International journal of science, engineering, and information technology
Volume 07, Issue 02, July 2023
Journal homepage: https://journal.trunojoyo.ac.id/ijseit

Optimization of Welding Parameters and Cooling Media on the Mechanical Properties of SMAW Welding on CNP Channel Steel Material using Taguchi Method

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A B S T R A C T

CNP channel steel, commonly referred to as lightweight C-channel steel, is a steel bar characterized by its 'C' shaped cross-section, produced through the cooling process of steel plates or strips. This type of steel holds significant importance in construction, as the strength of its connections plays a critical role in its load-bearing capacity. In this research, a low carbon steel, specifically CNP channel steel with a 3 mm thickness, was selected as the base material. The welding parameters included varying welding currents (70 A, 80 A, and 90 A), welding speeds (2 mm/s, 3 mm/s, and 4 mm/s), and different cooling media (NaCl solution, mineral water, and lubricant). Following the welding process, tensile tests were conducted to evaluate the mechanical properties of the welded joints. The Taguchi Orthogonal Array $L_9(3^3)$ method, comprising 9 experiments with 3 replications, was utilized to determine the optimal combination of parameters. The results show that the highest tensile strength recorded was 38.75 N/mm² in the combination of a welding current of 80 A, welding speed of 4 mm/s, and cooling media using mineral water. On the other hand, the lowest tensile strength recorded was 12.70 N/mm² (70 A, 3 mm/s, NaCl solution). The welded joints indicated that 16 specimens experienced brittle fractures, while 11 specimens exhibited ductile fractures. Brittle fractures mainly occurred at the welding joints, while ductile fractures were found in the base material. Based on the Taguchi method, the optimal parameter values were identified a welding current of 90 A, a welding speed of 4 mm/s, and using lubricant as the cooling media which welding current holds the highest percentage of contribution.

Keywords: Welding parameters, CNP channel steel, Cooling media, Tensile strength, Taguchi

Article History
Received 30 May 23 Received in revised form 02 June 23 Accepted 04 July 23

1. Introduction

Shielded Metal Arc Welding (SMAW) is one of the most widely used welding methods. SMAW is a welding technique that employs a metal electrode coated with flux to create an electric arc between the electrode tip and the parent metal. The heat generated by the electric arc causes the electrode tip and the parent metal to melt and solidify simultaneously [1].

Azwinur et al. [2] state that SMAW welding is extensively utilized due to its ease of process, excellent weld quality in terms of both physical and mechanical properties, as well as its cost-effectiveness. However, this welding technique heavily relies on the skill of the welder, the type of electrode (welding wire), welding speed, and the welding current strength used. Additionally, the cooling media type also influences the cooling rate during the process, wherein the cooling capacity of the cooling media determines the grain structure that forms and subsequently affects the tensile strength of the welding results [3].

This study conducts experiments to determine the optimal parameters of welding current, welding speed, and cooling media type with regards to the mechanical properties (tensile strength) of SMAW welding on CNP channel steel material. The characteristics of the welded joints are also analyzed to find the brittle and ductile fractures indicated on the welded joints.

2. Methods

This study is an experimental research conducted in the laboratory. In this research, the test specimen used is CNP channel steel, which is a commonly used material in the construction industry. Based on the Indonesian National Standard (SNI) [4], lightweight C-channel steel is a steel bar that has a cross-section shaped like the letter 'C', which is manufactured through the cooling process of steel plates or steel strips. The surface of this C-channel steel must be flat and free from visible defects such as cracks or other detrimental flaws when the C-channel steel is in use. C-channel steel is made from raw materials of steel plates that conform to the SNI 07-0724-1989 standard for channel steel used in construction or in the form of sheets. The chemical composition of this CNP channel steel is shown in Table 1.

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Table 1. The chemical composition of CNP channel steel [4]

Composition (%)		
C (karbon)	*P (fosfor)*	*S (sulfur)*
Max. 0,25	Max. 0,050	Max. 0,050

The material undergoes SMAW welding process with variations in welding current, welding speed, and cooling media type, each of the parameters is having 3 levels of variation. Subsequently, a tensile test is performed to evaluate the mechanical properties of the weldments. To proceed the tensile strength test, the speciments are formed and dimensioned as shown in Figure 1 following the ASTM A370 standard.

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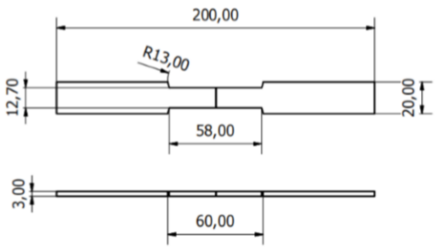

Figure 1. Design of the speciment (in mm) based ASTM A370

In order to assess the impact of welding parameters on mechanical properties, specifically tensile strength, and determine the optimal machining parameters, a carefully design of experiment (DOE) approach is necessary. In this study, the experiments are conducted using the Taguchi method with orthogonal arrays to create a comprehensive design matrix that encompasses all potential combinations of process parameters. The purpose of this study is to identify the optimal machining parameters that maximize tensile strength in welding CNP channel steel. Table 2 shows the factor levels of each welding parameters.

Table 2. Welding parameters and factor levels

Symbol	Parameters	Level 1	Level 2	Level 3
I	Welding current (A)	70	80	90
V	Welding speed (mm/s)	2	3	4
C	Coolant type	NaCl	Mineral water	Lubricant

According to Kamenichny, as cited in Viantoro [5], the use of common salt or sodium chloride (NaCl) for cooling welding results is due to NaCl having a strong ionic bond and easy solubility in water. Water, which is used for cooling, can rapidly decrease the temperature, reaching 600 degrees at 18 degrees Celsius. On the other hand, when salt dissolves in water, it can significantly increase the cooling rate, reaching 1100 degrees at 18 degrees Celsius. The mineral water used in this research has pH 8+ and the lubricant used for cooling was Oil SAE 40, a lubricant with viscosity of 40 at a temperature of 100°C. When used for cooling, the lubricant will create a carbon layer on the object, depending on the viscosity and carbon content of the test specimen. Viscosity becomes a critical factor in the properties of the oil, as it is related to the thickness or resistance of the oil to flow [6].

In this research, the behavior of three control factors, namely welding current, welding speed, and coolant type, were investigated. The observed results were then converted into Signal-to-Noise (S/N) ratios. The Taguchi method employs three main characteristics for S/N ratios: "larger is better," "nominal is best," and "smaller is better." [7]. For the tensile strength, the "larger is better" characteristic was considered, indicating that higher values represent superior performance, while the "smaller is better" characteristic suggests that lower values indicate better performance. To calculate the S/N ratio for the "larger is better" characteristic for each level of parameter combination, a specific formula need to be applied. To compute the larger is better S/N ratio for each level factor combination, this formula is applied, which n denotes the number of applications and yi represents the value of measured observation [7].

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (1)$$

3. Results and Discussions

Figure 2 shows the first speciment for mechanical properties testing before test and after test, and Figure 3 shows the laboratory test for tensile strength.

Before After

Figure 2. Speciment before and after tensile test

Figure 3. Tensile strength test in the laboratory

3.1. General guidelines for the preparation of your text

The design of experiment is following Taguchi method steps with orthogonal arrays of L_9 (3^3). The welding process parameters was analysed using Minitab 19 software. Table 3 shows the results of tensile strength test and signal-to-ratios (S/N Ratio) for each values. The tensile strength values shown in Table 3 represent the average value of the three replication for each experiment.Avoid hyphenation at the end of a line.

Table 3. The experimental design and results

Exp. Number	I (A)	V (mm/s)	Cooling Media	Tensile Strength, TS (N/mm^2)	S/N Ratio
1	70	2	Water	19.16	25,64
2	70	3	NaCl	12.70	19,52
3	70	4	Lubricant	30.31	29,08
4	80	2	NaCl	30.28	29,06
5	80	3	Lubricant	36.24	31,04
6	80	4	Water	38.75	31,74
7	90	2	Lubricant	28.67	29,07
8	90	3	Water	38.16	31,61
9	90	4	NaCl	37.51	31,47

Based on Table 3, response table for tensile strenght S/N Ratio was made as shown on Table 4. Following that, the main effects plot for S/N ratio which shows the effect of each factor parameters on tensile strenght can be seen on Figure 4.

Table 4. S/N response table for TS

Level	I	V	C
1	25,79	28,14	29,99
2	30,86	28,30	27,73
3	30,75	30,96	29,68
Delta	5,07	2,82	2,26
Rank	1	2	3

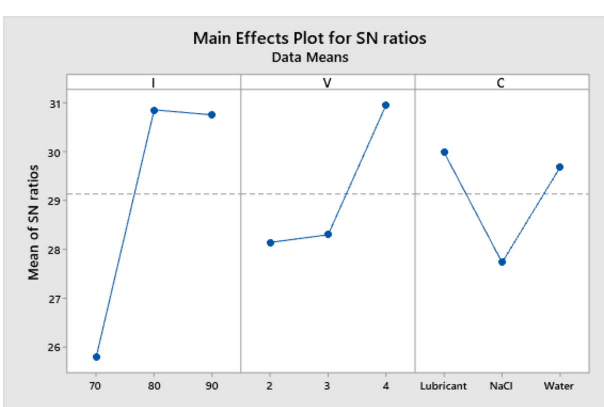

Figure 4. Main effect plot for S/N ratio

Based on Table 4, it is noticed that welding current has dominated the result of tensile strentgh, followed by welding speed and coolant media type. Figure 4 shows a linear graph illustrating the influence of each factors on the larger is better Signal-to-Noise Ratio (SNR). Based on Figure 4, the optimal values for the larger is better SNR are a welding current of 80 A, welding speed of 4 mm/s, and coolant type as lubricant.

3.2. Analysis of variance (ANOVA)

An Analysis of Variance (ANOVA) is conducted at a 95% confidence interval to assess the main effects of input parameters on individual responses. The results of the ANOVA for tensile strength are presented in Table 5. A parameter or factor is considered significant or significantly influences the response parameter when its P-value is less than 0.05.

Table V. ANOVA for Tensile Strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
I	2	404,09	202,04	6,68	0,130	61,52
V	2	141,10	70,55	2,33	0,300	21,48
C	2	51,16	25,58	0,85	0,542	7,79
Error	2	60,53	30,26			9,21
Total	8	656,87				100

Table 5 reveals that tensile strength is predominantly influenced by the type of welding current, followed by welding speed and coolant media. The percentage contribution of welding current, welding speed, and coolant media type to tensile strength is 61.52%, 21.48%, and 7,79%, respectively, as indicated in Table 5. This result similar to S/N ratio analysis discussed on A. The ANOVA analysis indicated that the tensile strength are not significantly influenced by the control parameters, as the P-value for all parameter were found to be more than 0.05.

3.3. Fracture analysis of welded joint

After the completion of mechanical testing, a fracture analysis is performed to identify the type of fracture that has occurred in the specimens. Figure 5 and Figure 6 illustrates the various fracture patterns observed in the specimens resulting from the tested mechanical combinations.

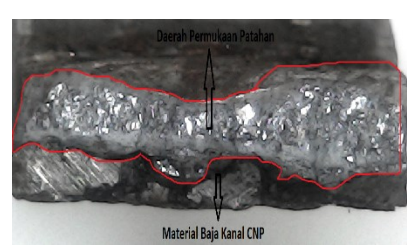

Figure 5. Brittle welded joint

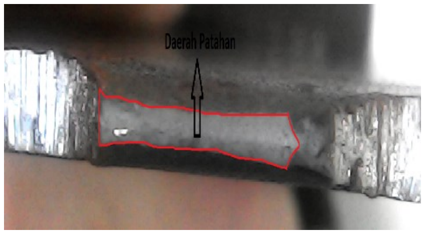

Figure 6. Ductile welded joint

Table 6 presents the distribution of different fracture types observed from the experiments conducted in this research.

Table 6. Distribution of Fracture Types

Parameter	Level	Quantity	
		Brittle	Ductile
I	70	8	1
	80	3	6
	90	5	4
V	2	8	1
	3	5	4
	4	3	6
C	Water	4	5
	NaCl	6	3
	Lubricant	6	3

According to Zulhafril *et al.* [8], the post-welding use of cooling media has a significant impact on the tensile strength of carbon steel. Different cooling media variations lead to varying cooling rates, which in turn affect the tensile strength differently. When the welded material transfers heat to the cooling media, it creates a vapor sheath around the steel's surface, slowing down the heat transfer process. The effectiveness of cooling media depends on factors such as temperature, viscosity, solution content, and alkaline properties. As stated by Kurniawan *et al.* [9], the fracture shape of a material is affected by its carbon content. Higher carbon content leads to the formation of more martensitic structures, resulting in increased hardness. Additionally, slow cooling plays a role in determining the fracture shape since slow cooling prevents the formation of hard and brittle martensitic structures [10].

The results of this study revealed a higher occurrence of brittle fractures compared to ductile fractures. Upon close examination, it was evident that lower welding currents and welding speeds predominantly contributed to the occurrence of brittle fractures. As for the cooling media, mineral water displayed the fewest occurrences of brittle fractures, whereas NaCl solution and oil exhibited an equal number of fractures. Additionally, brittle fractures were observed to take place in thin welds, particularly at the welding joints.

On the other hand, this research revealed that ductile fractures were predominantly associated with a welding current of 80 amperes and a welding speed of 4 mm/s when using mineral water as the cooling medium. Ductile fractures are recognizable by the presence of a concave area with a bluish-gray surface color at the fractured region. The gray color on the fracture surface indicates the missing portion. Upon examining the ductile fractures that occurred in the specimens, it was observed that thicker and wider welding results led to fractures occurring not at the welding joints but within the body of the specimen. Before experiencing ductile fractures, the specimens underwent necking in the necking area until they ultimately fractured.

4. Conclusion

This research examines the influence of welding parameters and cooling media on the mechanical properties, specifically tensile strength, of CNP channel steel welding joint. The experiment was conducted based on The Taguchi orthogonal array $L_9(3^3)$ method to find the optimal combination of welding parameters. The findings revealed that the highest recorded tensile strength was 38.75 N/mm², achieved with a welding current of 80 A, welding speed of 4 mm/s, and mineral water as the cooling media. Conversely, the lowest tensile strength recorded was 12.70 N/mm², obtained with a welding current of 70 A, welding speed of 3 mm/s, and NaCl solution as the cooling media. Among the welded joints, 16 specimens experienced brittle fractures, while 11 specimens exhibited ductile fractures. The brittle fractures were mainly observed when using lower welding currents and slower welding speeds. On the other hand, ductile fractures were more common with a welding current of 80 amperes and a welding speed of 4 mm/s, with mineral water used for cooling. Ductile fractures can be identified by the presence of a concave depression and a bluish-gray surface color at the fracture area. Brittle fractures mainly occurred at the welding joints, while ductile fractures were found in the base material.. According to the Taguchi method, the optimal parameter values were determined as a welding current of 90 A, welding speed of 4 mm/s, and using lubricant as the cooling media..

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