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CHALLENGES IN DETECTING DAMAGE IN THE PRESENCE OF MICROSTRUCTURAL INHOMOGENITIES IN A FRICTION STIR WELDED ALUMINUM ALLOY FOR REUSABLE CRYOTANKS (PREPRINT)

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14. ABSTRACT
Continuous real time structural health monitoring will be a requirement for future space launch missions. Reusable metallic cryotanks manufactured using Friction Stir Welding (FSW) technology for multiple missions, demands weld and microstructural integrity. The FS weld contains multiple interfaces and a variety of microstructures. To develop NDE-based health monitoring capability which detects damage and monitors the progression of damage, in the presence of these microstructural inhomogeneities, is a challenging task. Most structural health monitoring techniques are based on acoustic wave propagation. To design and develop efficient and optimized health monitoring capability based on acoustics, it is necessary to incorporate local elastic property variations that arise due to differences in the weld microstructure. These local elastic property changes across FSW regions have been measured using a focused acoustic beam. Measurements across the weld line show variations with a maximum change of 1% in the sound velocities. Macroscopic measurements of velocity of surface acoustic waves propagating across and also parallel the weld line in a large plate show significant variation. Experimental results of local and macroscopic sound velocity measurements from the changing microstructure along with their impact on the design of structural health monitoring system are discussed.

15. SUBJECT TERMS Structural health monitoring, cryotanks, microstructure, friction stir weld, residual stress, longitudinal wave velocity

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Challenges in Detecting Damage in the Presence of Microstructural Inhomogenities in a Friction Stir Welded Aluminum Alloy for Reusable Cryotanks

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ABSTRACT

Continuous real time structural health monitoring will be a requirement for future space launch missions. Reusable metallic cryotanks manufactured using Friction Stir Welding (FSW) technology for multiple missions, demands weld and microstructural integrity. The FS weld contains multiple interfaces and a variety of microstructures. To develop NDE-based health monitoring capability which detects damage and monitors the progression of damage, in the presence of these microstructural inhomogeneities, is a challenging task. Most structural health monitoring techniques are based on acoustic wave propagation. To design and develop efficient and optimized health monitoring capability based on acoustics, it is necessary to incorporate local elastic property variations that arise due to differences in the weld microstructure. These local elastic property changes across FSW regions have been measured using a focused acoustic beam. Measurements across the weld line show variations with a maximum change of 1% in the sound velocities. Macroscopic measurements of velocity of surface acoustic waves propagating across and also parallel the weld line in a large plate show significant variation. Experimental results of local and macroscopic sound velocity measurements from the changing microstructure along with their impact on the design of structural health monitoring system are discussed.

Keywords: Structural health monitoring, cryotanks, microstructure, friction stir weld, residual stress, longitudinal wave velocity

INTRODUCTION

Development of reliable and robust continuous monitoring techniques for materials and structures is the goal of Structural Health Monitoring (SHM) research. At present many of the systems under development utilize acoustic wave propagation techniques. These include bulk acoustic waves as well as plate waves. The advantage of these techniques is that the waves propagate over large distances and hence suitable for evaluation of large structures. Technically this is feasible since the generation and detection of the plate waves depend on the elastic properties of the material. Large structures, in many situations consist of components designed with varying microstructures. To develop and optimize the techniques for detection of damage as well as monitoring, it is necessary to understand the behavior of the wave propagation in presence of varying microstructure. When the microstructure changes, the elastic properties will vary accordingly and hence the wave propagation conditions are expected to be modified. So it is necessary to incorporate varying elastic properties due to changing characteristics of microstructure into the SHM monitoring system.

The next generation cryotanks that are expected to be used for launching reusable space vehicles will be designed and built using Friction Stir Weld (FSW) technology. In order to reduce the turn around time of the vehicle and for efficient usage of the vehicle, structural health monitoring techniques are in development. Some of the techniques for SHM of FSW cryotanks are based on acoustic wave propagation methods [1, 2]. Aluminum alloy cryotanks designed and built using FSW technology will hold low temperature liquid fuels. The FSW is a solid state welding technique [3], which produces significantly low residual stress compared to other welding methods. The process uses a nonconsumable rotating tool, pressed against the two plates abutted against each other. During FSW, due to rotating friction, the temperature of the material, in the immediate vicinity of the tool increases and makes the material soft for easy deformation.

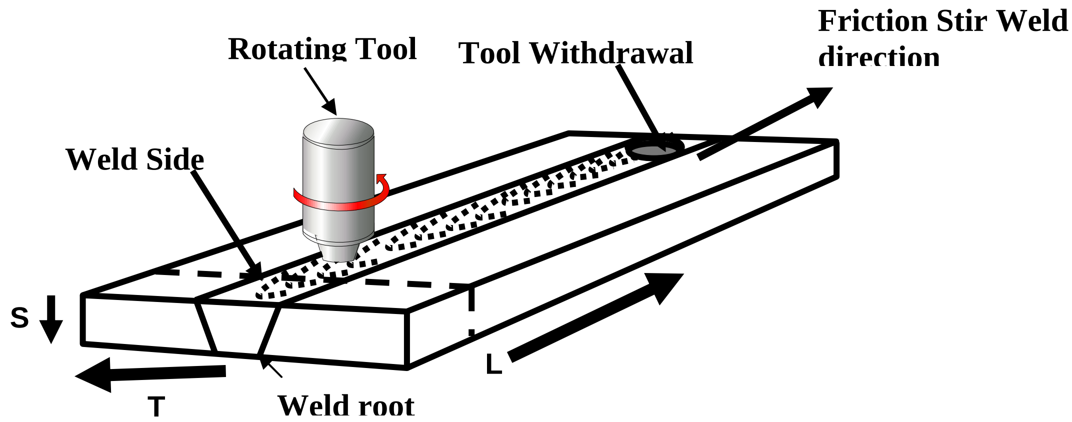

Fig 1. General features of a Friction Stir Weld plate (S, T and L indicate the directions of the plate)

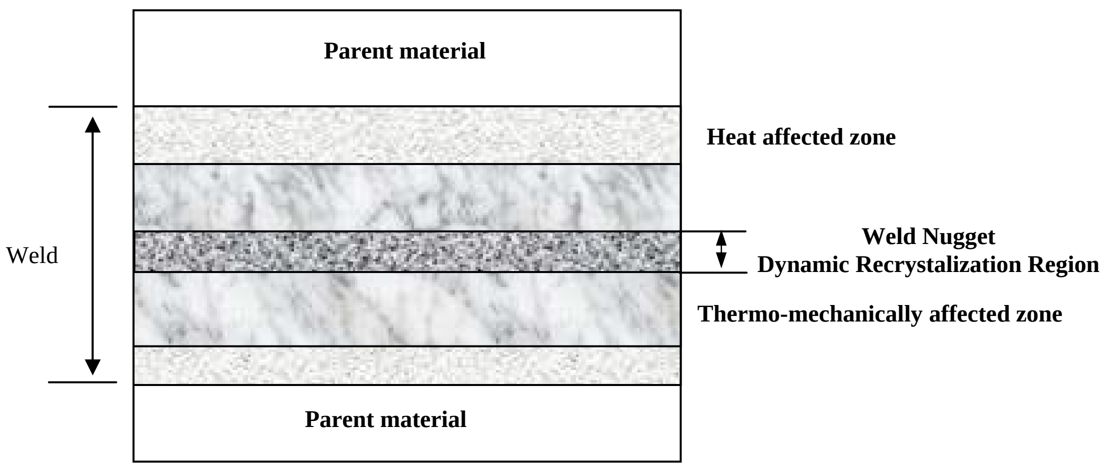

Fig 2. Schematic diagram showing different regions of the weld

The material is swirled from the front of the tool towards the back and in the process the two plates are welded together. Figure 1 shows a schematic of FS welded plate identifying different parts of the weld and the nomenclature used to identify the directions of the plate. The FSW welding zone consists of a weld nugget, a thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) [4]. The microstructure in the welded region is quite complex and depends on the position across the weld. Figure 2 shows a schematic of the different regions of the FSW indicating different microstructures and the parent material. Extensive research has been performed to develop fundamental understanding of the complex microstructure of the material [5-8] in the FS weld zone. To understand and optimize the welding characteristics, several physical properties have been measured across the weld zone. The residual stress [9-12], hardness [13], mechanical properties, strength and ductility [14] have been shown to vary across the weld line. While these measurements are extremely important for understanding and optimization of the welding methodology, for the purpose of development of SHM methodology there is a need for evaluating the local elastic properties of the material across the weld. The local elastic properties significantly impact the wave propagation characteristics, when elastic waves propagate across the weld during inspection and continuous monitoring.

The aim of the present paper is to investigate methods to measure the local elastic property changes across the weld line using NDE techniques and discuss their impact when elastic waves propagate across the weld line. The local measurements are performed using focused acoustic beam technique to get higher spatial resolution. Macroscopic measurements are performed to determine the weld properties by propagating acoustic waves across the weld line.

MATERIALS AND EXPERIMENTAL METHODS

Two samples of Al-Li alloy were used for the measurements. A small sample of dimension 52 mm (L) x 8 mm (W) x 6 mm (T) was cut from a large plate with the weld in the middle. The two sides parallel to the weld (S) and the other two sides perpendicular to the weld (T) were polished on both sides to be flat and parallel. The measurements were performed through the thickness of the polished sample. The bigger plate [Figure 3: 540 mm (L) x 190 mm (W) x 6 mm (T)] was used for measurement without further surface preparation using direct contact surface acoustic wave transducers. During FSW the temperature changes along the weld are observed. In this plate the temperature varies from 480 C – 514 C.

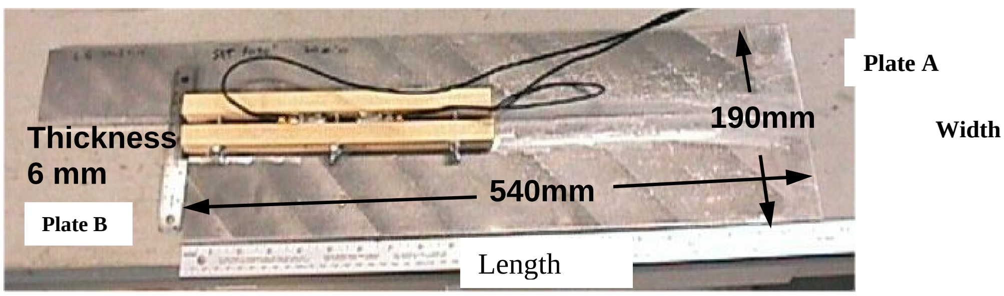

Fig. 3: Large FSW plate and fixture used for SAW velocity measurements.

Local ultrasonic velocity measurements were performed using a High Precision Scanning Acoustic microscope (HIPSAM) [15]. The basic principles of the measurement are shown in figure 4. The transducer of the acoustic lens was excited with a short radio frequency pulse. The generated acoustic beam generated is bought into focus by the lens on the surface of the sample in presence of water. The acoustic energy is partially reflected and partly transmitted through the sample. The transmitted acoustic wave propagates through the sample and at the other parallel face is reflected back. The reflected signal propagates back to the lens. The transmitted signal, the reflection from the top surface of the sample and the reflected signal from the bottom surface of the sample are all displayed on one oscilloscope trace. By measuring the time difference between the top and bottom surface signals the velocity of longitudinal wave is determined with the knowledge of the thickness of the sample.

The system can also be used to measure the local surface acoustic wave (SAW) velocity [16]. This is performed by generating SAW by defocusing the acoustic lens. By measuring the time difference between the arrivals of SAW signals at two different defocuses local SAW velocity with a spatial resolution of one millimeter can be measured. The amplitude of the SAW signal at any defocus can be mapped to image of the microstructure of the material. With the present system, local longitudinal and Rayleigh Surface Wave (RSW) velocity with an accuracy of a few parts in 10,000 m/s can be measured [17]. To measure the RSW velocity on large plate, contact transducers with appropriate wedges were used to generate and detect RSW. A fixture was designed and built, to hold the transducers and the wedges, in place at a fixed distance apart during measurements [Figure 3]. The fixture was moved in steps to measure the RSW variation in different parts of the large plate. Measurements were performed parallel as well as perpendicular to the weld line.

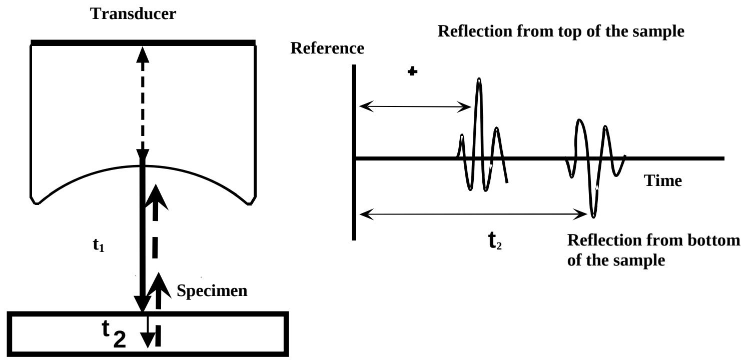

Fig. 4: Principles of thru the thickness localized longitudinal wave velocity using focused acoustic beam.

RESULTS AND DISCUSSION

1. Microstructure

Figure 5 shows an acoustic image of the weld side [L-T plane] of the small sample. The image covers both parent materials and the welded region. The image was obtained by an acoustic microscope lens operating at a frequency of 25 MHz. The amplitude of the RSW was measured at each location and mapped to produce the image. The contrast in acoustic image is mainly due to variation in the local elastic properties. In the figure three regions, namely the parent materials and the weld region can be observed. The difference in the contrast among the regions is not very high. The weld region is known [4] to consist of a dynamically recrystallized region, a thermo-mechanically affected zone and a heat affected region. In Fig.5 is difficult to observe all the three regions individually. On the other hand faint partial ring pattern is observed in the image. This may be attributed to the “onion ring” pattern formed due to swirling of the material from the front of the tool towards the back. This is known to produce severe plastic deformation producing dynamic recrystallization. Sever plastic deformation is expected to cause significant change in the elastic modulus in the region. The elastic modulus in the partial rings is higher than the region around it and hence observed in the acoustic image. The RSW used to produce the image, penetrates into the interior of the material to about a wavelength. At 25 MHz the penetration depth is about 130 μm. Since the information of the amplitude is an average over this thickness we believe that the ring structure extends below the surface.

In the region of the parent material, the image shows with a hazy contrast, features similar to the elongated grains. Optical and Scanning Electron Microscopic observations show that the parent materials have elongated grain structure that is typical of the aluminum plates [4, 7]. The grain structure of materials can be imaged using an acoustic lens without etching the surface of the sample and a strong contrast is observed whenever the elastic anisotropy in the material is high. In the case of aluminum the elastic anisotropy [$\eta = (C_{11} - C_{12})/2C_{44}$] is quite small (1.2) and hence it is not easy to observe grain structure with high contrast [18]. In spite of this low elastic anisotropy, the hazy pattern of elongated grains observed in the parent material indicates that it is possible to observed grain structure in aluminum alloys. In the weld region, the grain structure is known to be equi- and the grain size is smaller than 20 μm. The spatial resolution of the acoustic lens at the operating frequency of 25 MHz is about 60 μm. The grains are much smaller than the spatial resolution of the acoustic lens and hence individual grains can not be observed in the image.

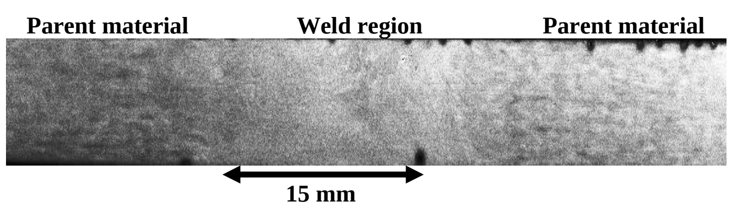

Fig.5. Surface acoustic wave amplitude image of the small sample [S-L plane].

2. Longitudinal and Surface Wave Velocity Measurements

2.1 Local longitudinal wave velocity

Local longitudinal wave velocity measurements were performed, on the small sample, across the middle, along a line covering the weld region and the parent materials. The average diameter of the acoustic spot is approximately 1 mm. The measurements are through the thickness of the sample, parallel to the S direction of the plate. Travel time difference between the top and the bottom of the sample are measured in steps of 1mm across the sample and the velocity is calculated with the knowledge of the thickness. Figure 6 shows the variation of longitudinal wave velocity across the sample. The prominent feature in the variation is “M” like structure is observed inside the weld region. A maximum change of about 0.2%- 0.3% in the velocity is observed at the two highest peaks. The variation in the velocity can be attributed to the residual stress changes in the weld. Acoustic wave velocity measurements have been used in the past to measure residual stress in materials and components [19-22]. This is based on a small change in the velocity in the materials due to stress, which is known as acousto-elastic constants. Following this method and measuring acoustic wave velocities [longitudinal, shear and RSW] along different directions it is possible to determine different components of the residual stress. In order to compute the actual residual stress, the acousto-elastic constant is measured on a stress free sample. In the present discussion instead of determining the actual residual stress the relative changes are discussed based on velocity variations. The longitudinal wave velocity shown in Fig 6 is along the direction parallel to “S” and thru the thickness of the plate. Hence, the changes are related to the residual stress along the S direction and average through the thickness. Acousto-elastic constant measurements performed on other materials [22] in configuration similar to the one described here show that the residual stress is tensile in nature. Although many residual stress investigations on FSW [9-12] have been reported, most of them are based on x-ray diffraction and provide only near surface residual stress. Neutron diffraction measurements provide residual stress as a function of depth into the material. Reynolds et al [11] have reported average through the thickness residual stress variations across the weld on FSW 204L steel measured using neutron diffraction. Their results show that the average through the thickness residual stress is tensile and the variation across the weld shows a diffuse “M” like structure. The thru the thickness longitudinal wave velocity variation shown in Fig 6 can be directly correlated with local residual stress variation in the weld. The residual stress is tensile and exhibits a strong “M” like structure.

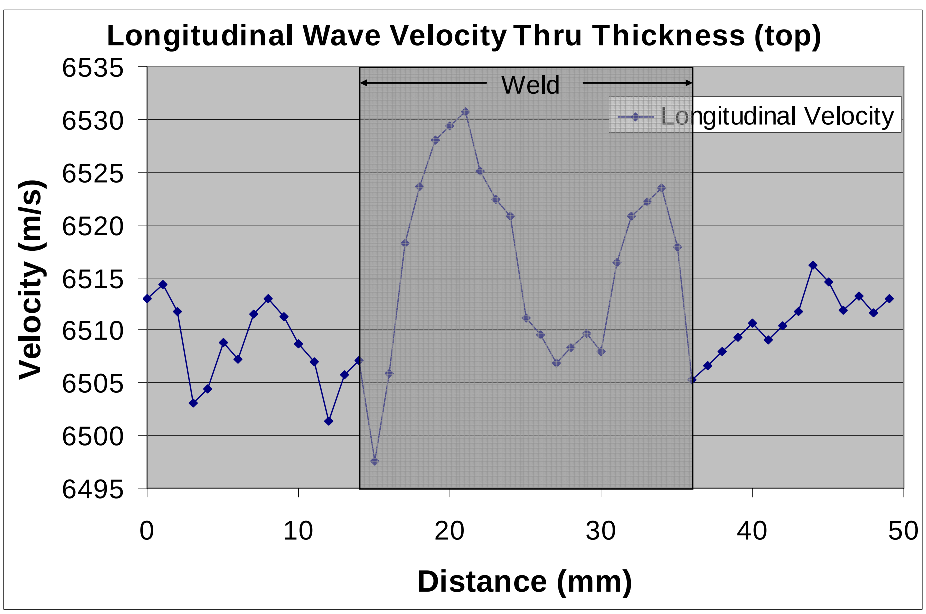

Fig. 6: Variation of the longitudinal wave velocity across FSW [Thru the thickness: Parallel to S]

3. Macroscopic RSW measurements

Measurements of RSW velocity were performed using contact wedge transducers on the large plate. The distance between the two transducers was set to be 55 mm. Two identical wedges and transducers [dia. 6mm] were used to generate and receive the RSW. Measurements were performed, by moving the fixture in steps of 10 mm starting from plate A, across the weld (scan direction as shown in Fig7) into Plate B. Figure 7 shows results of RSW velocity measurements taken at a location about the middle of the length direction of the plate (approximate position is indicated in the figure). The average RSW velocity over a length of 55 mm in plate A is approximately 3080 m/s, and decreases as the weld is approached and reaches a minimum of 3052 m/s inside the weld line. The RSW increase again as the center of the weld line is approached to 3070 m/s, and decreases to a minimum of 3058 m/s close to the other side of the weld. As the plate B is approached it increases and reaches approximate velocity of 3068 m/s. The average RSW in plate A is higher than in plate B. The RSW variation in the weld region shows an inverted “M” like structure. As discussed in section (2.1.1) the changes in the RSW can be related to the residual stress in the material. In the present case the measurements are an average over 55 mm of length. It is well known from residual stress measurements using acoustic velocity [19-22], that under tensile loading the RSW velocity decreases, and with compressive stress it increases. Thus the RSW velocity measurements indicate that across the FS weld region the residual stress parallel to the weld direction is tensile in nature and exhibits an inverted “M” like pattern across the weld region.

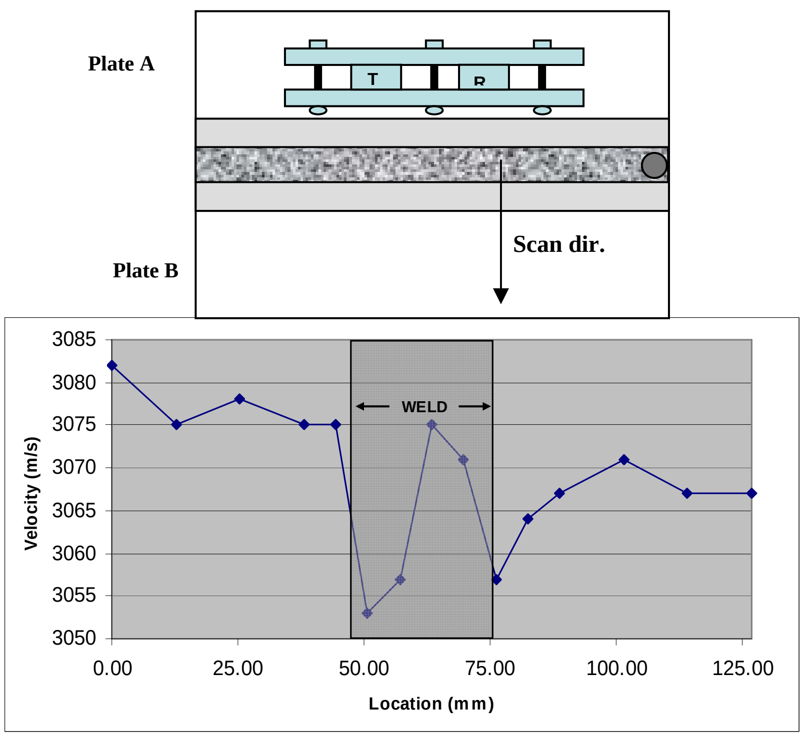

Fig. 7: RSW Velocity across the FSW plate with contact transducers scanned parallel to welding direction.

Figure 8 shows results of RSW velocity measurement as the waves propagate through the weld. The RSW were generated on one of the plates and propagated across the weld into the other plate in a direction perpendicular to the FSW [parallel to T]. The placement of the transducer and the fixture is also shown in Fig. 8. The fixture and the transducers were moved in steps of 10 mm from the left edge and moved towards the right side of the plate. It was also noted that the temperature of the material in the weld during the process increases from right to left. In fact the FSW started from the right and the tool advanced towards the left. The RSW velocity measurement shows fluctuations, but an average gradual increase in RSW is observed as we move towards the right side of the plate. The measurements were performed on the plate without much surface preparation. The surface had a noticeable curvature and it was also rough. The fluctuation in the RSW velocity may be attributed to combined effects of surface curvature and surface roughness. The gradual increase in the average RSW velocity is due to combined effect of the temperature changes produced during the FSW process and changes in the average residual stress.

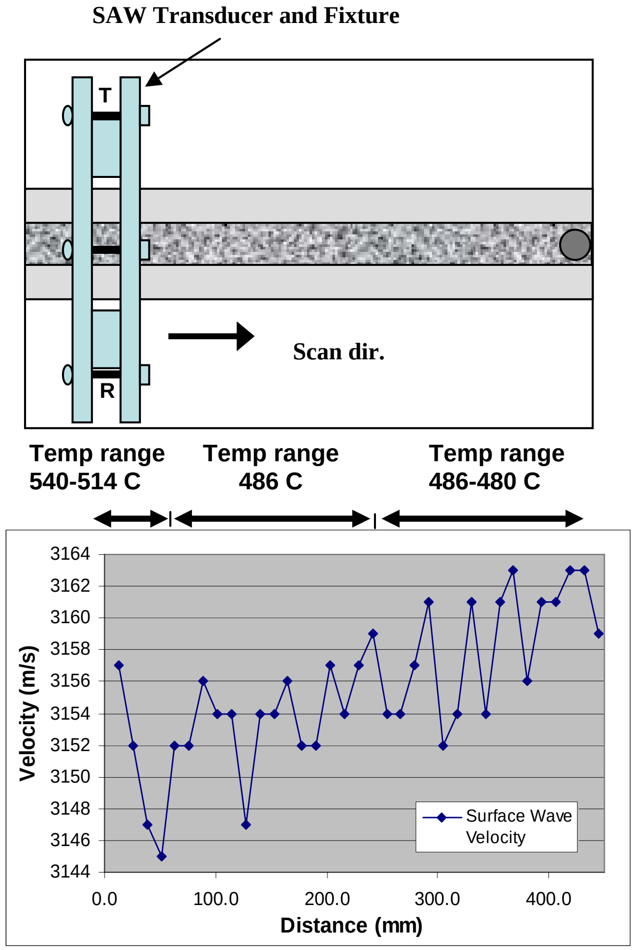

Fig. 8. RSW velocity perpendicular to the welding direction across the entire plate

Figure 9 shows measurements of the velocity of the RSW propagating parallel to the weld direction [along the length of the plate L], in plate A, plate B and on the center line of the weld. Each measurement is an average over the distance between the two transducers [55 mm]. The measurements in plate A and plate B were performed approximately 45 mm away from the center of the weld line. The results show that the plate A has a higher RSW than the plate B. More over the fluctuation in the RSW velocity in plate A is smaller than in plate B. In plate B approximately between 80 -300 mm a minimum in RSW is observed. Apart from this the RSW variations are similar to that observed in plate A. The RSW velocity in the center of the weld line appears to be approximately the average of the RSW velocity in plate A and plate B. It is interesting to note that in the region of 80 – 300 mm the RSW in the center of the weld line shows a maximum where as in plate B in the same region shows a minimum. Further investigation are necessary to gain an understanding of this behavior.

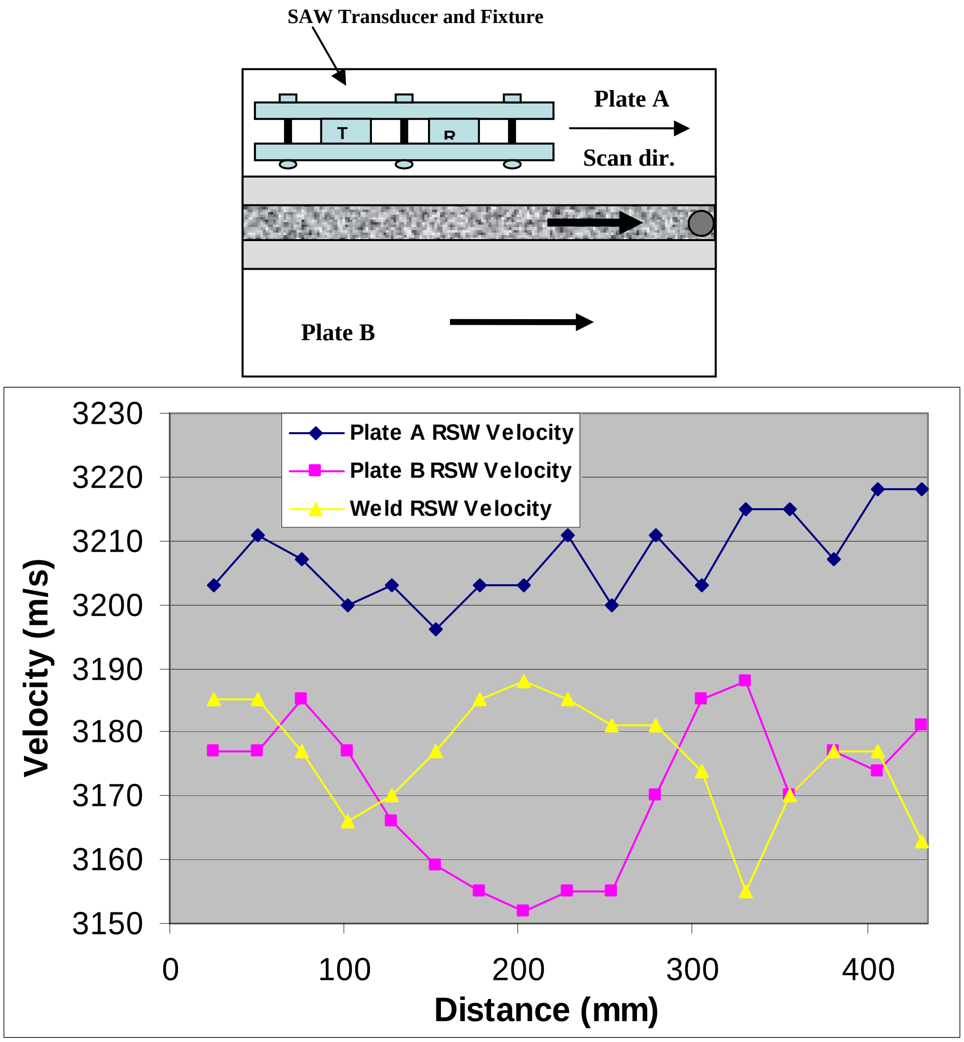

Fig. 9: Rayleigh Surface Wave velocity propagating parallel to weld along the length of the plate.

SUMMARY

The through-the-thickness local longitudinal wave velocity parallel to the S direction of the FSW plate varies by a maximum of 1% across the weld. A prominent "M" like structure is observed in the longitudinal measurements across the weld. The changes in the longitudinal wave velocity across the weld indicate presence of tensile residual stress parallel to the "S" direction in the weld. The macroscopic Rayleigh wave velocity [parallel L and parallel to S directions] variation across the weld is also about 1%. The variation in the velocities in the plate along different directions and locations can vary by 5 to 10%. This variation is comparatively large compared to the variation due to microstructure in the weld zone. Long wavelength acoustic waves like the plate waves, used for structural health monitoring, will see an average over the width of the weld line instead of local variations. The local variations might induce changes in the frequency characteristics of these waves. For a robust system development, it is necessary to measure not only the wave velocity but also the amplitude and frequency characteristics. The variation in macroscopic velocities in the parent material is a major concern for the design of the systems. These variations appear to be over length scales much larger than the wavelengths. It is extremely important to have knowledge of both local as well as macroscopic variations of elastic properties for proper interpretation of the damage induced changes in the wave propagation characteristics.

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