METAL MAGNETIC MEMORY TESTING OF WELDED JOINTS OF FERRITIC AND AUSTENITIC STEELS

Maciej ROSKOSZ
The Silesian University of Technology, 44-100 Gliwice, ul. Konarskiego 18, Poland
maciej.roskosz@polsl.pl

Abstract

The method of the metal magnetic memory testing is a passive method of non-destructive testing based on the residual magnetic field (RMF) of a component. It allows the localization of stress concentration zones in the objects under examination. The defects in welded joints are places of stress concentration. Also, due to the geometric notch effect and thermal deformations after welding, the welded joint is a stress concentrator. Therefore, not all indications obtained in the method of the MMM testing are defects in the common, standard meaning. Additionally, in the weld seams of austenitic steels, the non-uniformity of delta ferrite in the joint results in changes in the RMF distribution and gives rise to indications. The paper presents the ways of examination and assessment of welded joints by means of the method of the MMM testing. The presented research methodology is the outcome of a synthesis of own experience and the provisions of standards ISO 24497-1, 2, 3: 2007. The results obtained in the MMM testing were compared to the results of the radiographic testing (RT). It was found that the MMM testing allowed the detection of imperfections, including defects, in welded joints at the production stage. Knowing the potential of the method of the MMM testing it seems well justified that it should be used in the examination of welded joints at the operation stage. These joints, after non-destructive testing at the production stage, are not free from defects. The defects, together with imperfections at the micro-level, concentrate stresses from working loads. Wear processes and the development of micro- and macro-cracks proceed in them the fastest. By finding the stress concentration zones, the areas of potential cracks can be found. The development of reliable procedures of examination and assessment of welded joints with the use of the method of the metal magnetic memory testing still needs a lot of research.

Key words: metal magnetic memory; welded joints

1. Introduction

The method of metal magnetic memory testing is a passive magnetic method of non-destructive testing which makes use of the strength of the residual magnetic field (RMF) of the component as a diagnostic signal [1, 2]. The physical basis of the method consists in: the magnetomechanical effect [3, 4, 5], the effect of the leakage of external magnetic fields caused by discontinuity or structural non-uniformity of the material, and the processes of mutual interaction of magnetic fields with dislocations and their accumulation. The method allows the localization of stress concentration zones in the component [1, 2]. The introduction of standards ISO 24497-1, 2, 3: 2007 [6] concerning the method of the MMM testing became a great stimulus for its development and promotion. It confirmed and strengthened its presence in the field of the methods of non-destructive testing by propagating the basic notions used in it and by describing its potential and limitations.
The presented methodology for testing welded joints is the outcome of a synthesis of own experience and the provisions of these standards.

The defects in welded joints are potential stress concentrators. But stress concentration in a welded joint does not have to be the result of only the occurrence of defects. Looking more broadly at the problem of stress concentration, the welded joint, due to the notch effect and thermal deformations after welding, is a stress concentrator itself. Therefore, not all indications obtained in the MMM testing are defects in the common, standard meaning. Some of the indications of the method of the MMM testing of welded joints can result from the occurrence of a non-uniform distribution of stress after welding [7].

On the other hand, a question arises whether all defects of welded joints which can be detected by means of standard methods of non-destructive testing yield indications in the MMM testing. To answer this question, research based on the comparison of the results of the RT method to those obtained in the method of the MMM testing was undertaken. The study was conducted on weld seams of both ferritic and austenitic steels. The programme of the MMM testing comprised the testing of weld seams from the side of the face and back of the weld at the production stage and after static loads applied to selected joints.

2. Methodology of MMM testing of welded joints

2.1. Testing conditions
Welded joints do not require, compared to other methods of non-destructive testing, any preparation of the surface to be examined. At the production stage, it is required that the surface should be cleaned after welding. At the operation stage, the removal of loose deposits from the surface of the joint is required. The impact of the thickness of the corroded layer or other coatings of the joint on the examination results should be taken into consideration, and sensitivity tests of the detection of indications should be conducted. A substantial limitation on the application and reliability of the indications of the method are the sources of external magnetic fields such as magnetization during magneto-powder testing, or the passage of current in the vicinity of the examined component during welding.

2.2. Testing procedure
The testing is conducted through scanning the surface of the welded joint both along and perpendicularly to the axis of the weld seam so as to embrace both the weld seam and the heat effect zone.

2.3. Assessment of indications
As an immediate result of the testing, the values of the RMF components measured on the surface of the welded joint are obtained. In order to quantify the level of concentration of residual stress, the gradient of the RMF components, referred to as $K_{inn}$, is determined. The area of maximum concentration of stress corresponds to the maximum value of the gradient of the RMF components – the maximum value of coefficient $K_{max,inn}$. Additionally, the average values of the RMF components – $K_{med,inn}$ – are determined. The ratio of the maximum value of the gradient to its average value is determined by what is, according to standard PN-ISO 24497-1, referred to as magnetic index $m$. According to standard ISO 24497-3, it is assumed that $m_{inn}$ is contained within the range from 1.05 to 3 and more, depending on the quality of the welded joint. If coefficient $m$ exceeds the boundary value $m_{inn}$, what we have to do with is the stress concentration zone. The determined stress concentration zones have to be put to standard non-destructive and/or metallographic testing.
3. Testing results

The presented testing results are representative of the whole research that was conducted. Radiographic testing of welded joints was made according to standard EN 1435. The assessment was carried out according to the provisions of standard EN ISO 5817. The measurements of the RMF were made with a scanning increment of 1mm along lines parallel to the axis of the weld seam and separated from each other by a constant value (for individual joints). The area under examination included both the weld seam and the heat effect zone.

The magnetometer TSC-1M-4 with the measuring sensor TSC-2M supplied by Energodiagnostika Co. Ltd. Moscow was used for the measurements. The instrument was calibrated in the magnetic field of the Earth, whose value was assumed as 40A/m. The measurements gave the values of three RMF components:
- \( H_{t,x} \) – tangential component measured in the direction perpendicular to the axis of the weld seam,
- \( H_{t,y} \) – tangential component measured in the direction parallel to the axis of the weld seam,
- \( H_n \) – normal component.

For the purposes related to the assessment of the joint, they were used to determine the values of the gradients of the RMF components. Dividing the local values of gradients by the average value for a joint, the values of what is referred to as magnetic index – \( m \) for each point were obtained. The areas of the largest values of the index are stress concentration zones (SCZ's), i.e. the indications of the testing method. For editorial reasons, the paper presents only selected magnetograms (distributions of magnetic index \( m \) for individual RMF components) which allow a justification of the drawn conclusions.


Ferritic steel S235JR, one-sided MIG welding, testing at the production stage. The indications of the method of the MMM testing occur in the vicinity of defects, but the largest values of the relative derivative \( m \) were obtained in defect-free areas according to the RT method.

![Fig. 1. Radiogram of joint A, welding incompatibility 30 ÷ 60 mm – bubble cluster (2013); 140 ÷ 160 mm – bubble cluster (2013).](image_url)
Fig. 2. Magnetogram $m - H_{n,y}$ of joint A, indications: 30 ÷ 50 mm – SCZ coincides with the location of the occurrence of the defects of the weld seam; 120 ÷ 150 mm – SCZ partly coincides with the location of the occurrence of the defects of the weld seam; the area of the largest values of $m$ are probably the place of arc reignition, which may also suggest the occurrence of imperfections 517 or 601 according to standard EN ISO 5817; 160 ÷ 180 mm – SCZ.

Fig. 3. Magnetogram $m - H_{n,z}$ of joint A, indications: 90 ÷ 120 mm – SCZ, 140 ÷ 170 mm – SCZ coincides with the location of the occurrence of the defects of the weld seam.

3.2. Welded joint B

Ferritic steel S235JR, one-sided MIG welding, testing at the production stage and after static load. Despite the defect found by means of the RT method (Fig. 4) no indications were obtained in the MMM testing at the stage of production (Fig. 5). After static load was applied to the joint, which induced stresses of 100 MPa, indications occurred – Fig. 6.

Fig. 4. Radiogram of joint B, welding incompatibility 35 ÷ 35 mm – lack of side fusion (4011).
3.3. Welded joint P8
Austenitic steel X15CrNiSi20-12 with a thickness of 6 mm, two-sided TIG welding, testing at the production stage.

The analysis of the Schaeffler and Delong diagrams shows that the weld seam in steel X15CrNiSi20-12 welded with Thermanit C Si (W 25 20 Mn) should not contain delta ferrite. However, in real conditions of weld solidification, because of fast heat dissipation and related to it fast cooling of melted metal and limited diffusion conditions, a tiny amount of ferrite can be present in the structure [9]. In the test samples both in the parent material and in the weld seam, as well as in the heat effect zone, a distinct presence of delta ferrite was found. The structure of the parent material contains austenite grains elongated in the direction of plastic working with narrow strips of delta ferrite distributed mainly in the form of a grid on the boundaries of austenite grains. The tested weld seams have an austenitic structure with the presence of a varied amount of delta ferrite which occurs mainly as interdendritic areas. The heat effect zone (HEZ) is characterized by transitory structures in which delta ferrite also appears locally in a lamellar configuration (Fig.2) [9].

Magnetogram m – \( H_{t,x} \) (Fig. 9) gives a clear indication (SCZ) in the place of the defect occurrence. In the magnetograms of the other components the defect gave no indications. There are indications in them, with values even higher than in magnetogram m – \( H_{t,x} \), which do not coincide with the location of the defect.
3.4. Welded joint P12
Austenitic steel X15CrNiSi20-12 with a thickness of 6 mm, two-sided TIG welding, testing at the production stage.

An indication in the defect area occurs in magnetogram \( m - H_{i,y} \) (Fig. 12). In magnetogram \( m - H_{i,x} \) one half of the length of the joint is characterized by large values of the magnetic index while in the other half the values are distinctly smaller. Metallographic testing of the structure was conducted in two sections of this joint. In the 50 mm section a significant amount of largely elongated delta ferrite was found in an interdendritic configuration (Fig 13.). This indicates a considerable overheating of the weld metal during welding and a relatively high cooling rate of the material after welding. The area of the weld seam of the 150 mm section (Fig. 14) shows an austenitic structure with narrow areas of interdendritic ferrite characterized by smaller elongation than for the 50 mm section, and the share of ferrite in the weld seam is smaller, too [9].
Fig. 10. Radiogram of sample P12, welding incompatibility: 80 ÷ 90 mm – single bubble (2011), 80 ÷ 115 mm – lack of side fusion (4011).

Fig. 11. Magnetogram $m - H_{tx}$ of joint P12, indications: 20 ÷ 110 mm – SCZ in the area of the weld seam coincides partly with the location of the occurrence of defects.

Fig. 12. Magnetogram $m - H_{ty}$ of joint P12, indications: 50 ÷ 120 mm – indication in the area of the weld seam coincides with the location of the occurrence of defects.

Fig. 13. Joint P12 – 50 mm section – structure of the weld seam. Austenitic structure with a significant amount of interdendritic ferrite, etched with ferric chloride, magnification: 200x.

Fig. 14. Joint P12 – 150 mm section – structure of the weld seam. Austenitic structure with narrow areas of interdendritic ferrite, etched with ferric chloride, magnification: 200x.
4. Discussion

4.1. Ambiguity and lack of indications of existing defects of the weld seam in the method of the MMM testing.

The imperfections of the weld seams visible in the radiograms did not always give unequivocal and clear indications in the method of the MMM testing. It was not established which of the RMF components was best suited as a diagnostic signal. For the welded joints under examination, a clear indication of a defect, if there was any, usually occurred in the image of only one component; for other components the indications were none or barely visible. The problem is additionally complicated by the fact that, for different joints, they were different components. It is also difficult to define the values of magnetic index $m_{\text{lim}}$ for individual RMF components. It is puzzling that the same defects, located at the same depth in the joint, in some cases give indications (both when measured from the face and back of the weld) while in others they do not, cf. joint A. It is probably decided by the level of postweld stresses at the location of defect occurrence. The test was made on fragments of steel plates which could deform freely after welding. For this reason postweld stresses occurring in them were smaller than those in rigidly fixed joints of welded structures. This may be the reason for the ambiguity and lack of indications.

4.2. Indications of the method of the MMM testing in places where defects were not found by means of the RT method

Many indications were obtained in places where defects were not found by means of the RT method. The reasons for this were partly explained in the introduction to this paper. The indication in the method of the MMM testing, i.e. the stress concentration zone, can be a result of a non-uniform distribution of stresses due to postweld thermal deformations [7, 10]. In the search for volumetric geometrical defects of the weld seam such indications are erroneous. But the information is very valuable if an assessment of the quality of postweld thermal treatment of the weld seam was to be made. A comparison of the magnetic images of the weld seam before and after thermal treatment can be the basis for the assessment of its efficiency. Another reason for obtaining phantom indications is the fact that neither the face nor the back of the weld seam forms a uniform smooth surface. The irregularities occurring in them, and affecting the sensor lift-off, cause further disturbances in the diagnostic signal of the method [11]. This results in rapid local changes in the measured values of the RMF components, and – consequently – in the formation of areas with a large RMF gradient in the obtained image of magnetization. The reasons for the appearance of additional indications which are not defect-related, for weld seams of austenitic steels, were discussed in Point 4.4.

4.3. Due to working load the probability of defect detection in weld seams by means of the method of the MMM testing is higher.

Welded joints, after non-destructive testing at the production stage, are not free from imperfections. They can have acceptable defects and those which were not detected. These defects, together with imperfections at the micro-level, concentrate stresses from working loads [1, 2]. In stress concentration zones, wear processes and the development of micro- and macro-cracks, proceed the fastest. By finding stress concentration zones, the areas of potential or existing cracks can be found. An example of stress concentration in the defect area are the results obtained for joint B – Point 3.2. At the production stage, no indications of lack of fusion were found by means of the method of the MMM testing. After static load was applied to the joint, an indication was obtained in the place of the defect occurrence.
4.4. Weld seams of austenitic steels – more problems but also more potential for the application of the method of the MMM testing

Austenitic weldable steels are often materials which ensure a formation of a certain amount of delta ferrite in the weld seam – usually 5-10% – which prevents cracks and improves the mechanical properties of the material. On the other hand, the presence of delta ferrite adversely affects creep strength. Delta ferrite is formed as single areas on the grain boundaries, but when heating exceeds 1340°C, a certain amount of it also occurs inside austenite grains. With a very fast solidification of the weld seam, ferrite can also occur in the form of a grid blocked in interdendritic areas. The amount of delta ferrite in the weld seam depends also on the phenomenon of the liquid material of the weld metal mixing with the liquid metal of the components being welded. With higher contents of ferrite above 4%, it usually takes the shape of a continuous grid on the boundaries of austenite grains. Weld seams working at temperatures of 600 – 850ºC cannot contain a higher content of delta ferrite because in these conditions a formation of a very brittle sigma phase occurs in it together with formations of carbides and austenite. This kind of phase can also appear as a result of the stress-relieving thermal treatment, and even as a consequence of the heat effect in multilayer welding [7].

The presence of delta ferrite in a weld seam of the austenitic steel allows the application of the method of the MMM testing. The value of the strength of the RMF for austenitic steel weld seams are much lower than those for weld seams of ferritic steels. Therefore external disturbances (sources of the magnetic field, closely located ferromagnetic objects) can easily and substantially distort the measurement results. The magnetic image of the joint is decided by the amount and distribution of delta ferrite. The higher the amount of it, and the more uniform its distribution in the weld seam, the higher the probability that disturbances caused by the occurrence of defects will be seen in the image of the RMF. If the distribution of delta ferrite happens to be non-uniform, the distribution of the RMF is more often an image of this non-uniformity rather than the result of the occurrence of defects. This is clearly visible in the presented P12 joint – Point 3.4.

5. Conclusion

The paper presents selected results of the MMM testing of weld seams which were compared to the results obtained by means of the RT method. Welded joints in austenitic and ferritic steels were examined. The main aim of the research was to define the effectiveness of the application of the method of the MMM testing as a defect detection method. The obtained results show that at the present stage of development the method of the MMM testing does not guarantee the same effectiveness of defect detection as the RT method used as the reference method. This applies particularly to the testing of weld seams at the production stage. In the detection of defects of weld seams already in service, the method of the MMM testing works much better. The imperfections which occur in weld seams, by concentrating stresses from working loads, create favourable conditions for the development of cracks. At the same time, due to the magnetomechanical effect [3, 4, 5] they result in indications of the method of the MMM testing. By finding stress concentration zones, the areas of potential or existing cracks can be found. It was found that the method of the MMM testing, apart from being applied to defect detection in weld seams, could be used to assess the level of residual stress, the quality of the thermal treatment after welding and to define the amount of delta ferrite in weld seams of austenitic steel. The analysis of the changes in the RMF can also be used to assess the residual lifetime of weld seams [12, 13, 14]. Each of these applications requires an analysis of signals (the RMF components) with a view to developing criteria. The best way to develop such criteria is a combination of the
results of experimental research and the results of the modelling of the RMF distributions [7, 15].

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References