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Design and Fabrication of Eddy Current Ionic Probe for NDT of Friction Stir Welded Metals

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Abstract
In this paper, an eddy current ionic probe is particularly designed to find the micro size defects in the friction stir welded metal (FSW). The innovative system is organized by a type of eddy current ionic probe, electronic devices, mechanical arrangement and analysis software. This probe is planar design and has functionality of hybrid mode of operation. The finite element method is used for modeling the eddy current probe which is developed in printed circuit board. It can be able to detect the defect up to 60 µm in friction stir welding metals. This eddy current ionic probe output is compared with ultrasonic reference sensor.

Keywords: Eddy current probe, non-destructive testing, friction stir welding

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INTRODUCTION

The material imperfection leads to large difficulties when using conventional or advanced NDT techniques in case of localization and micro structural characterization. [1] In FSW, superficial microdefects of less than 100 µm are present [2] and it creates impact in joint process of performance with very small sizes and have minimal physical material discontinuities because of very low energy deflection of small defects. [3]

In order to overcome these types of problems and increase the ability of defect detection on application, a new type of differential eddy current planer probe was designed and evaluated. [4,5] The measuring system is designed and fabricated for new eddy current ionic probe. This probe is used to measure the defects depth up to 60 µm in friction stir welding (FSW) specimen which significantly increase NDT reliability for micro superficial imperfection detection.

MATERIALS AND METHODS

Friction Stir Welding

Friction stir welding is a joining process of solids or two materials, which was developed in 1991. [1] In this technology large potential is used and it has been main procedure in joining process during last decade. FSW is performed at lower temperature than fusion temperature of materials without any gas protection or filler material. It is performed in low level of residual tension and joint distortion. In FSW, primarily used on aluminum, and mostly extruded aluminum (non-heat treatable alloys), and on structures which need superior weld strength without a post weld heat treatment. In this technique non consumable cylindrical and shoulder tool is transversely rotated at constant speed through a joint lines of work pieces to be joined as shown in Figure 1.

Frictional heat is generated between tool pin and shoulder and which is placed in the work piece material. This heat results the materials to soften without meeting melting point. The tool is moved transversely in the welding direction, face of the tool forces the material to be welded. There are some welding parameters taking place over the final welding quality. They are rotation speed, tool geometry, tilt angle between tool and welding materials, vertical speed and travel speed. Welding speed depends on the tool design. FSW defects have different origins, size and morphology than other welding methods.

Fig. 1: *Friction Stir Welding.*

FSW has been used in wide range of applications like aerospace, automobile, robotics, railway, shipbuilding and others. FSW consolidation method needs reliable NDT techniques to be able to find the FSW defects.

Eddy Current Ionic Probe

The main innovative objective of this system is unique design of eddy current ionic probe. This probe has pickup coils around the driver trace and it has differential mode of operation. Its structure depends on the hybrid mode of operation. In center, the driver element is placed which made by copper and two planer pickup coils made up of copper wires and placed on the opposite direction of driver element.

Fig. 2: *Eddy Current Ionic Probe.*

When an alternating current I is passed through the driver trace, the magnetic field is generated in the pickup copper lines and both the magnetic fields are concentric and orthogonal around it. This magnetic field is capable of inducing eddy currents on the conducting material and at correspondingly same time which is sensed by the electromotive force on the pickup coils. Since both the pickup coils are symmetrical and share common terminal, they make a differential magnetic field sensor. In the presence of any perturbation that changes magnetic field among the driver trace axis, the output voltage signal U_{out} is taken from the pickup coils. The relation between the output voltage and stimulus current U_{out}/I, is used to characterize the defect along the test material. This result will be a complex quantity due to measuring two; amplitude and phase difference. As the output voltage result, imaginary part is greater than the real part from the stimulus current electromagnetic induction.

Design of Eddy Current Ionic Probe

The eddy current ionic probe model was done by CST EM Studio software which is used to verify the eddy current disposition inside the reference test material. [6] The probe model is shown in the Figure 3.

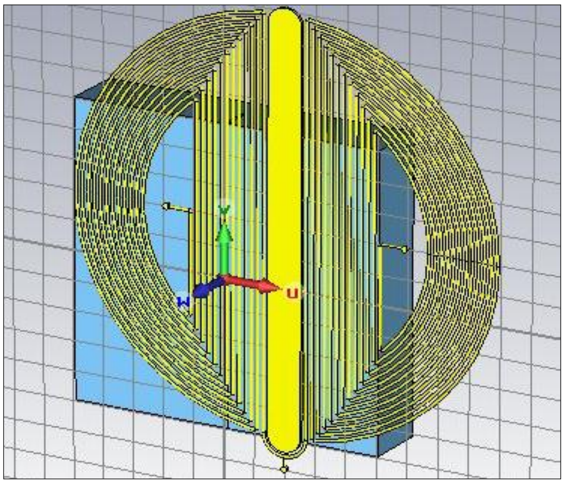

Fig. 3: *Probe Design in CST.*

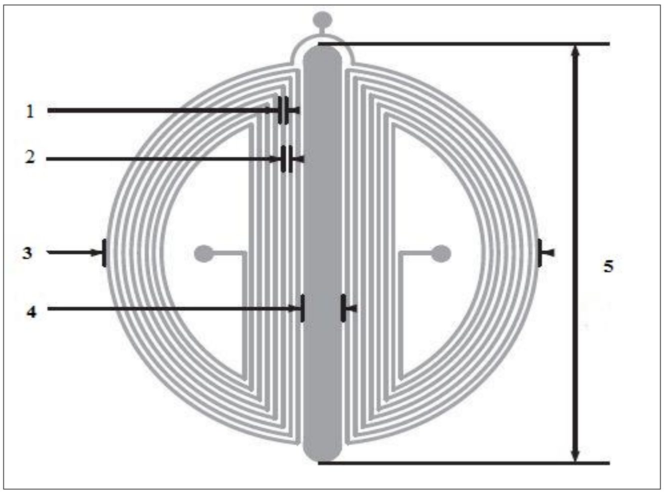

Fig. 4: *Probe Parameters Representation.*

A piece of aluminum is placed 300 µm below the probe model and air is the medium.

When eddy current appears in the material; as a reaction, oppose the magnetic field of driver trace. The figure represents the electromagnetism in the eddy current probe with frequency 500 KHz and 1 A amplitude. This FEM analysis is used to determine the simulation and experimental results. U_{out} value is calculated as difference between sums of the electromotive force sensed in each coils. The probe parameters and description are shown in below in Figure 4 and Table 1.

***Table 1:** Probe Parameters and Description with Figure 4.*

1	Sensing coils winding width	100 µm
2	Sensing coil winding Clearance	100 µm
3	Sensing coils external dimension	1.4 mm
4	Driver trace width	1 mm
5	Driver trace length	1.4 mm
	Number of windings on each sensing coil	12

Calculation of Inductance and Skin Depth

The calculation of both inductance and skin depth are important. It is very helpful to find out depth of the defect in the friction stir welding. The inductance and skin depth equations are,

$$L = \frac{r^2 n^2}{8r + 11w}$$

L= Inductance in µH,
r = radius to center of windings in inches,
w = width of the conductor in inches,
n = No. of turns.

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \ \sigma}}$$

δ = skin depth of the component,
f = required frequency,
μ_0= the permeability of free space,
μ_r= relative magnetic permeability of conductor.

Measurement System

The total system assembly is shown in Figure 5 and individual components are explained along this section. U_{out} Signal directly acquired from DAQ; is not possible for all frequency range which has limits to frequency. So in this method, amplitude and phase detection is measured by analog mixed signal circuits.

The ionic probe was fabricated on 1.6 mm dual layer FR4 PCB substrate as shown in Figure 2. The driver trace has 14 mm length and 1 mm width. Two sensitive coils have 12 turns with 100 µm clearance.

The XY table is used for move the probe along with test material. It is controlled by the stepper motor attached to controller circuits.

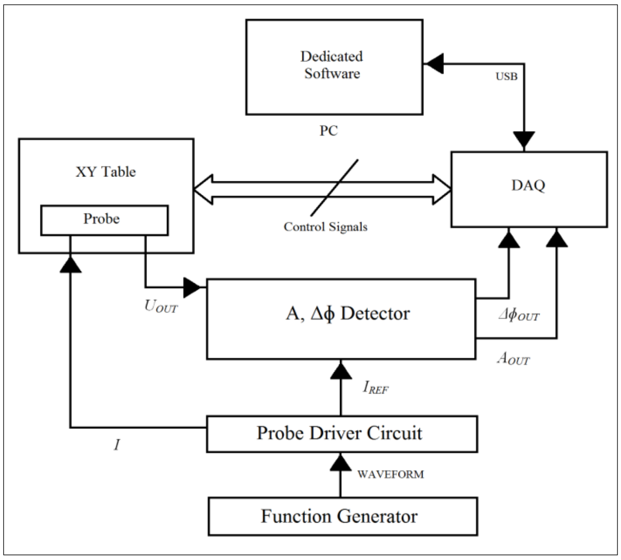

Fig. 5: *Over All System Function.*

The 16 bit DAQ from National Instruments, which is used to acquire the amplitude and phase signal and transfer information to the personal computer through the USB.

The excitation magnetic field is created by substantial current on the excitation filament of an ionic probe. A current buffer was designed by high-speed, high-current operational amplifier (OPA561 from TEXAS) with slew rate 50 V/µs and 1 MHz full power band width. The operational amplifier has $1\ AV^{-1}$ transconductance gain and it is controlled by function generator signal. In this circuit maximum output current was set to 1.1 A and frequency from 10 to 1 MHz

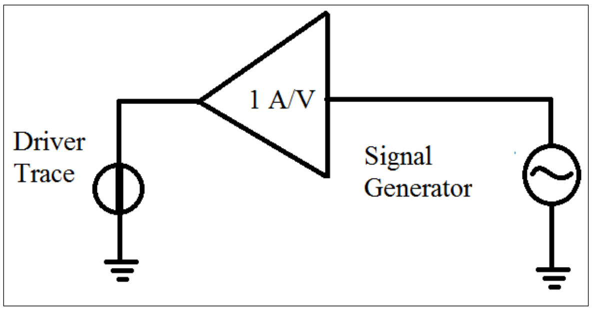

Fig. 6: *Probe Driver Circuit.*

The amplitude and phase detector are generating DC signals proportional to the amplitude of probe output signal and phase difference between this signal and driver trace reference current. This detector circuit is used for boost up amplitude value. Because 1 A amplitude sine wave passing on the driver trace, probe output signal is 2.4 mV for extreme defect. In amplitude detector, the first circuit is 40 dB voltage amplifier created by using rail-rail road amplifier, high speed 80 MHz with 30 V/µs slew rate (AD8031). After amplified, RMS-DC (AD8361) convertor is used for signal process with 7.5 V/V_{RMS} gain. The amplitude detector Eq. (1) is,

$$A_{out} = \frac{7.5}{\sqrt{2}} \times 100 \times A(U_{out}) \qquad \text{Eq. (1)}$$

Where; A_{out} is the pickup coil amplitude signal.

The phase detection is captured by comparator and its output is given into XOR for binary signal whose average value is proportional to phase difference of two input signals. The average value is obtained by RC low pass filter with 100 Hz cut off frequency. XOR gate has 5 V digital logic. And the phase difference detector is based on this Eq. (2) is,

$$\Delta\Phi_{out} = \frac{5}{180} \times \Delta\Phi(U_{out}, I_{ref}) \qquad \text{Eq. (2)}$$

Where; $\Delta\Phi(U_{out}, I_{ref})$ is the phase difference between driver trace reference current and output signal.

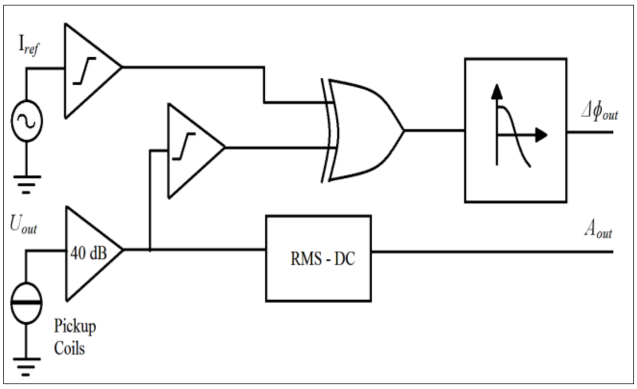

Fig. 7: *Amplitude and Phase Detector.*

The phase and amplitude detector output is acquired by using 16 bit DAQ instruments from national instruments and transfer into dedicated software in PC through USB. [7]

INTIAL WORK

The reference friction stir welded metal is tested by Olympus ultrasonic testing method. This FSW aluminum metal has 4 mm thickness as shown in Figure 8. The Figure 9 explains ultrasonic sensor waveform obtained by sensing the aluminum metal with 50 gain, 5700 m/s velocity and 10 MHz in defect free area of aluminum metal.

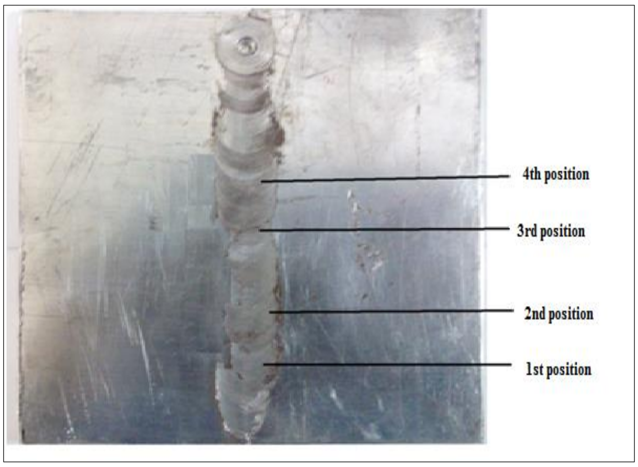

Fig. 8: *Friction Stir Welded Aluminum Metal's Position.*

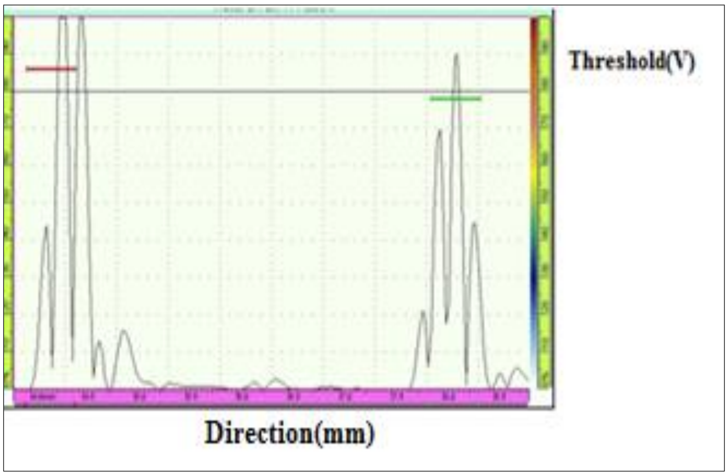

Fig. 9: *Ultrasonic Output taken in Aluminum Metal.*

The ultrasonic output is taken from 1st position of friction stir welded aluminum metal shown in following Figure 10. This output is comparatively similar to result obtain in Figure 9.

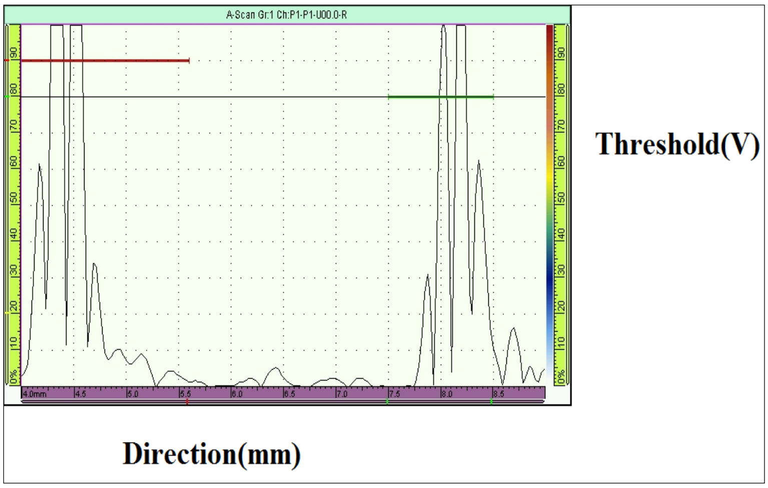

Fig. 10: *Ultrasonic Output taken in 1st Position of FSW Metal.*

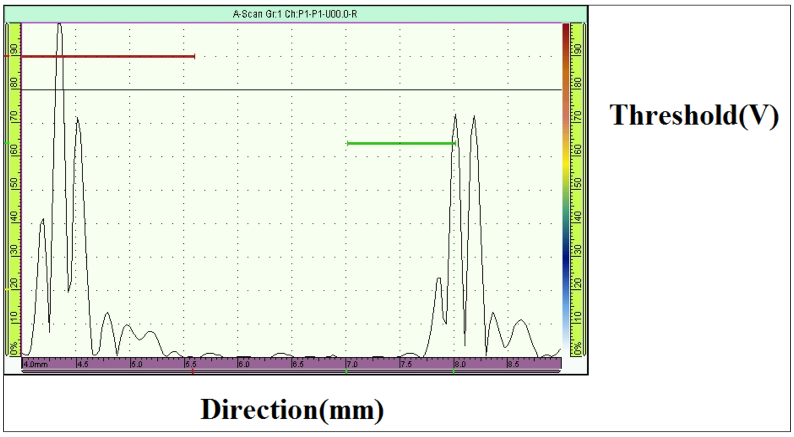

Fig. 11: *Ultrasonic Output taken in 2nd Position of FSW Metal.*

It explains about Result in 2nd Position of Friction Stir Welded (FSW) Metal.

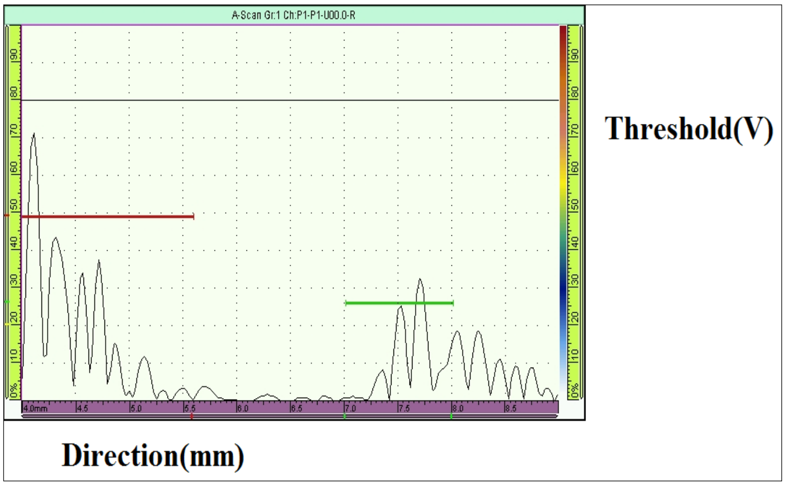

Fig. 12: *Ultrasonic Output Taken in 3rd Position of FSW Metal.*

The Figures 13 and 14 show results of 3rd and 4th position of FSW metal output. These outputs have more defects than 1st and 2nd position. This output will be compared with eddy current ionic probe output.

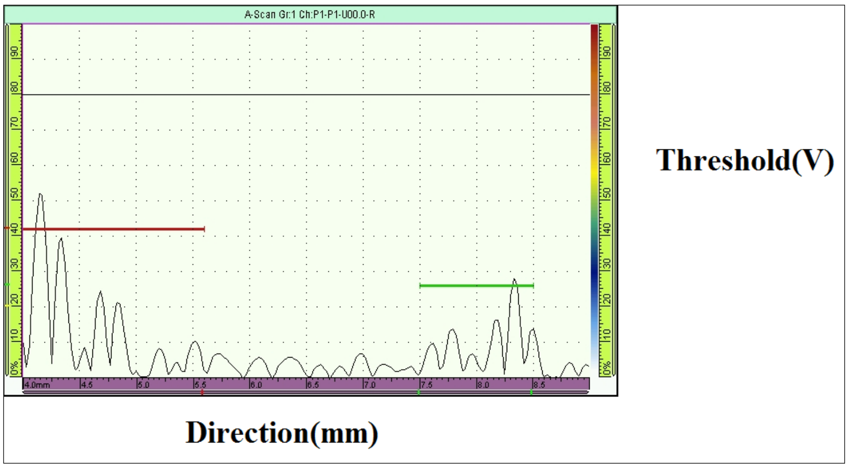

Fig. 13: *Ultrasonic Output Taken in 4th Position of FSW Metal*

CONCLUSION

The specific new eddy current ionic probe is designed and fabricated to find defects in joints of friction stir welded metals up to the level of 60 µm. This probe is mainly designed for increasing the sensitivity to detect the defect in FSW aluminum metals. Probe output is compared with reference standard ultrasonic sensor.

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