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The Effect of Spot Welding Current on Shear Strength in St 40 Steel Plate Joints

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Abstract

Steel has several classifications, one of which is low carbon steel St 40. Low carbon steel plate St 40 is usually used for industry, machinery, shipping, household appliances and others. Although it is a low carbon steel and relatively easier to weld, St 40 steel still requires attention to the effects of heat. Excessive heating can change the microstructure of steel in the heat affected zone (HAZ), which has an impact on its mechanical properties. Controlling the electric current in the spot welding process greatly affects the characteristics of the welding results, such as the quality of the weld, tensile strength, hardness, area of the HAZ, and the strength of external influences. This study aims to investigate the effect of electric current in the spot welding process on the shear strength of St 40 steel plate material. The method used is an experimental test, in which the spot welding process was carried out nine times on St 40 steel with three variations of input current (20.36A, 24.54A, and 28.95A) and a welding time of 8.0 seconds, using the shear test method according to the AWS D8.9M shear test standard.Based on the research results, it can be seen that the highest average shear strength is 6.72 MPa, which occurs at an input current of 28.95 A with an output current of 6011.47 A, a welding time of 8.0 seconds with a heat input of 88007.92 J and the lowest average shear strength is 1.67 MPa at an input current of 20.36 A with an output current of 6011.47 A, a welding time of 8.0 seconds with a heat input of 61894.30 J. This shows that increasing the electric current increases the shear strength value and vice versa.

Keywords: *electric current*; *shear strength; spot welding*

Abstrak

Baja memiliki beberapa macam klasifikasi, salah satunya adalah baja karbon rendah St 40. Plat baja karbon rendah St 40 biasanya dipakai untuk industri, permesinan, perkapalan, perkakas rumah tangga dan lain-lain. Meskipun merupakan baja karbon rendah dan relatif lebih mudah dilas, baja St 40 tetap memerlukan perhatian terhadap pengaruh panas. Pemanasan berlebihan dapat mengubah struktur mikro baja di zona terpengaruh panas (HAZ), yang berdampak pada sifat mekaniknya. Pengontrolan arus listrik pada proses pengelasan titik (spot welding) sangat mempengaruhi karakteristik hasil pengelasan, seperti kualitas hasil las, kekuatan tarik, kekerasan, luas daerah HAZ, dan kekuatan pengaruh dari luar.Penelitian ini bertujuan menyelidiki pengaruh arus listrik pada proses *spot welding* terhadap kekuatan geser pada bahan plat baja St 40. Metode yang digunakan adalah uji eksperimental, yang mana proses pengelasan titik dilakukan sembilan kali pada baja St 40 dengan tiga variasi arus *input* (20,36A, 24,54A, dan 28,95A) dan waktu pengelasan 8,0 detik, dengan menggunakan metode pengujian geser sesuai standar uji geser AWS D8.9M. Berdasarkan hasil penelitian dapat diketahui bahwa kekuatan geser tertinggi rata-rata adalah 6,72 MPa, terjadi pada arus *input* 28,95 A dengan arus *output* 6011,47 A, waktu pengelasan 8,0 detik dengan *heat input* 88007,92 J dan kekuatan geser rata-rata yang terendah adalah 1,67 MPa pada arus *input* 20,36 A dengan arus *output* 6011,47 A, waktu pengelasan 8,0 detik dengan *heat input* 61894,30 J. Hal ini menunjukkan bahwa peningkatan arus listrik meningkatkan nilai kekuatan geser dan sebaliknya.

Kata kunci: arus listrik; kekuatan geser; spot welding

1. Introduction

The development of welding technology in every company is required to improve production quality in order to compete with various companies [1]. Welding technology is currently not only used to produce a tool, but welding also functions as a repair of all tools made of metal [2]. Welding is a process of joining two or more metals using heat energy or pressure [3]. The welding method most often used to form neat joints with a fast process, saving joint materials, more efficient, and effective is the Resistance Spot Welding (RSW) method [4].

Resistance Spot Welding (RSW) was developed along with the increasingly easy and cheap use of electrical energy [5]. Electrical resistance welding is a welding method where the surfaces of the plates being joined are pressed against each other and at the same time an electric current is passed through so that the surfaces become hot and melt due to electrical resistance [6]. Spot welding is a type of electrical resistance welding used to weld various sheet metal products, through a process where the points of the metal surfaces in contact are brought together with heat obtained from resistance to electric current [7,8]. The process electric current is determined to control the amount of heat generated in the transformation of electrical energy into heat in the material to be welded, the main process variables are electrode pressure (force), electric current, welding cycle (time), and the type of electrical equipment output [9,10].

The spot welding method is used because it has the advantage of being easy to operate because it does not require special skills like other welding methods, shorter time, thus increasing production speed which has an impact on time efficiency [11]. Controlling the welding electric current greatly affects the characteristics of the welding results because it can affect the quality of the weld, shear strength, hardness, and strength of external influences [12]. If the welding current used is too low, the heat generated is not enough to melt the material, resulting in a small weld metal area and less deep penetration, conversely if the welding current is too high, the melting of the parent metal is too fast and results in a wide weld metal area and deep penetration, resulting in low shear strength and increasing brittleness [12]. Therefore, variations in electric current become a reference for measuring the shear strength of spot welded joints.

The combination of 1.85 kA welding current and 1 second welding time produces the highest tensile strength in dual phase steel (Ferrite-Martensite), while the combination of 0.9 kA current and 0.25 second welding time gives the lowest tensile strength [4]. In spot welding joints between aluminum and steel, a welding current of 75 A provides the highest tensile-shear strength [13]. And a welding current of 8000A and a welding time of 4 cycles produces optimal welding conditions in spot welding joints of AISI 316L austenitic stainless steel [14]. The highest tensile/shear strength and the highest hardness are achieved at a pressing time of 20 seconds on galvanized plate material [15].

Based on the results of research conducted by several researchers in different years, it can be concluded that the variables of pressing welding time, welding current, and welding time have a significant influence on the characteristics of mechanical and physical properties in the resistance spot welding (RSW) process. In this study, a spot welding process was carried out with three variations of input current, namely 24.36 A, 28.54 A, and 32.89 A with a welding time of 8.0 seconds aimed at finding out which welding current is good to be applied to St 40 steel.

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2. Material and Method

2.1. Testing Tools

The equipment used in this research is as follows:

1. Spot Welding Machine, Type DN-16, Model KW14-1031.
2. A milling machine for cutting St 40 steel plate in accordance with the AWS D8.9M shear test standard.
3. A Universal Testing Machine (UTM) for testing the shear strength of St 40 steel plate.

2.2 Materials

The material used in this study was 1 mm thick St 40 steel plate using the AWS D8.9M shear test standard. St 40 steel contains Iron (Fe) = 99.092%, Carbon (C) = 0.16%, Manganese (Mn) = 0.385%, Silicon (Si) = 0.221%, Cobalt (Co) = 0.077%, Cuprum (Cu) = 0.036%, Tungsten (W) = 0.001%, and Phosphorus (P) = 0.026 %.

2.3 Research Procedures

St 40 steel plate material was formed according to the shape and size according to the AWS D8.9M shear test standard as a requirement for conducting shear testing. The spot welding process was carried out nine times on the St 40 steel plate material with three tests at an input current of 20.36A, three tests at an input current of 24.54 A, and three tests at an input current of 28.95 A.

The welding time for each test was 8.0 seconds, then the results of the nine welding samples were transferred to the shear testing chamber. After testing the nine samples with the same work steps, then comparing the data from 3 variations of input currents, namely 20.36A, 24.54A, and 28.95A, and drawing conclusions from the data.

The working steps of this research are as follows:

1. Prepare St 40 steel plate material, then form it according to the size of the standard used for shear testing, namely the AWS D8.9M standard.

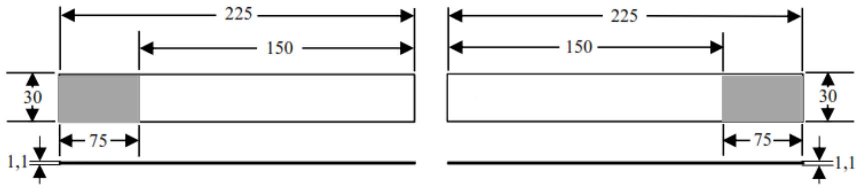

Figure 1. Top and side views of St 40 steel plate [16]

2. Stack 2 pieces of St 40 steel plates using overlap joints with an overlap distance of 30 mm..

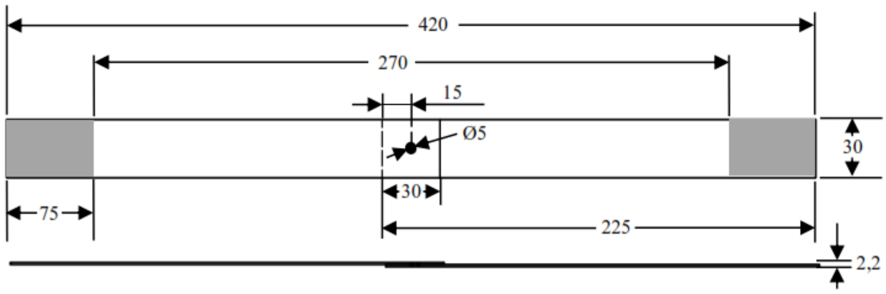

Figure 2. Side and top views of St 40 steel plate [16]

3. The results of spot welding on St 40 steel plate material, then taken to the shear testing room according to the shear test standards on St 40 steel plate with AWS D8.9M standards..
4. Place the shear test specimen on the upper grip and down grip of the shear test machine so that the specimen does not move when performing the shear test..

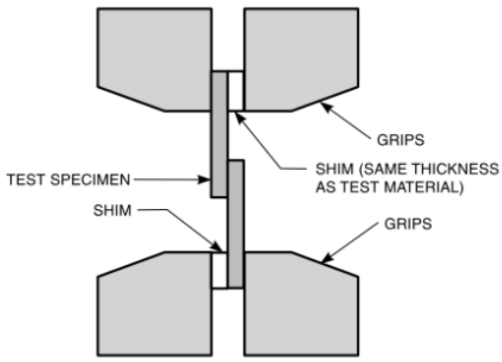

Figure 3. Placing the shear test specimen on the grip [17]

5. Conducting the shear testing process by slowly applying a shear force load until failure or fracture occurs on the St 40 plate according to the AWS D8.9M shear test standard..
6. After carrying out the shear testing process on the specimen, take measurements again on the specimen using a vernier caliper to find the final length and final width, then calculate the shear stress.

3. Results and Discussion

3.1 Research result

From the shear test process on the St 40 steel plate connection, three graphs of loading against elongation were obtained at various input current variations, namely; 20.36 A; 24.54 A and 28.95 A, as shown in Figure 4, Figure 5, and Figure 6..

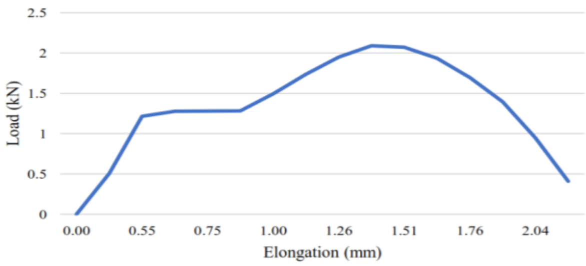

Figure 4. Results of the input current shear test of 20.36 A

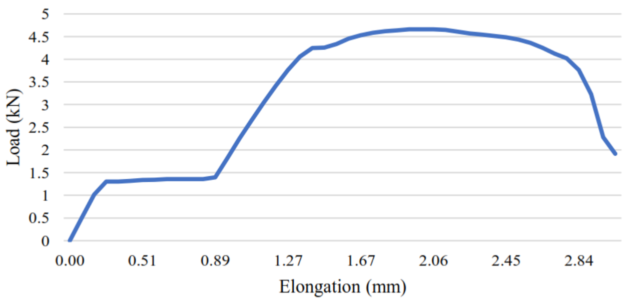

Figure 5. Results of the input current shear test of 24.54 A

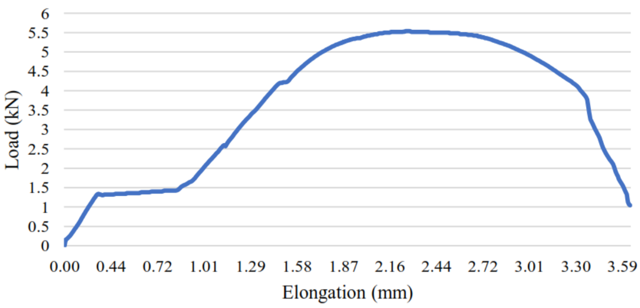

Figure 6. Results of the input current shear test of 28.95 A

3.2 Discussion

3.2.1 Calculation of heat input in spot welding

This spot welding process is carried out using varying electric current parameters. The measured electric current input using an ammeter is 20.36 A, 24.54 A, and 28.95 A. And the welding voltage measured using an ammeter is 1.46 V, 1.64 V, and 1.83 V. Meanwhile, the constant welding time (t) is 8.0 seconds. So that it can be obtained (Q) for each variation of the welding electric current is as follows:

- It is known:

  t = 8,0 detik — $I_{input} = I_1 = 20{,}36$ A ; $I_2 = 24{,}54$ A ; $I_3 = 28{,}95$ A

  V_{input} = 380 V — $V_{output} = V_1 = 1{,}46$ V ; $V_2 = 1{,}64$ V ; $V_3 = 1{,}83$ V

- With: $P_{input} = P_{output} \Leftrightarrow V_{input}\ x\ I_{input} = V_{output}\ x\ I_{output}$

$$380\ V\ x\ 20{,}36\ A = 1{,}46\ V\ x\ I_{output} \quad \Leftrightarrow \quad I_{output} = 5299{,}17\ A \tag{1}$$

$$380\ V\ x\ 24{,}54\ A = 1{,}64\ V\ x\ I_{output} \quad \Leftrightarrow \quad I_{output} = 5686{,}09\ A \tag{2}$$

$$380\ V\ x\ 28{,}95\ A = 1{,}83\ V\ x\ I_{output} \quad \Leftrightarrow \quad I_{output} = 6011{,}47\ A \tag{3}$$

- So that: *Heat input* (Q_1, Q_2, Q_3) $\Rightarrow Q = P_{output}\ x\ t = V_{output}\ x\ I_{output}\ x\ t$

$$Q_1 = 1{,}46\ V\ x\ 5299{,}17\ A\ x\ 8{,}0\ detik = 61894{,}30\ Joule$$

$$Q_2 = 1{,}64\ V\ x\ 5686{,}09\ A\ x\ 8{,}0\ detik = 74601{,}50\ Joule$$

$$Q_3 = 1{,}83\ V\ x\ 6011{,}47\ A\ x\ 8{,}0\ detik = 88007{,}92\ Joule$$

From the calculation above, the amount of heat input (Q) is obtained for each current, the details can be seen in Table 1.:

Table 1. Results of heat input calculations for spot welding

Time (s)	Input Current (A)	Output Current (A)	Heat Input (Joule)
8,0	20,36	5299,17	61894,30
8,0	24,54	5686,09	74601,50
8,0	28,95	6011,47	88007,93

3.2.2 Discussion of the formula used in shear testing

The shear stress formula (τ) connects the shear force (F) with the cross-sectional area (Ao), so that (τ) can be obtained for each variation of welding electric current as follows.:

- Cross-sectional area: A_0 = Length x Width = 30 mm x 30 mm = 900 mm^2
- Shear stress of elastic region:

$$\tau_{1y} = \frac{F_y}{A_o} = \frac{1210\ N}{900\ mm^2} = 1{,}34\ Mpa \Rightarrow \tau_{2y} = \frac{F_y}{A_o} = \frac{1300\ N}{900\ mm^2} = 1{,}4\ Mpa \Rightarrow \tau_{3y} = \frac{F_y}{A_o} = \frac{1340\ N}{900\ mm^2} = 1{,}48\ Mpa$$

- Elastic region shear strain:

$$\varepsilon_{1y} = \frac{\Delta_s}{S_o} = \frac{0{,}55\ mm}{30\ mm} = 0{,}018 \Rightarrow \varepsilon_{2y} = \frac{\Delta_s}{S_o} = \frac{0{,}31\ mm}{30\ mm} = 0{,}010 \Rightarrow \varepsilon_{3y} = \frac{\Delta_s}{S_o} = \frac{0{,}36\ mm}{30\ mm} = 0{,}012$$

- Shear modulus:

$$G_1 = \frac{\tau}{\varepsilon} = \frac{1{,}34\ Mpa}{0{,}018} = 74{,}4\ MPa \Rightarrow G_2 = \frac{\tau}{\varepsilon} = \frac{1{,}4\ Mpa}{0{,}010} = 140\ MPa \Rightarrow G_3 = \frac{\tau}{\varepsilon} = \frac{1{,}48\ Mpa}{0{,}012} = 123{,}3\ MPa$$

Table 2. Shear test results data

No.	Current Input (I_{in}) (Ampere)	Current Output (I_{out}) (Ampere)	Welding Time (t) (Second)	Elastic Region Shear Strength (τ_y) (MPa)	Shear Modulus (G) (MPa)
1	20,36	5299,17	8,0	1,34	74,4
2	24,54	5686,09	8,0	1,40	140
3	28,95	6011,47	8,0	1,48	123,3

➢ Maximum shear stress:

$$\tau_{1max} = \frac{F_{max}}{A_o} = \frac{2090\ N}{900\ mm^2} = 2{,}32\ MPa \Rightarrow \tau_{2max} = \frac{4660\ N}{900\ mm^2} = 5{,}17\ MPa \Rightarrow \tau_{3max} = \frac{5440\ N}{900\ mm^2} = 6{,}15\ MPa$$

➢ Maximum shear strain:

$$\varepsilon_{1max} = \frac{\Delta_s}{S_o} = \frac{1{,}38\ mm}{30\ mm} x\ 100\% = 4{,}6\ \% \Rightarrow \varepsilon_{2max} = \frac{1{,}99\ mm}{30\ mm} x\ 100\% = 6{,}6\ \% \Rightarrow \varepsilon_{3max} = \frac{2{,}26\ mm}{30\ mm} x\ 100\% = 7{,}5\ \%$$

From the results of the shear test, the shear force value obtained from the spot welding joint on St 40 steel plate material is shown in full in Table 3.:

Table 3. Shear test results data

No.	Current Input (I_{in}) (Ampere)	Current Output (I_{out}) (Ampere)	Welding Time (t) (Second)	Shear Force (F_{max}) (Newton)	Shear Strength (τ_{max}) (MPa)
1				1274	1,41
2	20,36	5299,17	8,0	2090	2,32
3				1167	1,29
4				3904	4,33
5	24,54	5686,09	8,0	4660	5,17
6				3640	4,04
7				5892	6,54
8	28,95	6011,47	8,0	6740	7,48
9				5540	6,15

Table 4. Average shear strength data

No.	Current Input (I_{in}) (Ampere)	Current Output (I_{out}) (Ampere)	Welding Time (t) (Second)	Shear Strength (τ_{max}) (MPa)	Average Shear Strength (τ_{max}) (MPa)
1				1,41	
2	20,36	5299,17	8,0	2,32	1,67
3				1,29	
4				4,33	
5	24,54	5686,09	8,0	5,17	4,51
6				4,04	
7				6,54	
8	28,95	6011,47	8,0	7,48	6,72
9				6,15	

➢ Determine the standard deviation; $S = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n}}$

With:

S = Standard deviation ; xi = Data i ; $\bar{x}$= Average ; n = The number of sample data

Shear test results data 1,41 Mpa, 2,32 Mpa, 1,29 Mpa, with n= 3, the standard deviation can be determined;

a) Average shear strength of test results: $\bar{x} = \frac{1,41+2,32+1,29}{3} = \frac{5,02}{3} = 1,67$ MPa

b) Variance of shear strength of test results: $\sigma^2 = \frac{(1,41-1,67)^2+(2,32-1,67)^2+(1,29-1,67)^2}{3} = 0,21$ MPa

c) Standard deviation: $S = \sqrt{0,21\ MPa} = 0,45\ MPa$

Shear test results data 4,33 Mpa, 5,17 Mpa, 4,04 Mpa. with n= 3, the standard deviation can be determined ;

a) Average shear strength of test results: $\bar{x} = \frac{4,33+5,17+4,04}{3} = \frac{13,54}{3} = 4,51$ MPa

b) Variance of shear strength of test results: $\sigma^2 = \frac{(4,33-4,51)^2+(5,17-4,51)^2+(4,04-4,51)^2}{3} = 0,22$ MPa

c) Standard deviation: $S = \sqrt{0,22\ \text{MPa}} = 0,46$ MPa

Shear test results data 6,54 Mpa, 7,48 Mpa, 6,15 Mpa, with n= 3, the standard deviation can be determined ;

a) Average shear strength of test results: $\bar{x} = \frac{6,54+7,48+6,15}{3} = \frac{20,17}{3} = 6,72$ MPa

b) Variance of shear strength of test results: $\sigma^2 = \frac{(6,54-6,72)^2+(7,48-6,72)^2+(6,15-6,72)^2}{3} = 0,3$ MPa

c) Standard deviation: $S = \sqrt{0,3\ \text{MPa}} = 0,54$ MPa

Table 5. Data on average shear strength values with standard deviation

No.	Current Input (I_{in}) (Ampere)	Current Output (I_{out}) (Ampere)	Welding Time (t) (Second)	Shear Strength (τ_{max}) (MPa)	Average Shear Strength (τ_{max}) (MPa)	Standard Deviation (MPa)
1				1,41		
2	20,36	5299,17	8,0	2,32	1,67	0,45
3				1,29		
4				4,33		
5	24,54	5686,09	8,0	5,17	4,51	0,46
6				4,04		
7				6,54		
8	28,95	6011,47	8,0	7,48	6,72	0,54
9				6,15		

Based on Table 5, it can be seen that the shear stress at an input current of 20.36 Amperes has an average shear strength of 1.67 MPa with a standard deviation of 0.45 MPa. The data spread is not too large, indicating that the shear stress values are mostly close to the average. The shear stress at an input current of 24.54 Amperes has an average shear strength of 4.51 MPa with a standard deviation of 0.46 MPa. The spread is slightly larger than the first input current variation, but is still quite consistent around the average value. The shear stress at an input current of 28.95 Amperes has an average shear strength of 6.72 MPa with a standard deviation of 0.54 MPa. The largest spread of the data occurs here, indicating that there is a greater variation in the shear stress values.

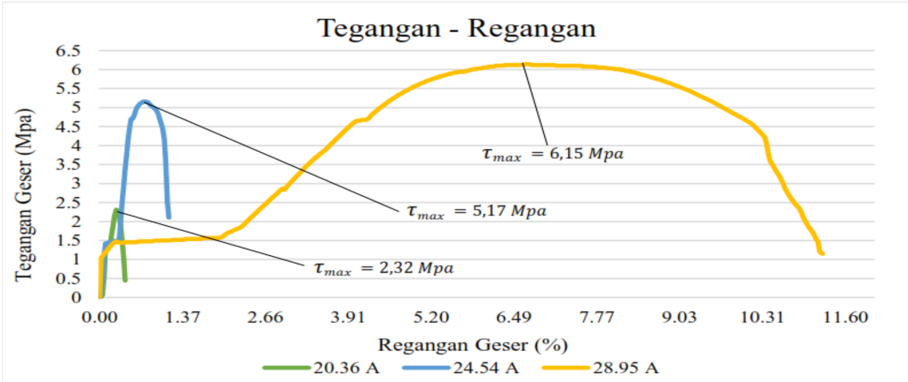

Figure 8. Graph of shear stress against shear strain with variations in electric current

Based on Figure 8, it can be seen that the shear test result curve with an input electric current of 20.36 A at the beginning of the curve, there is an elastic phase where the steel experiences temporary deformation that will return to its original shape after the force is released. This is marked by a straight line showing a linear relationship between stress and strain, in accordance with Hooke's Law. After reaching the elastic limit point (τy = 1.34 Mpa), the steel enters the plastic phase, where permanent deformation begins to occur. The curve begins to bend and shows a significant increase in strain without a large increase in stress. This is the stage where the steel experiences energy absorption before finally reaching the peak point, namely the maximum stress or maximum tensile strength (τmax = 2.32 Mpa). After the maximum stress, the curve will decrease indicating that the connection on the St 40 steel plate begins to experience necking and finally breaks/detached at the last point on the curve..

Meanwhile, the results of the shear test with an input electric current of 24.54 A at the beginning of the curve, there is an elastic phase where the steel experiences temporary deformation that will return to its original shape after the force is released. This is marked by a straight line that shows a linear relationship between stress and strain, in accordance with Hooke's Law. After reaching the elastic limit point (τy = 1.4 Mpa), the steel enters the plastic phase, where permanent deformation begins to occur. The curve begins to bend and shows a significant increase in strain without a large increase in stress. This is the stage where the steel experiences energy absorption before finally reaching the peak point, namely the maximum stress or maximum tensile strength (τmax = 5.17 Mpa). After the maximum stress, the curve will decrease indicating that the connection on the St 40 steel plate begins to experience necking and finally breaks/detached at the last point on the curve.

And the results of the shear test with an input electric current of 28.95 A at the beginning of the curve, there is an elastic phase where the steel experiences temporary deformation that will return to its original shape after the force is released. This is marked by a straight line that shows a linear relationship between stress and strain, in accordance with Hooke's Law. After reaching the elastic limit point (τy = 1.48 Mpa), the steel enters the plastic phase, where permanent deformation begins to occur. The curve begins to bend and shows a significant increase in strain without a large increase in stress. This is the stage where the steel experiences energy absorption before finally reaching the peak point, namely the maximum stress or maximum tensile strength (τmax = 6.15 Mpa). After the maximum stress, the curve will decrease indicating that the connection on the St 40 steel plate begins to experience necking and finally breaks/detaches at the last point on the curve.

The higher the welding current for the same welding time, the greater the shear strength. This is because the higher the welding current, the greater the heat input, which causes structural and grain changes in the weld area, resulting in a region with high hardness. High hardness is also influenced by room temperature cooling, which increases the weld area, which in turn increases the shear strength.

For each increase in welding current, a significant increase in shear strength is observed. This is because variations in welding current result in an increase in heat input, resulting in a weld area that does not increase significantly, but a significant increase in shear force. Therefore, with shear force as the numerator with a large increase and weld area as the denominator with a small increase, the shear strength value obtained drastically increases in Figure 8 for each increase in heat input.

4. Conclusion

From the results of the research and analysis carried out, several conclusions can be drawn as follows:

The lowest average shear strength value is found at an input current of 20.36 A with a welding output current of 6011.47 A, a welding time of 8.0 seconds, with a heat input value of 61894.30 J, which is 1.67 MPa. And the highest average shear strength value is found at an input current of 28.95 A with a welding output current of 6011.47 A, a welding time of 8.0 seconds, with a heat input value of 88007.92 J, which is 6.72 MPa. The electric current is limited because the St 40 steel plate will have holes at an input current of 32.45 A with an output current of 6323.58 A, a welding time of 8.0 seconds, with a heat input value of 98647.84 J.

It can be concluded that increasing the electric current used actually increases the value of the shear force (N) which will also increase the shear strength. This is because as the electric current increases, the heat input will increase, the greater the heat input will increase the ability to melt the metal so that more metal will be melted.

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