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The Back Stress Behavior Study Analyzed in Residual Stress of Welded Naval Plates in Different Lamination Directions and Different Thermal Contributions

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The lamination process adds the anisotropy characteristic in the final product. This anisotropy influences the yield strength according to the direction in question, the difference between the value of the yield tension in one direction and the value of the yield tension in another direction referred to as the back stress. Naval plates were welded by the GMAW process in the longitudinal direction to the lamination and in the transverse direction, and with different thermal loads. The residual stresses were calculated by displacement coordinate points method (DCP) and the back stress was found by tensile tests in specimen subjected made with either the longitudinal lamination direction and transverse lamination direction. The material used was ASTM A131 naval steel grade AH-36. The welded plates with greater thermal load in the longitudinal direction presented smaller residual stress in this direction, in relation to the transverse lamination direction. In the welded plates with greater thermal load, in the transverse lamination direction, the displacements in different directions were close, showing that the back stress does not act reversing the displacement (flow). Finally, for the welded plates with lower thermal load, both welded in the longitudinal and transverse direction, the displacements were small. In addition, the back stress did not act reversing such displacements.

Keywords: *back stress, lamination, thermal load, displacement coordinate points method (DCP), GMAW.*

1. Introduction

The main objective of this paper is to study the influence of welding speed change and the effect of anisotropy in residual stress calculation using the displacement coordinate points method (DCP) in welded laminated plates with GMAW process. Siqueira Filho[1] developed the DCP method in 2012 as an alternative theoretical-experimental method to Hole-Drilling method. The DCP method measures residual stresses using a Coordinate Measuring Machine.

In order to reach a conclusion on the influence of welding speed and the change of lamination direction in relation to the weld bead in the residual stress, and if exists interaction between these two conditions, hypothesis test and the ANOVA were used.

In the lamination process, the residual stress is introduced by non-uniform plastic deformations caused by the compressive forces of the rollers on the plate.

The residual stress in welding process is due to the cooling process, when there is a temperature difference between different parts in the plate, the material expands and contracts in different ways depending on the temperature in each region. However, in the welding process, if there is any restriction on the movement of contraction and expansion, the residual stresses will appear at room temperature. For the weld bead, the accumulation of residual stresses will be tensile stress, reaching values of the order of the yield strength of the material[2].

The Bauschinger effect is connected to anisotropy and Bauschinger studied it in 1886. Where he performed a mechanical loading cycle on a specimen subjected to a tensile stress in the plastic regime, then discharged, recharged again in the compression direction, showing that the yield strength in tensile is different from the compression yield strength[2].

Abel and Ham[3] analyzed the Bauschinger effect through the back stress. They showed that the stress produced by the deformation in the initial direction could be observed only in terms of the contributions of the directional and non-directional material strain hardening. Using a tensile testing in materials until the plastic deformation and posteriorly applying a compressive force in discharge operation, the residual stress are not relieved, so the back stress exhibits a loss of elasticity. This loss between the value of the yield strength in one direction (tensile force) and the value of the yield strength in the other direction (compressive) is designated as the back stress.

2. Materials and Methods

The material chosen for this paper was supplied by Atlântico Sul Shipyard, located in the port of Suape - Cabo

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de Santo Agostinho - PE and with the classification of ASTM A131 grade AH-36.

The specimen plates were welded with 70 x 200 x 13.7 mm dimensions and weld with longitudinal and transverse lamination direction, so that the weld beads were produced transversely and parallel to the rolling direction.

The GMAW process was performed with a semiautomatic machine ESAB Smashweld 318 Topflex welding machine and an oxyfuel machine (tortoise) provided by the PRH PB203 program. The calculation of the average thermal input is shown in Table 1.

The welding procedure was performed on top plates with a 25 ° bevel (Figure 1), a V-shaped chamfer with a 2 mm nose and a welding position 1G. The chamfers were manufactured in a machining center of the Mechanical Engineering Department of the Federal University of Pernambuco.

The plates were welded with multiple-layer in the shed of the Department of Mechanical Engineering of the Federal University of Pernambuco. After each pass, the residual material of the wire was removed with a steel brush.

After the welding process, holes were drilled 2mm apart from the weld bead line with center drills of 2.5 mm diameter by 2 mm depth on the HAZ. Each hole was drilled 15 mm apart and the first hole with 85 mm from the reference hole as shown in Figure 2.

Then, the coordinates (x, y) of the center of each hole were mapped based on the reference hole coordinates on a Computer Coordinate Measuring Machine (CMM) with computerized numerical control, model CRYSTA 574 (measuring stroke 700 mm and resolution 0.0005 mm), MITUTOYO manufacture, year 2004, with calibration certificate 03206/2013, from the Coordinated Measurement Laboratory (LAMECO) of the Department of Mechanical Engineering of the Federal University of Pernambuco - UFPE.

After the initial mapping of the points in each plate, it was necessary to carry out a thermal stress relief treatment at a temperature of 680 °C for 30 min. At the end of the relief treatment of the material, the mapped points in the HAZ moved due to the yield of the material. The reference hole zone was not affected by relief treatment because this zone's microstructure is not affected by the welding process and with that, they were again mapped. From these new coordinates of the centers of the holes measured in the CMM, the deformations generated by the welding process were found using equations A and B below.

$$\varepsilon_X = \frac{x_f - x_i}{x_i} \quad \text{(A)}$$

$$\varepsilon_y = \frac{y_f - y_i}{y_i} \quad \text{(B)}$$

Where:

ε_x: Specific deformation in the x-direction;

ε_y: Specific deformation in the y-direction;

x_i: Initial coordinate of the hole in the x-direction (mm);

x_f: Final coordinate of the hole in the x-direction (mm);

y_i: Initial coordinate of the hole in the y-direction (mm);

y_f: Final coordinate of the hole in the y-direction (mm).

With the values of the specific deformation in both directions (x and y), the residual stresses in the plane state of stresses generated by the welding process can be calculated by equations C and D[4]:

$$\sigma_x = \frac{E}{1-\nu^2}(\varepsilon_x - \nu\varepsilon_y) \quad \text{(C)}$$

$$\sigma_y = \frac{E}{1-\nu^2}(\varepsilon_y - \nu\varepsilon_x) \quad \text{(D)}$$

Where:

σ_x: residual stress in x-direction (MPa);

σ_y: residual stress in y-direction (MPa);

E: Young's modulus (GPa);

v: Poisson's coefficient.

According to Okumura[4], the residual stress values σ_x and σ_y are obtained by measuring ε_x and ε_y, which are the residual deformation values of each hole.

The design of experiment is recommended when varing input variables and could introduce and produce significant response in the process. The main experiment purpose is to recognize which input exerts the greatest influence in the response, quantifiy it, and show if there is any combination between inputs that can influence the response in a significant form[5].

Table 1. Welding parameters used in the welding of the plates.

Plate	*Lamination direction*	*Welding voltage (V)*	*Welding current (A)*	*Welding speed (mm/s)*	*Thermal input (kJ/m)*
1	Longitudinal	19,3	220	3,5	979,1
2	Longitudinal	19,7	199	3,5	914,3
3	Transverse	18,9	213,3	3,5	896,5
4	Transverse	19	212,7	3,5	611,9
5	Longitudinal	18,8	219,7	5,4	572,8
6	Longitudinal	18,1	213,6	5,4	554,5
7	Transverse	18,1	206,8	5,4	554,7
8	Transverse	18	208	5,4	971,7

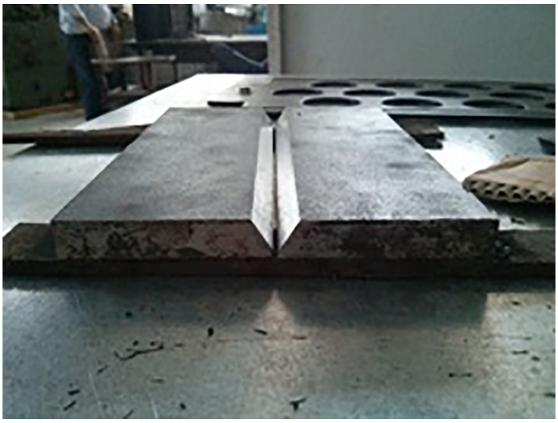

Figure 1. V-shaped chamfer with nose

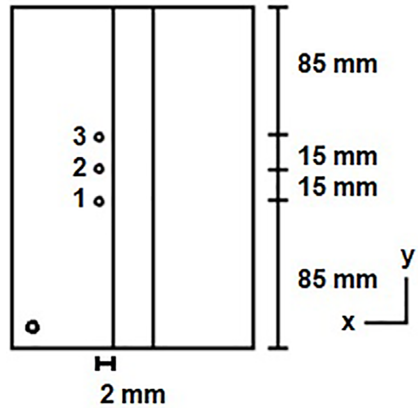

Figure 2. Distribution of the holes in the plate

Table 2. Displacement of the coordinate points measured by the DCP.

Welding speed (mm/s)	*Lamination direction*	*Displacements in X (mm)*						*Average for X (mm)*
		Plate 1			Plate 2			
3,5	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,005
		0,010	0,001	0,006	0,007	0,006	0,001	
		Plate 5			Plate 6			
5,4	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,032
		0,014	0,014	0,013	0,036	0,035	0,081	
		Plate 3			Plate 4			
3,5	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,006
		0,011	0,010	0,006	0,003	0,003	0,004	
		Plate 7			Plate 8			
5,4	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,006
		0,003	0,003	0,002	0,016	0,004	0,006	
Welding speed (mm/s)	***Lamination direction***	***Displacements in Y (mm)***						***Average for Y (mm)***
		Plate 1			Plate 2			
3,5	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,010
		0,013	0,001	0,012	0,011	0,010	0,013	
		Plate 5			Plate 6			
5,4	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,046
		0,024	0,028	0,031	0,055	0,047	0,089	
		Plate 3			Plate 4			
3,5	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,011
		0,017	0,019	0,014	0,005	0,006	0,006	
		Plate 7			Plate 8			
5,4	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	0,011
		0,005	0,005	0,004	0,026	0,008	0,015	

Analysis of variance or ANOVA of two factors works with how each factor influence the response in isolated or combined form. The factors are α-factor and β-factor. When α-factor affects the response in an isolated form, the analyzed effect is called main effect, as well as for β-factor. If one or any factors do not introduce any response effect, they will be considered as non-disturb factors. Another analysis is also made: if the combination between these two factors exists, it will be called a specific combination between α-factor and β-factor. Each factor have or can have a different number for its level, with or without repetition.

For primaries' investigations, factorial experiment with two levels is recommended because it studies if there is a chance of one or two factor affecting the response, even though they do not severely describe this possible influence. Each level can have two or more replication.

The statistical hypothesis test analyzes one statistic hypothesis considering two data sets, where a H0 (null hypothesy) and H1 (alternative hypothesis) will be statistically tested. When H0 is rejected, with a significance level of 5%, for example, the researcher automatically accepts the alternative hypothesis[6]. The The p-value is defined as the probability, under the null hypothesis, of obtaining a result equal to what was actually observed. The smaller the p-value, the larger the significance because it tells the investigator that the hypothesis under consideration may not adequately explain the observation. The null hypothesis is rejected if any of these probabilities is less than or equal to a value of 0.05, that means the null hypothesis can be reject with 95% of level of significance[7].

3. Results and Discussion

Table 2 shows the displacements of the coordinate points measured in the coordinate measuring machine.

For all combinations of parameters, V (welding speed) and factor L (direction of lamination), the values of the displacements of the points were greater in the direction y (direction of the weld bead). However, when working with the weld beads in the transverse direction, the displacements assume closer values.

Table 3. Residual stress values calculated from the DCP method.

Welding speed (mm/s)	*Lamination direction*	*Residual stress in X (MPa)*						*Average for X (MPa)*
			Plate 1			Plate 2		
3,5	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	44,4
		81,6	5,0	55,7	61,1	56,9	6,1	
			Plate 5			Plate 6		
5,4	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	134,5
		124,9	129,8	128,5	162,9	143,6	117,4	
			Plate 3			Plate 4		
3,5	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	57,2
		97,3	92,5	60,7	25,3	30,1	37,1	
			Plate 7			Plate 8		
5,4	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	51,4
		26,9	24,8	18,6	138,2	37,2	62,8	
Welding speed (mm/s)	*Lamination direction*	*Residual stress in Y (MPa)*						*Average for Y (MPa)*
			Plate 1			Plate 2		
3,5	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	48,1
		79,7	5,4	65,7	64	65,9	7,7	
			Plate 5			Plate 6		
5,4	Longitudinal	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	166,0
		135,7	154,4	165,3	163,5	154,6	222,7	
			Plate 3			Plate 4		
3,5	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	62,7
		99,6	104,7	74,8	26,6	34,5	36,1	
			Plate 7			Plate 8		
5,4	Transverse	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	59,4
		28,0	28,8	23,9	148,8	44,1	82,6	

This condition occurs because during the TT the back stress acts by reversing the barriers (blocked dislocations) contributing to the displacement (yield) in the opposite direction to the plastification. However, with the transverse lamination welding, the back stress does not act to reverse the barriers, since the yield is in the direction of the plastification.

Table 3 shows the results of residual stress measurements in X and Y by the DCP method.

Where it is shown that the residual stresses are higher with higher welding speed (lower thermal load) and welded in the longitudinal direction. The results show that the increase of the thermal input through the reduction of the welding speed results in the reduction of the residual stress of welded joints([8]).

The hypothesis tests for factor V and factor L, then:

H0: There is no main effect of welding speed;

H0: There is no main effect of the lamination direction;

H0: There is no combination of effects;

H1: There is an effect in each of the three cases.

Table 4 shows the P-value values for the effects of the factors individually and the interaction effect for both residual stresses in X and Y, the P-value is directly calculated using the software Action Stat version 3.1.43.694.649 year 2016.

Using the p-value of 0.05, the null hypotheses are rejected. Therefore, we are 95% sure that the null hypotheses are false, so there is effect of the welding speed and the lamination direction on the residual stress, and there is a combination of these two effects in the response. Therefore, we can observe these effects through the effect graphs and interactions.

To observe the main effects and interactions of the effects a factorial design 2^2 was performed. The factors were the welding speed and the direction of lamination in relation to the weld bead and for each factor two levels were used. For the welding speed, two velocities of 3.5 (V0) and 5.4 (V1) mm/s were chosen, and the longitudinal direction (L0) and transverse (L1) were also chosen for lamination direction. For each combination of factors and levels, six points were worked out. When the DCP method was used to measure the residual stresses, we were able to assemble our planning matrix shown in Table 3 above.

Using the software Action Stat version 3.1.43.694.649 year 2016 we can analyze the effects of welding speed and lamination direction in the calculation of residual stresses.

We can quantify the value of the main effect of the welding speed, the lamination direction and the interaction effect between the two factors. The main effect is the difference

Table 4. P-value values for the hypothesis test.

ANOVA's table	*P-value for X:*	*P-value for Y:*
Welding speed	0,005	0,001
Lamination direction	0,016	0,007
Welding speed: lamination direction	0,002	0,0007

between the mean response at the upper level and the mean response at the lower level of each factor, equation E:

$$Factor = \overline{y}_{+} - \overline{y}_{-} \quad \text{(E)}$$

Where:

Factor: the factor you want to calculate;

$\overline{y}_{+}$: difference of mean response at the upper level;

$\overline{y}_{-}$: difference of mean response at the lower level.

For the interaction effect, we used the difference between the mean of the tensions between each factor, equation F.

$$Interaction = \left(\frac{\Delta Tension2 - \Delta Tension1}{6} \right) \quad \text{(F)}$$

Where:

Interaction: interaction between factors;

Δ*Tension* 1: difference of the mean response for factor 1;

Δ*Tension* 2: difference of the mean response for factor 2.

Figure 3 shows that the residual stress at X is more sensitive to changing the welding speed than the change in the lamination direction.

When increase the welding speed from 3.5mm/s to 5.4mm/s the average residual stress in X increases from 44.4MPa to 134.5MPa resulting in a gain of 90.1MPa. And when we change the lamination direction the average residual stress at X decreases from 57.2MPa to 51.4MPa resulting in a loss of 5.8MPa. This shows that the effect of the welding speed on the residual stress depends on the lamination direction and the lamination direction on the residual stress depends on welding speed.

Figure 4 shows the graph of interactions of the two factors.

For the welding speed the value of the main effect is, equation G:

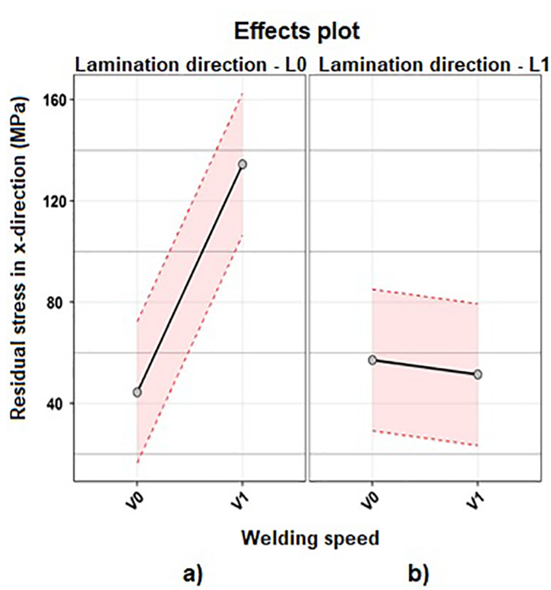

Figure 3. Graph of effects of welding speed and lamination direction a)L0 and b)L1 in the residual stress in X.

$$V\chi = 134{,}5 - 51{,}4 = 83{,}1.MPa \quad \text{(G)}$$

And for the lamination direction, equation H:

$$Lx = 44{,}4 - 57{,}2 =- 12{,}8MPa \quad \text{(H)}$$

For the interaction effect, we use the value of the V effect corresponding to the lower level of the welding speed (which is type A, by our signal convention) of the value corresponding to the upper level (type B), equation I:

$$VL\chi = \frac{90{,}1 - (-5{,}8)}{6} = 16.MPa \quad \text{(I)}$$

Figure 5 demonstrates that the residual stress in Y is also more sensitive to changing the welding speed than changing of lamination direction.

When increase the welding speed from 3.5mm/s to 5.4mm/s the average residual stress in X increases from 48.1MPa to 166.0MPa resulting in a loss of 117.6MPa. And when we change the lamination direction the average residual stress at X decreases from 62.7MPa to 59.4MPa resulting in a loss of 3.3MPa. This shows that the effect of the welding speed on the residual stress depends on the lamination direction and the lamination direction on the residual stress depends on welding speed.

Figure 6 shows the graph of interactions of the two factors.

For the welding speed the value of the main effect is, equation J:

$$Vy = 166{,}0 - 59{,}4 = 106{,}6.MPa \quad \text{(J)}$$

And for the lamination direction, equation K:

$$Ly = 48{,}1 - 62{,}7 =- 14{,}6MPa \quad \text{(K)}$$

For the interaction effect we use the value of the V effect corresponding to the lower level of the welding speed (which is type A, by our signal convention) of the value corresponding to the upper level (type B), equation L:

$$VLy = \frac{117{,}6 - (-3{,}3)}{6} = 20{,}1MPa \quad \text{(L)}$$

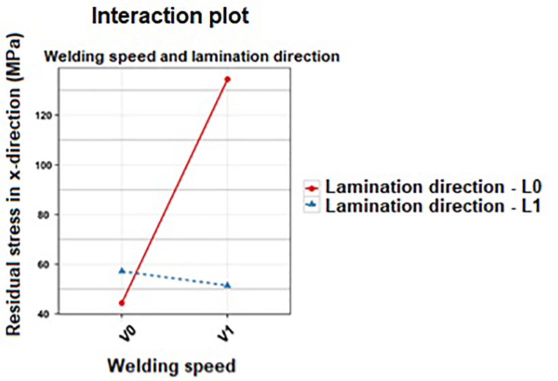

Figure 4. Graph of interactions of welding speed and lamination direction in the residual stress in X

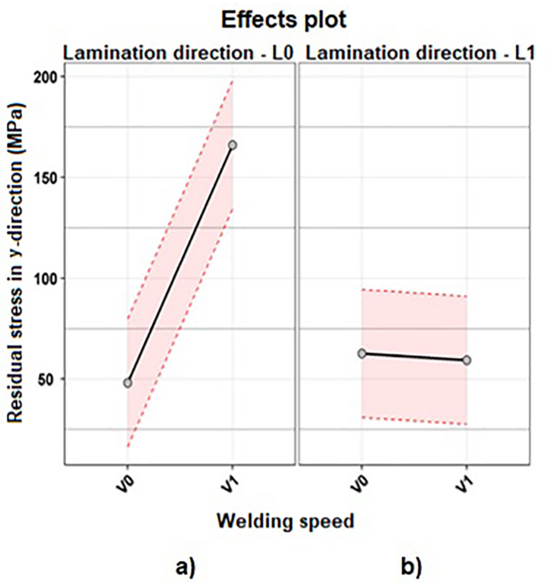

Figure 5. Graph of effects of welding speed and lamination direction a)L0 and b)L1 in the residual stress in Y

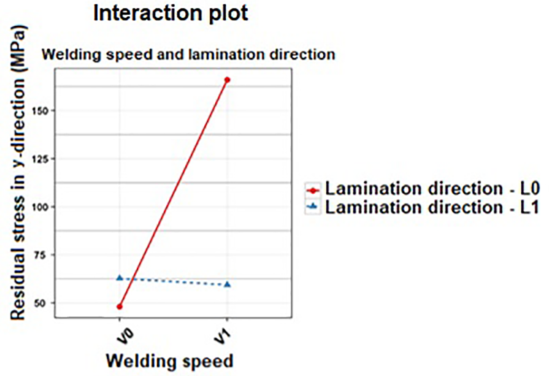

Figure 6. Graph of interactions of welding speed and lamination direction in the residual stress in Y

These results show that the residual stress in both X and Y are more affected by the change in welding speed than in the lamination direction. However, the effect of the interaction of these two factors is greater than the effect produced by the change in lamination direction.

4. Conclusions

For the parameters chosen in this work and the chosen levels, it is concluded that:

By lowering the welding speed, we were able to reduce the residual stress by up to 107 MPa. This happens because this was a multiple-layer welding process, therefore each bead acts as a heat treatment mechanism for the previous bead, decreasing residual stress[9].

When the welding is made in transverse direction, we increase residual stress by up to 15MPa. However, when we increase the welding speed and change the lamination direction, the residual stress increases by up to 20MPa.

In this way, the use of minor welding speed for smaller residual stresses should be preferred.

When welding in the lamination direction the effect of the residual stress on Y way is increased by the back stress of the material.

5. References

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