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Impact of Trailing Heat Sink, Filler Type, and Current Variation on Distortion in GMAW Welding of Stainless Steel 304

Mukhlis[1], Imah Luluk Kusminah[2], Rivan Andri Kurniawan[3]
Department of Welding Engineering, Politeknik Perkapalan Negeri Surabaya (PPNS),
Surabaya, Indonesia
Corresponding author: imahluluk@ppns.ac.id

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Abstract

The use of welding technology in the manufacturing industry has become increasingly widespread due to its ability to enhance production effectiveness and efficiency. Stainless steel 304 is commonly used in industrial applications but is highly sensitive to weld-induced thermal expansion, making it prone to distortion. Such distortion is considered detrimental as it leads to deformation of the design, reduced dimensional accuracy, decreased mechanical strength, and increased costs for welded product repairs. To address this issue, a study was conducted using trailing heat sink-assisted welding. The Gas Metal Arc Welding (GMAW) method was applied with variations in filler electrodes (ER316LSi and ER308LSi) and welding currents (100 A and 120 A). The welding results were visually inspected and distortion was measured. The findings indicate that welding with a trailing heat sink can effectively reduce distortion, particularly at higher current levels. ER308LSi with current 100 A, maximum distortion 11.89 mm (right)/11.32 mm (left). ER308LSi with current 120 A, slightly reduced distortion about 11.30 mm (left)/11.29 mm (right). ER316LSi with current 100 A, distortion values 11.90 mm (right)/11.27 mm (left). ER316LSi with current 120 A highest overall distortion, reaching 11.32 mm.

1. Introduction

The advancement of modern manufacturing industries demands production processes that are not only fast but also efficient and high in quality. One of the key technologies supporting this need is welding. Among the many materials widely used in industrial applications, stainless steel 304 holds an important position due to its corrosion resistance, good mechanical strength, and ease of fabrication. However, welding stainless steel 304 presents specific challenges, particularly its sensitivity to thermal expansion, which makes it prone to distortion.

According to Conrardy et al. (2006), distortion frequently occurs during plate welding, and the thinner the plate, the greater the distortion. This leads to an increase in labor costs associated with correcting the shape of welded products (European Commission, 2000) [1] [2].

Welding-induced distortion poses a serious problem as it can affect dimensional accuracy, structural strength, and the final design integrity of the product. The consequences include reduced component performance and increased production costs due to the need for rework or repairs. Therefore, controlling and minimizing distortion has become a crucial aspect of welding technology, particularly in industrial applications requiring high precision.

One innovative approach to mitigate distortion is the application of a trailing heat sink, a method that involves localized cooling immediately after the welding arc to manage heat distribution and prevent excessive thermal deformation. When combined with Gas Metal Arc Welding (GMAW) and process parameters such as filler metal type and welding current, this method is believed to have a significant impact on weld quality.

Previous research has investigated the effect of GMAW on stainless steel 304 by varying travel speeds (5 mm/s, 7 mm/s, and 9 mm/s), analyzing distortion, mechanical properties, and metallographic structure. The results showed low distortion, high tensile strength, and predominantly ferritic microstructures [3].

The study conducted by Mohammad Azwar Amat, Dhedhe Rodat Budi, and Ario Sunar Baskoro (2023) explains that the greater the welding current used, the larger the resulting angular distortion. Conversely, the higher the welding speed applied, the smaller the angular distortion produced. Furthermore, welding current has a more dominant effect on angular distortion compared to welding speed [4].

Shigetaka Okano and Masahito Mochizuki (2016) experimentally validated that using a water-cooled trailing heat sink in welding can monotonically reduce both residual stress and welding distortion [5].

More recently, Rohmad Syamsudin Azis (2024) found that the use of a trailing heat sink effectively reduced distortion due to rapid cooling, which inhibited excessive heat propagation. The highest tensile strength achieved was 641.08 MPa under the trailing heat sink condition with a travel speed of 9 mm/s [3].

In light of these findings, the present study aims to evaluate the influence of trailing heat sink application, in conjunction with variations in electrode type (ER316LSi and ER308LSi) and welding current (100 A and 120 A), on distortion in stainless steel 304. The results are expected to serve as a valuable reference for industrial welding practices, especially in optimizing parameters to minimize distortion in thermally sensitive materials.

This study is the first to investigate the combined influence of filler type (ER308LSi vs. ER316LSi), welding current (100 A and 120 A), and trailing heat sink application on distortion in GMAW of stainless steel 304. The novelty lies in a multi-parameter approach that the metallurgical role of filler composition (Mo-containing vs. Mo-free) on heat transfer and shrinkage, Explores the interaction of current level and heat sink in controlling thermal gradients and Employs 132-point distortion mapping with 3D visualization, offering a spatially detailed analysis beyond conventional linear/angular distortion measurements.

This research is expected to provide benefits and impact for both industry and academia. For companies, the findings may serve as a valuable reference in the field of welding, particularly as additional information and literature regarding the application of trailing heat sinks on stainless steel 304 using the GMAW welding method, with respect to distortion, hardness values, radiographic testing, and metallographic analysis.

2. Research Methods

This research began with a literature review to identify the research gap, which involved gathering relevant references and data to serve as the foundation for the study. Problem identification in the field, particularly issues related to welded pipe joints, also played a significant role in determining the major problems that needed to be addressed. The material used in this study was stainless steel SA 240 Type 304. The specimens were in the form of plates with dimensions of 300 mm in length, 300 mm in width, and 5 mm in thickness. The dimensions of the plate specimens are illustrated in the following Fig. 1.

Fig. 1. Specimen Material Design

The welding process was carried out using the Gas Metal Arc Welding (GMAW) method. The filler wires used in this study were selected to match the base material, consisting of ER308LSi and ER316LSi wires, each with a diameter of 1.2 mm.

The procedure began with the preparation of the trailing heat sink device, which utilized water as the cooling medium, adjusted and integrated with the welding machine. The trailing heat sink was then mounted onto the GMAW torch, which was installed on an automatic flame-cutting machine. A backing gas system was also set up using argon gas with 99.98% purity. It is illustrated in Fig. 2.

Next, the joint fit-up process was conducted to align the stainlesssteel plates. Welding was then performed according to the predefined parameters, with current variations of 100 A and 120 A.

Fig. 2. Welding Scheme Using Heatsink

Visual testing is the first step conducted in the Non-Destructive Testing (NDT) process. Its purpose is to directly inspect the test specimen for any visible surface defects. This visual inspection was carried out in accordance with ASME Section IX (2021) standards. According to ASME Section IX (2021) [6], Visual Examination requires that the weld must achieve proper fusion, be free from cracks and porosity, and the root penetration must not exhibit burn-through.

Following the visual inspection, each stage of the welding process was followed by measurements to determine the amount of deformation, ensuring the straightness of the specimen. This visual measurement of distortion difference is also considered part of the NDT procedure. The purpose of this process is to evaluate the distortion delta resulting from each application of the trailing heat sink.

A bevel box was used as the primary tool for measuring deformation. A levelling table was utilized to properly position the specimens during the application of the trailing heat sink.

The distortion testing process was carried out to measure the amount of distortion resulting from each application of the Trailing Heat Sink. This distortion test refers to the method used in a study by Gunawan (2019), which involved measuring distortion using a dial indicator at fixed points marked at 30 mm intervals across a 300 mm wide material [7]. The steps of the testing procedure are as follows:

1. Prepare the welded material for testing.
2. Place the material on a stable surface to prevent movement during measurement, ensuring accuracy.
3. Set up the dial indicator and calibrate it using an undistorted (reference) section of the material.
4. Perform calibration of the dial indicator.
5. Position the dial indicator at each designated measurement point.
6. Record the distortion readings displayed on the dial indicator.
7. Repeat the process for all 132 points. Measurements were taken at each intersection point, and the results were documented accordingly.

The setup for distortion measurement is illustrated in Fig. 3, while the fixed-point marking layout is shown in Fig. 4.

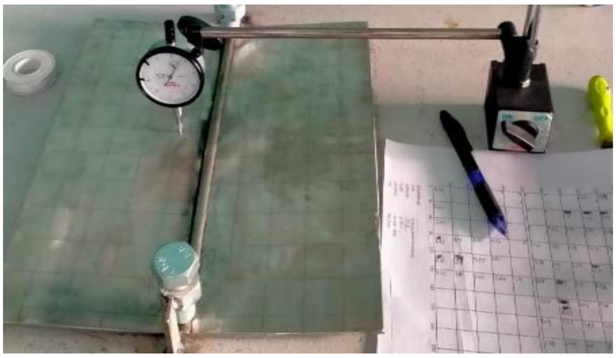


Fig. 3. Setup for Distortion Measurements

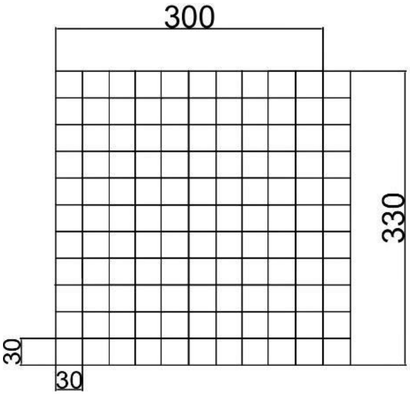


Fig. 4. Welding Scheme Using Heatsink

3. Results and Discussion.

The welding process was carried out over a period of six months, starting from the preparation of tools and materials to the completion of welding and the collection of welding data. All welding and testing activities were conducted at the State Polytechnic of Shipbuilding Surabaya (Politeknik Perkapalan Negeri Surabaya).

The welding procedure was based on references from scientific journals, applicable standards and codes such as AWS, PQR, and was refined through a trial-and-error approach to achieve optimal welding results [8]. The welding process data obtained are as follows Table 1.

Table 1. Welding Process Data

Data	Description
Material	Stainless steel 304
Shape	Plate thickness 5 mm
Welded joint design	Backweld
Welding Process	GMAW
Filler Metal	ER 308LSi ER 316Lsi
Welding Weld Shape	Double Groove
Position	Flat 1G

Welding parameters used in the welding process that refer to the journal to obtain the desired welding results. The parameters that have been recorded can be seen in below.

1. **ID Joint: A1**
   Welding Method: Trailing Heat Sink
   Electrode Diameter: 1.2 mm
   Electrode Type: ER308LSi
   Polarity: DCEP
   Current (Ampere): 100 A
   Voltage: 20.5 V
   Travel Speed: 175.22 mm/s
   Shielding Gas: Argon (99.98%)

2. **ID Joint: A2**
   Welding Method: Trailing Heat Sink
   Electrode Diameter: 1.2 mm
   Electrode Type: ER308LSi
   Polarity: DCEP
   Current (Ampere): 120 A
   Voltage: 21.5 V
   Travel Speed: 180 mm/s
   Shielding Gas: Argon (99.98%)

3. **ID Joint: B1**
   Welding Method: Trailing Heat Sink
   Electrode Diameter: 1.2 mm
   Electrode Type: ER316LSi
   Polarity: DCEP
   Current (Ampere): 100 A
   Voltage: 20.5 V
   Travel Speed: 204.12 mm/s
   Shielding Gas: Argon (99.98%)

4. **ID Joint: B2**
   Welding Method: Trailing Heat Sink
   Electrode Diameter: 1.2 mm
   Electrode Type: ER316LSi
   Polarity: DCEP
   Current (Ampere): 120 A
   Voltage: 21.5 V
   Travel Speed: 152.31 mm/s
   Shielding Gas: Argon (99.98%)

To facilitate the identification of the welding results, variation labels were assigned, as shown in Table 2.

Table 2. Variation Labeling Scheme

Code	Welding Variations
A1	*Trailing Heat Sink, ER308LSi*, 100 A
A2	Trailing Heat Sink, ER308LSi, 120 A
B1	Trailing Heat Sink, ER316LSi, 100 A
B2	Trailing Heat Sink, ER316LSi, 120 A

3.1 Visual Test Analysis

Visual testing is a post-welding inspection method aimed at evaluating the quality of the weld. This test is conducted through direct observation and can be performed with the naked eye, assisted by several tools such as a welding gauge, flashlight, and magnifying glass.

In this study, visual inspection was conducted on GMAW welds applied to 5 mm thick stainless steel using the Trailing Heat Sink method, with variations in filler metal and welding current (100 A and 120 A). The purpose of this visual inspection was to assess weld quality and ensure it meets acceptable tolerance limits.

The visual testing procedure in this research refers to the standard ASME Section IX (2021) to evaluate the weld quality and compliance with permissible defect criteria.

According to ASME Section IX (2023), Visual Examination requires that the weld must exhibit proper fusion, be free from cracks, and the root penetration must not show signs of burn-through.

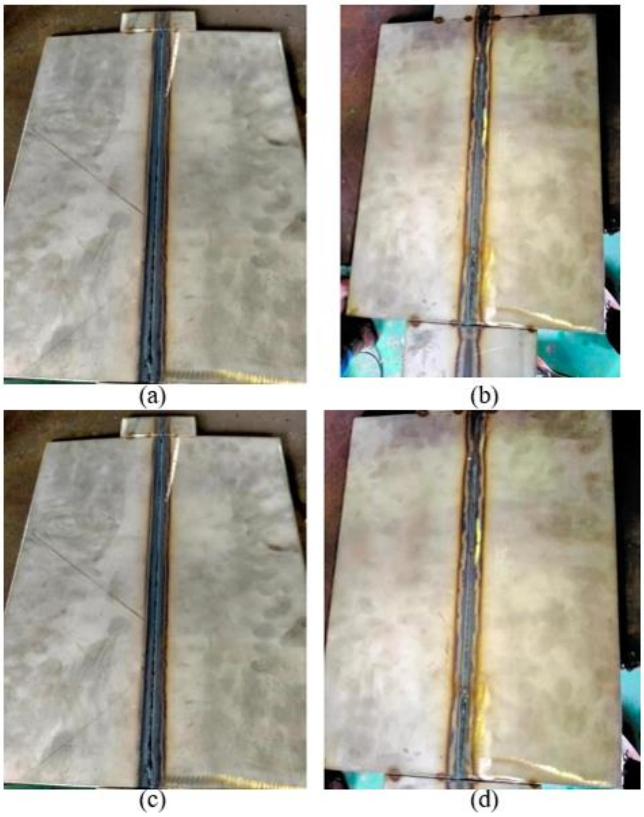


Fig 5. Visual Inspection Results on Root (a) Specimen A1 (b) Specimen A2 (c) Specimen B1 (d) Specimen B2

Fig. 5. illustrates the welding outcomes for the trailing heatsink variation, which were performed using different filler materials and welding currents. Each specimen was subjected to visual examination, particularly on the root area, using appropriate tools to assist in the inspection. This method ensured that all critical aspects of the weld root could be clearly observed and evaluated.

From the inspection results, it was found that none of the specimens exhibited visual defects such as underfill or cracking. In addition, the reinforcement height in the welding area for all specimens averaged around 2 mm. This value remains within the acceptable range as defined by the applicable welding standards, indicating that the welding process used for each combination of filler and current produced sound and reliable joints in terms of surface quality and dimensional conformity.

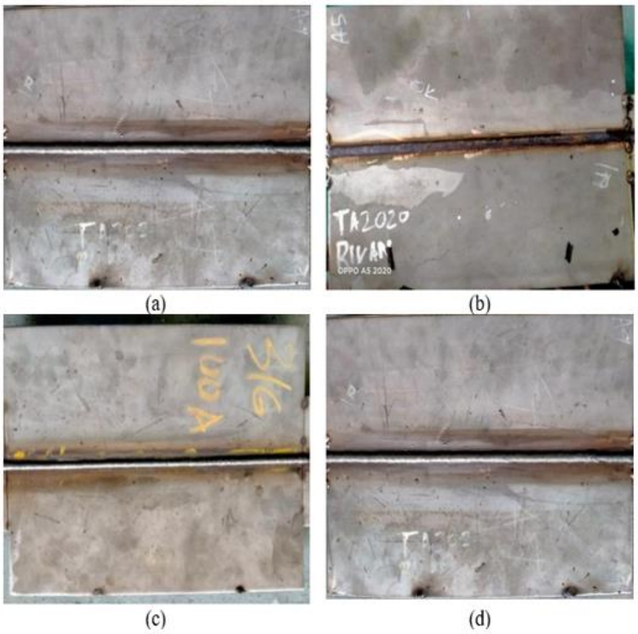
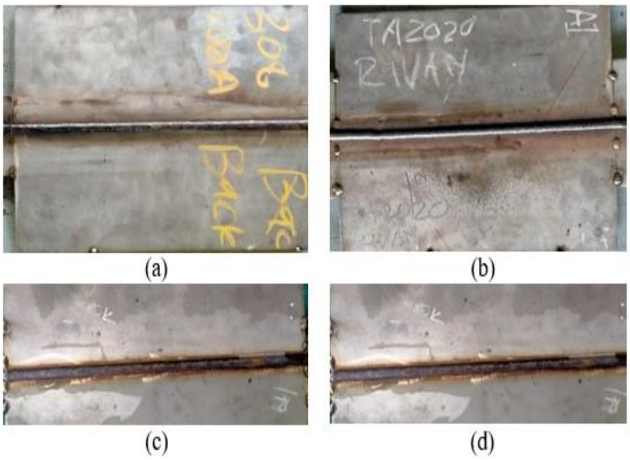


Fig 6. Visual Inspection Results on Capping. (a) Specimen A1 (b) Specimen A2 (c) Specimen B1 (d) Specimen B2

Fig.6. shown the welding results on the trailing heatsink variation, which were produced using different filler materials and variations in welding current. These specimens were fabricated using the Gas Metal Arc Welding (GMAW) method, with specific attention to how the filler type and current level influence the surface quality of the welds. Each specimen underwent visual inspection, particularly focusing on the capping area, which is crucial for assessing surface uniformity and cleanliness after welding.

From the visual inspection conducted using appropriate tools across all specimens, it was observed that the capping area exhibited certain welding defects. One of the dominant imperfections found was the presence of spatter—small droplets of molten metal that adhered to the surface around the weld bead. This defect was primarily attributed to the use of high welding currents in combination with argon gas as backing. The high thermal input caused by elevated current levels contributed to the forceful ejection of molten metal during arc transfer, leading to splatter formation.

The presence of spatter on the weld surface indicates that post-welding surface cleaning is necessary to ensure the weld meets visual and functional quality standards. Although the structural integrity of the weld may remain unaffected, the aesthetic and surface finish requirements—especially for applications involving pressure or visual exposure—necessitate additional treatment. Therefore, further optimization of welding parameters such as current level, travel speed, or gas flow rate may be needed to minimize spatter formation and improve the overall weld quality in future trials.



(a) (b) (c) (d)

Fig. 7. Visual Inspection Results on Backweld. (a) Specimen A1 (b) Specimen A2 (c) Specimen B1 (d) Specimen B2

The visual inspection results shown in the Fig. 7. focus on the backweld area of all specimens welded using variations of trailing heatsinks, different filler materials, and varying welding currents. The backweld area is a critical zone for assessing the consistency and integrity of weld penetration and overall weld quality. Upon careful observation, it was found that there were no significant welding defects such as incomplete fusion, undercut, or cracking across all specimens, indicating that the welding parameters used were generally effective in producing structurally sound joints.

However, minor surface imperfections in the form of spatter were observed in the outer regions of the weld area. These small metal droplets were not located directly within the weld bead but were scattered around the surrounding surface. The occurrence of spatter can be attributed to the use of the Gas Metal Arc Welding (GMAW) process with argon gas backing at relatively high welding currents. The combination of high energy input and shielding gas conditions promotes the formation of molten metal splashes during the metal transfer process, which then adhere to the surrounding base metal.

While the presence of spatter does not compromise the mechanical performance of the weld joint, it affects the surface cleanliness and appearance of the final product. Therefore, additional post-weld cleaning, such as grinding or brushing, is necessary to remove the spatter and improve surface finish—especially for applications that require high aesthetic quality or further processing such as painting or coating. To reduce the need for excessive cleaning, future process optimization may involve adjusting current levels, modifying travel speed, or implementing spatter-reducing techniques in the GMAW setup.

3.2 Distortion Test Analysis

The distortion measurement process after welding was conducted to evaluate and compare the distortion values of each specimen, which differed due to variations in welding parameters. Each specimen underwent welding using different configurations, including variations in welding current and filler wire types. The purpose of this evaluation was to observe how these variations affected distortion levels, especially in the context of identifying which welding approach—conventional welding or welding with a trailing heat sink—offered better control over thermal-induced deformation.

Distortion testing in this study was essential to determine whether the use of a trailing heat sink could provide a more optimized welding result, particularly in minimizing distortion caused by high welding currents. High heat input is known to induce significant thermal expansion and contraction, which can lead to undesirable warping or bending of the welded plates. By comparing the distortion levels from conventional welding and trailing heat sink-assisted welding, the research aimed to assess the effectiveness of heat sink implementation in stabilizing temperature gradients during welding and thus reducing distortion.

The distortion values were measured using a dial gauge (dial indicator) after the welding process was completed. This instrument allowed for precise quantification of the actual contour and displacement of the welded plates. The results from these measurements were then processed and analyzed using Origin software to visualize the distortion profiles. The data and corresponding graphical representations are summarized and presented in Table 3 and Fig. 8, providing a clear comparison of distortion behavior across all welding variations used in the study.

Table 3. A1 Distortion Measurement Results

	0	30	60	90	120	145	155	180	210	240	270	300
0	9.62	8.17	6.02	3.49	1.31	0	0	1.28	3.20	4.10	6.60	7.45
30	10.68	9.25	7.37	5.26	3.22	1.74	1.23	2.45	4.34	3.81	7.24	8.33
60	11.23	10.88	9.05	7.17	5.13	2.53	3.44	4.49	6.11	7.43	8.45	10.16
90	11.28	11.08	9.97	8.29	6.48	4.99	5.22	6.17	7.60	8.06	10.34	11.04
120	11.18	11.44	10.97	9.40	7.36	5.79	6.28	7.88	8.70	10.10	11.11	11.24
150	11.27	10.92	10.43	10.4	7.46	6.09	7.08	8.47	9.36	10.58	11.04	11.28
180	11.25	11.16	11.06	9.93	7.99	6.56	7.12	8.11	9.60	10.92	11.20	11.27
10	11.26	11.19	10.94	9.54	7.61	6.14	6.82	7.88	9.22	10.50	11.11	11.24
240	11.22	11.15	10.50	9.27	7.35	5.70	5.30	7.25	8.78	10.24	11.11	11.20
270	11.20	11.11	10.29	8.48	6.55	5.05	5.30	5.20	6.35	7.83	9.27	11.10
300	11.19	11.08	9.57	7.54	5.64	4.11	4.45	5.11	6.63	8.47	9.12	11.08
330	10.53	8.87	6.69	4.61	2.43	1.17	0.24	1.34	3.02	4.30	6.10	7.54

The table above presents the distortion measurement data for specimen A1, which was welded using the Gas Metal Arc Welding (GMAW) method with a trailing heat sink and a current of 100 A. The measurement process was conducted using a dial indicator, where distortion was recorded at 132 fixed measurement points across the surface of the specimen. This comprehensive approach provided a detailed profile of the deformation that occurred as a result of the welding process. From the data collected, the highest distortion value was recorded at 11.28 mm, indicating localized deformation likely influenced by heat concentration and material response during cooling.

To enhance the clarity and interpretation of the results, the distortion data was further visualized in the form of a graph. This graphical representation allows for a more intuitive understanding of the distortion patterns across the welded surface. Using Origin software, a 3D simulation graph was generated to illustrate the distribution and intensity of the distortion levels more effectively. The 3D model, shown in Fig. 8, serves not only as a visual aid but also as a tool for analyzing the spatial behavior of distortion, providing valuable insight into the effect of welding parameters on dimensional stability.

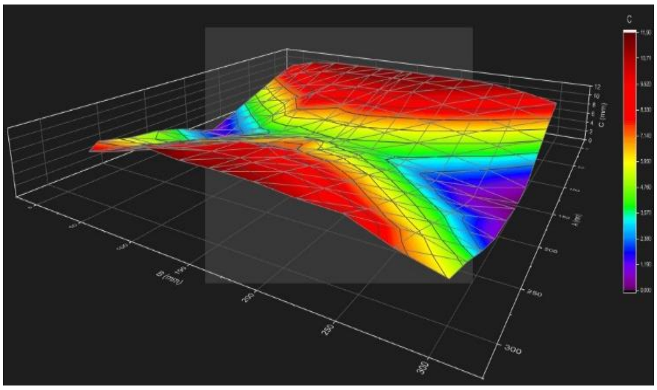


Fig 8. 3D Graph of A1 Distortion Test Results

The following are the results of measuring the distortion of specimen A2 in Table 4.

Table 4. A2 Distortion Measurement Results

	0	30	60	90	120	145	155	180	210	240	270	300
0	10.26	8.86	6.81	5.96	3.06	2.88	1.57	2.41	4.41	6.10	7.79	9.07
30	10.88	10.03	8.69	6.80	5.09	4.05	3.45	4.19	5.98	7.38	8.97	10.09
60	10.28	10.05	9.98	8.44	6.79	5.81	4.84	5.69	7.00	8.34	9.24	10.76
90	11.27	10.47	9.90	9.45	6.93	6.94	5.89	6.59	7.94	9.28	10.72	11.08
120	11.29	11.22	10.94	7.73	8.18	7.20	6.38	7.03	8.36	9.61	10.82	11.22
150	11.30	11.18	10.80	9.74	9.46	7.74	6.56	7.42	8.64	9.96	10.99	11.21
180	11.29	11.25	11.05	10.30	8.49	8.08	6.32	6.98	8.17	9.40	10.70	11.14
210	11.22	11.01	10.37	9.66	8.04	7.41	5.81	6.46	7.72	9.06	10.42	11.00
240	10.96	10.29	9.11	8.01	6.94	6.28	4.72	5.42	6.65	8.64	9.53	10.57
270	9.47	8.47	7.42	6.29	5.23	4.53	3.21	4.22	5.58	7.03	8.54	9.67
300	7.22	6.54	5.55	4.44	3.34	2.64	1.61	2.63	4.14	5.68	7.24	8.31
330	7.04	3.92	2.88	1.71	0.36	0	0	1.03	2.75	4.50	6.19	7.30

The Table 4 presents the distortion measurement results for specimen A2, which was welded using the Gas Metal Arc Welding (GMAW) method with a trailing heat sink and a welding current of 120 A. Distortion measurements were conducted using a dial indicator by recording displacement values at 132 fixed points on the specimen surface. This method ensures high accuracy and consistency in capturing the deformation profile caused by thermal effects during and after welding. According to the table, the highest recorded distortion value reached 11.30 mm, suggesting a slightly increased level of deformation compared to lower current settings, likely due to the greater heat input.

To facilitate better analysis and visualization, the distortion data were processed into a three-dimensional graph using Origin software. This graphical representation provides a clearer understanding of how distortion is distributed across the specimen surface, highlighting areas of peak deformation and identifying patterns that correlate with the welding parameters used. The 3D distortion profile, illustrated in Fig. 9, serves as a valuable tool for interpreting the spatial effects of thermal expansion and contraction, and it supports further evaluation of the trailing heat sink's effectiveness in minimizing distortion under higher current conditions.

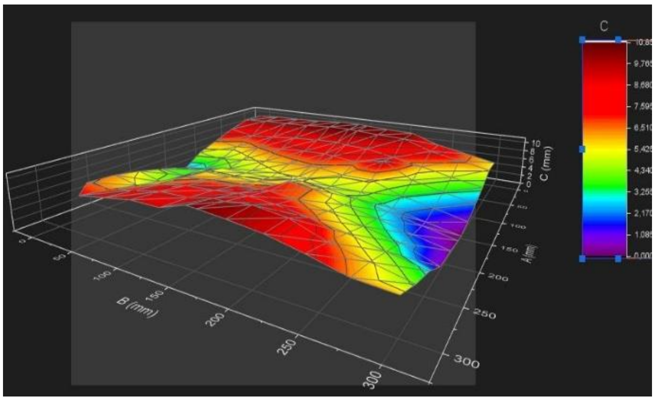


Fig 9. 3D Graph of A2 Distortion Test Results

Table 5. show the distortion measurement results for specimen B1.

Table 5. B1 Distortion Measurement Results

	0	30	60	90	120	145	155	180	210	240	270	300
0	9.62	8.17	6.02	3.49	1.31	0	0	1.28	3.20	4.10	6.60	7.45
30	10.68	9.25	7.37	5.26	3.22	1.74	1.23	2.45	4.34	3.81	7.24	8.33
60	11.23	10.88	9.05	7.17	5.13	2.53	3.44	4.49	6.11	7.43	8.45	10.16
90	11.28	11.08	9.97	8.29	6.48	4.99	5.22	6.17	7.60	8.06	10.34	11.04
120	11.18	11.44	10.97	9.40	7.36	5.79	6.28	7.88	8.70	10.10	11.11	11.24
150	11.27	10.92	10.43	10.43	7.46	6.09	7.08	8.47	9.36	10.58	11.04	11.28
180	11.25	11.16	11.06	9.93	7.99	6.56	7.12	8.11	9.60	10.92	11.20	11.27
210	11.26	11.19	10.94	9.54	7.61	6.14	6.82	7.88	9.22	10.50	11.11	11.24
240	11.22	11.15	10.50	9.27	7.35	5.70	5.30	7.25	8.78	10.24	11.11	11.20
270	11.20	11.11	10.29	8.48	6.55	5.05	5.30	5.20	6.35	7.83	9.27	11.10
300	11.19	11.08	9.57	7.54	5.64	4.11	4.45	5.11	6.63	8.47	9.12	11.08
330	11.03	10.17	8.28	5.34	4.30	3.18	2.64	3.61	5.23	6.49	7.90	8.36

The distortion measurement data for specimen B1, which was welded using the GMAW method with a trailing heat sink and a welding current of 100 A, are shown in the table above. Using a dial indicator, measurements were taken at 132 fixed points along the surface of the specimen to capture the extent of distortion caused by the welding process. This method provided a comprehensive set of data points, enabling an accurate assessment of the deformation pattern. From the results, the highest distortion value recorded was 11.28 mm, indicating localized warping likely influenced by thermal gradients during welding and cooling.

To enhance clarity and allow for better interpretation, the measurement data were visualized in the form of a 3D graph. This graphical representation, created using Origin software, illustrates the contour and intensity of the distortion across the entire surface of the specimen. Such visualizations serve not only to support the numerical data but also to simulate the distortion profile in a more intuitive manner. The 3D distortion map for specimen B1 is presented in Fig. 10, providing valuable insight into how the trailing heat sink and welding current influence the dimensional stability of the welded plate.

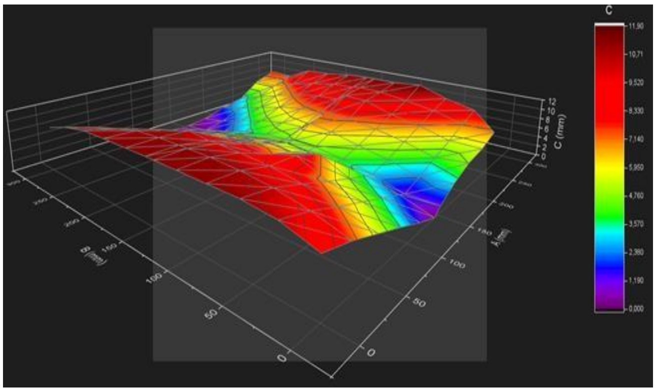


Fig 10. 3D Graph of B1 Distortion Test Results

Distortion measurement outcomes for specimen B2 are detailed in Table 6.

Table 6. B2 Distortion Measurement Results

	0	30	60	90	120	145	155	180	210	240	270	300
0	10.26	8.86	6.81	5.96	3.06	2.88	1.57	2.41	4.41	6.10	7.79	9.07
30	10.88	10.03	8.69	6.80	5.09	4.05	3.45	4.19	5.98	7.38	8.97	10.09
60	10.28	10.05	9.98	8.44	6.79	5.81	4.84	5.69	7.00	8.34	9.24	10.76
90	11.27	10.47	9.90	9.45	6.93	6.94	5.89	6.59	7.94	9.28	10.72	11.08
120	11.29	11.22	10.94	7.73	8.18	7.20	6.38	7.03	8.36	9.61	10.82	11.22
150	11.32	11.18	10.80	9.74	9.46	7.74	6.56	7.42	8.64	9.96	10.99	11.21
180	11.29	11.25	11.05	10.30	8.49	8.08	6.32	6.98	8.17	9.40	10.70	11.14
210	11.22	11.01	10.37	9.66	8.04	7.41	5.81	6.46	7.72	9.06	10.42	11.00
240	10.96	10.29	9.11	8.01	6.94	6.28	4.72	5.42	6.65	8.64	9.53	10.57
270	9.47	8.47	7.42	6.29	5.23	4.53	3.21	4.22	5.58	7.03	8.54	9.67
300	7.22	6.54	5.55	4.44	3.34	2.64	1.61	2.63	4.14	5.68	7.24	8.31
330	7.04	3.92	2.88	1.71	0.36	0	0	1.03	2.75	4.50	6.19	7.30

Specimen B2 was welded using the Gas Metal Arc Welding (GMAW) method with a trailing heat sink and a current setting of 120 A. After welding, distortion measurements were conducted to assess the degree of deformation resulting from the thermal input. These measurements were taken using a dial indicator, targeting 132 fixed points on the specimen surface. This method provides detailed and accurate data that reflect the real contour changes caused by heat during the welding and cooling processes.

The distortion data collected from specimen B2 are summarized in the table above. Among all the measured points, the highest distortion value recorded was 11.32 mm, indicating the presence of significant thermal stress and expansion during welding. This value is slightly higher than that of the specimen welded at 100 A, which suggests that increased current levels contribute to greater distortion, even when a trailing heat sink is applied. These findings highlight the influence of welding current on plate deformation, even under assisted cooling conditions.

To facilitate better understanding and visual interpretation of the distortion behavior, the data were converted into a three-dimensional graph using Origin software. The resulting 3D plot displays the spatial distribution of distortion across the surface of the welded plate, making it easier to identify high-deformation zones and analyze distortion patterns. This graphical representation, shown in Fig. 11, serves as a useful reference for evaluating the effectiveness of the trailing heat sink at higher current settings and for optimizing welding parameters in future applications.

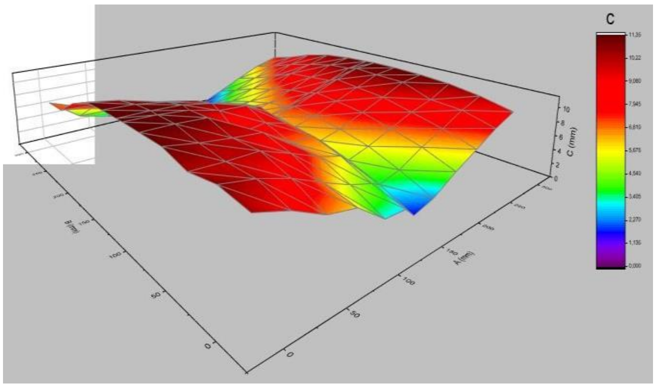


Fig 11. 3D Graph of B2 Distortion Test Results

Based on the simulation data obtained using Origin software, it was observed that welding with ER308LSi filler wire at a current of 100 A resulted in the highest distortion values—11.89 mm on the right side and 11.32 mm on the left side of the specimen. Similarly, welding with ER316LSi wire at the same current produced distortion values of 11.90 mm (right) and 11.27 mm (left). When the current was increased to 120 A using ER308LSi, the distortion values were slightly lower, recorded at 11.30 mm on the left and 11.29 mm on the right. These variations indicate that distortion occurs due to non-uniform heat distribution, which leads to localized thermal expansion in different regions of the material.

When the distortion data are plotted—particularly using 3D surface plots—it becomes evident that the maximum distortion points are concentrated near the center of the welded material. This is consistent with the region where the heat accumulates most intensely during welding. As previously explained by Wiryosumarto (2000), welding distortion is primarily caused by the combination of high heat input and mechanical constraints applied to the specimen during the welding process [9]. The longer the welding duration, the greater the thermal energy introduced to the material, leading to excessive localized heating and subsequent distortion once the material cools and contracts unevenly.

This study implemented an experimental approach by applying the Trailing Heat Sink method as a strategy to reduce welding distortion. By analyzing distortion values point-by-point and generating contour plots using Origin software, it was found that distortion could be significantly reduced with the use of a trailing heat sink. The trailing heat sink enhances the cooling process by absorbing heat immediately behind the welding arc, resulting in a faster temperature drop and a higher heat transfer coefficient. According to Okano & Mochizuki (2016), this mechanism contributes to minimizing thermal gradients and reducing residual stresses, ultimately leading to improved dimensional stability of the welded specimens [5].

The distortion results demonstrate a clear quantitative relationship between filler type, welding current, and heat input. At 100 A, the specimens welded with ER308LSi (A1) showed maximum distortion of 11.89 mm (right) / 11.32 mm (left), while ER316LSi (B1) produced 11.90 mm (right)/ 11.27 mm (left). Increasing the current to 120 A resulted in slightly lower distortion for ER308LSi (A2: 11.30 mm left / 11.29 mm right), whereas ER316LSi (B2) reached the highest distortion overall at 11.32 mm.

These differences are consistent with variations in heat input (HI) where V is voltage, I is current, and TS is travel speed. For instance, B2 (ER316LSi, 120 A, 21.5 V, TS = 152.31 mm/min) produced a higher heat input compared to A2 (ER308LSi, 120 A, 21.5 V, TS = 180 mm/min) due to its slower travel speed, leading to greater local thermal accumulation and higher distortion. Conversely, the higher travel speed in A2 distributed heat more evenly, thereby reducing distortion despite the increased current.

This correlation indicates that heat input, rather than current alone, plays the dominant role in governing distortion levels. The filler composition further modulates this behavior: the presence of Mo in ER316LSi reduces thermal conductivity, amplifying localized heat retention and resulting in greater distortion at higher heat input. On the other hand, ER308LSi, with relatively higher thermal conductivity, dissipates heat more effectively, producing more stable distortion profiles across different current settings.

4. Conclusions.

The influence of using a trailing heat sink in combination with various electrode types and welding currents on stainless steel 304 welded by the Gas Metal Arc Welding (GMAW) method has demonstrated a clear effect on reducing distortion. The experimental results indicate that the application of a trailing heat sink effectively minimizes distortion levels, primarily by providing a constant and localized cooling effect during the welding process. This cooling mechanism helps regulate the temperature gradient and mitigates excessive thermal expansion and contraction, which are the primary causes of distortion in welded joints. Specifically, the lowest distortion of 11.28 mm was obtained when using ER308LSi filler at 100 A with a trailing heat sink, whereas the highest distortion of 19.74 mm occurred when using ER316LSi filler at 140 A without a trailing heat sink. These results highlight the combined influence of electrode type, current setting, and cooling assistance on overall dimensional stability. Furthermore, it was observed that the use of lower welding currents, in conjunction with the trailing heat sink, consistently yielded smaller distortion values compared to higher current settings.

References.

[1] European Commission, The Automation and Integration of Production Processes in Shipbuilding: State-of-the-Art Report, Joint Research Centre, 2000.

[2] C. Conrardy, T. D. Huang, D. Harwig, P. Dong, L. Kvidahl, N. Evans, and A. Treaster, “Practical welding techniques to minimize distortion in lightweight ship structures,” Journal of Ship Production, vol. 22, no. 4, pp. 239–247, 2006, doi: 10.5957/jsp.2006.22.4.239.

[3] R. S. Azis, “Analisis pengaruh penggunaan trailing heat sink dengan variasi travel speed pada material stainless steel 304 metode pengelasan GMAW terhadap distorsi, sifat mekanik, dan metalografi,” Skripsi, Politeknik Perkapalan Negeri Surabaya, Surabaya, Indonesia, 2024.

[4] M. A. Amat, D. R. Budi, and A. S. Baskoro, “Pengaruh besaran arus dan kecepatan las terhadap angular distorsi pada SS304 dengan GMAW,” Jurnal Teknik Las, vol. 12, no. 1, pp. 23–30, 2024.

[5] S. Okano and M. Mochizuki, “Experimental and numerical investigation of trailing heat sink effect on weld residual stress and distortion of austenitic stainless steel,” ISIJ International, vol. 56, no. 4, pp. 647–653, 2016, doi: 10.2355/isijinternational.ISIJINT-2015-659.

[6] American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section IX: Welding, Brazing, and Fusing Qualifications, ASME, New York, NY, USA, 2021.

[7] A. Gunawan, “Pengaruh parameter pengelasan terhadap distorsi dan tegangan sisa pada baja tahan karat,” Jurnal Teknik Mesin Indonesia, vol. 21, no. 2, pp. 45–52, 2019.

[8] American Welding Society, Specification for Bare Stainless Steel Welding Electrodes and Rods, AWS, Miami, FL, USA, 2022.

[9] H. Wiryosumarto and T. Okumura, Teknologi Pengelasan Logam, Jakarta, Indonesia: Pradnya Paramita, 2000.

[10] R. A. Pranoto, N. A. Mufarida, and Kosjoko, “Pengaruh variasi media pendingin terhadap kekerasan dan kekuatan uji tarik pada hasil pengelasan SMAW material stainless steel AISI 304,” 2017.