Friction Stir Welding Inspection by Non-Contact Ultrasonic Technique

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ABSTRACT

Friction stir welding (FSW) is an innovative process that has been successfully used in joining normally difficult to weld Al alloys. Welding takes place in the solid phase below the melting point of the material, offering important advantages over fusion welding such as better retention of baseline material properties, lower residual stresses, and excellent mechanical properties.

Defects that occur in FSW are due to improper tooling or setup, depending mainly on tool rotation and traverse speeds, tool size and tilt. Insufficient weld temperature, due to low rotation speed, may results in long, tunnel defects running along the weld. Low temperatures may also reduce the continuity of the bond between the material from each side of the weld, causing what is named kissing bond.

Non-destructive techniques used to inspect FSW joints are X-ray, conventional ultrasonic testing and dye penetrant, proper only for surface breaking defects.

In the proposed work a non-contact ultrasonic technique is used to inspect FSW Al joints. Pulsed laser and air-coupled piezoelectric transducer are used to generate and to receive, respectively, ultrasonic guided wave in the material. Several FSW samples were manufactured using first optimum parameters, then setting different ones to create defects along the weld. Ultrasonic waveforms were highly repeatable on parts without discontinuities, whereas showed different attenuation on some samples made with different process parameters thus giving indication of defects.

First results obtained with the proposed technique are promising. Further research is in progress on samples with different thicknesses and defects. The laser-based ultrasonic technique allows remote single-side inspection, with fast unidirectional ultrasonic L-scan.

INTRODUCTION

Traditional welding processes join same or similar materials by locally heating the parts to a temperature higher than the melting point; filler material can be added to form a pool of molten material that cools to become a strong joint. This process produces on the material surrounding the weld a heat-affected zone (HAZ), varying in size and strength, showing a decay of mechanical properties. Moreover, welding methods involving the melting of metal at the site of the joint necessarily are prone to shrinkage as the heated metal cools. Shrinkage, in turn, can introduce residual stresses and both longitudinal and rotational distortion.

An innovative welding process based on friction heating, said friction stir welding (FSW), has several advantages over traditional fusion welding methods. In fact, welding takes place in the solid phase below the melting point of the material, thus avoiding problems associated with cooling from the liquid phase and offering better retention of baseline material properties, lower residual stresses, and excellent mechanical properties. Moreover, FSW allows one pass welding of thickness from 1.6 to more than 50 mm, with excellent results on aluminium alloys otherwise difficult to weld with traditional processes due to presence of Al oxide on the surface.

The FSW process uses a cylindrical tool with a specially profiled pin (Figure 1). The rotating tool is pressed into the joint of the pieces clamped to a backing plate. As friction softens the material, the pin is pushed in to its full depth and then along the desired weld direction. Disadvantages of FSW include necessity for rigid clamping, a hole remaining when the pin is removed and need for run-on and run-off plates.

Defects that occur in FSW are due to improper tooling or setup, depending mainly on tool rotation and traverse speeds, tool size and tilt [1-3]. Insufficient weld temperature, due to low rotation speed, may

results in long, tunnel defects running along the weld. Low temperatures may also reduce the continuity of the bond between the material from each side of the weld, causing what is named kissing bond [4].
Non-destructive testing (NDT) methods currently used to evaluate FSW integrity are X-ray, conventional ultrasonic testing and dye penetrant, proper only for surface breaking defects. X-ray allows to detect internal defects that are about 6% of the weld thickness but the equipment is expensive, bulky and its use is dangerous for the operator. Conventional ultrasonic methods have been used for long time to non-destructively test structural components [5]. State of art on welding inspection shows, especially on steel, extensive works with contact techniques and innovative probes, such as piezoelectric phased arrays [6-7] and electromagnetic acoustic transducers [8-9]. The described methods require always contact with the structure and employ usually bulk waves. Ultrasonic contact phased array inspection of FSW samples with cracks simulated by electric discharge machining (EDM) notches has been performed in [10]. In the last years, trend has been directed to search and to develop non-contact methods as they have potential for fast and automated inspection both post-manufacturing and in service [11-13].
In this paper a non-contact laser-based ultrasonic technique is proposed to assess the integrity of aluminium FSW samples manufactured by changing the process parameters. Generation of ultrasonic waves was performed by a Nd:YAG pulsed laser and detection by piezoelectric air-coupled transducer. Linear laser source on a thin Al plate generates guided waves that propagate through the thickness, allowing a unidirectional single L-scan inspection of the weld [14].

EXPERIMENTAL PROCEDURE

Samples

Several FSW samples were manufactured by changing tools and welding parameters in order to have welds with different characteristics. Process parameters that affect quality of FSW are tool rotation R and traverse speeds V, tool size and tilt γ (Figure 1). Welding speeds affect the heat input in a way that increasing the peripheral speed of rotation or decreasing the traverse speed results in a hotter weld. Tilting the tool at γ = 2-4° increases the pressure below the tool and ensures adequate forging of the material at the rear of the tool.

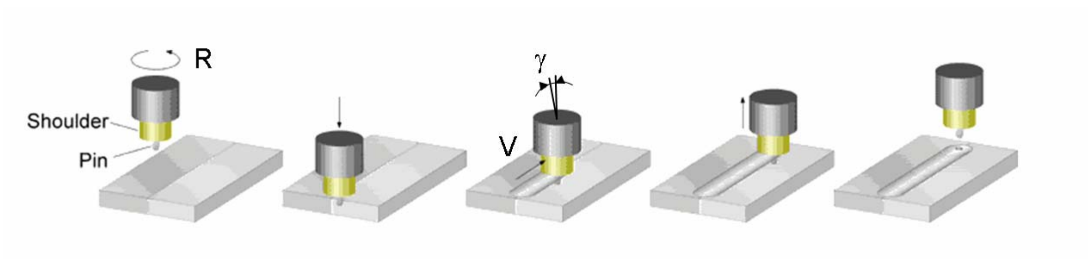

Fig. 1. Parameters and scheme of FSW phases.

Two sets of four samples each were manufactured with dimensions reported in Tables 1 and 3, and with processing parameters reported in Tables 2 and 4.

Table 1: Dimensions of 1st sample set.

Al 1040 sample	Thickness [mm]	Weld length [mm]	Welded plate width [mm]
A, B, C, D	3	150	200

Table 2: Welding parameters of 1st sample set.

Al 1040 sample	V [mm/min]	R [rpm]	Tool
A,B	100	1040	γ = 2°
C	320	715	Shoulder ϕ = 10 mm
D	465	715	Pin ϕ = 3 mm, L=2.8 mm

Table 3: Dimensions of 2nd sample set.

Al 6082 sample	Thickness [mm]	Weld lenght [mm]	Welded plate width [mm]
A,B	3	100	150
C,D	3	60	150

Table 4: Welding parameters of 2nd sample set.

Al 6082 sample	V [mm/min]	R [rpm]	Tool
A,B	100	1040	$\gamma = 2°$ Shoulder ϕ = 8 mm Pin ϕ = 2 mm, L=2.8 mm
C, D	465	715	

Samples C and *D* of both sets were welded with different process parameters, higher V and lower R compared to those of samples A and B, obtaining a colder weld and thus decrementing the recrystalization. The weld surface resulted in lower quality due to the high rugosity left by the tool. Samples of the 2nd set were manufactured using a tool with different size.

Setup

The ultrasonic inspection system consisted of Nd:YAG infrared pulsed laser and air-coupled piezoelectric transducer. The laser beam was directed to a cylindrical lens to produce a 10 mm linear laser source and to give directionality to the generated guided waves, perpendicularly to the line. Ultrasonic waves propagating through the weld were acquired by the transducer, with 1 MHz nominal frequency, located in pitch-catch configuration. After being properly filtered and amplified, signals were processed. Figure 2 shows the scheme of the experimental setup.

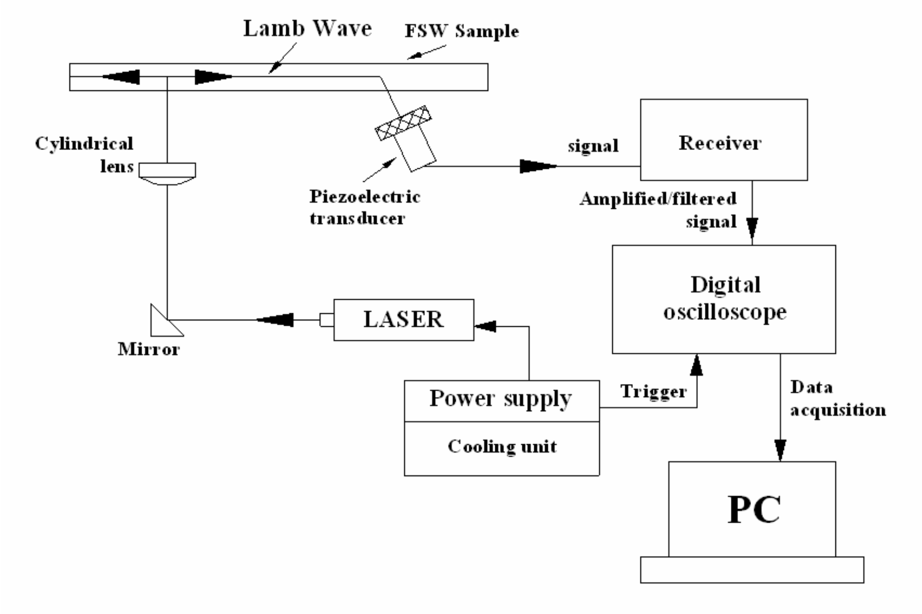

Fig. 2. Scheme of experimental setup.

Inspection was performed in two configurations, named traversal and longitudinal, with the guided waves propagating across (Figure 3) and along (Figure 4) the weld respectively. In the transversal setup scanning was done at 5 mm steps parallel to the weld, whereas in the longitudinal a single laser shot allowed inspection of the weld in all its length (config. *00*) with great time saving. However, overlapped acquisitions were taken in the longitudinal setup for a more accurate evaluation with source and receiver at half distance than in the previous configuration (config. *01*).

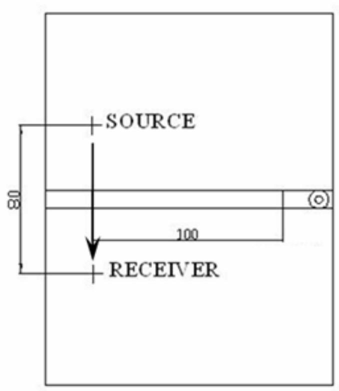

Fig. 3. Transversal setup.

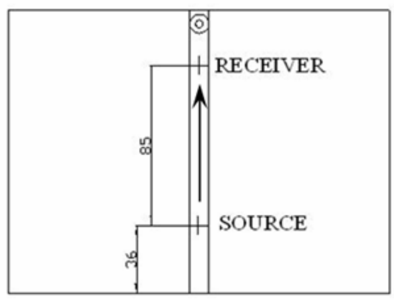

Fig. 4. Longitudinal setup (config. *00*).

RESULTS

Analysis of signals acquired from the first set of samples was done by measuring peak-to-peak amplitude of the dominant guided mode and by comparing the Fourier transform of signals from samples A, B to those from C, D. Accurate examination of results did not show significant differences in waveform amplitude and spectrum, both in the longitudinal and transverse configurations. In particular, twenty highly repeatable signals were acquired in the transversal configuration for each sample of the 1st set and three in the longitudinal configuration. Figure 5 shows waveform and spectrum of signals acquired in longitudinal configuration *00* from samples A and C.

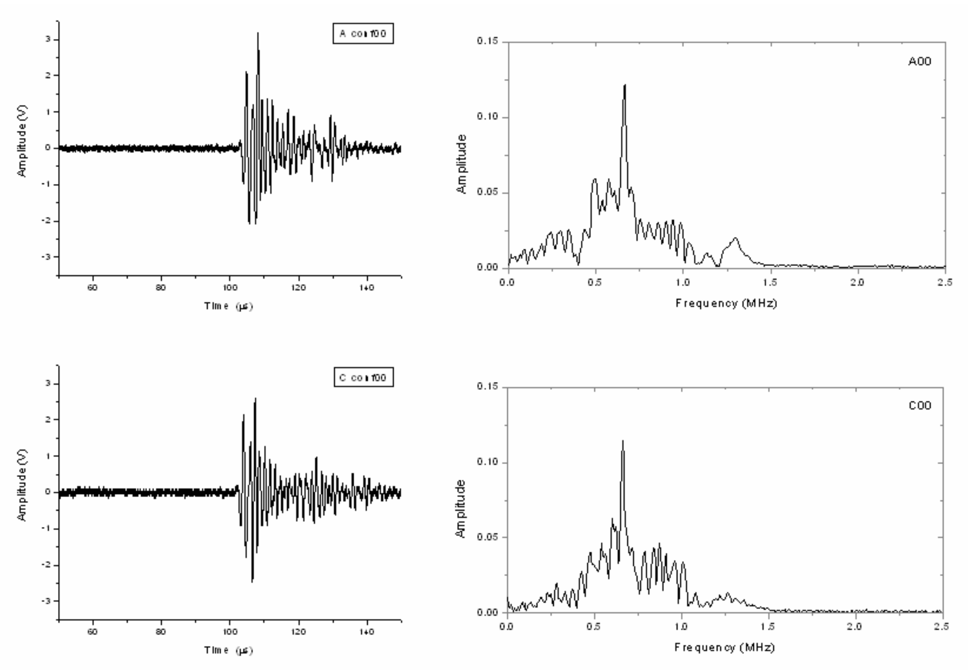

Fig. 5. Signal waveform and Fourier transform from samples A (top) and C (bottom) along the weld in the longitudinal configuration 00.

X-ray radiographs and then weld macrographs were carried out on the 1st set of samples to validate ultrasonic results.

X-ray analysis

Radiography relies on detecting a change in transmitted intensity of X-ray beam, arising from differences in the absorption coefficient of a defect and the surrounding material. As the X-ray absorption coefficient depends strongly on material density, radiography is particularly effective at detecting volumetric defects (such as slag inclusions or porosity). Table 5 summarizes condition of test and Table 6 the results. As sensibility of the technique was 2%, minimum dimension of inclusion that could be detected was about 0.06 mm. X-ray analysis did not give indication of defects along the weld.

Table 5: X-ray test condition.

Equipment:	MHF 200 D-C GILARDONI **Kv** 45, **mA** 5
Technique	Single wall
Film type	AGFA D4
Source to film distance	700 mm
Sensibility	2%
Exposure time	45"
Examination procedure	UNI 7452
Acceptance criteria	UNI 30042
Test extension	100%

Table 6: X-ray results.

Weld sample	Evaluation
A (V100)	Defect free
C (V320)	Defect free
D (V465)	Defect free

Macrography

Macrography allows visual inspection through magnified images taken by high resolution cameras. Inspection is not expensive or complex but requires cutting the specimen. Samples, 15 mm wide and 10 mm long, were taken out from the weld of specimens A and D (Figure 6a). They were enclosed with phenolic resin and heated to 160°C for about seven minutes; successively mounted in the mandrel (Figure 6b) to be polished to obtain a surface roughness of about 3÷4 μm, then acid-etched to get better contrast. Photographs were taken with a digital camera at 7 Megapixel and 5x optical zoom.

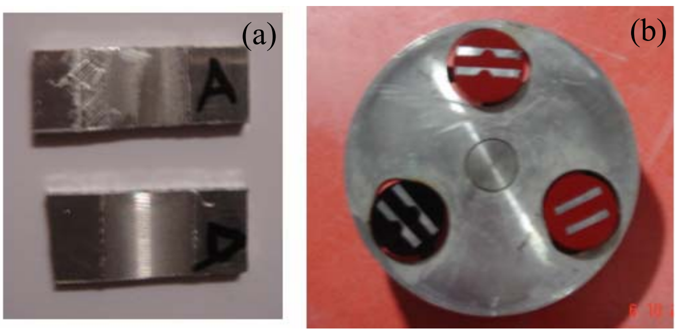

Fig. 6. Samples taken out from specimens A and D (a), and mounted in the mandrel (b).

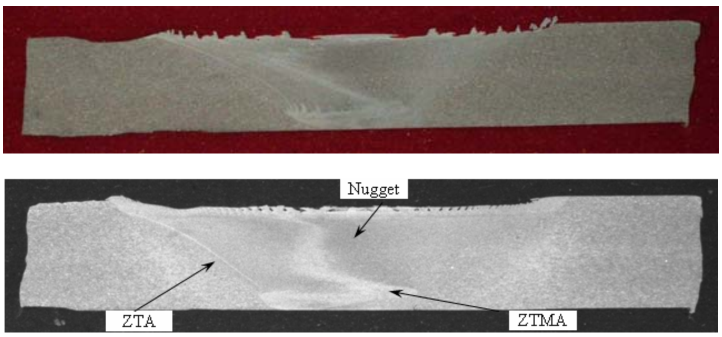

Fig. 7. Detail of welds from samples A (top) and D (bottom).

Macrographs showed characteristic zones of the weld (thermically altered zone (ZTA), thermo-mechanically altered zone (ZTMA), nugget) but did not show discontinuities (see Figure 7).

None of the methods used to characterize friction stir welds revealed differences among samples from the 1st set, manufactured with optimum and different process parameters. X-ray analysis and macrographs validated the results obtained using the laser-based ultrasonic method.

Laser-based ultrasonic tests were repeated on the 2nd set of samples. As ultrasonic signals showed differences in the waveform of guided modes, they were analyzed using the wavelet transform (WT), that is very suitable for the analysis of guided waves as provides the time-frequency representation of the signal. The software used here is based on the Gabor wavelet mother.

Comparison of WT of signals acquired across the weld of the 2nd sample set, in transversal setup, showed:

- signals from samples A and B were highly repeatable (see Figure 8) at any position along the weld;
- on samples C and D, manufactured with maximum traverse speed V and the lowest peripheral speed, weld presented two zones (Figure 9) with different WT pattern (Figures 10 and 11). In zone I there are two dominant modes, like in samples A and B, whereas zone II was characterized by a single mode.

Results obtained using the laser-based ultrasonic method indicated invariability of signals from samples A and B, and partial presence of anomalies in the weld of samples C and D.

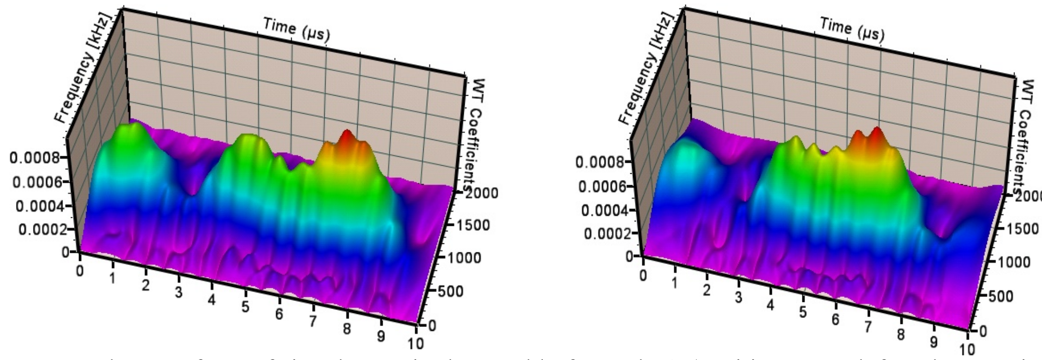

Fig. 8. Wavelet transform of signals acquired on weld of sample A (position 35 on left and 60 on right).

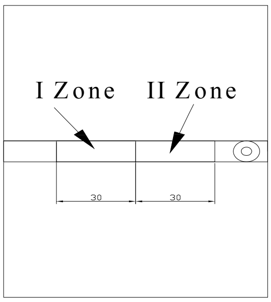

Fig. 9. Zones with different wavelet signals on sample C and D.

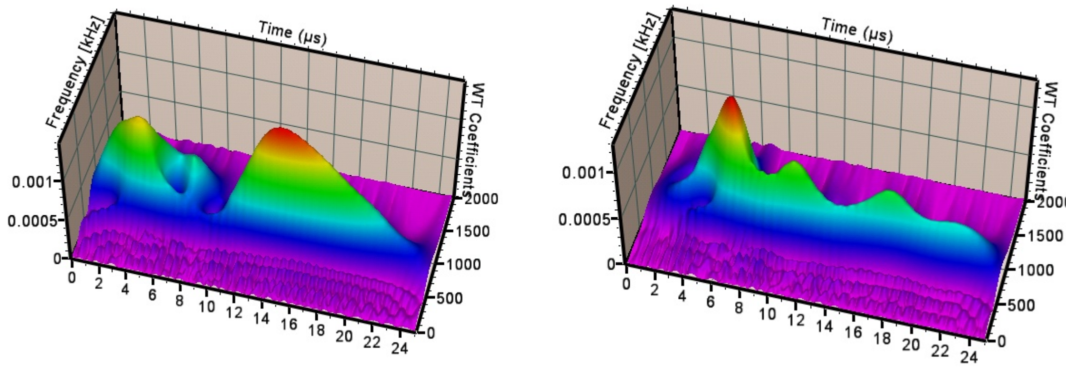

Fig. 10. Wavelet transform of signals acquired on weld of sample C (zone I on left and II on right).

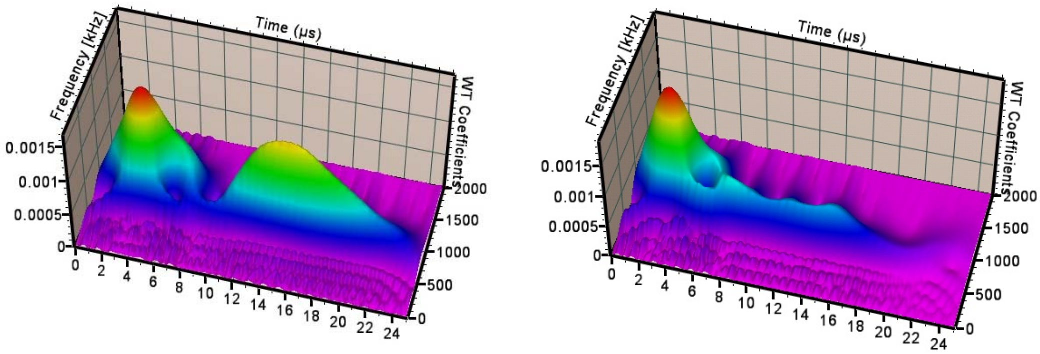

Fig. 11. Wavelet transform of signals acquired on weld of sample D (zone I on left and II on right).

CONCLUSIONS

Friction stir weld process is an efficient alternative to fusion welding, for its cost-effectiveness and ability to weld dissimilar material combinations with minimal distortion.

In this work a laser-based ultrasonic technique was used to inspect FSW Al joints. Pulsed laser and air-coupled piezoelectric transducer were used to generate and to receive, respectively, ultrasonic guided waves in the material. Source/receiver test configuration was pitch-catch single-side to prove feasibility if access on the other side is not allowed. Several FSW samples with identical geometry were manufactured using first optimum parameters then setting different ones to create defects along the weld. Ultrasonic waveforms were highly repeatable on parts without discontinuities, whereas showed different attenuation on some samples made with different process parameters.

Tests on 1st set of samples with the laser-based system did not give indication of defects in the weld; results were confirmed by X-ray analysis and then macrography. Results of tests performed on 2nd set of samples using the laser-based system showed signal repeatability on samples A and B, whereas samples C and D, manufactured with maximum traverse speed V and the lowest peripheral speed among all samples, showed variation in the wavelet diagrams. First results obtained with the proposed technique are promising. Further research is in progress on samples with different thicknesses and defects.

ACKNOWLEDGMENT

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REFERENCES

1 K. V. Jata, S. L. Semiatin, 2003. Continuos dynamic recrystallization during Friction Stir Welding of high strength aluminium alloys. *Scripta Materialia*, 48, 740-756.

2 M. Sutton, A. Reynolds, B. Young, R. Taylor, 2003. Mode I-II fracture of 2024-T3 Friction Stir Welds. *Engineering Fracture Mechanics*, 2215-2234.

3 W. M. Thomas, 1992. *Improvements relating to Friction Welding"* The Welding Institute, Cambrige.

4 A. Oosterkamp, L.D. Oosterkamp, A. Nordeide, 2004. Kissing bond phenomena in solid-state welds of aluminum alloys. *Welding Journal*, 225-231.

5 J. Krautkrämer, H. Krautkrämer, 1990. Ultrasonic testing of materials. *Springer-Verlag, Berlin*.

6 J. Poguet, J. Marguet, F. Pichonnat, L. Chupin, 1998. Phased array technology: concepts, probes and applications. *Proceedings of EPRI*.

7 H. Fukutomi, S. Lin, A. Nitta, 2004. Ultrasonic examination of type IV cracking in high energy steam piping using TOFD and phase array techniques. *Proc. of the 16th WCNDT.*

8 D. MacLauchlan, S. Clark, B. Cox, T. Doyle, B. Grimmett, J. Hancock, K. Hour, C. Rutherford, 2004. Recent advancements in the application of EMATs to NDE. *Proc. of the 16th WCNDT.*

9 H. J. Salzburger, G. Hübschen, F. Niese, 2004. Dry UT by guided shear horizontal using EMAT's. *Proc. of the 16th WCNDT.*

10 A. Lamarre, M. Moles, 2000. Ultrasound phased array inspection technology for the evaluation of friction stir welds. *Proc. of the 16th WCNDT.*
11 D. W. Schindel, 1999. Air-coupled ultrasonic measurements of adhesively bonded multi-layer structures. *Ultrasonics,* 37 (3), 185-200.
12 D. A. Hutchins, 1998. Ultrasonic generation by pulsed lasers. *Physical Acoustics, W. P. Mason and R. N. Thurston eds., Academic Press, New York*, XVIII, 21-143.
13 S. Kenderian, B. B. Djordjevic, D. Cerniglia, G. Garcia, 2006. Dynamic railroad inspection using the laser-air hybrid ultrasonic technique. *Insight*, 48 (6), 336-341.
14 M. Arone, D. Cerniglia, V. Nigrelli, 2006. Defect characterization in Al welded joints by non-contact Lamb wave technique. *J. Materials Processing Technology*, 176, 95-101.