Developing heat sink method in gas metal arc welding to minimize distortion

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Abstract. Efforts to minimize distortion of welding results need to be done, considering that it can reduce the accuracy of the weld dimensions, increase the repair process, and increase the production costs. This study aims to reduce distortion by the heat sink (HZ) method and its effect on mechanical properties. The heat sink method was applied in conjunction with Gas Metal Arc Welding (GMAW) process by liquid nitrogen coolant with a variable of the HZ’s contact area. The HZ areas of contact were designed in 3 dimensions, namely 10 L, 20 L, and 30 L, and it was placed on the surface of the plate with 10 mm space from the welding line. The results show that the surface area in contact with the coolant affects the quality of the welding joint. Based on visual tests, the greater the HZ’s contact area, the greater the defected impacts due to the lack of penetration. Besides, the greater the surface area of the HZ, the more effective it is to minimize welding distortion, especially the distortion in the longitudinal direction. The HZ contact area has somewhat little influence on the hardness and microstructure of the weld metal (WM) and heat affected zone (HAZ), but probably does not affect the tensile strength of the welding joint.

1. Introduction

Welding is a material-joining technique widely used in various manufacturing industries, such as automotive, shipping, airplanes, trains, and so on. The welding has been preferred as a joining technique as it has various advantages including saving production costs, precision of measurements, and the adjustable shape of the structure. In addition to these advantages, adverse side effects of this welding technique result in welding distortion, decreased strength and toughness, increased residual stress, and changes in microstructure [1].

Distortion is a change in shape due to local heating in the weld, while residual stress is the stress on the material after the outside stress has been removed. Distortion and residual stresses are interrelated and have unexpected effects on welding, but these effects are unavoidable. These effects are actually detrimental because the shape may not fit the design, have inaccurate size, lead to big repair costs, and damage earlier due to residual stress. Conrardy, et al. states that plate welding tends to be easily distorted [2], and severe distortion of the plate affects the welding repair cost [3]. Distortion and residual stress problems also occur in welding projects of the state-owned train manufacturing company PT. INKA Madiun, East Java, and state-owned shipbuilder PT. PAL Surabaya, Central Java, Indonesia. In PT. INKA applying the GMAW on the train wagon welding, there exist some distortions between the thin wall plate and the door frame. Welding products at PT. PAL are distorted as well especially in the joints between the stiffeners and thin plates of the ship's wall. Attempts have
been made to correct the distortion on the thin plates by reforming techniques. However, this process has several disadvantages including the addition of acetylene oxy welding equipment, water pumps, and the extra time and energy for completing the product [4].

Efforts to minimize welding distortion have been carried out by researchers, among others, by computer simulation methods and experimental methods. The experimental method carried out is to give additional treatment to welding by giving mechanical treatment or thermal treatment. Thermal treatment by the HZ method was investigated by water cooling through pressurized pipes [5] and liquid nitrogen cooling through the nozzle burst on multi-pass welding [6] [7] with the result that out of plane distortion can be reduced but not significantly. The residual stress of the weld was successfully reduced significantly in the weld metal area.

As these welding problems which cause high cost of fabrication, research on welding needs to be carried out to reduce or eliminate welding distortion and residual stress effectively. The HZ method is a relatively new method of welding which seems quite effective in reducing welding residual stress and easily applied in the welding process but the reduction in distortion is still not optimal. Driven by this, the current research developed an HZ method by modifying the area of the cooling contact so as to minimize the level of distortion and residual stress without reducing the welding quality.

2. Methods

The work piece uses an A36 low carbon steel plate with a thickness of 4 mm. Before the welding process is carried out, the work piece is cut to a size of 400 mm x 100 mm, and a V groove is made with a 60 degree groove angle. Before welding, both ends of the plate are tack welded on a completely flat surface.

Gas metal arc welding (GMAW) is used to weld work pieces that are operated automatically by a welding rig. Besides, the welding electrodes use ER70S-6 type electrodes with 0.8 mm diameter. The GMAW parameters used in this study were 145A current, 23Volts voltage, 3.94 mm/sec welding speed, 135 mm/sec wire feed, and 5 liters/minute of gas discharge. This parameter is based on the previous research which states that the optimal welding heat input on a 4 mm thick carbon steel plate is 756 J/mm [7].

The HZ method is applied in conjunction with the welding process. The HZ’s that function as a heat absorber are placed on both sides of the welding line which is 10 mm from the welding center as shown in Figure 1. The HZ was made of steel filled with liquid nitrogen which is a cryogenic liquid with a melting point of -196 ºC. Liquid nitrogen was chosen as a cooling medium based on the research of Kala et al. [6] who suggest that the HZ with liquid nitrogen bursts is effective in reducing residual stress and distortion. The HZ is designed with 3 different sizes of contact areas to get the best size. Henceforth, the three HZ designs are referred to as HZ 10, HZ 20, and HZ 30.

1) Design 1 size 10 x L = 10 L (mm2), with L = length of the welding line
2) Design 2 size 20 x L = 20 L (mm2), with L = length of the welding line
3) Design 3 size 30 x L = 30 L (mm2), with L = length of the welding line

![Figure 1. The position of the heat sink in the welding process](image-url)

The steps of experimental procedure are: (1) Weighing 3 kg of aluminium, melted, and let it solidify in the crucible pot; (2) Warmed up the furnace up to 30-40 ºC and placed pot support; (3) Heating the aluminium that had been prepared in the first step until it melt; (4) Measure the temperature changes on
aluminium surface and at inside wall of pot. Temperature changes of inside pot was measured at 25, 85, and 150 mm from top side. The aluminium surface 185 mm from top side of pot. The temperature was measured every 5 minutes using infrared thermometer Krisbow KW06-409 until the aluminium melted.

(5) Repeat the steps above for other pot support variation.

Visual inspection of welding under the study was done by a welding gauge on the surface of the cover pass and root pass. Based on the results of such visual observations, a cross check with the acceptance criteria of the visual test standardized by the American Welding Society (AWS) was done. Distortion measurements were carried out through the fixed point method using a dial indicator, with an accuracy level of 0.01 mm. A dial indicator was placed on the surface of the work piece and measured along the welding line at 20 mm intervals. The bending test was carried out by a Universal Testing Machine (UTM) until the test specimen forms a “U” with a minimum angle of 120°. The bending test breakout was verified by measuring the crack lines on the curve of the test object according to the American Standard Testing and Material (ASTM) bending test standards. The tensile test was carried out on the transverse welding joint test specimen with the Universal Testing Machine’s (UTM) ASTM E-8 standards [8]. In addition to that, hardness test was done by using Vickers hardness test with a load of 500 grf so as to obtain the distribution of hardness in the welding area, HAZ, and the base metal. Microstructure observations were carried out by an optical microscope with a 100X magnification of objective lens.

3. Result and Discussion

3.1. Distortion Test

The welding distortion test was carried out by utilizing a dial indicator measuring instrument with an accuracy level of 0.01 mm. It was carried out along the welding line or longitudinal distortion. Welding distortion was investigated on the 4 welding plates, respectively: non-HZ, HZ 10, HZ 20 and HZ 30 as shown in Figure 2.

![Figure 2. Welding distortion in various heat sink treatments](image)

Based on Figure 2, distortion degradations of the longitudinal direction that occurs at every point can be displayed. The measurement results show the maximum distortion values in the longitudinal direction of non-HZ, HZ 10, HZ 20, and HZ 30, correspondingly, they are 9.8; 8.9; 8.05 and 7.1 mm. These data show that there is a linear relationship between the extent of the HZ and the decrease in longitudinal distortion that occurs, meaning that the wider HZ, the smaller the longitudinal distortion. In this study, HZ 30 has the lowest weld distortion in the longitudinal direction so that this treatment is stated to be the most effective treatment to reduce distortion.
3.2. Welding Visual Inspection

Visual inspection is carried out on both the upper and lower surfaces to see the quality of the welding joints with unaided eyes before further tests were performed. Observations were made with the help of a camera for documentation purposes and were also made with reference to visual test as observational instruments established by the AWS D1.1 standard [9]. Visual inspection results with the camera especially in the root pass section for non-HZ, HZ 10, HZ 20, and HZ 30 are shown in Figure 3.

![Welded Surface of the Root](image)

**Figure 3.** Welded Surface of the Root: (a) Non-HZ, (b) HZ 10, (c) HZ 20, and (d) HZ 30.

Based on the welding visual inspection, Figure 3 shows that the welding without a heat sink somewhat shows a perfect copy of the entire welding line with 1-3 mm root pass size. On the other hand, the treatment of HZ10 shows 2 points of the welding line that were identified as lack of penetration. Furthermore, HZ 20 treatment shows several areas that are identified with a lack of penetration, likewise for HZ 30 show more than 50% points identified as lack of penetration. These data show a linear tendency between the surface area of the heat sink and the welding penetration results where the surface area of the heat sink will result in a greater area of lack of penetration. Lack of penetration that exceeds a certain threshold in the visual test causes rejections or the results do not meet the AWS standards for welding quality.

Based on AWS welding standards for visual testing, parts of the cover pass and root pass must be observed in detail to ensure welding imperfections. The criteria for welding imperfections are outlined in more detailed items and each has a different breakthrough standard. AWS standards for visual test breakouts were applied in this test to detect proper HZ treatment and further testing. Table 1 shows the
results of welding visual tests applying the AWS standards to determine the feasibility of welding results with HZ treatment.

### Table 1. Visual Test Results of Welding Joints

| Types of Imperfection                  | Acceptance Criteria                  | Test Object       |
|----------------------------------------|--------------------------------------|-------------------|
|                                        |                                      | Non-HZ | HZ 10 | HZ 20 | HZ 30 |
| Crack                                  | Zero                                 | Zero    | Zero  | Zero  | Zero  |
| Groove/under fill                      | Zero                                 | Zero    | Zero  | Zero  | Zero  |
| Slag inclusion or porosity             | No more than 1 defect                | Zero    | Zero  | Zero  | Zero  |
| Misalignment                           | Max 1 mm                             | 0       | 0     | 0     | 0     |
| Under cut (plate thickness < 25 mm)   | Max 1 mm depth                       | 0       | 0     | 0     | 0     |
| Irregular bead (bead width)           | Zero                                 | Zero    | Zero  | Zero  | Zero  |
| Arc stray (welding spray)             | No more than 2 mm arc stray          | 1 mm    | 1 mm  | 1 mm  | 1 mm  |
| Spatter                                | Should be Zero                       | Zero    | Zero  | Zero  | Zero  |
| Arc crater                             | Should be Zero                       | Zero    | Zero  | Zero  | Zero  |
| Start stop                             | No more than 0.5 mm height difference| 0.2     | 0.3   | 0.3   | 0.1   |
| Excessive reinforcement                | No more than 3 mm                    | 2 mm    | 2 mm  | 4 mm  | 4 mm  |
| Over lap                               | Must be Zero                         | Zero    | Zero  | Zero  | Zero  |
| Lack of penetration and lack of fusion| No more than 10 %                    | 3 %     | 10 %  | 40 %  | 60 %  |
| Excessive penetration (2 mm or more)  | Less than 2 mm                       | < 2 mm  | < 2 mm| < 2 mm| < 2 mm|
| Angular distortion                     | Less than 5 degree                   | 3 degree | 3 degree | 3 degree | 2 degree |
| Conclusion of Visual Welding Test      | Accepted                             | Accepted | Accepted | Rejected | Rejected |

Based on the welding visual test results in Table 1, it can be seen that non-HZ and HZ 10 treatments are declared "accepted" or passed the test because they meet the AWS criteria. HZ 20 and HZ 30 are declared "rejected" or did not pass the test because some of the test items do not meet the AWS requirement. It can be seen that HZ 20 and HZ 30 have a percentage of lack of penetration much above 10% as the minimum amount allowed by the standard, as shown in Figure 3. Thus, it can be concluded that non-HZ and HZ 10 meet the welding quality requirements and can be further tested.

#### 3.3. Tensile Test

The joint tensile test was carried out to determine the maximum joint strength of the tensile load. The results of the tensile joint test in Figure 4 show the same value between those of non-HZ and HZ 10, which are around 475 MPa to 485 MPa. Even when compared to the base metal, they also have a similar value. This shows that welding of both the heat sinks does not lose the tensile strength of both the metal and HAZ, so that the damage of the joints only appears in the base metal. This also proves the electrode selection is appropriate so that there exists no breakage on the weld metal. The results of the tensile test also prove that the HZ treatment does not result in the losing of the tensile strength of the welding joint.
Figure 4. Tensile test fracture: (a) Non-HZ (b) HZ 10.

When inspected from the tensile test fracture in Figure 5, a fracture occurs in the base metal area by necking and deformation before breaking, while in the weld metal area, necking does not occur. This indicates that the base metal has good tenacity, yet the weld metal is stronger than the base one.

Figure 5. Tensile test fracture: (a) Non-heat sink (b) Heat sink HZ 10.

3.4. Bend Test
Bend testing was carried out on the welding work piece, either the HZ 10 or non-HZ. This test used a couple of testing methods, namely the root bend and face bend. Root bend testing was done by giving the right load on the welding line of the cover and analyzing the number of cracks in the root pass (Figure 6), while the face bend was done vice versa, namely giving a load on the welding root and analyzing the number of cracks in the cover pass. The radius of the bend test was 10 mm according to the AWS test standard for plates with a 4 mm thickness.
Figure 6. The bend test root pass: (a) Non-heat sink (b) Heat sink HZ 10

The test object was bent to form an angle of approximately 135°. Bend testing was done by measuring the crack length that occurs after bending or calculating the number of cracks according to the applicable criteria. The crack size obtained was used to determine the breakout of the bend test by ensuring that the crack size does not exceed the AWS criteria for the bend test. The bend test results can be seen in Table 2.

Table 2. The Results of the Crack Length Testing Results of the Bend Test.

| Welding Work Piece | The crack length of the root bend test results | The crack length of the face bend test results | Description |
|--------------------|-----------------------------------------------|-----------------------------------------------|-------------|
|                    | Spec. 1 | Spec. 2 | Spec. 1 | Spec. 2 | Pass the test (crack length does not exceed 3 mm) | Pass the test (crack length does not exceed 3 mm) |
| Non-Heat Sink      | -       | -       | -       | -       | Pass the test (crack length does not exceed 3 mm) | Pass the test (crack length does not exceed 3 mm) |
| Heat Sink HZ 10    | -       | -       | 3 mm    | -       | Pass the test (crack length does not exceed 3 mm) | Pass the test (crack length does not exceed 3 mm) |

From the crack length test results in table 2, it is clearly seen that the root bend and face bend tests for all test objects of non-HZ and HZ 10 are stated to meet the AWS criteria which require the total length of the crack lines to be measured on all the direction on the curved surface is 3 mm and the largest tip crack does not exceed 6 mm.

Even though all bending specimens meet the bending test criteria, when observed in the bending specimens for HZ 10, cracks appeared between the weld metal edge and HAZ or in the fusión line. It can be said that the weakest area in this welding results was the HAZ and it was possible that an initial crack had occurred previously in the fusión line. This area becomes the weakest because of the imperfect fusion between the welding filler metal and the base metal. This might be caused by the initial cooling of the work piece by liquid nitrogen which resulted in the lack of heat input to meet the minimum requirements for fusion in welding.

Based on the results of the bend test crack measurements above, it is identified that the HZ method with liquid nitrogen has the potential to reduce the quality of welding joints, especially in the less optimal welding fusion.
3.5. Hardness Test
The hardness test of the welding joint was carried out to determine the degradation of its mechanical properties. The results of the hardness test to non-heat sink and heat sink HZ objects 10 are displayed in Figure 7 by dividing the level of hardness in 3 welding areas.

Based on the hardness distribution of the 3 welding areas for both treatments, it was apparent that the highest hardness was in the weld metal area. This is because it is filled by filler metal having a higher strength than the base metal, so the hardness value is also higher than that of the base metal. Test specimens with HZ 10 tend to have the same hardness than non-HZ; the difference in the value of hardness is less than 5%, so it is declared insignificant. This shows that the heat sink treatment does not affect the hardness, so it does not affect the tensile strength of the welding joint.

![Figure 7. Hardness distribution of Non-HZ and HZ 10 joints](image)

3.6. Microstructure Test
The microstructure test of welding results was carried out to determine changes in the structure of the metal phase due to heat sink treatment at the welding joint. Observation of the microstructure at the welding connection of carbon steel materials is clustered in 3 zones, namely weld metal (WM), heat affected zone (HAZ), and base metal (BM). Figure 8 and 9 show the welding microstructure non-heat sink and heat sink HZ 10 treatment in all three zones.

Figures 8 (a) and 9 (a) show the microstructure of the WM area showing the microstructure differences between Non-HZ and HZ-10 welding. The difference is seen in the microstructure density which shows the percentage of acicular ferrite (AF) structure in the HZ 10 treatment more than that of non-HZ. This AF structure tends to have a higher strength than other ferrite phases in the base metal.

Next, Figure 8 (b) and 9 (b) show the microstructure of HAZ area which differs in its particle size between Non HZ and HZ-10 treatment. The particle structure in the HZ treatment looks a little bigger than non-HZ’s, showing a difference in the level of hardness and strength in this HAZ area. Both of them also show particles that are coarser than BM. This happens due to particle growth because of the welding process. This HAZ area is estimated to be 4 - 5 mm from the fusion line.

Figures 8 (c) and 9 (c) display the microstructure of the base metal (BM) which is similar between Non-HZ and HZ-10 treatment with an elongated oval structure in accordance with the rolling direction. This structure does not change due to HZ treatment. The structures seen in the BM area are ferrite in bright particle color and perlite in dark particle color.
Figure 8. Non-HZ Welding Microstructure at (a) WM, (b) HAZ, and (c) BM.

Figure 9. HZ 10 Welding Microstructure at (a) WM, (b) HAZ, and (c) BM.
4. Conclusions
Based on the findings and discussion above, three conclusions are formulated as follows.

- The heat sink contact area affects the quality of the welding joint. Based on visual tests, the greater the HZ contact area, the greater the lack of penetration.
- The greater contact area of the heat sink minimizes the welding distortion of the longitudinal direction.
- Heat Sink contact area has little influence on the hardness and microstructure of the weld metal and HAZ, but does not affect the tensile strength of the welding joint.

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