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Experimental Investigation into the Effects of Weld Sequence and Fixture on Residual Stresses in Arc Welding Process

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This study concentrates on the effects of weld sequence and welding fixtures on distribution and magnitude of induced arc welding residual stresses built up in butt-joint of Gas Tungsten Arc Welding (GTAW) AA5251 plates. Aluminum plates have been welded under different welding conditions and then, longitudinal and transverse residual stresses were measured in different points of the welded plates employing hole-drilling technique. The results indicate that welding sequence significantly alters the distributions of both longitudinal and transverse residual stresses while the changing in the weld sequence leads to 44% decrease in longitudinal residual stress. Besides, both the geometry of weld pool and distribution of residual stresses are affected by the welding fixtures while implementation of fixture causes about 21 and 76% reductions in the depth of weld pool and transverse residual stress, respectively, for the material and welding conditions used in this research.

Keywords AA 5251, Gas Tungsten Arc Welding (GTAW), residual stress, welding conditions

1. Introduction

Welding processes are widely used in the fabrication of buildings, bridges, ships, oil pipelines, and pressure vessels; however, these processes are often associated with undesirable phenomena such as residual stresses and distortions (Ref 1, 2). Both tensile and compressive residual stresses as well as induced deformations are usually undesirable. Tensile residual stress could contribute to brittle fracture or stress corrosion cracking, and it may even reduce fatigue life of the weldment (Ref 3, 4). On the other hand, compressive residual stress can be harmful for buckling strength of welded beams and thin plate when they are subjected to compressive axial loading (Ref 5). Distortion is also an unwanted phenomenon when it causes joint mismatch, cracking of the weld metal, or changing the final geometry of the welded structure (Ref 6). Residual stresses in welded structures arise because of both structural mismatching and the complex temperature changes during the process. These temperature variations cause transient thermal stresses and strains in regions close to the fusion line, while the thermal stresses are highly dependent on the degree of restraint on the weldment, e.g., the use of external constraints such as fixtures and clamps as well as applying different welding sequences (Ref 7). On the other hand, the problem of welding distortion during large fabrications leads to dimensional inaccuracies and misalignments of structural members, which increases the cost of production and leads to delays. Therefore, the problems of distortion and residual stresses are always of great importance in welding operations. To overcome these problems, it is necessary to understand the conditions that make them less effective such as employing clamps to minimize distortion, and different welding sequences that could alter distribution of residual stresses (Ref 8-10). There are many factors, such as the process type, process parameters, welding sequence, preheat patterns, level of constraint, and joint design, which can affect the distortion of the welded structure and also extent and values of residual stresses. Thus, residual stress and distortion within the weld parts may be controlled by the appropriate selection of the above factors (Ref 11). In this regard, many of recent investigations have been devoted to study temperature and residual stress fields mainly by employing the modeling and simulation techniques. For instance, Teng and Lin (Ref 12) have employed ANSYS software to predict the residual stresses during single-pass arc welding of steel plates while the effects of traveling speed, specimen size, and preheating on residual stresses have also been discussed. In a similar study, Long et al. (Ref 13) have determined distortions and residual stresses induced in butt joint of thin plates during metal inert gas welding using numerical approaches. They have found that the welding speed and plate thickness have considerable effects on welding distortions and residual stresses. In another study, Chang and Teng (Ref 14) have carried out a thermal elastic-plastic analysis using finite element techniques, to analyze the thermo-mechanical behavior and evaluate the residual stresses in butt-welded joints of ASTM A36 steel plate and then verified the model with empirical results. They measured residual stresses at the surface of the weldments using x-ray diffraction. Similarly, Deng and Murakawa (Ref 15) have proposed a three-dimensional model to predict welding distortion and distribution of induced longitudinal and transverse residual stresses in low carbon steels with butt-welded joints.

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Although these theoretical studies have significant role in achieving better understanding of the materials' behavior during welding process and finding a practical solution of difficulties of fusion welding like induced residual stresses however, studying the experimental aspects of these processes can also be useful to provide a realistic point of view. The main aim of this investigation is to study the residual stress distribution of the welded plate as well as to evaluate the effects of welding conditions including weld sequence and utilization of welding fixture on the induced residual stresses values and their extends during arc welding process. Experiments of bead-on-plate GTAW on AA5251 plates have been performed utilizing with and without fixture as well as employing two different welding sequences. Then, residual stresses have been measured by hole-drilling method to determine the distribution of residual stresses in and around the weld line and the base metal. Furthermore, macrographic experiments, and hardness and tensile tests have been performed on the welded samples.

2. Experimental Procedures

The as-received AA5251 plate with the chemical composition listed in Table 1 was cut to obtain the welding samples with dimensions of 200 mm in length, 100 mm in width, and thickness of 2 mm. Then, the samples were first heat treated at 345 °C for 1 hour to perform annealing. Then, the annealed samples were TIG (tungsten inert gas) welded by implementing a semi-automated machine. The welding electrode was made of W-2%Th with 2.4-mm diameter, and high purity (99.99%) argon was used as shielding gas. All the welding experiments were conducted employing 100 A direct constant welding current with electrode negative polarity (DCEN), arc voltage of 14.5 V, and torch speed of 12.5 mm/s along the fusion line, while the y-axis direction was taken as the welding direction or the longitudinal direction. However, with the purpose of investigating the effects of different weld sequence and implementation of fixtures on the arc welding residual stress induced, both longitudinal and transverse ones under four different welding layouts have been considered and measured experimentally. Figure 1(a) shows that the first working condition was the common welding program as the weld torch moves straight from one edge to another side. The other welding condition is shown in Fig. 1(b) where the welding fixture was used to prevent distortion of the welded plate. A two-step welding sequence was employed in the third working condition as shown in Fig. 1(b), and in the last welding experiment, two-step weld sequence together with welding fixture were used. It should be noted that the residual stress measurements of the welded plate have been made at the positions of $y = 100$ mm and $y = 133$ mm, as displayed in Fig. 1(a). Hole-drilling method according to ASTM E837 was utilized to experimentally measure both the longitudinal and transverse stresses within the welded plates. The points for residual stress measurements were located along a perpendicular line to the weld line as displayed in Fig. 1(a). In order to study the differences between weld pool shapes of these four welding conditions, macroscopic observations have also been conducted. After the process, the welded samples were sectioned normal to the welding direction and then prepared by grinding disks, polished and finally etched with a modified Poulton's reagent with the composition of 75 mL HCl (38%), 25 mL HNO_3 (70%), 5 mL HF (40%), and 25 mL distilled water. Furthermore, in order to determine the effects of residual stresses on the mechanical properties of the welded samples, tensile and hardness tests have been carried out. The tensile test specimens in accordance with ASTM E8M were prepared from the regions with 8-mm distance from fusion line. Tensile tests were carried out at room temperature with mean strain rate of 10^{-3} s^{-1} utilizing an INSTRON machine. The hardness tests along the weldment cross section were also performed at the position of $y = 133$ mm with applying 0.5 kgf and holding time of 20 s.

Table 1 The chemical composition of the employed aluminum alloy

Elements	Al	Mg	Mn	Fe	Si
wt.%	Balance	2.1	0.24	0.35	0.1

3. Results and Discussions

The variations of longitudinal and transverse residual stresses versus transverse distance from weld line after the first welding program at two different positions are demonstrated in Fig. 2. It is observed that the distributions of longitudinal and transverse stresses are almost similar. However, the residual stress values at mid-length of the plate are higher than those at the position of $y = 133$ mm. As the arc moves forward to the end of the plate, the workpiece becomes warmer, leading to lower temperature gradients inside the weld sample (Ref 16). As a result, the amount of thermal stresses is reduced, and it may result in reduction in thermal stresses as well as residual stresses values. It is found that the longitudinal residual stress at $y = 133$ mm is about 27% smaller than that at $y = 100$ mm and the longitudinal residual stresses in regions close to fusion line are tensile while by moving from the weld line toward the free edge of the plate, theses stresses decrease to zero and after that, as it is expected because of the fact that residual stresses are supposed to be self-balancing within the bulk, longitudinal stresses become compressive in regions far away from the weld line. In other words, tensile stresses are generated on the weld line and its vicinity and they are balanced by compressive residual stresses on the zones far from the fusion line. This trend in longitudinal residual stress has been reported by Long et al. (Ref 13) and Chang and Teng (Ref 14), in which they have employed simulation of butt-welded plate. The heat transfer during welding can also influence the weld pool shape, and its size. The macro-examination study of the melt pools may be useful tool to have a viewpoint of heat transfer during the process. In this regard, macrographs of the weld in cross section were made to measure the weld dimensions. The depth and width of fusion pool measured for the first welding program is displayed in Fig. 3.

The previous researchers have shown that in bead-on-plate typical welding condition, the longitudinal component is often much higher than the transverse one and its maximum can be as high as the yield stress of the material. That is because of the existing sharper temperature gradient along the welding direction than along the perpendicular to the weld line. On the other hand, as demonstrated in Fig. 4(a), by applying the

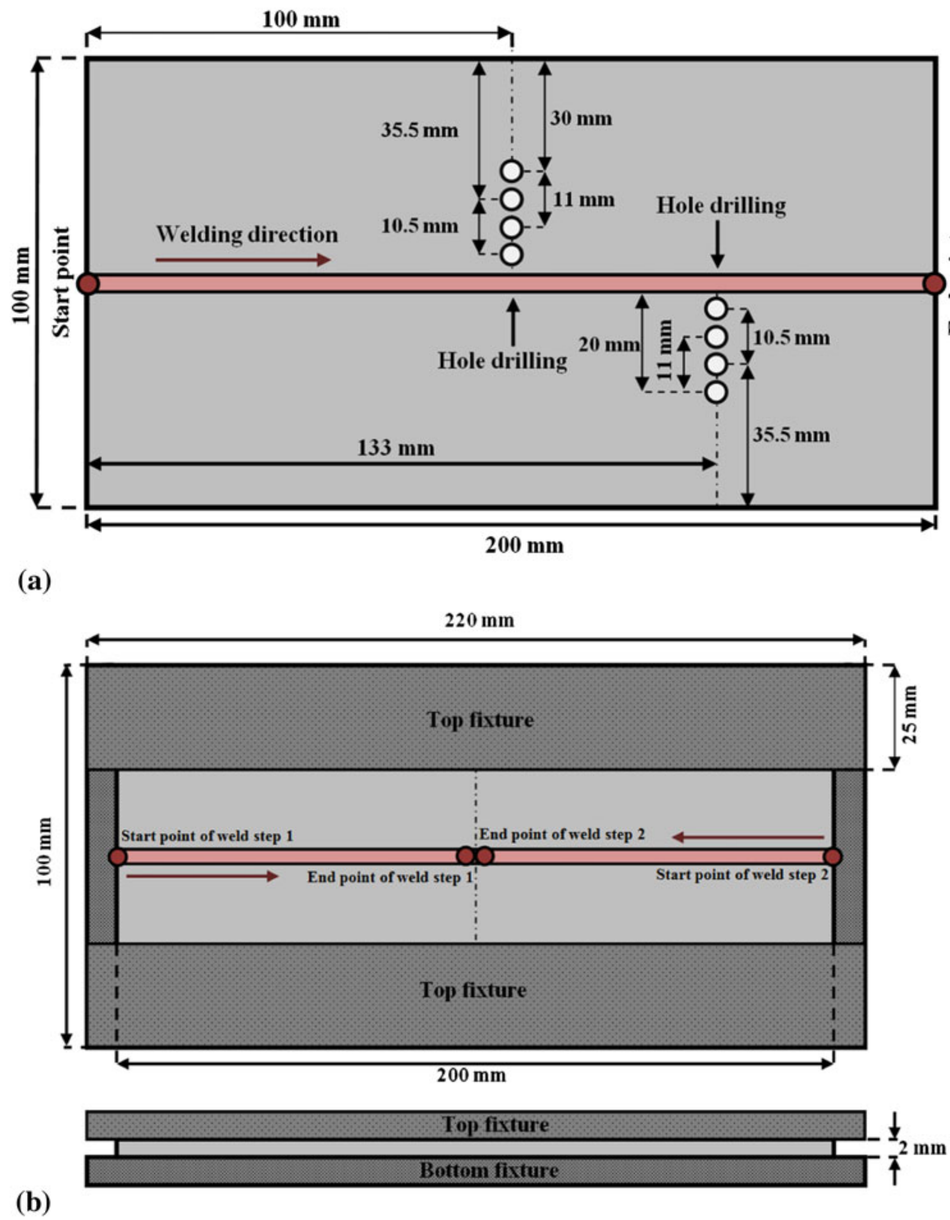

Fig. 1 Schematic presentations of (a) the ordinary welding condition and positions of residual stress measurements and (b) the implementation of fixture and also applying different weld sequence

welding fixture on the plate during welding, the distribution and magnitudes of longitudinal residual stress changes significantly. It should be mentioned that the residual stresses are the elastic ones, and they are induced inside the welded plate because of thermal stresses and non-uniform plastic deformation of the plate. Therefore, because the constraint minimizes the deformation and also it affects the temperature distribution within the plate being welded as a result, utilization of welding fixture causes the lower residual stress. Conversely, as shown in Fig. 4(b), distribution of transverse stress does not vary considerably in case of fixing the welding plate; however, the magnitudes of transverse residual stresses increase considerably. Macrograph of the weld pool under the second welding conditions is shown in Fig. 5. Utilizing the fixture contributed to about 21% reduction in the depth of weld pool as comparing Fig. 3 and 5. It is because the fixtures act as heat sinks throughout the welding. As shown in these figures, obviously there is no difference between the widths of weld pools in the two weld conditions. Also, through careful observation of the result provided in Fig. 4, it can be found that employment of fixture leads to about 76% increase in the transverse residual stress. Moreover, it leads to change significantly the distribution of longitudinal residual stress. In other words, maximum longitudinal stress, which was induced at about 8 mm from weld line, has been changed to minimum longitudinal residual stress in the case of the second welding program, wherein the welding fixtures have been used. It is noted that this variation in location of tensile residual stress could be useful for designing structures in view of fatigue strength and/or stress corrosion cracking. As demonstrated in this investigation as well as the study conducted by Cheng (Ref 2), the magnitude of tensile residual stresses at the weldment and adjacent zones is slightly larger than the yield stress of the parent material that is 80 MPa at room temperature. It should be noted that the stress state in

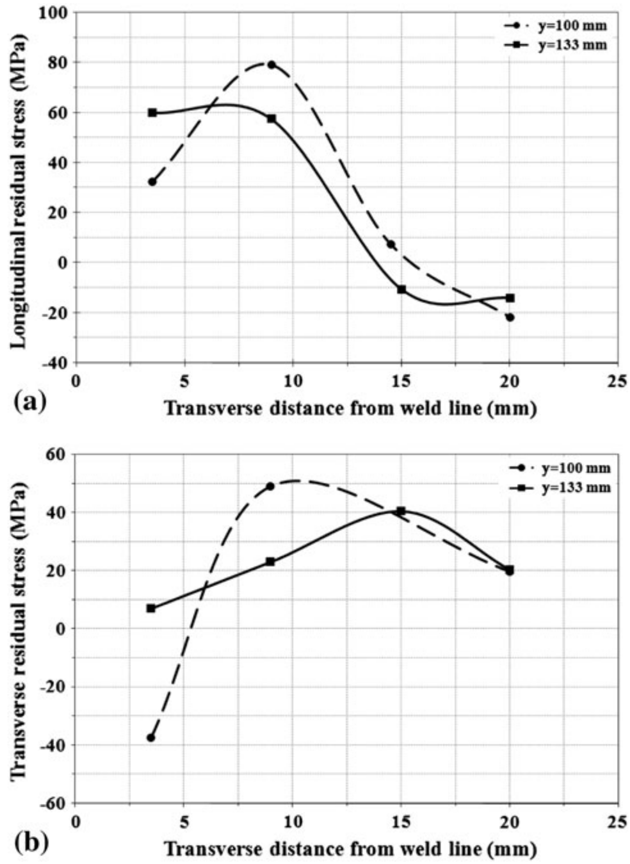

Fig. 2 Variation of residual stresses at different positions: (a) longitudinal stress and (b) transverse stress

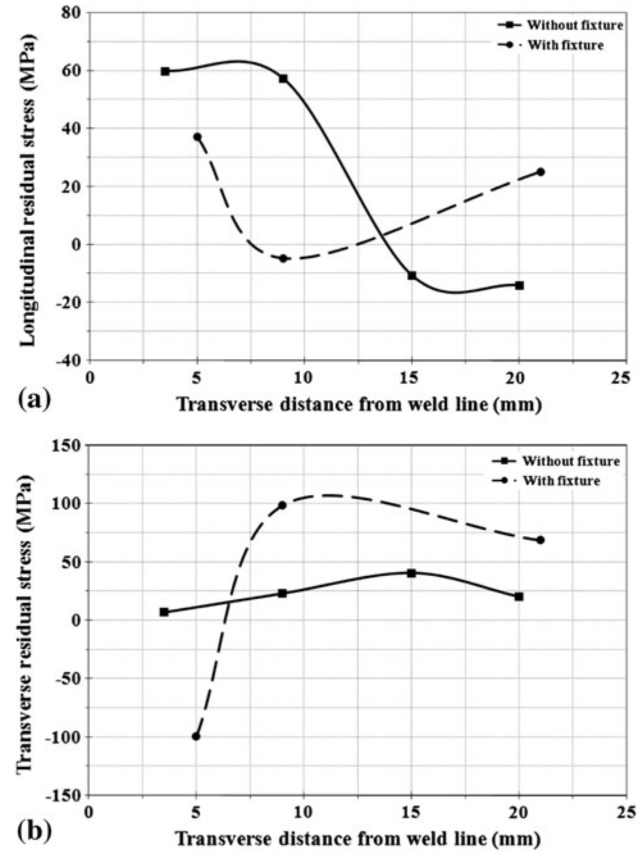

Fig. 4 Effect of welding fixture on residual stresses at the position of $y = 133$ mm: (a) longitudinal residual stress and (b) transverse residual stress

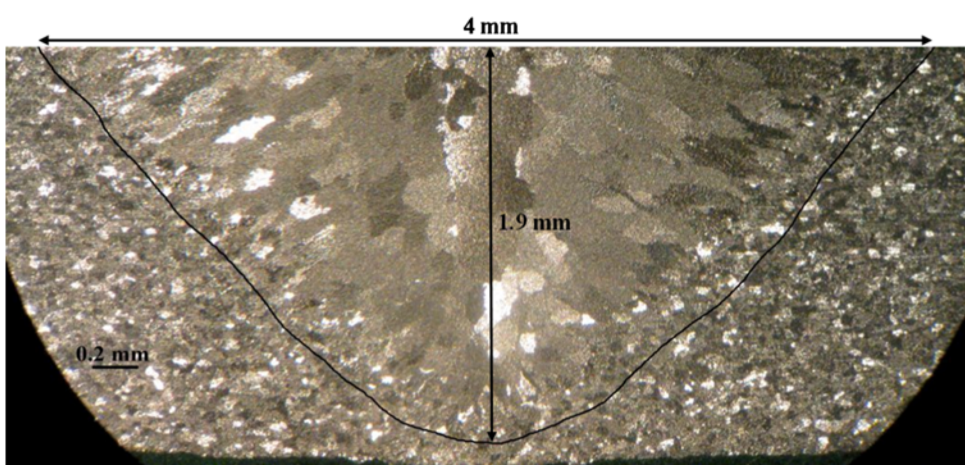

Fig. 3 Weld pool geometry under the first welding layout at the position of $y = 100$ mm

the plate is two-dimensional and thus, the effective stress not the longitudinal component should be compared with the yield stress. Therefore, the maximum value of the longitudinal residual stress could be greater than 80 MPa as displayed in Fig. 4(b), however; the effective stress is still lower than the yield stress regarding Mises-Hencky yielding criterion. Figure 6 also compares the stress-strain diagrams of the base metal and the welded material under the first welding layout. It is seen that the flow stress of the welded alloy is slightly higher than the base metal while a different result is usually expected because of grain growth in HAZ during and after welding process. This behavior may be attributed to the existence of residual stresses particularly tensile transverse residual stresses within the welded sample and their effects on initial yielding as well as on the flow stress. It is interesting to note that serrated flow is not observed compared to the flow

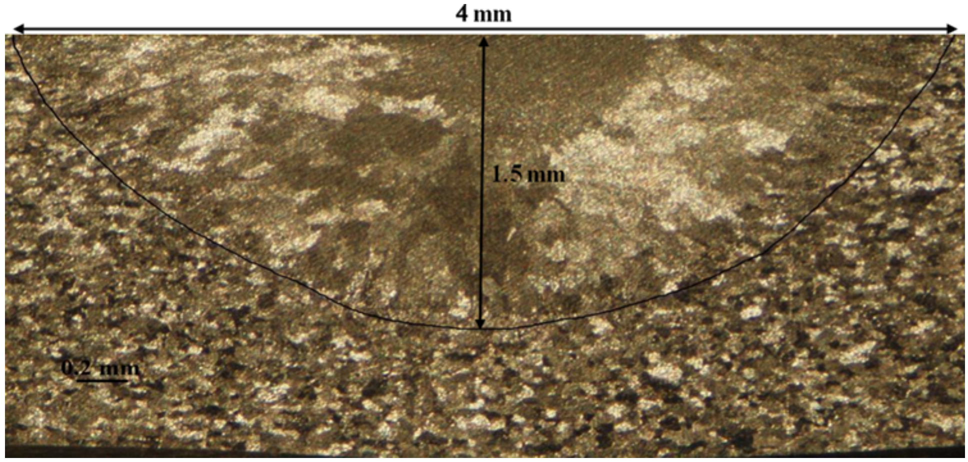

Fig. 5 Macrograph of weld pool at the position of y = 100 mm under the second welding layout

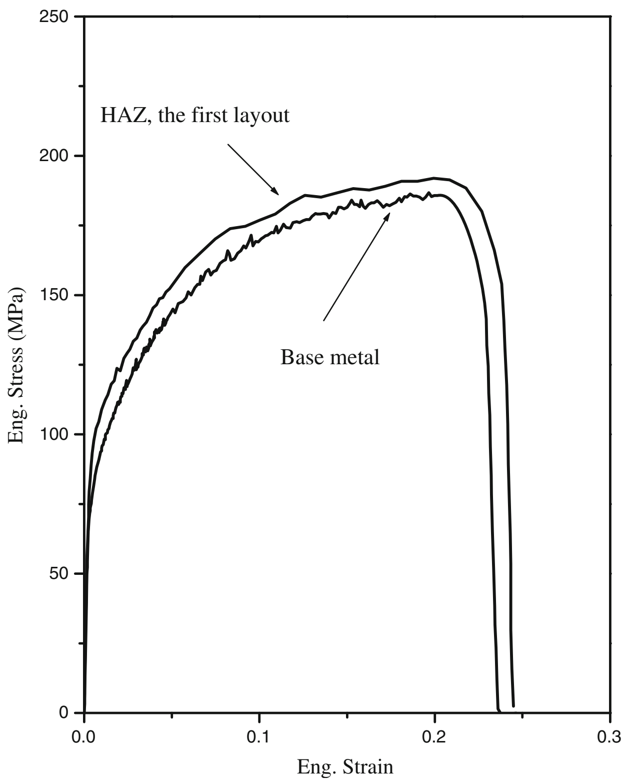

Fig. 6 Stress vs. strain curves of annealed and welded specimens under the first welding condition

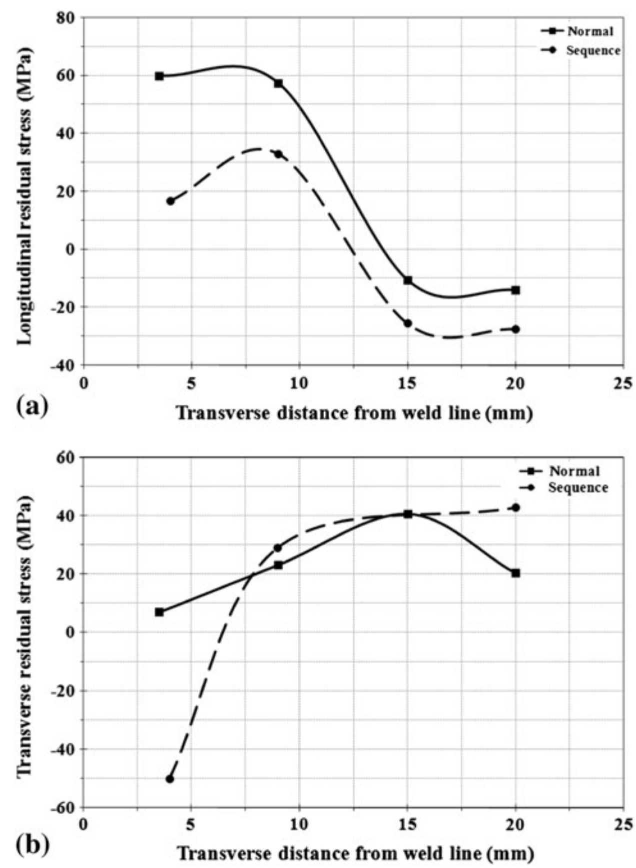

Fig. 7 Effect of different weld sequences on distribution and magnitudes of residual stresses at the position of y = 133 mm: (a) longitudinal stress and (b) transverse stress

stress behavior of the base metal, which may be attributed to the result of hydrostatic residual stresses on Portevin-le Chatelier effect (Ref 17) and/or formation of magnesium-rich precipitates during welding thermal cycle.

Another practical solution to reduce residual stress values and its distribution within the welded structures, is applying different welding sequence during the process. The comparison between two welding conditions, the first and the third welding layouts, in terms of longitudinal and transverse residual stresses are shown in Fig. 7. It can be observed that the distribution and values of transverse stresses are approximately the same for both conditions but the main point is longitudinal ones. The second welding sequence has caused substantial reduction in longitudinal residual stresses approximately by 44%. The influence of weld sequence on the plate deformation is also shown in Fig. 8(a) and (b) in which, the first figure shows distortion of the welded sample under the common welding conditions and the other one is the welded plate with applying the sequence, i.e., the third welding layout. Welding distortion is the result of induced stresses during process, and, as a

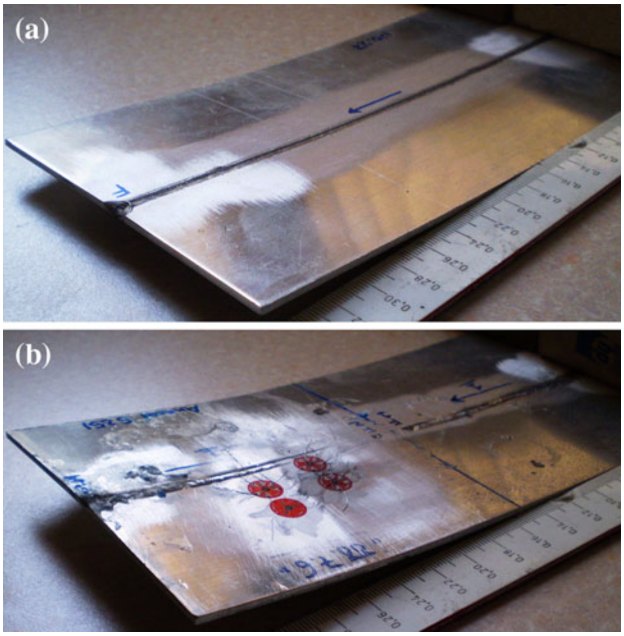

Fig. 8 Distortion of the welded plates: (a) the first weld layout and (b) the third welding layout

sequence, has changed the stress profile, and so it is obvious that the sequence could also change the deformation of the welded plate. As was mentioned above, the weld sequence causes reduction in the longitudinal residual stress, which is considered as the main stress component in the structural analysis of weld plates. On other hand, the utilization of weld sequence has caused higher level of distortion of the plate under the employed conditions as shown in Fig. 8(b).

Figure 9 compares residual stress distributions for the third and the fourth welding layouts used in this study. As the longitudinal residual stress is demonstrated in Fig. 9(a), utilization of both weld sequence and welding fixture (the fourth welding program) leads to different distribution of longitudinal stress within the welded plate rather than its normal extent which is explained earlier while about 78% decrease in magnitude of longitudinal stress is observed. Figure 9(b) shows transverse residual stress under the above-mentioned welding conditions. It is seen that for the forth layout where both welding fixture and sequence are employed, the larger transverse stresses are even produced comparing the longitudinal ones unlike the typical trend expected in normal welding conditions.

In case of mechanical properties of welded samples with different welding conditions, experimental tests have shown that the properties of weldment change as applying different welding conditions. Figure 10(a)-(d) display the variations in hardness of cross-sections of different samples at the position of $y = 133$ mm. It is found the hardness of HAZ particularly for the first and the third samples is higher than those for base metals, similar the data achieved from stress-strain diagrams. Normally the hardness of HAZ is expected to be lower than the hardness of other zones because the heat transfer from the weld pool through the plate causes grain coarsening in this region, and consequently it lowers the yield stress as well as the hardness. However, this phenomenon may be associated with existence of induced welding residual stress at these positions. Comparing between hardness profiles of normal condition and

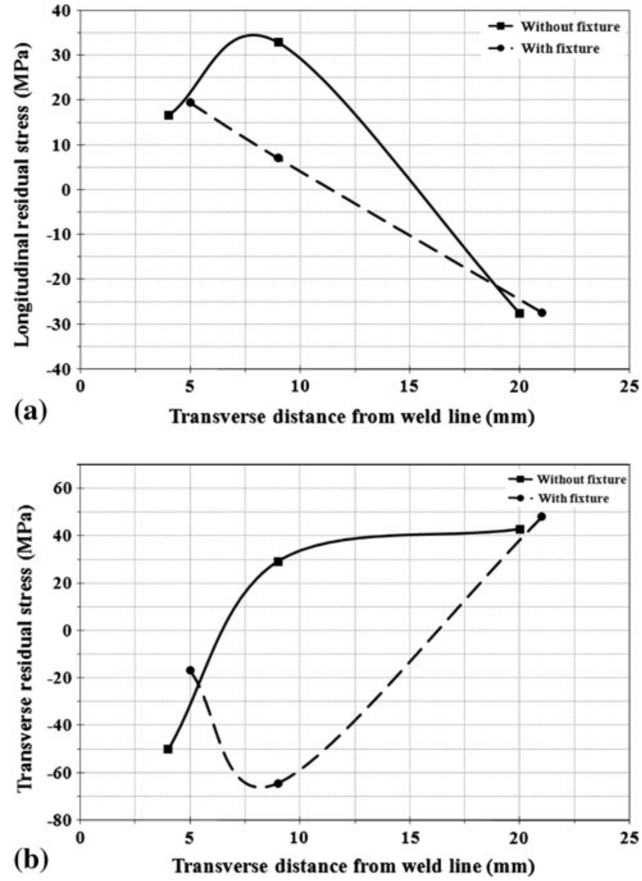

Fig. 9 Variation of residual stress values and their distribution with employing fixture and applying two different welding sequences at the position of $y = 133$ mm: (a) longitudinal stress and (b) transverse stress

sequence one, the first and the second programs, it can be realized that there is no difference between hardness values, but some disparities could be seen in their hardness distribution. By looking through Fig. 10(a) and (b), effects of different weld conditions can be shown clearly, because implementing fixture acts as heat sinks, and therefore the areas, which affected by welding heat input become smaller as displayed in Fig. 5. On the other hand, minor grain coarsening happens in HAZ as well as the weld pool solidifies faster and as a result it leads to higher hardness regarding Hall-Petch equation. The same behavior has been observed in comparing Fig. 10(c), sequence welding, and Fig. 10(d), welding with fixture and applying sequence. Similarly, the difference in values and distribution of hardness as shown in Fig. 10(c) and (d) may be attributed to the effect of welding fixtures acting as heat sink.

It should be noted that utilization of welding sequences and constraints, all depend on the desired the microstructures and the weld geometry. Sometimes it is impossible to use constraint or welding fixture to reduce the deformation, so different weld sequence should be applied, while in other welding cases, in which the microstructures and grain size are the important factors, it should be considered that the different sequence could act as preheating or post heating for other welding regions affecting the microstructures of HAZ as well as weld regions. For complex geometries, most of the time it is so sophisticated to design an appropriate welding fixture, so it is preferable to apply different welding sequences in terms

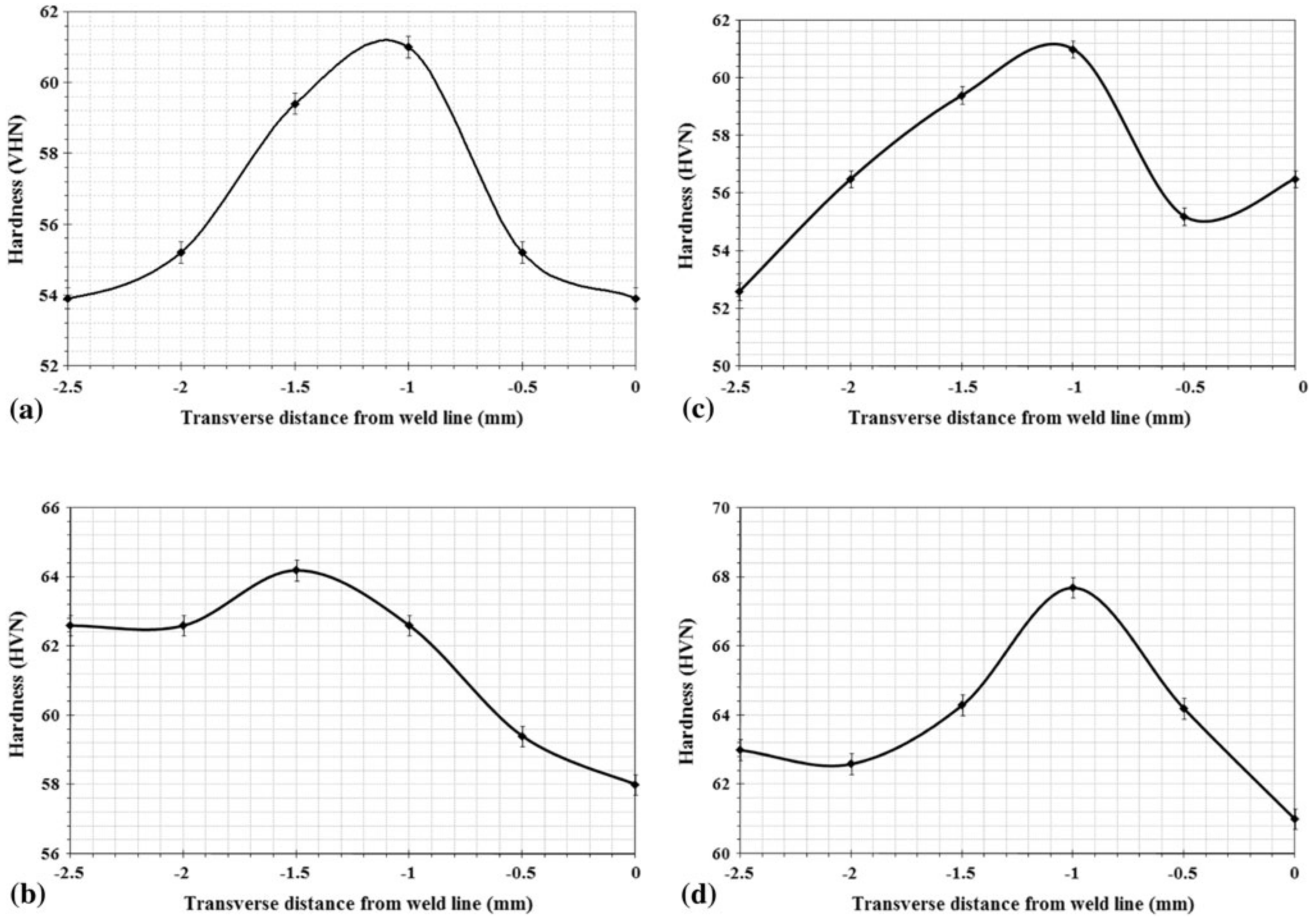

Fig. 10 Hardness variation from fusion zone to base metal for different weld layout: (a) The first welding layout, (b) the second welding layout, (c) the third welding layout, and (d) the forth welding layout

of welding direction and weld passes, but in each case understanding of how residual stress will distribute and how much the structure will deform could be a positive point to evaluate the material responses under different working conditions. Therefore, this kind of studies should be conducted in each case, which could be completely experimental and/or numerical investigation. However, it should be highlighted that the achieved results in this study, can give a reasonable initial estimation of distribution and values of residual stresses and therefore, can be used as a guide line in designing an appropriative welding program.

4. Conclusions

In this study, the experiments were conducted to investigate effects of welding fixture and weld sequences on residual stress distribution within the welded plate and the resulting mechanical properties of the welded region. It is found that the distribution of residual stresses are differently distributed along the welding direction, for instance, the longitudinal stress under the first welding program decreases about 27% by moving from $y = 100$ mm to $y = 133$ mm. Besides, it is observed that application of both fixture and weld sequence have a significant impact on distribution and values of longitudinal and transverse residual stresses. The implementation of welding fixture causes substantial changes in the distribution of residual stress as well as increases the maximum transverse stress about 76% while it decreases the longitudinal residual stresses. Furthermore, the geometry of the weld pool changes when the welding fixture is used, and it caused about 21% decrease in the depth of the weld pool for the welding conditions used in this research.

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