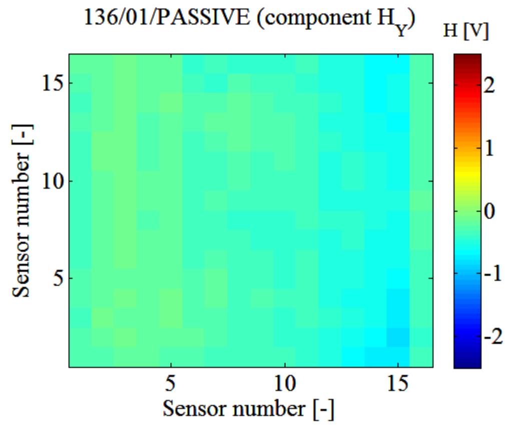

Fig. 14. Distribution of H_y component of the magnetic field on the surface of the faulty sample 136/01

Magnetograms of the sample surfaces performed by the passive magnetic method show that the intensity of measured magnetic field was very low and in practice constant on the whole surface. Therefore, it is difficult to use them for assessing the quality of performed welded joints, as the joint is not detected on the magnetograms. Magnetograms of samples with welded joints actually cannot be distinguished from the magnetogram of the homogeneous sample without any welded joint (Fig. 15 and 16).

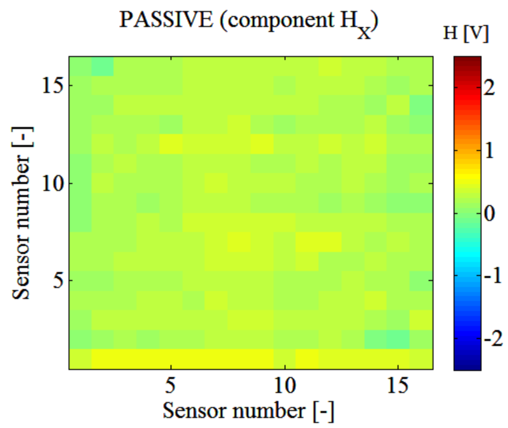

Fig. 15. Distribution of H_x component of the magnetic field on the surface of the homogeneous sample (without welded joint)

5. DIAGNOSTIC TEST OF WELDED JOINTS USING THE ACTIVE MAGNETIC METHOD

In the second stage of the experiment the samples were tested using the active magnetic method. Tested components were subjected to the action of an external artificial magnetic field generated by the defectoscope DMS-11 of the TechPan company that was powered with the stabilised power source P335 providing continuous regulation of voltage to 35 V and current to 6 A. Magnetisation of samples was carried out directly before the magnetograms were taken and the defectoscope magnet coil was powered by current of 3 A. Fig. 17 shows the set of instruments used at testing.

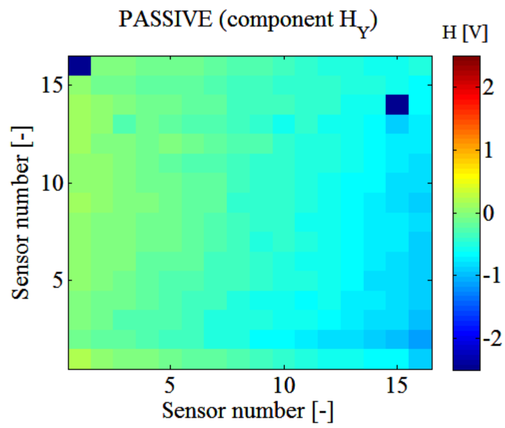

Fig. 16. Distribution of H_y component of the magnetic field on the surface of the homogeneous sample (without welded joint)

Fig. 17. Instruments used for active magnetic tests

The samples were X-rayed before starting the magnetic tests. Exemplary X-ray images of samples are presented in Fig. 18 and 19.

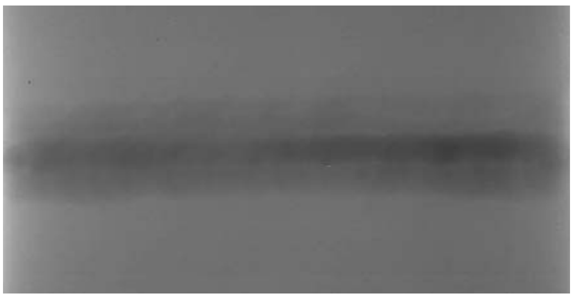

Fig. 18. X-ray image of the reference sample 141/02

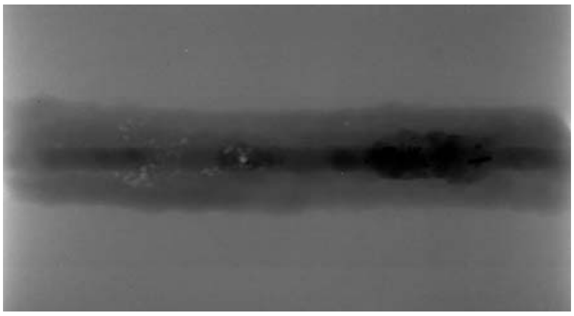

Fig. 19. X-ray image of the faulty sample 141/01

The measurement sensors were calibrated before starting each cycle of magnetic tests. The reference samples (without any faults) were tested three times. The results of measurements were averaged before recording on the memory card. In the next step, the magnetic field was measured in the same way on the surface of the faulty samples.

Fig. 20-23 show some exemplary magnetograms made at this stage of the experiment.

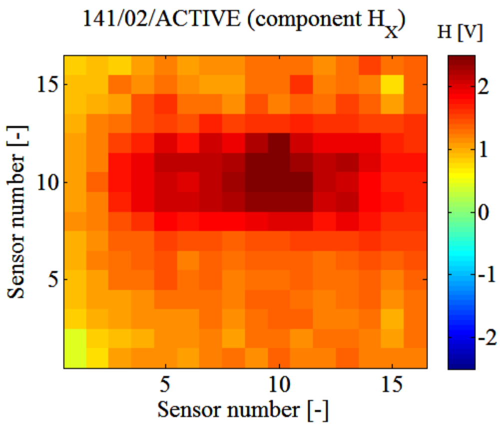

Fig. 20. Distribution of H_x component of the magnetic field on the surface of the reference sample 141/02

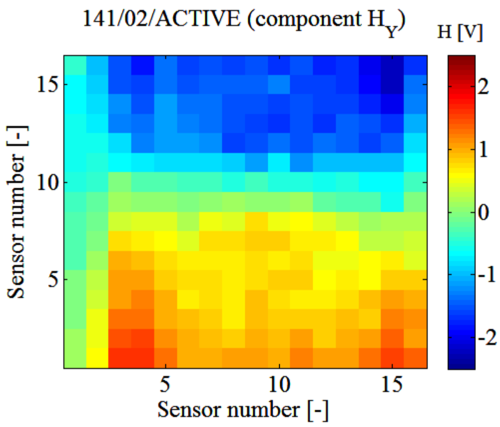

Fig. 21. Distribution of H_y component of the magnetic field on the surface of the reference sample 141/02

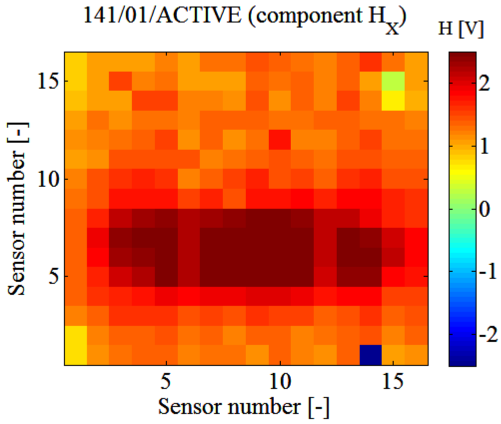

Fig. 22. Distribution of H_x component of the magnetic field on the surface of the faulty sample 141/01

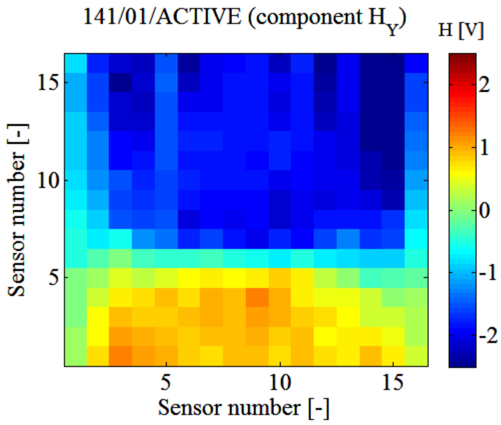

Fig. 23. Distribution of H_y component of the magnetic field on the surface of the faulty sample 141/01

Magnetograms of the surfaces of samples taken by the active magnetic method indicate that the intensity of magnetic field changes significantly on the surface of samples.

Component H_x of the magnetic field (perpendicular to the tested weld and tangential to the surface of the sample) has reached the greatest value above the root of the weld. In the case of a faulty sample the area of maximal values of H_x component of the magnetic field was greater than for the reference sample. The mere existence of a distinct maximum of H_x component of the magnetic field informs about the inhomogeneity of the sample caused by the presence of the weld which may be confirmed by the comparison of magnetograms for the welded sample and the homogeneous sample without any welded joint (Fig. 24).

Component H_y of the magnetic field (vertical to the surface of the sample) changes its sense above the root of the weld. In the case of the faulty sample the change of the sense of component H_x of the magnetic field was sharper than for the reference sample. In the lack of any inhomogeneity caused by the presence of the weld the sense of component Hx of the magnetic field changes more smoothly and steadily which may be observed on the magnetogram of the homogeneous sample without any welded joint (Fig. 25).

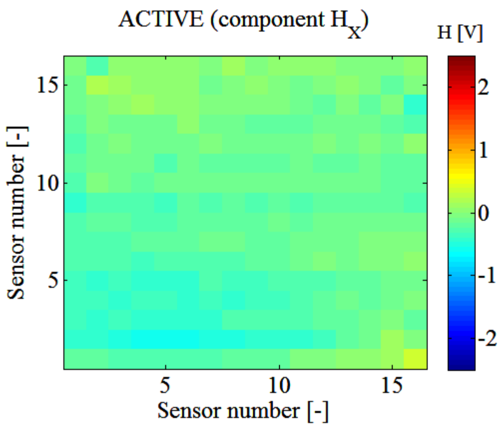

Fig. 24. Distribution of H_x component of the magnetic field on the surface of the homogeneous sample (without the welded joint)

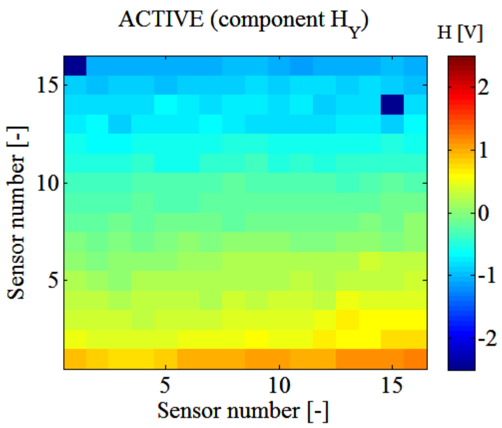

Fig. 25. Distribution of H_y component of the magnetic field on the surface of the homogeneous sample (without the welded joint)

6. CONCLUSIONS

Results indicate the benefits of the active magnetic method. Magnetograms received by means of the passive magnetic method have proved to be useless in practice whereas the magnetograms taken by the active magnetic method provided relevant information about investigated surfaces. Only the component H_z of the magnetic field (parallel to the tested weld and tangential to the surface of the sample) was useless. The analysis of distribution of two remaining components of the magnetic field above the tested surface can be useful at detection of material inhomogeneity and evaluation of its extension. It creates a possibility for detection of a "camouflaged" weld (e.g. ground and painted) which may be significant regarding inspection of the originality of identification marking of cars.

It is also possible to assess the quality of the weld workmanship or the technical condition of the used weld. The evaluation has a rough character of course as the value of magnetic flux leakage can provide only general information on the size of the inhomogeneity. On the other hand, the magnetic tests are rapid (short time for receiving the magnetograms and lack of special preparations of the tested surface) and, as a consequence, not expensive. The active magnetic method may be used as a "screening" method for detection of defects in welded joints.

It is worth to notice that magnetograms may be used in diagnostics of investigated surfaces not only for the welded joints but also for the detection of other types of inhomogeneities in tested components caused e.g. by forging cracks, fatigue cracks, hardening cracks, grinding cracks, tearing and dents, and corrosive losses. Magnetic method may be used to test elements made of ferromagnetic material: ferrite steels, cast iron and cast steel. It is possible to detect inhomogeneities and discontinuities on the material surface and relatively large subsurface faults, but located close to the tested surface.

In the future, the research work will be focused on developing a matrix consisting of AMR (Anisotropic MagnetoResistance) magnetometers which use the anomaly of the magnetoresistance phenomenon. Building the matrix of sensors is planned with changeable dimensions and curved surfaces to carry out rapid diagnostics for welded joints of rocket propellant burning chambers and tanks storing the compressed air.

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