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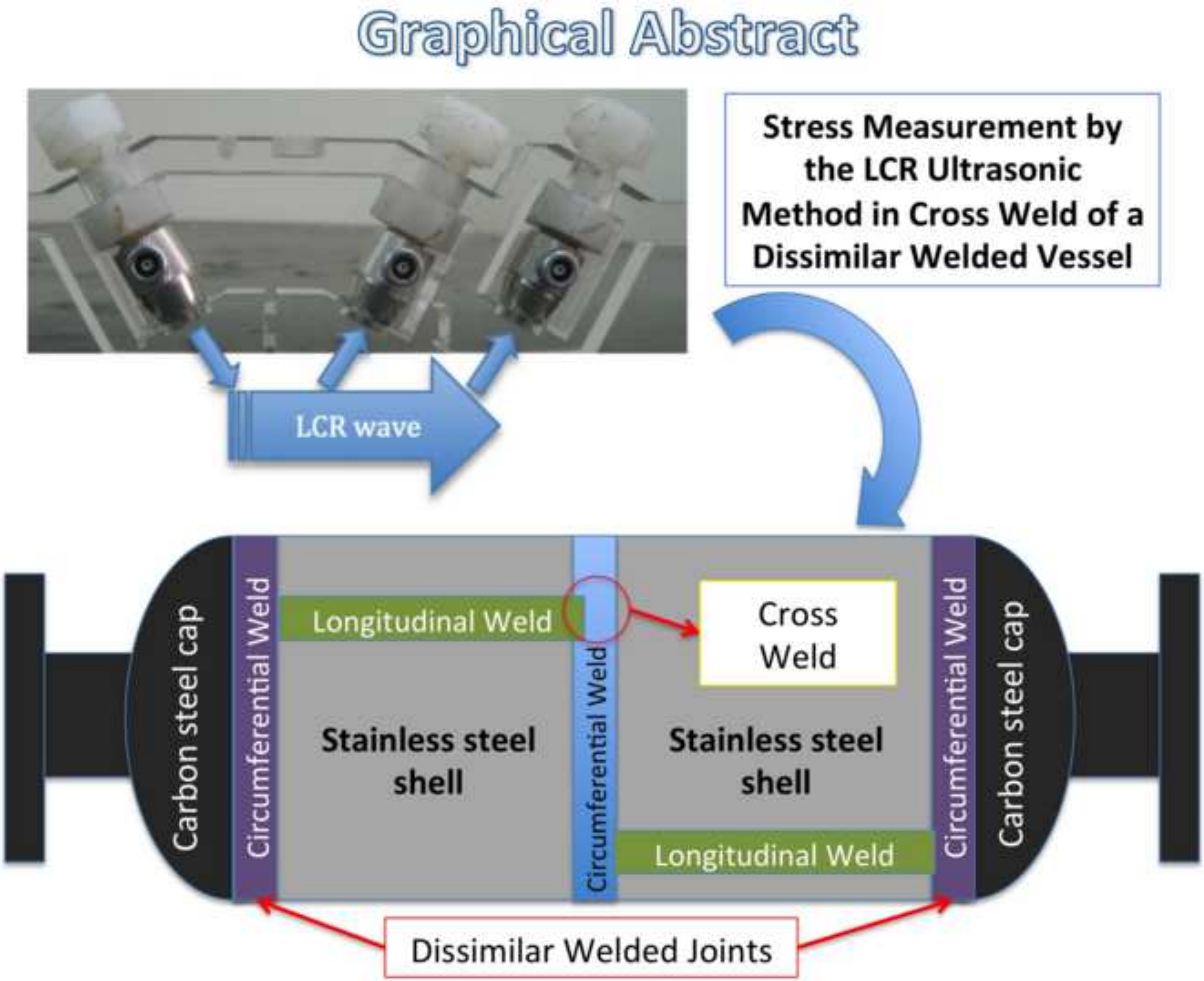
Abstract: Manufacturing process of pressure vessels used in high-temperature applications normally needs employing dissimilar metal welds (DMWs) between austenitic and ferritic steel. However, high amount of thermal stresses at the welds are induced due to differences in coefficient of thermal expansion between the types of steel. This study investigates the evaluation of welding residual stresses in a pressure vessel manufactured by DMW of 316L stainless steel shell to A106 carbon steel caps as well as similar welding of stainless steel shells. By using longitudinal critically refracted (LCR) ultrasonic waves, the residual stresses are experimentally measured. The ultrasonic method is based on acoustoelasticity law by which the ultrasonic wave velocity could be connected to the material stress. By changing the frequency in which the ultrasonic transducers are working, the LCR waves are able to penetrate in various depths of the material in order to measure the sub-surface residual stresses. Hence, four main aspects are considered in this study: (I) stress evaluation of the DMW; (II) sub-surface stress measurement; (III) stress evaluation of longitudinal weld and (IV) stress measurement in cross weld. It is demonstrated that the residual stresses of the DMW pressure vessel could be comprehensively evaluated by using the LCR method.

Graphical Abstract (for review)



Sub-surface stress measurement of cross welds in a dissimilar welded pressure vessel

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Abstract

Manufacturing process of pressure vessels used in high-temperature applications normally needs employing dissimilar metal welds (DMWs) between austenitic and ferritic steel. However, high amount of thermal stresses at the welds are induced due to differences in coefficient of thermal expansion between the types of steel. This study investigates the evaluation of welding residual stresses in a pressure vessel manufactured by DMW of 316L stainless steel shell to A106 carbon steel caps as well as similar welding of stainless steel shells. By using longitudinal critically refracted (LCR) ultrasonic waves, the residual stresses are experimentally measured. The ultrasonic method is based on acoustoelasticity law by which the ultrasonic wave velocity could be connected to the material stress. By changing the frequency in which the ultrasonic transducers are working, the LCR waves are able to penetrate in various depths of the material in order to measure the sub-surface residual stresses. Hence, four main aspects are considered in this study: (I) stress evaluation of the DMW; (II) sub-surface stress measurement; (III) stress evaluation of longitudinal weld and (IV) stress measurement in cross weld. It is demonstrated that the residual stresses of the DMW pressure vessel could be comprehensively evaluated by using the LCR method.

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1. Introduction

The industrial demand for dissimilar metal weld (DMW) is continuously increasing due to various advantages such as providing suitable mechanical properties along with cost reduction [1]. Dissimilar metal joints between pipes made of ferritic and austenitic steels are extensively employed in engineering structures such as pressure vessels working in high-temperature applications. The austenitic stainless steel (e.g., 316L which is employed in this study) has a thermal conductivity of one third of carbon steel (e.g., A106 which is considered in this study) [2]. Furthermore, the austenitic stainless steels have also a 50% greater thermal expansion in comparison with the carbon steels [2]. Differences in thermal conductivity as well as thermal expansion are prone to uneven expansion and distortion when the austenitic stainless steel is joined to the carbon steel. Theses phenomena could play an important role in producing high amount of welding residual stresses in the DMW.

Residual stress is defined as the stress that remains inside the material after the manufacturing process, in the absence of any external loads or thermal gradients. The residual stresses could undesirably change the fatigue life, dimensional stability, corrosion resistance, and brittle fracture. Unfortunately, the welding process produces high amount of the residual stresses in the structures. Differential shrinkages due to the weld solidification and cooling, as a natural phenomenon in the welding process particularly in the DMW, are responsible for the welding residual stresses. By mitigation of the welding residual stresses, it is expected to decrease risk of catastrophic failures in the welded structures. However, it is firstly required to assess the welding residual stresses.

There are various experimental methods for evaluation of the welding residual stresses. Ultrasonic stress measurement is a nondestructive method based on the acoustoelasticity law, which states that flight time of the ultrasonic wave is influenced by the material stress. Evaluation of third order elastic constants motivated the development of acoustoelasticity. Based on Murnaghan's theory of nonlinear elasticity, Hughes and Kelly developed the theory of acoustoelasticity in 1953 [3]. In 1967, Crecraft [4] showed that the acoustoelastic law along with the ultrasonic birefringence effect could be employed for non-destructive stress measurement on the metals. Tanala et al [5] and Schneider [6] described the stress assessment by the ultrasonic method. The ultrasonic shear wave has been used in ultrasonic stress measurement; however, in modern applications of the technique, longitudinal critically refracted (LCR) waves are substituted. The LCR wave is a longitudinal ultrasonic wave propagated inside the material and parallel to the surface. Egle and Bray [7] demonstrated high sensitivity of the LCR wave to the stress in comparison with other types of the ultrasonic waves. The LCR technique applications were given in a number of studies, remarkably Santos and Bray [8-9], Bray and Chance [10] and Javadi et al [11-15]. In this study, the LCR waves are employed to measure the welding residual stresses of DMW pressure vessel.

Sub-surface residual stresses are defined as the stresses within the depth of the materials. In the circumferential welding needed to manufacture the pressure vessels, the residual stresses in depth of material could be significantly varied from the surface stresses. However, the majority of nondestructive stress measurement methods, like X-ray diffraction and Barkhausen Noise, are capable of surface stress measurement in depth of a few micro-millimeters [16]. By altering testing frequency in which the ultrasonic transducers are working, the LCR wave is able to penetrate in different depths of the material in order to measure the sub-surface residual stresses. The ultrasonic method has shown the capability of sub-surface stress measurement in the stainless steel plates and pipes [11, 13]. However, potential of the sub-surface stress measurement in the DMW of the pressure vessels needs more investigations, which is considered in this study.

In the previous literatures, the LCR methods had been scantly considered in the DMW of the pressure vessels. The main goal of this study is residual stress evaluation of a pressure vessel in which the DMWs are employed. The LCR method is used to measure the sub-surface residual stresses in the DMW pressure vessel. The residual stresses are also measured by the hole-drilling incremental method in order to validate the ultrasonic measurement results. By comparing results of the LCR and hole-drilling methods, the welding residual stresses in DMW, similar welds as well as cross welds (interface of circumferential and longitudinal welds) are achieved.

2. THEORETICAL BACKGROUND

Principles of the stress measurement implemented by the LCR wave are simply shown in Fig. 1. The LCR wave is firstly produced in the first critical angle (calculated based on the Snell’s law) by a transmitter transducer; then propagated through a region of the material (parallel to the material surface) and is finally detected by the receiver transducer. In this wave path, velocity of the LCR wave is influenced by the material stress. Hence, the time of flight (TOF) related to the LCR wave propagated inside a stress-free material (T1) would not be equal to that obtained from a material with stress (T2).

The material stress could be achieved from the following formula:

$$\sigma = \frac{E}{L}\left(\frac{T_2 - T_1}{T_1}\right) \quad (1)$$

In Eq. (1), σ is the material stress, E is the elastic modulus, T1 and T2 are the TOFs as shown in Fig. 1.

In Eq. (1), L stands for the acoustoelastic constant, which is an unknown material property required to be measured in the sample. The tensile test method is usually employed to determine the acoustoelastic constant, as shown in Fig. 2. The measurement devices corresponding the LCR method are utilized to measure T1 and T2 in the tensile test specimen while the tensile test machine increases the material stress (σ) step by step. In each step, the acoustoelastic constant (L) could be calculated based on the Eq. (1). The stress increasing steps would be continued just before the material fails and the acoustoelastic constant is achieved by average of the results.

The LCR wave is able to penetrate in various depths of the material in order to measure the residual stress in the sub-surface layers. The depth of layer is related to the ultrasonic wavelength, often exceeding a few millimeters. As a practical method, the ultrasonic transducers (by which the LCR wave is produced and received) working with various testing frequencies are employed in order to reach different LCR waves propagating in various depths of the material (as shown in Fig. 3).

3. EXPERIMENTAL PROCEDURES

3.1. Sample Description

In this study, two pipes made of stainless steel (TP 316 L) are joined together in order to make shell of the pressure vessel. Two carbon steel caps (A 106) are then joined into the shell by dissimilar metal welding (DMW), as shown in Fig. 4. Tungsten inert gas (TIG) welding is employed to join all the caps and shells producing the only sample (pressure vessel) used in this study. The outer diameter and wall thickness of the pressure vessel are equal to 323.8 mm and 6 mm, respectively. The welding processes including two longitudinal welds to manufacture the stainless steel pipes, a circumferential weld to join the pipes making the shell, DMW to join the left cap into the shell as well as DMW used for the right cap are implemented according to the welding procedure specifications (WPS) mentioned in Table 1.

3.2. *Stress Measurement Devices*

The devices used for the ultrasonic stress measurement are shown in (Fig. 5), which include an ultrasonic box, computer, and time of flight (TOF) measuring unit. The ultrasonic box is a 100 MHz ultrasonic testing device capable of synchronization between the pulser signal and the internal clock, which controls the A/D converter. The TOF measuring unit includes three normal transducers assembled on an integrated wedge to measure the time of flight. By employing the LASER cutting process, an ultrasonic wedge is manufactured from poly methyl methacrylate (PMMA) material (commercially known as the trademark Plexiglas) to be used as positioner for the ultrasonic transducers. Axial and hoop wedges are employed to measure the TOF in the axial and hoop directions, respectively. Twelve transducers in four different frequencies are used to measure the sub-surface stresses while their nominal frequencies are equal to 1 MHz, 2 MHz, 4MHz and 5 MHz. Three normal transducers with the same frequency are assembled in each wedge where the diameter of the piezoelectric elements is 6 mm.

There are three scanning paths, which are considered in this study (Fig. 6):

a) Path 1: The scanning path 1 starts from the melted zone (MZ) of the left cap (L4), passes the main center weld (L3), and ends to MZ of the right cap (L2).

b) Path 2: The scanning path 2 covers the longitudinal weld (H2) and starts in 100 mm distance from the MZ of the H2, crosses the H2 and ends to 80 mm distance from the other side of the H2.

c) Path 3: The main goal of scanning path 3 is investigation of the cross weld between H1 and L3. Hence, the Path 3 starts on the H1 and 50 mm distance from the L3, passes from the cross weld (interface of H1 and L3) and ends to 80 mm distance from the L3 on the other side.

In all the scanning paths 1-3, the moving step is equal to 1 mm for the points near and on the MZ while it is increased to 5 mm far away the weld. The TOF is measured three times for each point and the average data is recorded. The Path 1 is also scanned four times by using four different frequencies of the transducers in order to measure the sub-surface residual stresses. In each ultrasonic scanning path, there are some points in which the hole-drilling technique is applied in order to verify the stress measurement results of the ultrasonic method (Fig. 6).

The residual stresses measured by the ultrasonic method are verified by the hole-drilling (HD) technique, which is standardized by ASTM: E837 for stress measurement. The hole-drilling method is implemented on the DMW pressure vessel in eight points in order to cover all the three ultrasonic scanning paths (Fig. 6). This semi-destructive technique measures the strains relaxed by incremental drilling of a small hole with diameter of 1.5 mm and depth of 2 mm. The strains are evaluated using a strain gauge rosette after each depth increment and the residual stresses are then calculated employing equations established by ASTM: E837.

After TOF and hole-drilling measurements, the pressure vessel is sent for stress-relief heat-treatment (at 450° C for 6 hours). This will facilitate measurement process of T1 and acoustoelastic constant (L), which need to be carried out on the stress-free material in order to complete the procedure of ultrasonic stress measurement. The stress-relieved sample is then evaluated by TOF unit to determine the value of T1 for all the points located in Paths 1-3. As a practical technique for measurement of the acoustoelastic constant, the sample should be pressurized in order to purposely produce stress on the surface. The sample is filled with the water and the internal pressure is increased step by step through an air compressor. The stress on the outer surface is calculated according to the ASME-Sec. VIII. The sample is retained in a certain pressure while the TOF unit is assembled on it in order to trace the LCR wave affected by the air pressure induced stress, as shown in Fig. 7. The acoustoelastic constant (L) throughout the sample and in all the scanning paths (Path 1-3) is then achieved based on Eq. (1). In comparison with the acoustoelastic constant measurement technique already described in the Introduction (as shown in Fig. 2), the pressure test technique considered in this study has the following advantages:

I) Practically, it is not simple to extract tensile test sample from a rounded shape sample (e.g., the pressure vessel considered in this study). Furthermore, it is needed to damage the sample in order to provide the tensile test sample while the pressure test method is able to measure the acoustoelastic constant nondestructively.

II) The effect of material texture, which could be considerably changed from the base metal to HAZ and MZ, is known as a source of error in the ultrasonic stress measurement [17]. To pass through this limitation, it is usually recommended to focus on precise measurement of the acoustoelastic constant which has different values in the base metal, HAZ and MZ. Javadi et al [11] reported a big challenge to evaluate the acoustoelastic constant of HAZ because its dimensions were not enough to extract the tensile test sample. They investigated various heat treatment procedures to find the proper thermal cycle in order to simulate the HAZ microstructure in a tensile test specimen extracted from the base metal [11]. It is believed that the DMW could intensify the challenge of HAZ simulation due to rapid change of the microstructure through the weld. Hence, the acoustoelastic constant measurement by tensile test technique would be faced with huge microstructural difficulties particularly in case of DMW investigated in this study. Alternatively, the pressure test technique is able to provide the acoustoelastic constant in a relative method. It means that, the acoustoelastic constant would be provided in a continuous diagram for all the Paths 1-3. As a result, each measurement point has its unique acoustoelastic constant which will be used in Eq. (1) for stress calculation of that point.

3.3. Sources of error

The ultrasonic stress measurement, like all the measurement methods, suffers from various technical difficulties resulted in different measurement errors. The ultrasonic method is able to measure the residual stress with minimum ±10 MPa error (the highest accuracy reported in a plate and measured by 1 MHz transduser [11]). On the other hand, it has been already reported that the error would be increased to ±40 MPa in case of measurement by higher frequencies (i.e., 5 MHz) [11]. The measurement errors could be caused by the ultrasonic technique and, additionally, by the sample on which the ultrasonic measurement is applied.

The ultrasonic method is able to measure the average of residual stresses in a penetration depth corresponding to frequency of the ultrasonic transducer by which the stresses are measured. This should be reflected in verification of the ultrasonic technique by the other measurement or numerical methods. For instance, the HD measurement is applied in a hole with depth of 1.5 mm, which is in good agreement with penetration depth of 4 MHz-transducer (as shown in Fig. 3). It means that the results obtained by the 4 MHz-transducer are the only ultrasonic results allowable to be compared with results of the HD measurement.

The ultrasonic error could be caused by the instrumentation including transducers, ultrasonic board and connectors. The manufacturing error of the wedge, particularly in creation of the first critical angle, could be another important source of error. Hence, employing high quality instruments as well as high accuracy manufacturing processes could result in reaching an acceptable range of error in the ultrasonic stress measurement.

The ultrasonic couplant is also an important source of error since its thickness could be changed during the measurement. Once the thickness of couplant film is changed, the TOF would be changed leading to a miscalculation of stress effect. A fixed thickness of the couplant film could be practically achieved by applying a constant pressure on the wedge throughout the scanning path.

The temperature effect on the TOF measurement is considered as another source of error. However, it could not be a big challenge in case of quick measurement in a well-equipped laboratory. It is also practical to monitor the temperature throughout the ultrasonic measurement and then insert its effect in calculation of the residual stress. In this case, it is firstly required to measure the temperature effect on the TOF in a material same as the investigated sample. To deal with this experimental job, a simple setup including a heater and thermocouple would be employed to increase and measure the temperature while the TOF unit is used to record any changes and temperature effect.

All the aforementioned errors could be amplified in case of stress measurement on a welded sample. First of all, the welding zone, HAZ and base metal have different microstructure leading to a considerable effect on the TOF measurement. This would be deteriorated in case of DMW investigation. The best practical technique to deal with this problem is measurement of the acoustoelastic constant in all areas of MZ, HAZ and base metal as described in the previous section.

As mentioned in the previous section, the sample is stress relieved before measurement of the T1 and acoustoelastic constant. The measurement of T1 and acoustoelastic constant is carried out by assuming that the sample is stress-free which is practically impossible to be achieved. Any amount of residual stress not relieved during the heat treatment could be considered later as an important source of error in measurement process of T1 and acoustoelastic constant.

Another measurement error caused by the sample is moving the ultrasonic wedge over the DMW area. Due to different materials, velocity of the ultrasonic wave is changed in two sides of the weld leading to difference in the first critical angle. It is needed to manufacture two wedges with different angles in order to move from one side to another side of DMW. However, production of two wedges with completely same dimensions is practically impossible. Alternatively, one single wedge could be produced with a critical angle equal to average of those calculated for both materials. It should be noted that, the mentioned solution is only applicable for DMW of two materials having close ultrasonic velocity. For instance, the velocity of ultrasonic wave in the carbon steel and stainless steel investigated in this study was measured equal to 5840 m/s and 5760 m/s, respectively. Based on the Snell's law, the first critical angle would be calculated equal to 28.2 degree and 28.6 degree, respectively. Hence, the angle of 28.4 degree has been considered in the manufacturing of the ultrasonic wedge.

The majority of acoustoelasticity relations, on which the ultrasonic stress measurement is based, are achieved by assuming uniaxial stress in the material [7]. However, this simplification is source of error particularly in case of stress measurement on circumferential welding due to high amount of both axial and hoop residual stress. By moving the ultrasonic wedge over the weld, particularly in case of DMW, the LCR wave is influenced by combination of hoop and axial residual stress while only a single effect could be considered in TOF measurement.

4. RESULTS AND DISCUSSION

4.1. Study of the DMW and sub-surface stresses by investigation of the Path 1

The results of hoop and axial residual stress measured by the ultrasonic LCR method are shown in Fig. 8 and Fig. 9, respectively. From Fig. 8, the hoop residual stress distribution is in tensile mode at the weld centerlines while it transforms to compressive stresses near the heat affected zone (HAZ) and finally tends to zero value in the points located far enough from the welds. As an opposite trend, Fig. 9 shows that the weld centerlines carry axial residual stress in the compressive mode. From Fig. 8-9, it is generally obvious that the hoop and axial residual stresses of DMWs (L2 and L4) are higher than similar welding of stainless steel pipes (L3).

The general trend of axial and hoop residual stress achieved in this study stands in good agreement with those obtained in previous investigation of the pressure vessels [12, 14]. However, the quantities of the residual stresses achieved from the ultrasonic stress measurement are verified by those obtained from the hole-drilling method. It is generally obvious that there is an acceptable agreement between the ultrasonic measurements with the hole-drilling results. The reason of employing 4 MHz transducers for comparing the ultrasonic and hole-drilling measurements is the 1.5 mm penetration depth of this transducer, which is fit with depth of the hole produced during the hole-drilling measurement.

From Fig. 8, the peak of residual stress is 326 MPa, 67 MPa and 353 MPa in the weld center of L4, L3 and L2, respectively. The corresponding values obtained from the HD measurement are 341 MPa, 83 MPa and 337 MPa for L4, L3 and L2, respectively. This shows that the maximum disagreement is less than 20 percent, which is an acceptable measurement error in the weld stress measurement. From Fig. 9, the peak of residual stress in L4, L3 and L2 is equal to 234 MPa, -112 MPa and 213 MPa in case of ultrasonic measurement while it is 214 MPa, -56 MPa and 210 MPa in case of HD measurement, respectively.

The sub-surface stress measurement is also considered in the Path 1 by changing the testing frequencies in which the ultrasonic transducers are working. The results of sub-surface stress measurement are shown in Figs. 10-11. From Fig. 10, it is obvious that the tensile stress at the weld centerline does not considerably change by increasing the depth of measurement. At the weld centerline of L4, the peak of hoop residual stress is 338 MPa, 326 MPa, 325 MPa and 339 MPa in case of ultrasonic stress measurement by 5 MHz, 4 MHz, 2 MHz and 1 MHz transducers, respectively. These values are 87 MPa, 67 MPa, 41 MPa and 60 MPa in case of L3 while they are 327 MPa, 353 MPa, 367 MPa and 386 MPa in case of L2. The fact of small change in hoop residual stress by moving from the surface into the depth of material has been already reported in the previous studies on the pressure vessel [12, 14]. However, this little changes could be modulated more in case of using ultrasonic method for stress measurement because the ultrasonic method provides the average of stress in the corresponding penetration depth of transducers (as shown in Fig. 3).

As a reverse trend shown in Fig. 11, increasing the depth of measurement decreases the absolute amount of stress at the weld centerline. At the weld centerline of L4, the peak of axial residual stress is 285 MPa, 234 MPa, 169 MPa and 68 MPa in case of ultrasonic stress measurement by 5 MHz, 4 MHz, 2 MHz and 1 MHz transducers, respectively. These values are -141 MPa, -112 MPa, -80 MPa and -40 MPa in case of L3 while they are 263 MPa, 213 MPa, 167 MPa and 60 MPa in case of L2. This simply shows that the peak of residual stress drops dramatically by increasing the depth of stress measurement. This was also expectable because the axial residual stress is usually in compressive mode at weld centerline of pressure vessel surface while it goes to a tensile mode in the inner surface [12, 14]. This huge change from compressive to tensile stress could make a considerable value variation. However, the tensile and compressive stresses have been substituted in case of DMW (L2 and L4) but the fact of huge change is still visible in all data.

4.2. Study of the longitudinal welding by investigation of the Path 2

There are two longitudinal welds in the DMW pressure vessel investigated in this study including H1 and H2. The H2 is located in the Path 2 and the residual stresses are measured by the ultrasonic method, as shown in Fig. 12. The ultrasonic results are also verified by the hole-drilling measurement, as shown in Fig. 12, and an acceptable agreement is achieved.

From Fig. 12, the trend of axial residual stress is very similar to distribution of the longitudinal residual stress in the butt welding of the plates where the peak of tensile residual stress (223 MPa) located at the weld centerline, rapidly transforms to the compressive stress near the HAZ (with peak of -110 MPa at 12 mm distance from the weld centerline) and finally tends to zero stress far away the weld. This similarity could be justified by the geometry of longitudinal weld in the pipes, which is very similar to the straight butt weld of plates particularly for the high diameter pipes.

4.3. Study of the cross weld by investigation of the Path 3

The interface of longitudinal weld, H1, with circumferential weld, L3, is located in Path 3. This interface is considered as the cross weld and the ultrasonic method as well as the hole-drilling technique are employed to evaluate the residual stresses, as shown in Figs. 13-14. An acceptable agreement is shown in Figs. 13-14 between results of the ultrasonic stress measurements with those obtained from the hole-drilling method. This validates the use of ultrasonic LCR method in stress measurement of the cross welds.

From Figs. 13-14, it is generally observed that the residual stresses are achieved in different trends in comparison with the normal stress distribution commonly reported for the pipe and pressure vessel analyses. From Fig. 12, it was concluded that the longitudinal welds of the pipe could produce the residual stress very similar to that is achieved from the plates. Hence, the interface of a longitudinal weld, H1, with a circumferential weld, L3, experiences a residual stress distribution based on combination of the plate and pipe weld analysis, as shown in Fig. 15. It should be noted that the H1 has been made before L3; hence, the residual stresses are basically thermo mechanical effect of L3 on the H1. This effect could be explained as following:

i) The welding procedure, joint geometry and dimensions of H1 have been very similar to the H2 that was already investigated in Path 2. However, the axial residual stress of H2, peaked at 223 MPa, is very different from H1, peaked at 125 MPa. This difference could be explained by the thermo mechanical effect of L3 on the H1. Furthermore, L3 has influenced the trend of residual stress distribution in H1 that has a rapid drop in the center of the weld instead of sharp and continuous growth near the weld centerline (like H2).

ii) The residual stress of L3 has been already investigated in Path 1 where the peak of hoop and axial residual stress is about 67 MPa and -112 MPa, respectively (as shown in Fig. 10b and Fig. 11b). As a very different trend, the peak of hoop and axial residual stress are equal to 430 MPa and 125 MPa, respectively (as shown in Figs. 13-14). This huge difference could be explained by the superposition of straight and circumferential welding stresses. The peak of axial residual stress in the cross weld is summation of axial stress in L3 (-112 MPa) and that value in H2 (223 MPa).

iii) In addition to the effect of L3 on the peak of residual stress in H1, the distribution of residual stress has been also changed. For instance, the axial residual stress of cross weld (as shown in Fig. 13) does not have any compressive stress area, which is usually produced near the HAZ of straight butt-welding. This is due to superposition of compressive residual stress of H1 with tensile residual stress of L3 in distance of about 15-30 mm from the weld centerline.

The above explanations simply shows that the residual stresses of the cross weld is similar to neither straight butt-welding (i.e., H2) nor circumferential welding (i.e., L3). Alternatively, the residual stress distribution in the cross welds could be explained by combination of both straight and circumferential welding, as shown in Fig. 15.

However, the aforementioned superposition effects could be considered as a simple and rough estimation of the residual stress distribution in the cross weld while this study confirmed again that the welding residual stresses are not easy to be predictable without direct measurement. For instance, the residual stress of cross weld in the circumferential direction is expected to be summation of transversal residual stress of H1 (or its similar weld, H2) and hoop residual stress of L3, as shown in Fig. 15. Due to some practical limitations, the transversal residual stress of H2 has not been measured in this study. However, it has been already reported that the peak of transversal residual stress in the straight butt-welding could be estimated to be about one third of its longitudinal residual stress peak [18]. By this rough estimation, the peak of transversal residual stress of H2 could be equal to about 74 MPa (one third of 223 MPa). Hence, the summation of transversal residual stress (in H1) and hoop residual stress (in L3) would be 141 MPa (74 MPa + 67 MPa), which is a huge underestimation of that achieved for hoop residual stress of the cross weld (430 MPa). On the other hand, it was expected that the residual stress of H1 would be decreased under annealing effect of L3 while, on the contrary, the residual stress are measured much higher than initial estimations. Hence, it is not recommended to predict the residual stress of cross welds before any direct measurement.

5. CONCLUSIONS

The main goal of this study is ultrasonic evaluation of welding residual stresses in a DMW pressure vessel. The ultrasonic stress measurements are compared with residual stresses obtained from the hole-drilling method in similar welding of two stainless steel pipes, dissimilar welding of stainless steel pipe into carbon steel cap, longitudinal weld on the shell and cross weld in the pressure vessel. According to the achieved results, it can be concluded that:

1- The hoop and axial residual stresses of DMWs are considerably higher than similar welding of stainless steel pipes.

2- The tensile hoop stress at the weld centerline does not considerably change by increasing the depth of measurement while increasing the depth of measurement decreases the compressive axial stress at the weld centerline.

3- The trend of axial residual stress in longitudinal weld of the pressure vessel is very similar to distribution of the longitudinal residual stress in the butt-welding of the plates.

4- The interface of a longitudinal weld with a circumferential weld could produce a residual stress distribution based on combination of the plate and pipe weld analysis.

The general trend of axial and hoop residual stress in similar and dissimilar welding and also for longitudinal, circumferential and cross welds investigated in this study stands in good agreement with those obtained from the hole-drilling measurements. This agreement is also achieved for the sub-surface stress evaluation showing that the LCR method is able to comprehensively investigate the DMW pressure vessel inspected in this study.

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LIST OF FIGURE CAPTIONS

LIST OF TABLE CAPTIONS

Table

Table 1. Welding procedure specifications of the pressure vessel

Weld Line (according to Fig. 4)	Welding-pass No.	Welding current (A)	Welding voltage (V)	Welding speed (mm/s)	Filler material	Filler diameter (mm)
L 2	Pass 1	250	85	1.35	309 L	2.4
	Pass 2	270	85	1.83		2.4
	Pass 3	253	85	2.33		2.4
L 3	Pass 1	150	85	0.83	316 L	2.4
	Pass 2	250	85	1.14		2.4
	Pass 3	200	85	1.50		2.4
L 4	Pass 1	250	85	1.35	309 L	2.4
	Pass 2	275	85	1.83		2.4
	Pass 3	250	85	2.33		2.4
H 1	Pass 1	225	85	0.7	316 L	2.4
	Pass 2	225	85	0.95		2.4
	Pass 3	255	85	1.1		2.4
H 2	Pass 1	225	85	0.7	316 L	2.4
	Pass 2	250	85	0.95		2.4
	Pass 3	250	85	1.1		2.4

Figure1

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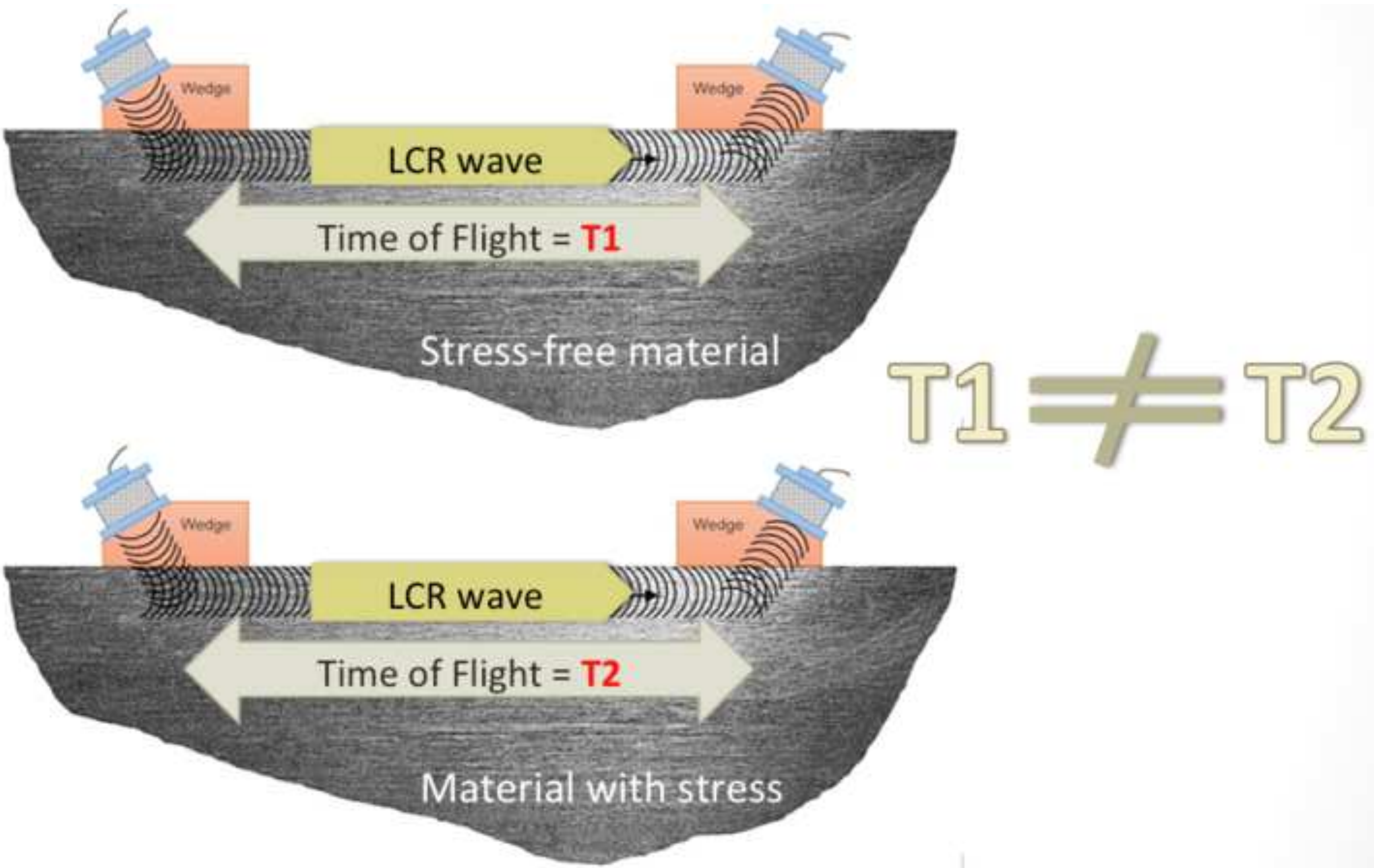

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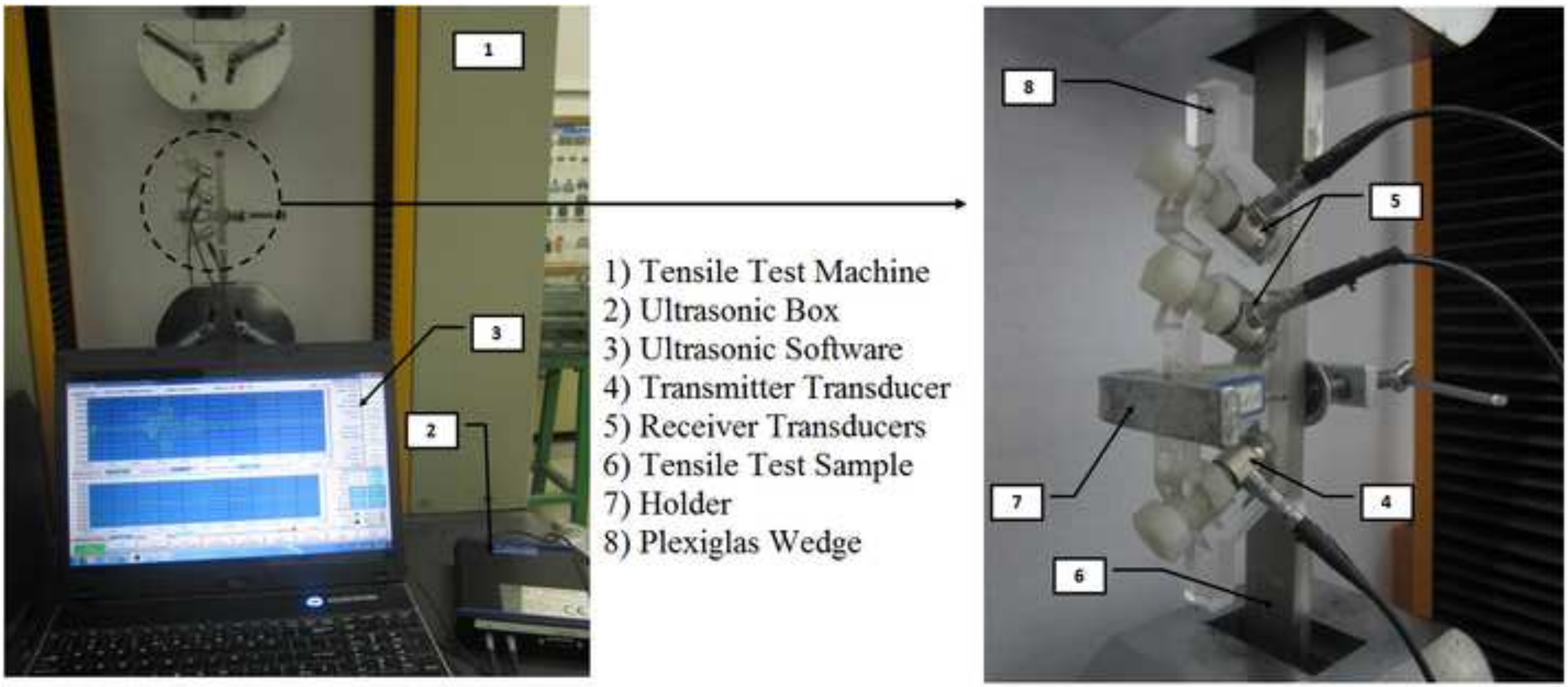

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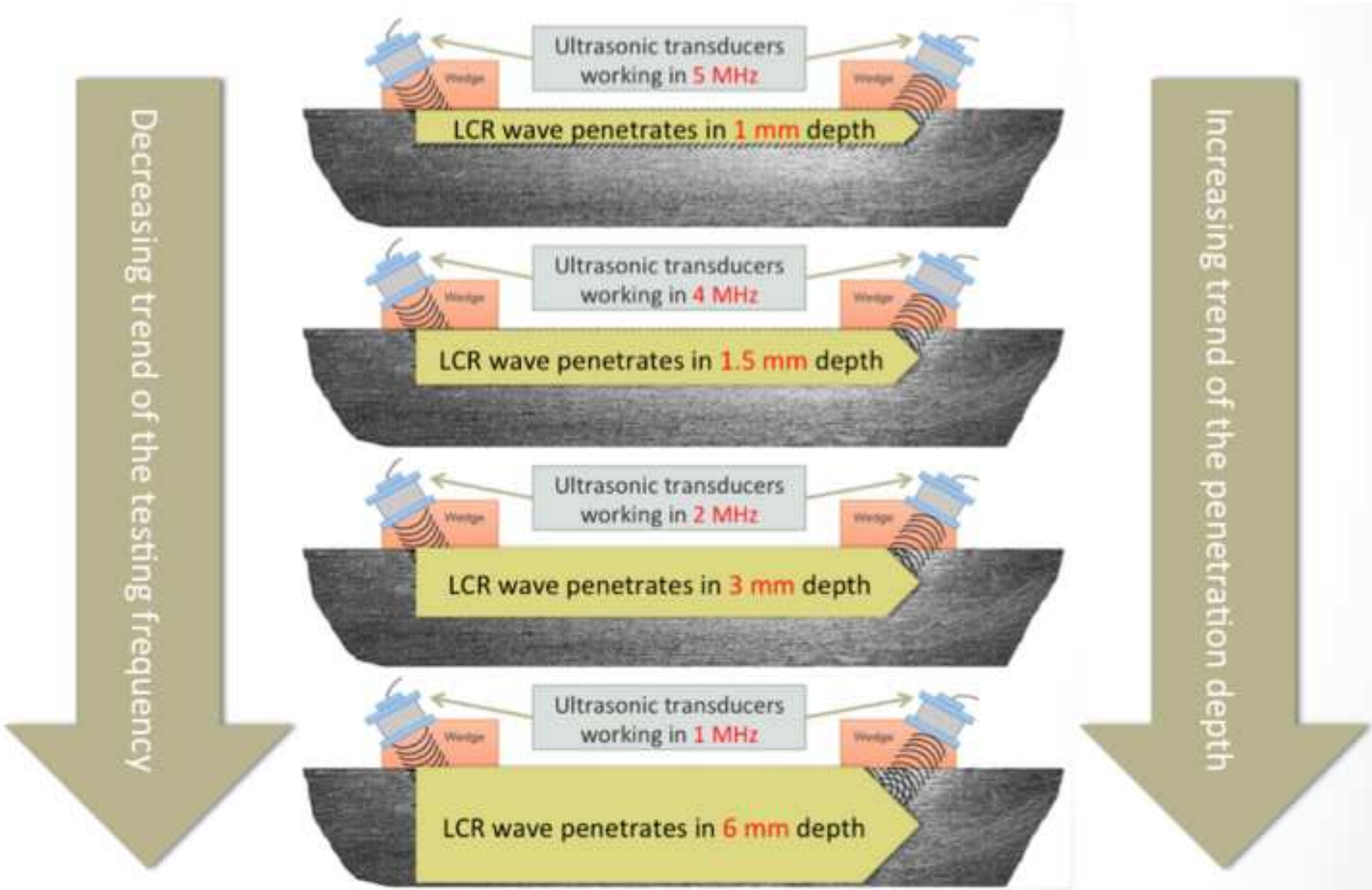

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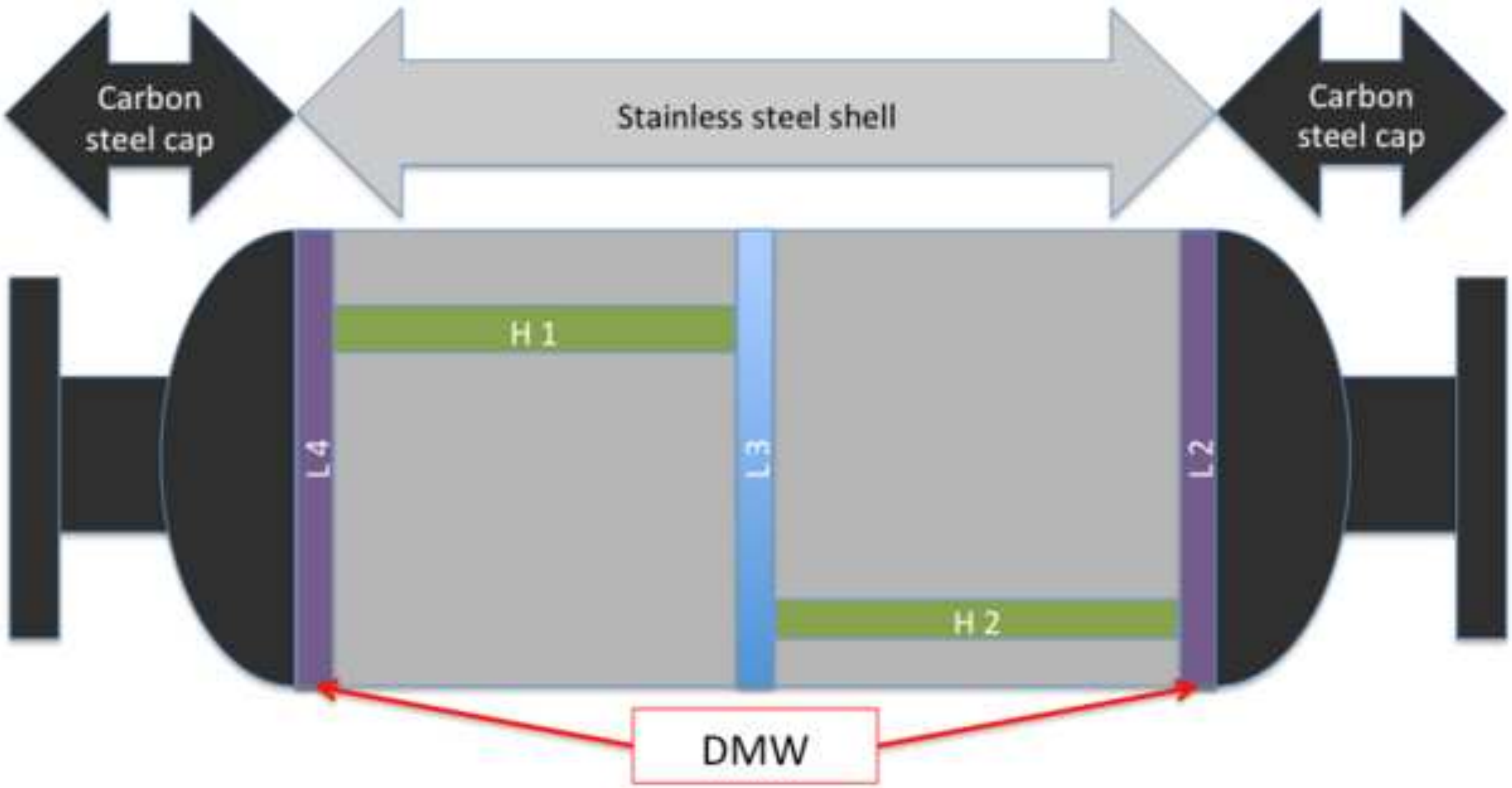

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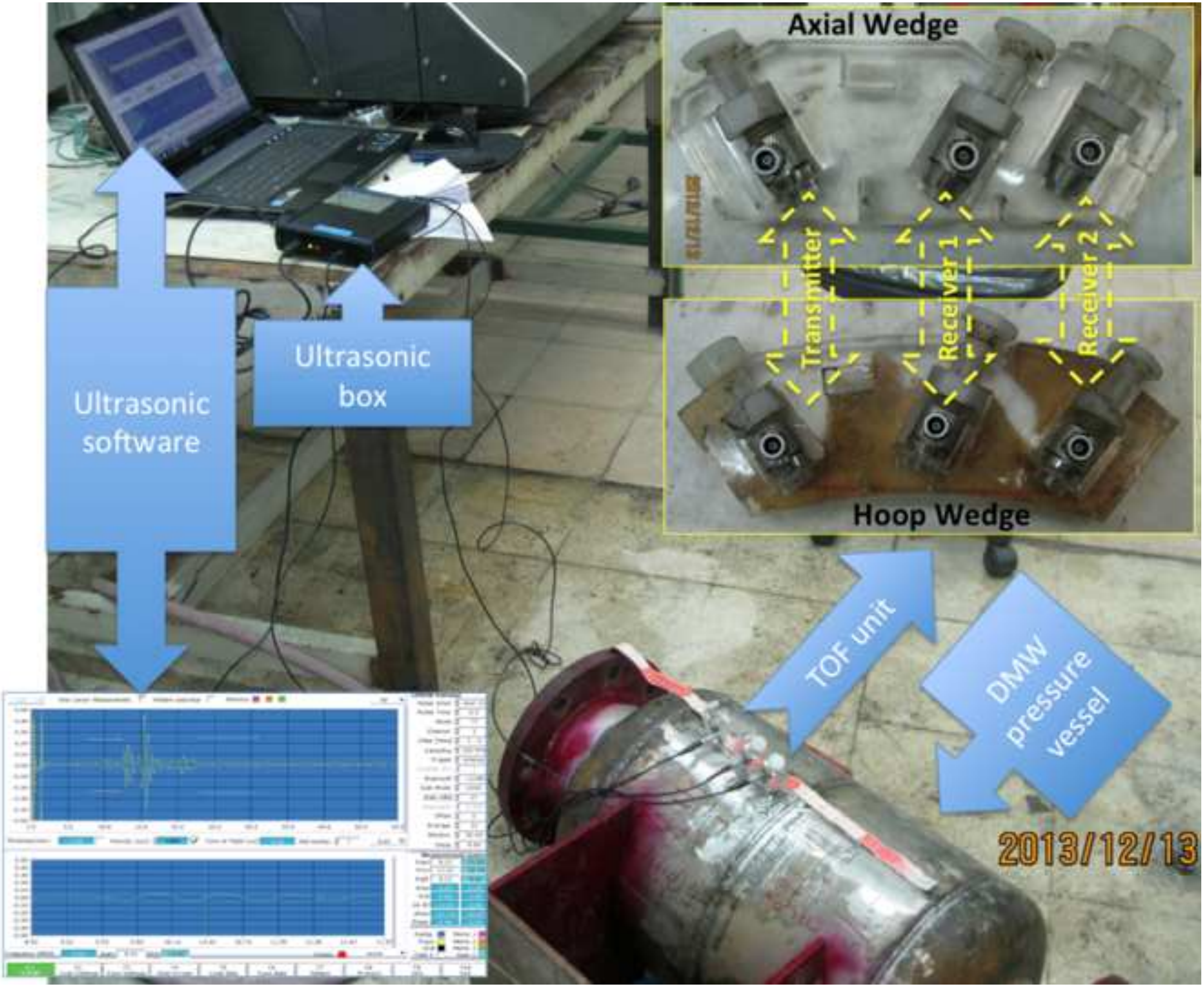

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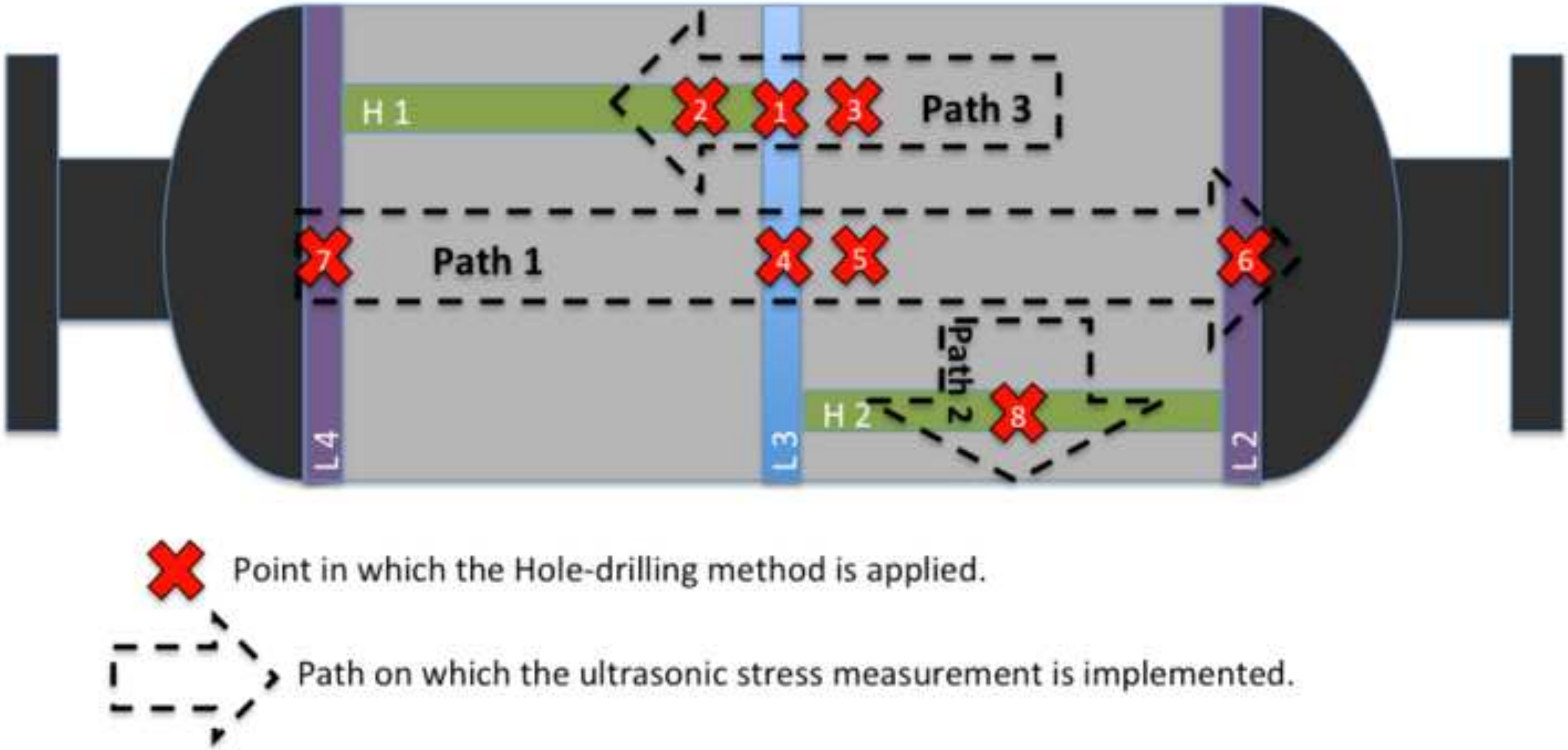

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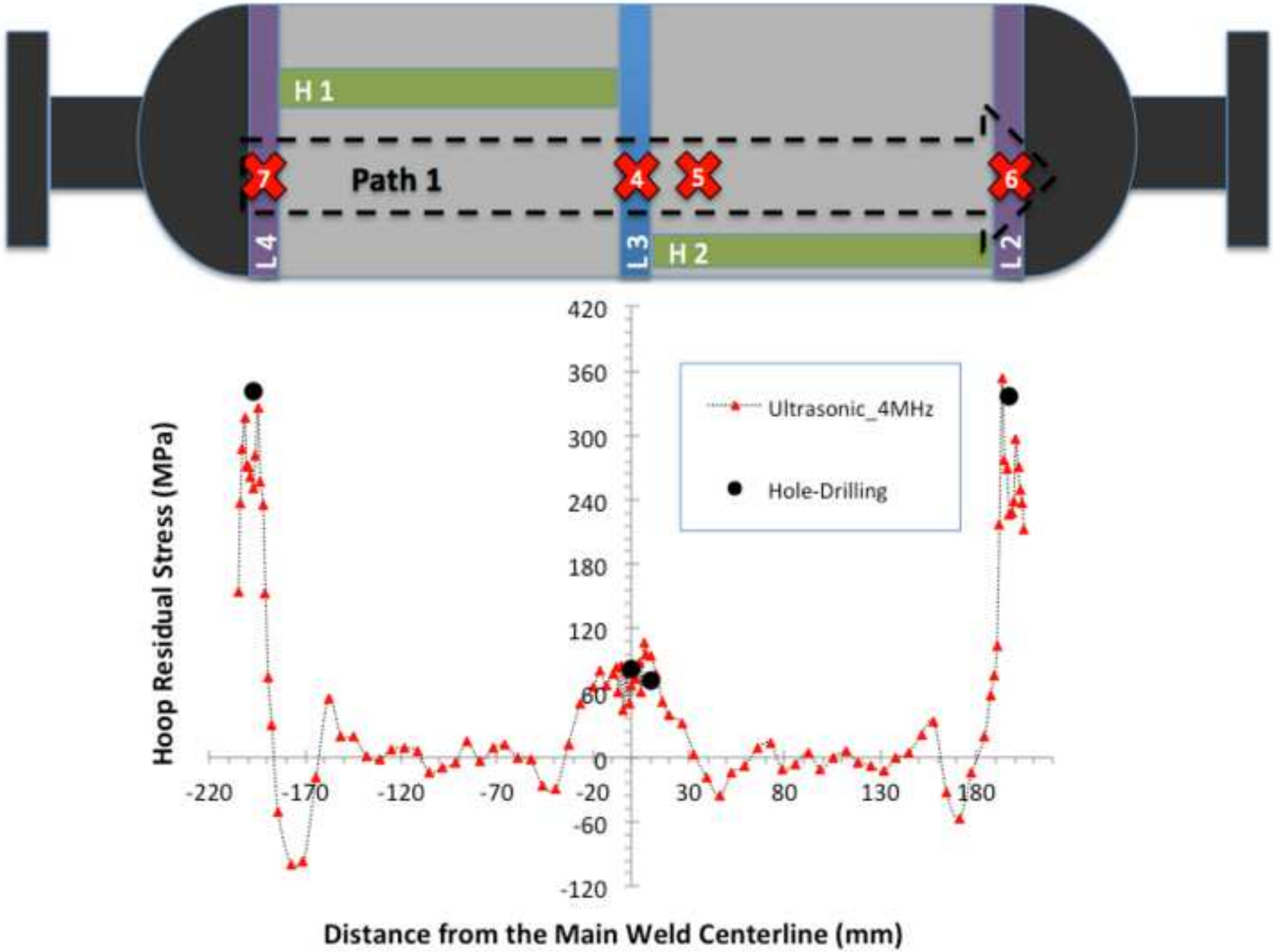

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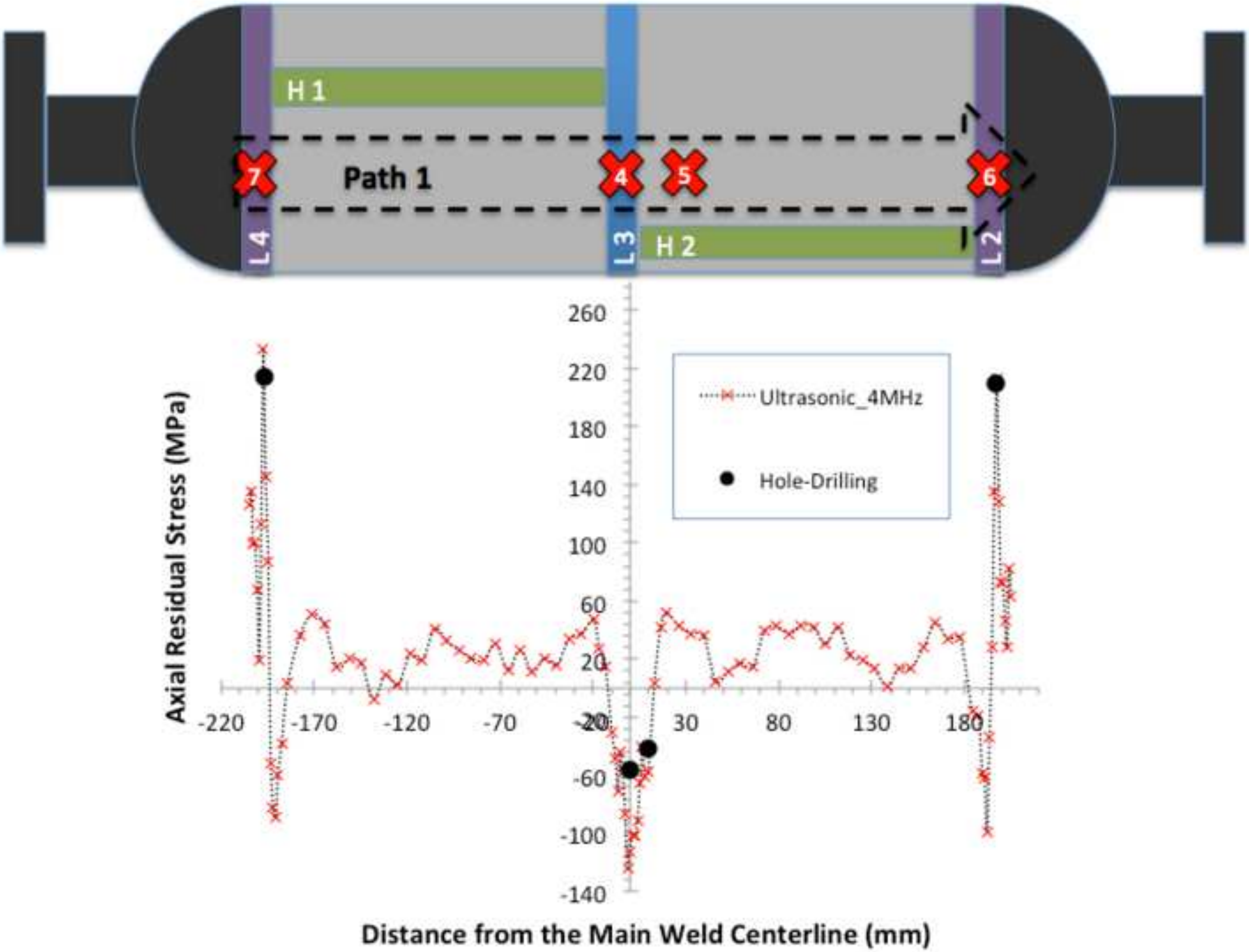

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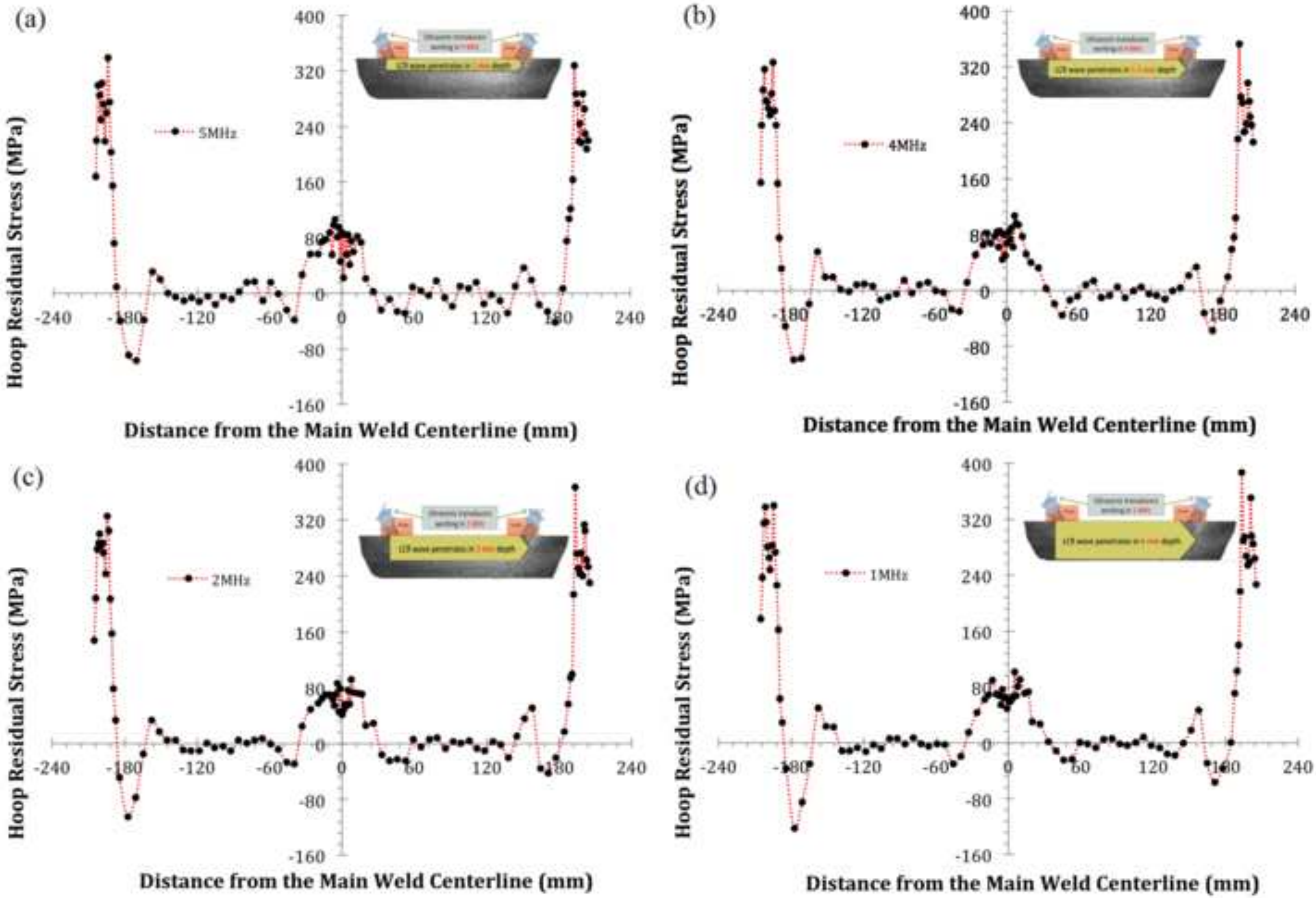

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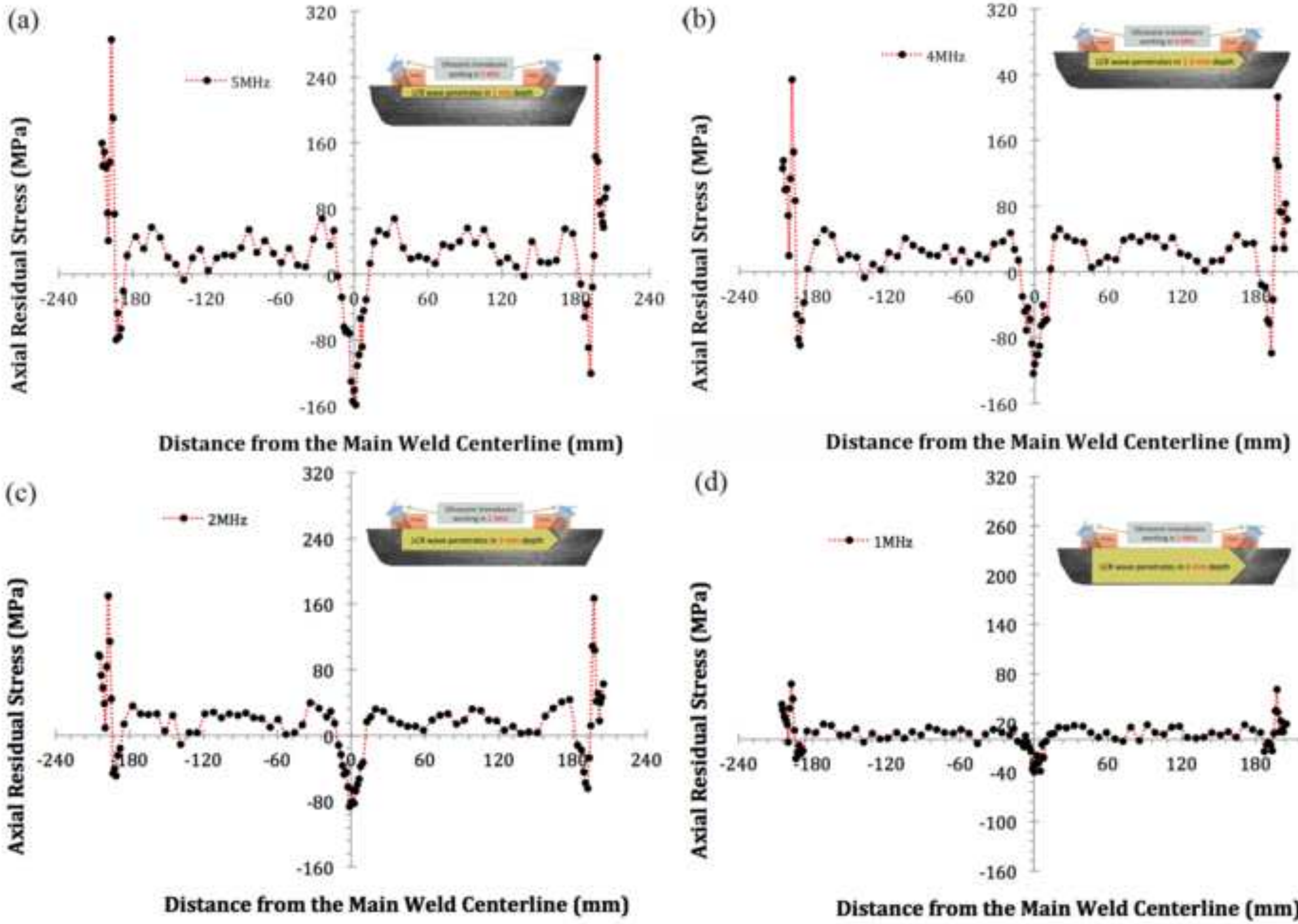

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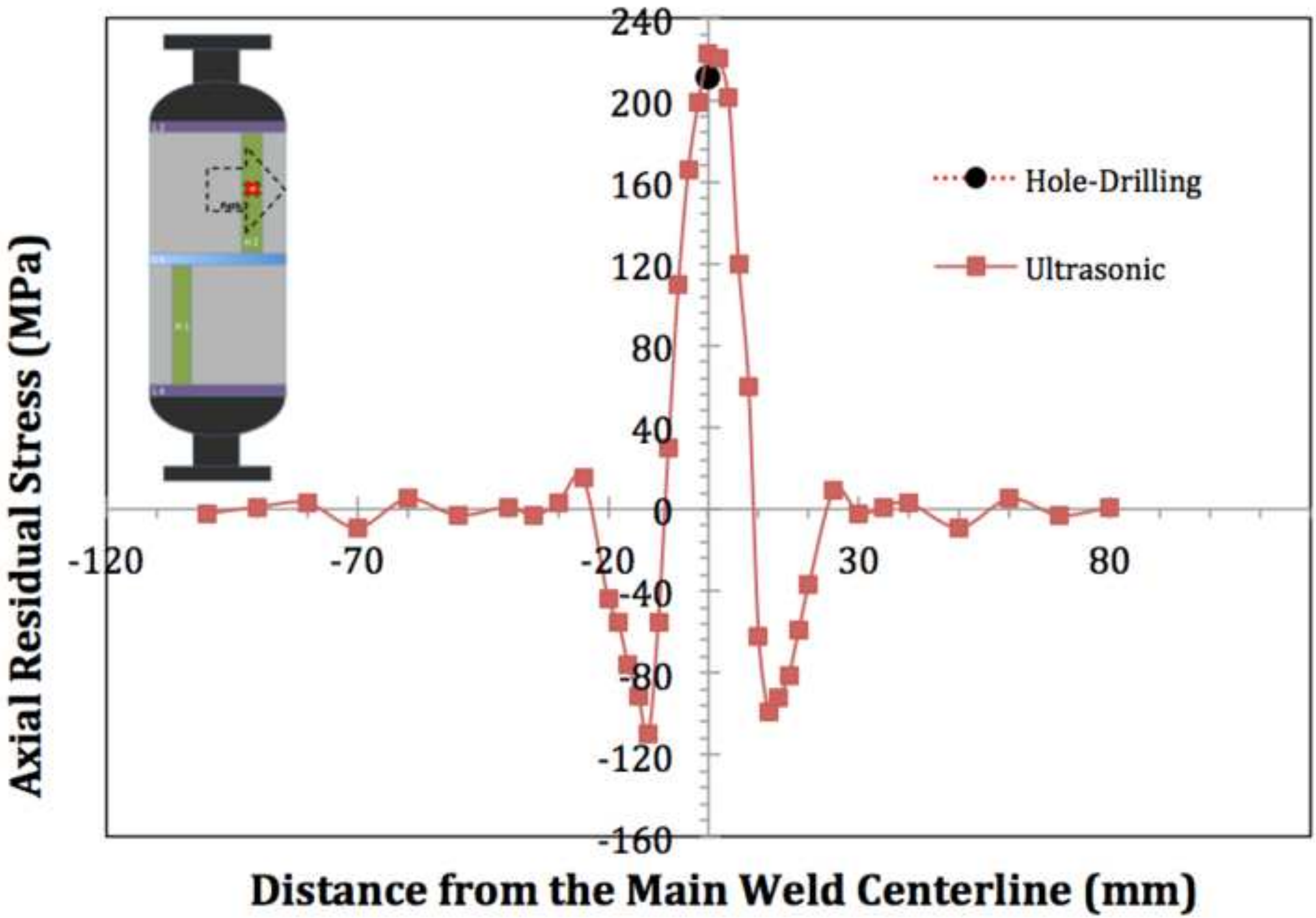

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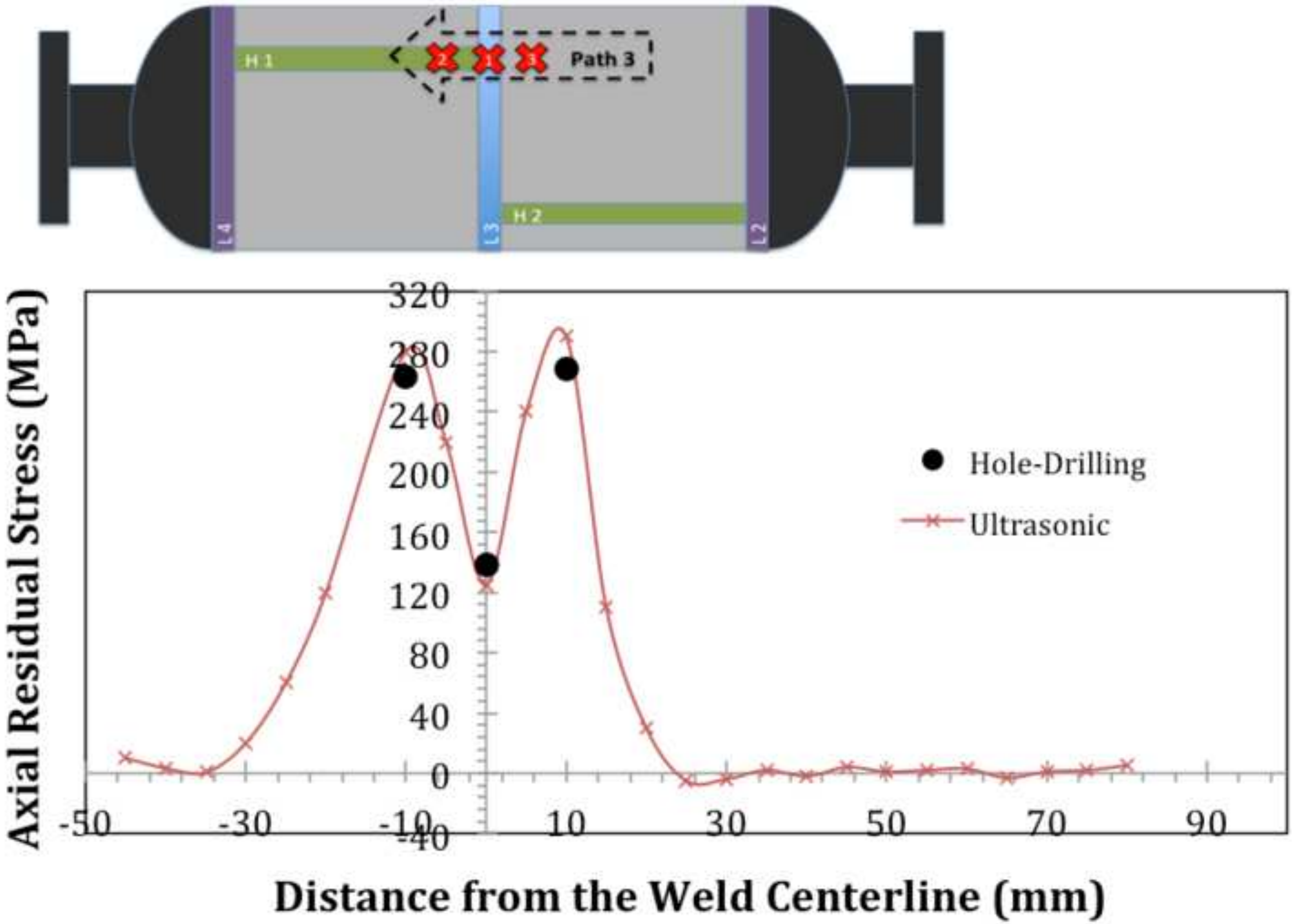

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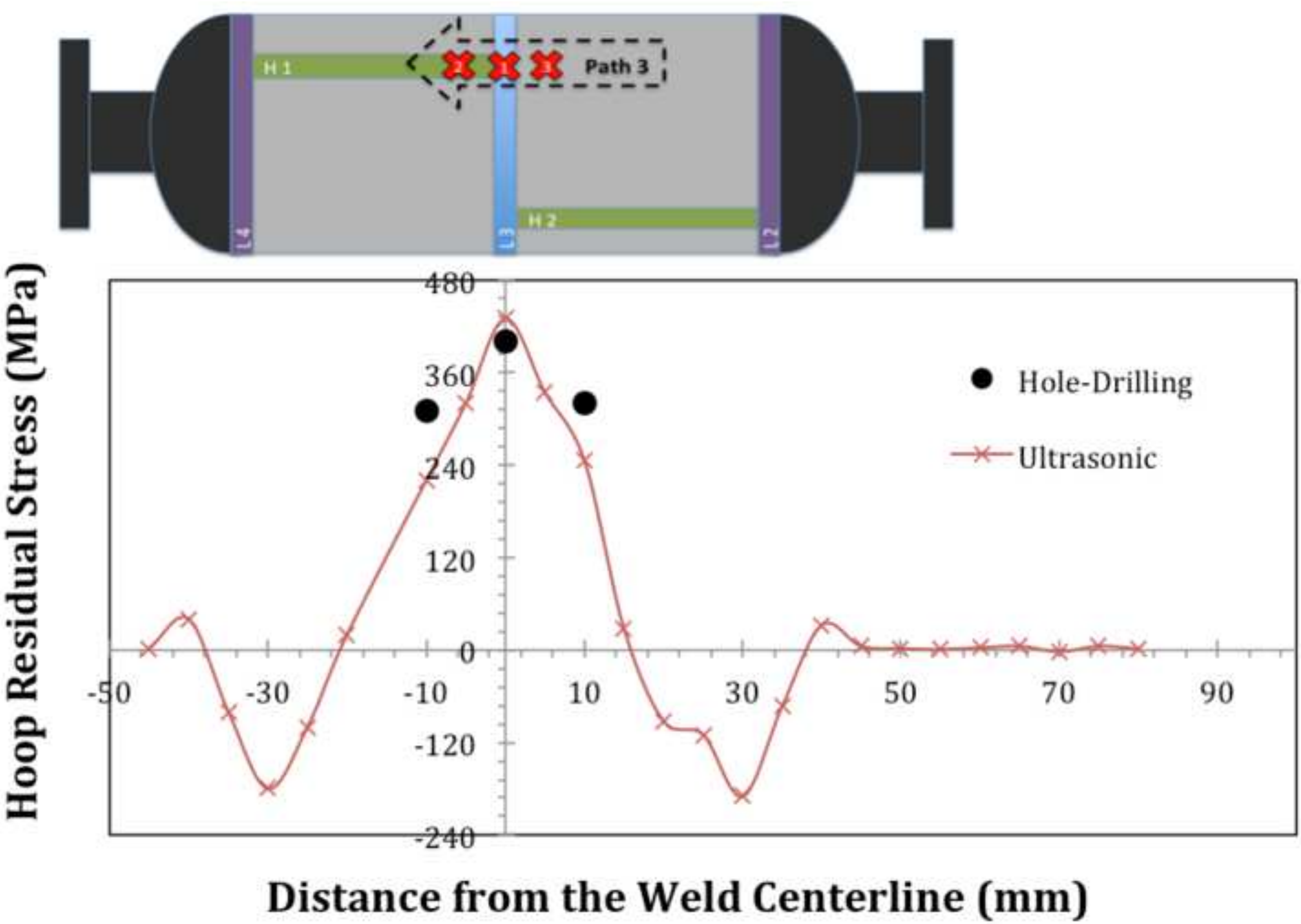

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