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Analysis of the effect of welding sequence and speed on the distortion of ASTM A36 joints by MIG method

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Abstract

The welding process with the Metal Inert Gas (MIG) method often produces distortions that are detrimental to product quality, one of the factors that affect the characteristics of the welding results is heat input. The heat input provided in the welding process is influenced by arc current, arc voltage, and welding speed, besides that the welding sequence can also affect the distortion of thin plates due to welding on materials such as ASTM A36 plates. The welding process uses welding wire/electrode type AWS ER 70S-6 with a diameter of 1.0 mm, the welding parameters applied are: voltage of 22 Volts, current of 150 Amperes, DC + Current type (DCEP), the shielding gas used is 100% Argon with a flow rate of 15 liters per minute, horizontal welding position (1G), the amount of heat input is differentiated by changing the welding speed and the welding sequence used is the stepping stone method. The results of the study using ANOVA indicate that welding distortion increases with an increase in input heat, the repetition of welding sequences leads to greater distortion due to thermal stress, and the welding sequence and input heat have an influence of 80.4% in reducing distortion.

Keywords:
MIG welding, heat input, distortion, weld speed, weld sequence.

1. Introduction

The production of metal components such as plates or other metal materials requires welding to join the parts[1]. One of the popular welding methods is the Metal Iner Gas (MIG) method. However, this welding process often results in distortion, which is detrimental to product quality [2]. Distortion is a change in the shape of the workpiece that does not conform to the planned shape, which can cause functional and aesthetic problems in the final product [3]. Distortion can be categorized into three types, namely transverse distortion, longitudinal distortion, and angular distortion as shown in Fig. 1. The angular distortion of a weld joint is determined by several factors such as the dimensions of the melting zone, the type of joint, the order in which the welds are arranged, and the material properties of the material [4].

ASTM A36 plate is one of the metal materials often used in the production of metal components. This plate has good mechanical properties such as durability and strength, making it suitable for use in structural components[5, 6]. However, ASTM A36 plate also has a high degree of distortion during the welding process when welded with the MIG method. These distortions can cause deformations and defects in the steel structure that affect its integrity and safety[7, 8]. The MIG welding process on ASTM A36 plates can have adverse effects such as structural changes in the material subjected to the weld, decreased mechanical strength in the material, and accumulation of residual stresses in the weld area [9]. There are several factors that affect the quality of the welding process, including weld planning, welding preparation, and welding procedures [9]. One of the parameters that can be adjusted in weld planning is heat input, which can be adjusted through voltage and welding current settings or welding speed. If the applied heat input is too high, this can cause distortion in objects that are not held at the ends. This distortion can be in the form of shape, size, and angle, caused by uneven thermal stresses getting bigger and this strain results in distortion of the object [10].

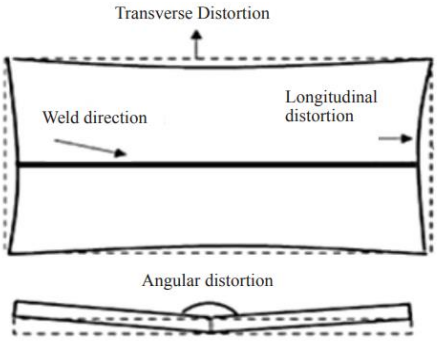

Fig. 1. Different types of distortion in welded joints [4]

One of the factors that affect the characteristics of welding results is heat input. The heat input provided in the welding process will affect the cooling rate and microstructure changes in the weld area. To reduce distortion in thin plates due to welding, one way that can be done is to optimize heat input through adjusting welding parameters such as arc current, arc voltage, and welding speed. This is in accordance with the results of FEM simulations conducted by Waheed et al[11]and the results of research by Wibowo et al[10]which showed that distortion in the transverse and longitudinal directions can be minimized by lowering the heat input. However, Moustahid et al. reported that high heat input can increase the tensile strength of the weldment, but also decrease the hardness value and increase the distortion[12]. Studies conducted by Tamlicha et al. showed that distortion in ASTM A36 steel welds can reach 5-10% of the original dimensions, depending on the welding parameter settings. This can cause deformation in the resulting steel structure, which affects the performance of the structure and can shorten its service life [13]. In addition, a study by Kadnar et al. showed that welding using the MIG method on carbon steel materials, including ASTM A36, can produce distortions in the weld joint of up to 4.5 mm [14]. This shows that controlling distortion in welding using the MIG method on ASTM A36 material is important to improve the quality and safety of steel structures. In addition, welding current and voltage control techniques can also be used to reduce distortion in welds, as shown by studies by [15].

The use of welding sequence also affects the amount of distortion in welding in addition to heat input. Fu et al. conducted a study by changing the weld sequence on a welded plate with a butt joint and found that the weld sequence significantly affected the longitudinal and transverse changes in the shape and structure of the welded plate[16]. In a study by Chen &GuedesSoares et al, the use of weld sequences was able to distribute heat better than welding with only one path [17]. Meanwhile, according to Subarmono et al, distortion can be minimized by using a sequence of welds in reverse and gradually, because in welding without variation in movement, the distortion will be greater[18].

According to the information above, it is important to research and find solutions to the problem of distortion in ASTM A36 metal plates during the welding process. One of the negative impacts of welding is distortion, which causes changes in the dimensions and geometry of the workpiece that are not in accordance with the initial design. These distortions also cause financial losses because they require additional costs to repair. Therefore, it is crucial to optimize distortion using the MIG welding method on ASTM A36 metal plates, and apply it in the metal component manufacturing industry. The purpose of analyzing the effect of welding speed and sequence is to achieve minimum distortion angle and greater weld strength. This research differs from other studies in a number of significant ways, not the least of which is the explicit investigation of the effects of welding speed and sequence on distortion. It's possible that earlier studies explored different variables or didn't particularly look at these elements. Additionally, this research strives to raise product quality to satisfy market demand for premium goods. This emphasis on market demand and product performance may set it apart from earlier studies that might have paid more attention to the technical aspects.

2. Research Methods

The material to be used in this study is ASTM A36 steel plate, the plate to be used is not subjected to any treatment before welding. The parent metal chemical composition and mechanical properties can be seen in Table 1.

Table 1. Chemical composition and mechanical properties of ASTM A36 [19]

<table>
<tr><th rowspan="2">Plate Type</th><th colspan="5">Chemical composition</th></tr>
<tr><th>C (%)</th><th>Mn (%)</th><th>Si (%)</th><th>P (%)</th><th>S (%)</th></tr>
<tr><td rowspan="4">ASTM A36</td><td>0.25</td><td>1.03</td><td>0.28</td><td>0.04</td><td>0.05</td></tr>
<tr><td colspan="5">Mechanical Properties</td></tr>
<tr><td colspan="2">YS (MPa)</td><td>TS (MPa)</td><td colspan="2">EL (%)</td></tr>
<tr><td colspan="2">301</td><td>441</td><td colspan="2">30</td></tr>
</table>

The test specimens will be formed into flat plates with length and width of 150 mm x 100 mm x 6 mm as many as 24 pieces, respectively, as shown Fig. 2. Welding will be done with a square butt joint type. The parameters that will be used as a comparison to determine the amount of distortion are the welding heat input obtained by changing the welding speed and the use of the welding sequence. Welding sequence: stepping stone method and not using and welding speed: 3, 3.5, 4 mm/s, using a semi-automatic MIG machine. To find out the treatment that produces the smallest deformation in welding, 6 types of specimens are made with each specimen made as many as 4 pieces to facilitate data analysis, then the configuration of each specimen can be seen in Table 2. During the welding process, one specimen will be clamped using a hand clamp and the other will be left free. This aims to see the deformation that occurs during the welding process.

The welding process on the workpiece uses the following provisions and configurations: a) The welding process uses the Metal Inner Gas (MIG) welding method, b) the welding wire / electrode used is AWS ER 70S-6 type with a diameter of 1.0 mm, c) welding parameters applied are: voltage 22 Volts[21], current 150 Amperes, DC + Current type (DCEP), shielding gas used is 100% Argon with a flow rate of 15 liters per minute, horizontal welding position (1G), the amount of heat input is differentiated by changing the welding speed and the welding sequence used is the stepping stone method type with a bead length of 3 mm and with an initial distance between beads of 3 mm. We used a liquid penetrant test, a non-destructive test, to make sure the welding outcomes were flawless.Measurement of the deviation that occurs after welding is carried out using a dial gauge and to see the amount of change that occurs during the welding process. The amount of data measured in distortion is the linear distance distortion at the output of the dial indicator.

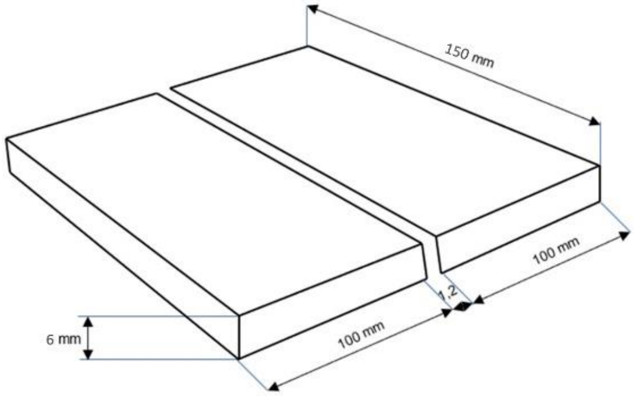

Fig. 2. Design of welding specimens

Table 2. Test specimen configuration

Specimen	Welding sequence	Welding Speed (mm/s)
A	Not Used	3
B	Not Used	3.5
C	Not Used	4
D	Used	3
E	Used	3.5
F	Used	4

The standard used in this study to assess the acceptability of the welding process is AWS D1.1/D1.1M: Structural Welding Code – Steel[20].

The number of specimens made in this study is 6 types with each specimen will be made as many as 4 pieces. Each specimen will be measured using 2 different dial indicators at each end so that the size of the distortion obtained on one sample is 2 pieces. The number of specimens to be analyzed is 24 pieces with the results of the measurements obtained totaling 48 measures The data obtained after conducting the experiment needs to be tested for normality to ensure that the data has a normal data distribution or is not homogeneous or not. After the normality test is carried out, data with normal distribution or homogeneous can be further tested using the ANOVA (Analysis of Variance) test. Analysis of variance (ANOVA) is a method for breaking down the overall data variability into several components that measure various sources of variability. The value obtained from the ANOVA test is a significance value which will be compared with the research confidence level to draw conclusions from the existing hypothesis.

3. Results And Discussion

3.1 Welding result data analysis

3.1.1 Use of weld order and no weld order

Table 3 is the data on the distortion results that occurred in specimens without using the weld sequence (specimens A, B and C) and specimens that used the weld sequence (specimens D, E and F). Specimens A, B and C show linear distortion in the welding results, with the smallest value found in sample C1, which is 0.62 mm at the starting point of the weld and 1.3 mm at the end point of the weld. The average amount of distortion on the plate is 0.96 mm, the sample with the largest distortion occurs in sample A4 with the maximum distortion occurring at the end of the weld of 2.03 mm and at the end point of the weld of 1.89 mm, the average distortion in these samples has a value of 1.96 mm.

when. The trend in Table 3 shows that the distortion will decrease the faster the welding process takes place. The faster welding speed can reduce the amount of heat energy received by the plate in the welding process[22]. This welding speed will affect the welding heat input.

Table 3. Result of distortion that occurs

Specimen	Sample	Large Distortion		
		Dial Gauge 1 (mm) (Weld Start)	Dial Gauge 2 (mm) (End of Weld)	Average distortion
A	1	1.44	1.91	1.675
	2	1.61	2.04	1.825
	3	1.89	1.99	1.94
	4	1.89	2.03	1.96
B	1	1.42	1.31	1.365
	2	1.51	1.44	1.475
	3	1.36	1.61	1.485
	4	1.73	1.49	1.61
C	1	0.62	1.3	0.96
	2	1.12	1.06	1.09
	3	1.21	1.17	1.19
	4	1.13	1.28	1.205
D	1	2.51	2.21	2.36
	2	2.81	2.44	2.625
	3	2.89	2.41	2.65
	4	3.15	2.81	2.98
E	1	1.74	1.86	1.8
	2	1.71	1.98	1.845
	3	2.17	1.66	1.915
	4	2.03	1.92	1.975
F	1	1.33	1.06	1.195
	2	1.65	1.29	1.47
	3	1.74	1.31	1.525
	4	1.53	1.6	1.565

While in specimens D, E and F, the welding distortion results that arise show an increase compared to without using the welding sequence. This is evidenced by the smallest distortion achieved in sample F1 with a distortion of 1.33 mm at the starting point of the weld and 1.06 mm at the end point of the weld with an average distortion of 1.195 mm. The largest distortion occurred in sample D4 with a distortion of 3.15 mm at the initial point of the weld and 2.81 mm at the final point of the weld with an average distortion of 2.98 mm. The use of the stepping stone method welding sequence has an influence that makes the distortion on the weld plate even greater, this is based on the distortion that occurs in specimens D, E and F which have a greater average distortion than in specimens A, B and C. The use of this welding sequence also results in a large enough distortion variance compared to without using the welding sequence, this large variance proves that the use of the stepping stone method welding sequence makes the weld distortion tend to be unstable[16]. It should be noted that the welding speed in this test does not have an exact value as specified in the initial conditions, but is an approach to the value. Therefore, the amount of distortion that occurs and the heat input received by the plate is not constant but fluctuates. this is because the welding process is carried out manually so that constant speed cannot be achieved To facilitate the interpretation of the distortion results in each specimen, the distortion results shown in Table 3 when plotted on the graph have results as shown in Fig. 3.

Based on Fig. 3, the data variation that occurs in the magnitude of welding distortion in specimens without the use of welding sequence is more stable than the use of welding sequence. In average, the amount of distortion that occurs in specimens without the use of welding sequence is smaller and uniform. This shows that the distortion will decrease as the welding process speeds up, according to Gery D. et al. welding speed has a close influence on the amount of heat input in the welding process. The greater the heat input will make the thermal stress accumulate greater in the weld seam area, this accumulated thermal stress will make the plate distorted during the cooling process, the greater the thermal stress, the greater the distortion that occurs [22].Then it can also be observed that the use of the stepping stone method welding sequence makes the distortion even greater due to repeated welding on the same weld seam which will accumulate thermal stress in the weld area. This accumulation of thermal stress will cause the plate to distort more than welding done in one go [16, 23]. Based on Table 3, the decrease in the amount of distortion that occurs due to the variable welding speed has an influence of 42% - 49% on the decrease in distortion that occurs during welding. While the use of the stepping stone method welding sequence, has an influence of 24% on the increase in distortion that occurs during welding. Angular distortion occurs due to the expansion and shrinkage forces that work between the weld and weld base areas. In the cooling process after the weld, the metal will try to shrink to the volume that can be achieved at low temperatures, but this is resisted by the adjacent base metal. Therefore, the control of heat input and heat distribution has a great influence on the amount of distortion that occurs.

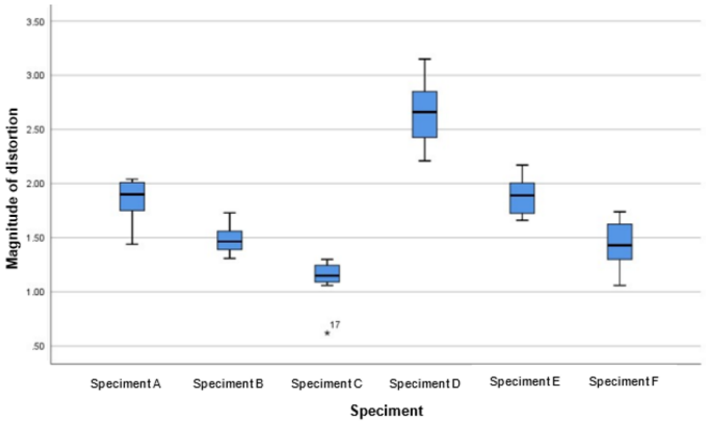

Fig. 3. Candlestick graph plot of welding distortion results

Fig. 4depictsthe standard deviation of the distortion of 6 welding samples. The standard deviation is a measure of how spread out the data is[24]. A lower standard deviation indicates that the data is more tightly clustered around the mean, while a higher standard deviation indicates that the data is more spread out[25].The standard deviation of the distortion of the 6 welding samples ranges from 0.05 mm to 0.25 mm. This indicates that there is a significant variation in the distortion of the welding samples. This variation could be due to a number of factors, such as the type of material being welded, the thickness of the material, the welding technique used, and the skill of the welder.

Based on the distortion's standard deviation, it is most likely that the data came from an unreliable or poorly managed method. Here are some further findings on the data: The subsequent samples (D, E, and F) typically have a higher standard deviation of distortion. This shows that the welding process's distortion may be getting worse over time. For sample F, the standard deviation of the distortion is quite considerable. This could indicate a unique issue with this sample, such as a flaw in the material or an error in the welding procedure.

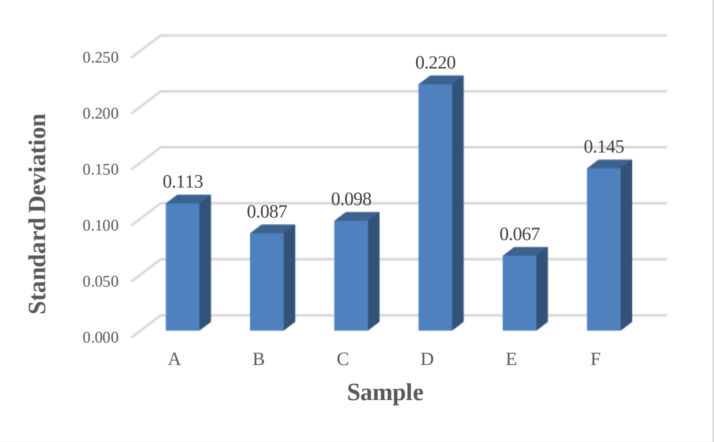

Fig. 4. Standard deviation of the distortion ofwelding samples

3.1.2 *Welding speed*

As mentioned earlier, welding speed is an important component in the amount of heat input that occurs during welding, this is in accordance with Eq. 1, namely:

$$Q = (60 \,.\, V \,.\, I)/(v \,.\, 1000) \qquad (1)$$

Q = heat input [ampere volts min/mm]
V = arc voltage [volts]
I = welding current [Ampere]
v = welding speed [mm/min]

Where other factors that affect the amount of heat input are the welding voltage and current during the welding process and the efficiency of the welding used, the efficiency of the MIG method is 1, based on this Eq., it can be concluded that the faster the welding process, the heat input received by the plate during welding will be smaller. Small heat input can minimize the amount of distortion that occurs. The amount of heat input for each specimen is presented in Table 4.

Table 4. Speed and heat input of each specimen

Specimen	Welding Speed (mm/s)	Heat Input (kj/mm)	Specimen	Welding Speed (mm/s)	Heat Input (kj/mm)
A	3.094	63.99	D	3.243	61.05
	3.076	64.36		2.953	67.04
	3.06	64.71		3.028	65.39
	3.025	65.46		2.865	69.12
B	3.583	55.27	E	3.693	53.62
	3.526	56.15		3.672	53.92
	3.435	57.64		3.544	55.88
	3.428	57.76		3.524	56.18
C	4.153	47.68	F	4.041	49
	4.152	47.69		3.997	49.54
	4.056	48.81		3.899	50.78
	4.039	49.02		3.936	50.31

The sample with the smallest distortion without using the weld sequence is sample C1 with an average distortion of 0.96 mm having a heat input of 47.68 kj/mm, while the sample with the largest distortion is sample A4 having an average distortion of 1.96 mm with a heat input of 65.46 kj/mm. Then in the sample using the welding sequence (specimens D, E and F), the smallest distortion is found in sample F2 with an average distortion of 1.195 mm with a heat input of 49 kj/mm, and in the sample with the largest distortion, sample D4 has an average distortion of 2.98 mm with a heat input of 69.12 kj/mm. When referring to the data calculations in Table 4, from the data it can be seen that the use of welding sequences can increase the amount of heat input received by the plate by 3% to 8%. However, the heat input that occurs in the plate with the welding sequence has a greater accumulation than without using the welding sequence (specimens A, B and C). In plates with weld sequences, welding is done three times (three passes) so that in one weld seam, there are three simultaneous heating and cooling processes. This consecutive heating and cooling of the weld seam causes the welding thermal cycle to be long and makes the weld pool area overlap so that when the welding area has begun to freeze, the weld pool will melt again and refill with filler. This overlapping filler and simultaneous heating and cooling is what makes more thermal stress accumulate in welding using a welding sequence so that the distortion that occurs is greater [17].

3.2 ANOVA (Analysis of Variance) Test

ANOVA test is conducted to determine significant differences in the mean values of several groups of data due to the influence of a variable and to detect interactions between factors in determining the dependent variable[26]. In this study, the type of ANOVA test used is the two-factor ANOVA type (Two Way ANOVA)[27], this is because there are 2 factors/variables that are thought to have an influence on the amount of welding distortion, namely welding speed and the use of welding sequences Statistical analysis of this research data uses a confidence level of 95%, with the hypothesis to be tested described as follows:

H_0 : The application of welding sequence affects the degree of distortion formed during the welding process.
H_1 :Differences in welding speed impact the amount of distortion that occurs during the welding process.

Two-factor ANOVA analysis using SPSS V.25 application can be seen in Table 5.

Table 5. Two-Way ANOVA Test Results

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	11.355	5	2.271	47.132	0.0000
Intercept	144.803	1	144.803	3005.201	0.0000
Weld Sequence	3.126	1	3.126	64.882	0.0000
Welding Speed	7.702	2	3.851	79.923	0.0000
Error	2.024	42	0.048		
Total	158.182	48			
Corrected Total	13.379	47			

Table 5 above shows the significance of each independent variable (welding sequence and welding speed) which will be used as a reference for the research hypothesis testing process. In determining the acceptance of the hypothesis, the following rules are followed: (1) If the significance value (sig.) <0.05, then the independent variable has an influence on the amount of welding distortion that occurs. (2) If the significance value (sig.) > 0.05, then the independent variable has no influence on the amount of welding distortion that occurs.

From the data obtained from Table 5, the results that will be used in determining the acceptance of the hypothesis are bolded using green for the welding sequence variable and blue for the welding speed variable. The interpretation of the data is as follows:

a. First Hypothesis Testing (Green Line)
   In the welding sequence variable, the significance value is very small (0.000), the first hypothesis which says that "The use of welding sequence has an influence on the amount of distortion that occurs in the welding process" is acceptable.
b. Second Hypothesis Testing (Blue Row)
   In the second variable, namely welding speed, a very small significance value is obtained (0.000), the first hypothesis which says that "Variations in welding speed have an influence on the amount of distortion that occurs in welding" can be accepted.

After conducting the ANOVA test to test the research hypothesis, the F test was then conducted to see if "there is a simultaneous influence of the independent variables, namely welding sequence and welding speed on the amount of welding distortion". The decision on this F test is as follows: (1) If the calculated F value > F table, the hypothesis is accepted, meaning that there is an influence between the use of welding sequence and changes in heat input with the amount of distortion that occurs during welding. (2) If the value of F Count < F Table, the hypothesis is rejected, meaning that the temperature of the weld sequence and the change in heat input simultaneously have no influence on the amount of distortion.

The test results using SPSS V.25 software are as follows:

Table 6: F test results of welding distortion data

F test results^a

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	10.761	2	5.38	92.471	.000^b
Residuals	2.618	45	0.058		
Total	13.379	47			

a.Dependent variable: amount of distortion b. Predictors: (constant), welding speed, weld sequence

Table 6shown that the value of F_{count} is92.471, then by looking for the value of F_{tabel} in the F $_{table0.05}$, the value of F_{tabel} is 3.20. So it can be concluded that the value of $_{\text{Fhitung is}}$ greater than the value of F_{tabel} (92.471> 3.20) so it can be concluded that there is a simultaneous influence on the use of welding sequence and welding speed on the amount of distortion that occurs.

Table 7. The coefficient of determination of the dependent variable F test.

Coefficient of Determination of Independent Variables

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.897	0.804	0.796	0.24121

After obtaining the conclusion that the independent variable has an influence on the amount of welding distortion, the percentage of the influence of the independent variable on the amount of distortion that occurs will be calculated. The calculation uses the coefficient of determination of the dependent variable in the F test, the test data is shown in Table 7.

In Table 7, the R_{square} value is 0.804. The R_{Square} coefficient has a percentage of 80.4%. This significant percentage indicates that the application of welding sequence and welding speed together affects about 80.4% of the distortion formed during the welding process. It should be noted that the welding speed in this experiment represents the amount of heat input received by the plate during the welding process, so that indirectly the difference in welding speed has an influence on the amount of heat input on the welded plate so that the heat input that occurs during welding has an impact on the level of distortion formed during the welding process. Then for the remaining percentage of the influence of the independent variable, which is 19.6%, it is influenced by external variables that are not included in this data analysis, which also has an impact on the level of distortion formed during the welding process.

4. Conclusion

The level of welding distortion is greatly affected by heat input, with distortion increasing as heat input rises. When the welding sequence is repeated on a single seam, the distortion can further escalate due to the accumulation of thermal stress resulting from multiple passes. Consequently, the stability of the heating and cooling process in the weld seam area is compromised. In terms of mitigating distortion, the variables of weld sequence and heat input carry significant influence, accounting for 80.4% of the reduction observed, while the remaining 19.6% is attributed to unspecified factors not examined in this study.

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