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AND FACULTY OF MECHANICAL ENGINEERING**
Aškerčeva 6, 1000 LJUBLJANA, SLOVENIA

ARE ORGANISING

**THE 12th INTERNATIONAL CONFERENCE OF
THE SLOVENIAN SOCIETY FOR NON-DESTRUCTIVE TESTING**

titled

**"APPLICATION OF CONTEMPORARY
NON-DESTRUCTIVE TESTING IN ENGINEERING"**

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Sound pressure signals during quenching are represented in spectrograms as a time record of sound signals, from which a frequency is evident at the ordinate and signal intensity as colour intensity.

F. Ravnik, J Grum

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NON-DESTRUCTIVE TESTING IN ENGINEERING"**

ORGANISED BY

THE SLOVENIAN SOCIETY FOR NON-DESTRUCTIVE TESTING

and

FACULTY OF MECHANICAL ENGINEERING

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PREFACE

The rapidly expanding role of Non-Destructive testing and evaluation (NDT & NDE) methods in manufacturing, power, construction, and maintenance industries, as well as in basic research and development, has generated a large demand for practitioners, engineers, and scientists with knowledge of the subject.

The Non-Destructive testing of materials is becoming more and more important, during the production process prior to building the constituent parts in individual devices and machines. It is becoming even more important in service inspection where the state of the material is checked and further safe operation of the device or machine is confirmed.

Demands that each part built in machine is manufactured in a qualitative manner require from each manufacturer removing bad or rejected parts prior to selling them to buyers or building them in a device or a machine. Therefore demands are set up that manufacturers develop proper Non-Destructive methods, in corresponding devices and also experts with adequately verified knowledge. Especially for the reasons, in automated production, there often come demands that workpieces, namely machine parts are tested in a very short time while the method must assure respective reliability and also repeatability.

The proceedings comprise papers presented at the 12th Int. NDT Conference held in Portorož, Slovenia from 4 to 6 September 2013. The conference was organized by the Slovenian NDT Society and Faculty of Mechanical Engineering, University of Ljubljana. The excellent scientific standard of the presented works, the presence of experts from 23 countries all over the globe and the inspiring venue of the Slovenian Adriatic Coast contributed to the success of the conference. The proceedings contain nine keynote papers presented by distinguished experts from the field, who I am grateful to for sharing their expertise with us.

The Scientific Committee reviewed 82 papers out of which 74 were presented at oral sessions and 8 at poster sessions.

The presented papers discussed ultrasonic testing, electromagnetic, acoustic emission, thermal and infrared techniques and radiographic techniques, NDT education and training and other methods.

The three-day event provided a forum for scientists, engineers and practitioners as well as end-users to review the latest developments, identify particular needs and opportunities for further advances, exchange knowledge and experience with other well-known experts as well as outlined the milestones for further progress in NDT & NDE fields. We are grateful to the European Federation for NDT for their auspices of the conference.

The editors would like to express their gratitude to the authors of these proceedings and the members of the International Scientific Committee for their intensive work, cooperation and constructive reviews in selecting the final papers. We are proud to have welcomed all well-known experts in the field who came to share their scientific knowledge during formal and informal discussions.

The success of the conference was also provided by vast preparatory work done by all members of the Department of Materials Technology at the Faculty of Mechanical Engineering, University of Ljubljana. We very much appreciate the diligence of the secretary of the department Mrs. Dušanka Grubor Železnik.

Finally, the editors would like to acknowledge the contribution of the authors who submitted their work for publication in this dedicated proceedings as well as the members of the Scientific Committee who contributed with their expertise in the peer review process.

Prof. Dr. Janez Grum

Asst. Prof. Dr. Tomaž Kek

SUBJECT OF THE CONFERENCE

- Applications of non-destructive methods for constructions testing;
- Control of materials and constructions with various non-destructive testing of materials and constructions;
- Mathematical modelling in non-destructive testing;
Computer-aided methods for non-destructive examination of materials and constructions;
- Applications of various non-destructive methods for materials testing in manufacturing and operation;
- Automation of non-destructive testing of materials and products in mass production;
- Innovations in non-destructive testing techniques;
Evaluation in indications, reliability estimations and estimation of defect acceptability;
- Training, personnel qualification and certification for non-destructive testing
- Facilities and equipment qualification and authorization of non-destructive testing;
- Standards and application of standards in the fields of non-destructive testing.

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INNOVATIVE CONCEPT AND APPLICATION OF EC PROBE FOR INSPECTION OF FRICTION STIR WELDS

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ABSTRACT

In this paper a new NDT system is presented. The system is composed by a planar eddy currents probe (IONic probe), electronic devices for signal generation, conditioning and conversion, automated mechanized scanning and analysis software. This new IONic probe allows a 3D induced current in the material, and an easy interpretation of the signal based, not on the absolute value, but on a comprehensible perturbation of the signal. This provides enhanced lift-off immunity and improved sensitivity for defects detection. The IONic system was developed mostly to be used for the micro-defects detection on aluminum solid state processed alloys by FSW.

The features of some material imperfections lead to significant difficulties in their identification when using existent NDT techniques. Results from an analytical simulation fully agree with the experiments. The experimental results in AA2024 welded by FSW clearly show that this system is able to detect imperfections around 50 µm, which contribute to increase the reliability on NDT of micro imperfections.

EC conventional probes are also applied as material characterization technique. Results are compared to microstructural analysis and hardness measurements show that eddy current can map the different zones providing a deeper understanding on precipitate dispersion and grain shape and size.

Keywords: IONic Probe, Eddy Currents, Non-Destructive Testing, Friction Stir Welding, Aluminium.

1 – Introduction

NDT is a vital function in achieving the goals of efficiency and quality at an acceptable cost. The consequences of failure of engineering materials, components and structures are well known and can be disastrous [1].

Withal, different materials and production technologies have different NDT needs. For example, the typical inspection needed for composite structures involves the problem of covered large areas [2]. On the other hand, composites such laminates are often damage tolerant and it is frequently only necessary to find relatively large defects, e.g. 20–30 mm. For these applications, some NDT techniques were developed and currently applicable, e.g. ultrasound (US) C-Scan [3], transient thermography [2], shearography and holography [4], laser ultrasound [5] and thermosonics [6].

However, this paper focuses other field of NDT inspections: the inspection of high performance components structures, processed by solid state welding technologies, namely Friction Stir Welding (FSW). Indeed, these applications have complete different NDT requests: covering a small area is typically enough, but a high reliably defect detection and sizing is required, e.g. 50 μm defects depth [7].

For this type of situations also advanced NDT techniques have been developed and implemented: Pulsed Eddy Currents (PEC), EC Arrays, Meandering Winding Magnetometer (MWM[®]), Superconducting Quantum Interference Device (SQUID), Giant Magnetoresistance (GMR), US Phased Array, Time of Flight Diffraction (ToFD), and digital radiography.

Nevertheless, in conductivity materials, when high reliability is required as mentioned before, Eddy Currents (EC) is the most common used technique. However, EC flow can change not only due to defects, but also due to the variations of the probe lift-off. The high-sensitive lift-off effect of conventional EC probes introduces noises which mask the signal of small defects, making their detection difficult or even impossible. Moreover, the low sensitivity of common EC probes as well as other electronic issues may not enable to distinguish between defect and non defective conditions [8], [9].

To improve the EC NDT reliability some variants were developed and are currently available. Neil Goldfine et al. [10] have developed a MWM[®] probe which is able to detect some FSW defects and also 50 μm depth defects on aluminium specimens under fatigue. However, it should be emphasized that this last result were achieved mainly because the probe was permanently mounted on the specimen during the tests, and therefore the lift-off effect was eliminated. Others promising EC variants are GMR [11] and SQUID [12] sensors: the probe has a coil to generate the induced current in the test material, and GMR or SQUID as a sensing element. It has the advantage of a higher sensibility, even under low frequencies, but the lift-off problem still remains. Catalin Mandache et al. [13] applied PEC in FSW, but even in the presence of significant size root defects the inspection accuracy is low. PEC variant has the capability to detect deeper defects, but micro defects can hardly be detected.

2 - The new EC NDT system: IONic probe

A new NDT system was developed and undergone testing under real non defective and defective conditions, in order to assess its NDT feasibility for FSW and FSpW. This innovative system is constituted by: i) new patented eddy current probes (IONic Probes) [14], ii) electronic devices for signal generation, conditioning and conversion, iii) customized support where the IONic probes are fixed and connected. This support also includes an electronic pre-amplifier allowing to measure very small amplitude signals without the influence of cables electromagnetic noise added.

iv) automated mechanized scanning, and v) dedicated software (Fig. 1).

Fig. 1: NDT system overview.

An innovative aspect of the system is the entirely new design of the IONic probe. This new patented design allows: a 3D induced eddy currents in the material; a deeper penetration; an independence of the deviation between the probe and the material surface (planar lift-off); an easy interpretation of the output signal based not on the absolute value but on a comprehensible characteristic change. In addition this probe can be manufactured on flexible substrates, allowing non-planar surfaces inspection. The IONic probe is constituted by one excitation filament, in the middle of two sensitive planar coils, in a symmetric configuration (Fig. 2). The two sensitive coils are wired on opposite directions to avoiding the auto inductance effect. Due to this layout the operation of the IONic probe is based on an integration effect along each sensitive coil, and simultaneous, on a differential effect between the two coils. The magnetic stimulus is induced by the current flow, $\vec{I}$, on the excitation filament, and the detection of the defects is based in the induced voltage ($\vec{U}_{out}$) on the terminals of the sensitive coils. Furthermore, the imperfections detection is done by characterizing $\vec{U}_{out}/\vec{I}$ along the test.

Fig. 2: The IONic Probe prototype.

The probe prototype was manufactured on dual layer FR4 PCB substrate with different external dimensions. The two sensitive coils are formed by tracks of width of about $100\ \mu\text{m}$ separated by constant dimension gaps.

One particular feature of the IONic probe comparing to the conventional axis-symmetric EC probes is the eddy current vector field display inside the material to be inspected. Fig. 3 show the qualitative eddy current display in both cases. The IONic probe, allow the detection of both defects quasi-parallel and quasi-perpendicular to the surface. In fact, conventional axis-symmetric EC probes induces a magnetic flux perpendicular to the surface of the material, causing an eddy current flux parallel to the surface and coaxial to the excitation coils. The IONic probe, in contrast, has an excitation filament, which induces a non-confined magnetic flux all around the filament. As a consequence, the eddy current flux flow parallel to the surface in the surface plane, but it flow also in other non-parallel planes, collinear with the axis of the excitation filament, in a radial arrangement.

Fig. 3: Eddy currents display in IONic Probe and conventional axis-symmetric EC probes.

3 - The morphology features of defects in FSW

The geometry, location, and microstructural nature of the FSW imperfections bear no resemblance to the imperfections typically found in fusion welds. Although FS welds can be produced free of imperfections, some imperfections may arise due to improper stirring of the parent material, inadequate surface preparation, lack of penetration of the probe, or inadequate axial forging forces.

Some typical FS weld imperfections include i) root with lack of penetration (also known as “kissing bond”, ii) root with weak or intermittent welding due to particles alignment, iii) particles alignment crossing/along the nugget (e.g. “silly s”), iv) internal cavities in the nugget, and v) particles alignment parallel to top surface, in the zone directly processed by the shoulder, or in the nugget (e.g. “silly s”), as well as in the weld root.

From the scope of these imperfections, the root defects (i and ii) are the ones more difficult to be detected and that present higher loss of mechanical resistance of the joints under fatigue loading [8]. Therefore these are the target defects of the present NDT analysis. In i) the materials are in close contact, (sometimes under severe plastic deformation), but with no chemical or mechanical bond. In ii) the dynamically recrystallized zone fills the total thickness of the joint, but there are still some second phase particles and/or oxides aligned from the root of the joint into the nugget, in a more or less continuous path.

In both situations there is a very low energy reflection/perturbation effect, when using US or EC NDT commercially available solutions, due to the very small defects size, and due to the non physical material discontinuities. Other additional difficulty related with the FSW inspection arise from the conductivity changes due to the existence of a stirred zone, even with no imperfections: in fact the FSW process causes material conductivity changes in the welded zone, even without any imperfection. These conductivity changes are a consequence of the microstructure changes due to the dynamical recrystallization, the decrease of the grain size, and the presence of precipitates due to the thermal cycle during the process.

Hence, when EC NDT inspection is perform on FSW the electric impedance of the probe changes are mainly due to the presence of the FS welded material, instead the presence of a imperfections. Therefore an accurate discrimination between this two diverse conductivity changes (due to the welded material and due to the imperfections) must be considered in order to detect and sizing defects. Conventional helicoidal and planar spiral absolute EC probes can hardly distinguish booth cases [9]. Consequently this type of conventional probes can hardly detect FSW defects.

Fig. 4 allows understanding the generic conductivity fields involved in a FSW joint with and

without root defect. The dotted line represent the typical conductivity field of a standard imperfection produced e.g. by wire electroerosion: the constant conductivity along the material is suddenly perturbed due to the locally inexistence of material. The dashed line represents the conductivity field across a FSW weld bead with no imperfections: a spreaded increase of conductivity occurs centered in the weld nugget. Finally, the red line represents the conductivity of a FSW weld bead with root imperfection: it is similar to the conductivity of a FSW with no imperfections, but it has a local and dip decrease in the center due to the root imperfection.

The conductivity field of a FSW with root imperfection can be understood as a sum of the conductivity field of a FSW with no imperfection and a conductivity field of a standard imperfection. Thereby the challenge of the FSW EC inspection is to distinguish and quantify booth conductivity changes.

Fig. 4: Typical conductivity fields across the FSW bead.

The typical FSW conductivity field in the vicinity of a joint ($\sigma(x)$) is properly described by the Equation 1. It is a Probability Density Function (PDF) of the Gaussian distribution, with a standard deviation (λ) typically near to 1/3 of the shoulder diameter. A factor K is used to normalize the curve.

$$\sigma(x) = K \cdot \frac{1}{\lambda\sqrt{2\pi}} \cdot \exp\left(-\frac{x^2}{2\lambda^2}\right); \quad \lambda \approx \frac{\phi_{Shoulder}}{3} \quad (1)$$

The accurately correlation between Equation (1) and the experimental FSW conductivity field is demonstrated in Fig. 5. This Fig. relates to a non-defective FSW on AA2024-T351 performed with an 18 mm shoulder diameter. The black line represents the normalized experimental conductivity measurement across the FSW weld bead, using a planar circular spiral EC probe with 20 coils and an outside diameter of 9 mm operating @ $f = 250$ kHz. The continuous line correspond to theoretical conductivity fields using the Equation (1) with $\lambda = 18/3$ and $K = 2.5$. The respective $\lambda_{Exp.} = 0.369$ and $\lambda_{Theo.} = 0.350$ confirm the good agreement between both curves.

Fig. 5: Comparison between the experimental and theoretical conductivity fields across an FSW joints.

In order to test and validate the NDT system, in particular the IONIC probe, a set of different

FSW defective joints were performed in AA2024-T351 plates with 3.8 mm thickness. The FSW tool used consists in an 18 mm diameter shoulder with a spiral scrolled profile, and a conical threaded probe with 3 helicoidal longitudinal channels. The conical probe has a 5 mm and 8 mm diameter at the top and at the bottom, respectively.

In Table (1) it is summarized the main FSW parameters used to produce three different root defect conditions: Type 0, Type I and Type II (Fig. 6).

Fig. 6: Transversal macrographs of three different FSW root defects conditions. Defect Type 0: particles alignment, Defect Type I: $\approx 60 \mu\text{m}$, Defect Type II: $\approx 200 \mu\text{m}$.

Defect Type 0 is characterized by some residual particles alignment in an intermittent path along $\approx 150 \mu\text{m}$, but the dynamically recrystallized zone (nugget) fills the total thickness of the joint. This condition is typically considered a non-defective weld. Defect Type I is characterized by a weak or intermittent welding since the materials are in close contact, under severe plastic deformation, but with no chemical or mechanical bond along $\approx 50 \mu\text{m}$. Defect Type II is characterized by $\approx 200 \mu\text{m}$ non welded zone, under less plastic deformation, followed by particles alignment in an intermittent path in direction to the interior of the nugget.

The three different conditions present a consecutive increase of the defect intensity, suitable for a reliability analysis of a NDT system.

4 - Results and NDT System Validation

The NDT system was applied on defects condition described before. The data $S(x) = \text{Im}\{\bar{U}_{out}/\bar{I}\}$ and $S(x) = \text{Re}\{\bar{U}_{out}/\bar{I}\}$ was acquired from the root side, along a sweep on the transversal direction to the weld joint, with the excitation filament of the IONIC probe parallel to weld joint. The starting point of the tests was set to 25 mm in the retreating side of the weld bead, and 50 mm long segments were characterized in direction to the advancing side, with 250 μm space within each acquisition. In all the acquisitions the real and imaginary part of $\bar{U}_{out}/\bar{I}$ was measured @ $f = 100 \text{ kHz}$ and $f = 50 \text{ kHz}$. The imaginary part of the three types of defects at these frequencies is shown in Fig. 7 and Fig. 8, respectively.

As FSW process causes material conductivity changes, even without imperfections, the weld bead is responsible for the large curve on the imaginary part. The presence of imperfections creates a small perturbation observed on the middle of the joint, highlighted in red on Fig. 7. This signal characteristic is presented also in Fig. 8.

This behavior can be understood taking into account the conductivity fields implicated in the FSW processed material, previously mentioned in Fig. 4. The large trend of $S(x)$, with a minimum in $x \approx -7 \text{ mm}$ and a maximum in $x \approx +7 \text{ mm}$, concerns to the spreaded increase of the conductivity field ($\sigma(x)$) due to the FSW joint, independent of the existence or absence of defects (consequence of the dashed line in Fig. 4). Thus, this trend is almost the same for all defect conditions.

On the other hand, the small perturbation observed at the middle of the joint concerns to the suddenly decrease of conductivity due to the local root defect of each defect condition. In fact

this trend has the same qualitative pattern of the last one, but with two main differences: 1) Less elongate in X direction, due to the localized and suddenly change of conductivity, unlike the spreaded increase of conductivity due to the FSW joint; 2) An inverse positions of the minimum and maximum values, i.e. first occurs a maximum in $x \approx -2$ mm and later a minimum in $x \approx +2$ mm. This is because locally the conductivity is decreasing instead of increasing. These results show that IONic probe is able to identify the three different types of defect conditions. It also becomes clear that there is a very good proportionality between the defect dimension and the previously mentioned perturbation on $S(x) = \bar{U}_{out}/\bar{I}$.

Fig. 7: Results for the FSW joints with defect types 0, I and II @ $f = 100$ kHz.

Fig. 8: Results for the FSW joint with defect types 0, I and II @ $f = 50$ kHz.

The same three defect conditions presented in Fig. 6 were tested under the same operating conditions previously described for the IONic probe tests. However, in this second NDT tests it was used a conventional planar circular spiral EC probe with 20 coils (Fig. 9). The spiral probe has an outside diameter of 9 mm and coils of 50 μ m width separated by the same dimension gaps. In Fig. 9 it is also presented the obtained results $S(x) = Re\{Z\}$ @ $f = 250$ kHz, because in this case the real part $Re\{Z\}$ present better results.

The three curves concerning to the previously defects conditions present a very similar trend

between them. In fact, unlike the IONic probe there is no distinctive signal feature that can allow to distinct between each defect condition. Indeed, the absolute planar spiral probe can only reproduce the global spreaded increase of conductivity field ($\sigma(x)$) due to the FSW bead (correspondent to the dashed line in Fig. 4). Such probes are not able to distinguish small suddenly variations of conductivity (correspondent to the continuous line in Fig. 4), caused by a local root defect with small size as those tested (Fig. 6). These results compared to the IONic probe results illustrate the difficulty of NDT of FSW when using conventional EC probes.

Fig. 9: Planar circular spiral probe with 20 coils and an outside diameter of 9 mm (left). Results for the FSW joints with defect types 0, I and II @ $f = 250$ kHz using a planar circular spiral probe (right).

5 - Electrical conductivity field analysis for evaluation of FSW joints

The EC technique had been recently exploited as a materials characterization technique for solid state processed components. This technique shown to be an alternative and/or complement to hardness measurements, although based in distinct physical phenomena. Electrical conductivity is controlled by electronic mobility and crystal defects, while hardness depends on the atoms mobility and thus a scale factor exists, as depicted in Fig. 10.

Fig. 10: Transversal macrograph of the FSW and reconstitution of electrical conductivity field across joint, revealing nugget, TMAZ, HAZ and base metal, and also the Vickers hardness profile (left). (right).

In the macrograph of Fig. 10 are clearly distinguished the different zones of the weld, as well as, the lamination effect previously described at half thickness. No weld defects are observed as volume defects, particles alignment or cracks. The electrical conductivity field clearly reproduces the features evidenced in the macrograph, with the lower values in the nugget (dark blue) and higher values in the TMAZ (red spots). The hardness profiles show some scatter of results with a computed standard deviation in the base material ($X = -20$ to -15 mm) of 2.57 which compared to the standard deviation calculated for the electrical conductivity measurements (0.048) show the less precision of hardness evaluation.

The presence of precipitates of alloy elements, as well as different grain sizes with defect content as dislocations, originates variations in the hardness profile. The original heat treatment condition highly affects the final microstructure and hardness profile across the weld joint. The artificial ageing T6 treatment is destroyed at the FSW processed zone with a drop in hardness in the nugget zone followed by peaks in this property in the HAZ. Depletion of precipitates due to the high temperature originated during the process is responsible for the material softening.

While the electric conductivity is governed by electron mobility, hardness is the resistance opposed by the material to plastic deformation that is controlled by the crystal structure, the existence of second phase particles and their coherence with the matrix, the density of microdefects, mostly dislocations and the grain size. That is, hardness is controlled by atomic mobility and thus a scale factor exists between electrical conductivity and hardness. Moreover, the electrical conductivity measurement is more precise when patterning a processed material structure. It can provide much more precise small scale features while hardness, even microhardness does not.

The two inspection techniques are complementary, since electrical conductivity can evaluate the presence of defects and provide information on the microstructural homogeneity of a material, while hardness gives an indirect qualitative measurement of the mechanical resistance which is of importance in engineering applications.

6. Conclusions

- 1) It was demonstrated that the typical FSW conductivity field is properly described by the Probability Density Function of the Gaussian distribution;
- 2) Conventional axis-symmetry EC probes such as planar circular spiral probes are not able to distinguish small local variations of conductivity, caused by typical FSW root defects with depth below 200 μm ;
- 3) The experimental results shown that the IONIC probe is able to identify different levels of FSW root defects by a distinctive perturbation on the output signal. It was also shown that exist a good proportionality between the defects size and this signal perturbation;
- 4) Measuring electrical conductivity field with eddy current probes shows potential to constitute a feasible, reliable and expedite procedure to pattern microstructural small scale features and is also able to detect superficial defects/discontinuities. Electrical conductivity is controlled by local electronic mobility and thus is very sensitive to local grain size and less sensitive to precipitation and dislocation;
- 5) For FSW of heat treatable aluminium alloys the electrical conductivity typically decreases in the nugget and increases in the TMAZ and HAZ. This evolution has typically an inverse consistence relation with hardness.

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