Jurnal Rekayasa Mesin
p-ISSN: 1411-6863, e-ISSN: 2540-7678
Vol.21, No.1, April **2026**, p. 39-50

Effects of Welding Current and Material Thickness on Hardness and Tensile Strength of SPCC Steel Welded Using the Metal Inert Gas (MIG) Process

Sutrisno[1], Yohanes Maria Astomo Dwi S[2], Aditya Nugraha[3], Adhi Setya Hutama[4], Rudi Kristianto[5], Yohanes Oscar Andrian[6]
[1]Teknologi Rekayasa Mekatronika, Politeknik ATMI Surakarta,
[2]Teknik Perancangan Mekanik dan Mesin, Politeknik ATMI Surakarta,
[3]Rekayasa Teknologi Manufaktur, Politeknik ATMI Surakarta,
[4]Perancangan Manufaktur, Politeknik ATMI Surakarta,
[5]Teknik Mekatronika, Politeknik ATMI Surakarta,
[6]Teknik Mesin Industri, Politeknik ATMI Surakarta
Jl. Mojo No. 01, Karangasem, Laweyan, Surakarta
*E-mail: sutrisno@atmi.ac.id

Submitted: 02-12-2025; Accepted: 21-04-2026; Published: 30-04-2026

Abstract

This study investigates the effect of welding current and material thickness on the hardness and tensile strength of cold-rolled SPCC steel welded using the Metal Inert Gas (MIG) process. Welding current was varied at 80 A, 90 A, and 100 A, while material thicknesses of 0.9 mm, 1.4 mm, and 2.0 mm were used. Specimens were prepared according to the ASTM E8 standard for tensile testing. Hardness measurements were conducted in the heat-affected zone (HAZ) and base metal using the Leeb hardness method, while tensile properties were evaluated through tensile testing. The results show that welding current and material thickness significantly affect the mechanical properties of the welded joints. The highest hardness value of 672 HLD was obtained at a welding current of 100 A with a plate thickness of 0.9 mm, whereas the lowest hardness value of 232 HLD occurred at 80 A with a thickness of 2.0 mm. The highest average tensile strength of 340.56 N/mm² was achieved at 90 A with a thickness of 1.4 mm. The results indicate that a moderate welding current provides optimal tensile performance, whereas higher current levels increase hardness due to greater heat input during the welding process. Therefore, appropriate parameter selection is essential to achieve optimal welding performance in thin SPCC steel plates.

Keywords: MIG welding; SPCC steel; welding current; plate thickness; hardness; tensile strength.

Abstract

Studi ini menyelidiki pengaruh arus pengelasan dan ketebalan material terhadap kekerasan dan kekuatan tarik baja SPCC canai dingin yang dilas menggunakan proses Metal Inert Gas (MIG). Arus pengelasan divariasikan pada 80 A, 90 A, dan 100 A, sedangkan ketebalan material yang digunakan adalah 0,9 mm, 1,4 mm, dan 2,0 mm. Spesimen disiapkan sesuai dengan standar ASTM E8 untuk pengujian tarik. Pengukuran kekerasan dilakukan di zona yang terkena panas (HAZ) dan logam dasar menggunakan metode kekerasan Leeb, sedangkan sifat tarik dievaluasi melalui pengujian tarik. Hasil menunjukkan bahwa arus pengelasan dan ketebalan material secara signifikan memengaruhi sifat mekanik sambungan las. Nilai kekerasan tertinggi sebesar 672 HLD diperoleh pada arus pengelasan 100 A dengan ketebalan pelat 0,9 mm, sedangkan nilai kekerasan terendah sebesar 232 HLD terjadi pada 80 A dengan ketebalan 2,0 mm. Kekuatan tarik rata-rata tertinggi sebesar 340,56 N/mm² dicapai pada arus 90 A dengan ketebalan 1,4 mm. Hasil ini menunjukkan bahwa arus pengelasan sedang memberikan kinerja tarik yang optimal, sedangkan tingkat arus yang lebih tinggi meningkatkan kekerasan karena masukan panas yang lebih besar selama proses pengelasan. Oleh karena itu, pemilihan parameter yang tepat sangat penting untuk mencapai kinerja pengelasan yang optimal pada pelat baja SPCC tipis.

Kata kunci: MIG welding; SPCC steel; welding current; plate thickness; hardness; tensile strength

1. Introduction

The rapid growth of modern manufacturing industries has increased the demand for reliable joining processes, particularly for thin-gauge steel components used in automotive, home appliances, and general fabrication [1]. Welding remains one of the most widely applied joining techniques due to its efficiency, structural integrity, and compatibility with mass-production requirements [2]. Among various welding processes, Metal Inert Gas (MIG) welding—also known as Gas Metal Arc Welding (GMAW)—is highly favored for its high deposition rate, ease of automation, and suitability for thin and medium-thickness steels [2], [3].

In MIG welding, the selection of process parameters such as welding current, arc voltage, gas flow rate, electrode feed rate, and travel speed significantly influences weld bead geometry, penetration depth, heat-affected zone (HAZ) characteristics, and ultimately the mechanical properties of the joint [2], [3], [13]–[15]. As noted variations in current and associated heat input directly affect fusion quality and microstructural evolution within the weld region [7], [13]–[15]. Similarly, [5], [7], [13] highlight that welding current and voltage govern heat generation, influencing cooling rate and resulting hardness.

Previous studies have shown that increasing welding current up to an optimum level improves tensile strength [7], [8]. Similar trends have been reported for aluminum alloys, where current variations affect both hardness and tensile properties [9]. Other studies also observed that intermediate current levels produce optimal tensile performance in GMAW-welded steels [8]. These studies confirm that welding current strongly influences weld metal integrity and joint strength [9].

However, most previous studies primarily focus on structural steels or aluminum alloys, while investigations on thin-gauge Steel Plate Cold Rolled Coiled (SPCC) steel remain relatively limited. Therefore, further studies are required to better understand the welding behavior of SPCC steel, particularly under varying welding parameters. SPCC steel, containing less than 0.15% carbon, is widely used in sheet-metal components such as automotive panels, housings, and structural enclosures due to its excellent formability, yet its weldability under MIG welding, particularly the combined effects of welding current and material thickness, has not been sufficiently explored. Although many studies analyze current variations, comprehensive investigations involving both current and thin-sheet thickness (0.9–2.0 mm) for SPCC steel are still limited.

This gap is important because thin sheets exhibit higher sensitivity to heat input, affecting distortion, HAZ width, hardness gradients, and tensile performance. Increased heat input may enhance fusion but can also cause excessive softening or hardening depending on cooling rates. Understanding these effects is essential for optimal welding parameter selection, especially for industrial processes involving precision and high-volume production of SPCC components.

Therefore, this study aims to investigate the combined influence of welding current and material thickness on the mechanical properties of MIG-welded SPCC steel in order to provide a clearer understanding of how heat input variations affect hardness and tensile behavior. Three current levels (80 A, 90 A, and 100 A) and three plate thicknesses (0.9 mm, 1.4 mm, and 2.0 mm) were examined. Hardness measurements were conducted in the HAZ and base metal regions using the LEEB method, and tensile tests were carried out according to ASTM E8 standards.

The findings of this study are expected to provide practical recommendations for selecting MIG welding parameters suitable for thin-gauge SPCC steel and contribute to improved weld quality in industrial applications. By understanding how variations in current and thickness interact to influence mechanical performance, manufacturers can optimize welding practices to achieve stronger and more consistent joints [1].

2. Methodology

This study adopted an experimental approach to investigate the effects of welding current and material thickness on the hardness and tensile strength of SPCC Steel welded using the Metal Inert Gas (MIG) Welding process.

In this experiment, welding current and material thickness were defined as the independent variables, while hardness and tensile strength were considered the dependent variables. A series of welded specimens were fabricated using different combinations of welding current and material thickness. The prepared specimens were subsequently subjected to mechanical testing to evaluate the resulting hardness and tensile strength of the welded joints.

2.1. Materials and Specimen Preparation

The material used in this study was SPCC Steel, which is commonly used in sheet metal applications due to its good formability and weldability. SPCC steel plates were prepared in three thickness variations to evaluate the influence of material thickness on the mechanical properties of the welded joints. The base material used in this study was Steel Plate Cold Rolled Coiled (SPCC), classified as low-carbon steel according to JIS G3141 [12]. Its nominal chemical composition is provided in Table 1.

Table 1. Chemical composition of SPCC material according to JIS G314 : 2011 [12]

Material	Chemical Composition (%)				Tensile Strength (N/mm ^{2})
SPCC	C (Max)	Mn (Max)	P (Max)	S (Max)	270
	0.15	0.60	0.05	0.05	

Three thicknesses—0.9 mm, 1.4 mm, and 2.0 mm—were selected to represent thin-gauge SPCC sheet commonly used in industrial components. Sheets were cut into 105 × 90 mm pieces using a semi-automatic shear cutting machine (Promecam GTH 430). For each thickness, six pieces were prepared, resulting in a total of 18 initial plate specimens on the Table 2.

Table 2. Initial dimensions of SPCC specimens

Material	W x W x H (mm)	Total
SPCC	105 x 90 x 0.9	6 pcs
	105 x 90 x 1.4	6 pcs
	105 x 90 x 2	6 pcs

After welding, the specimens were machined into tensile test samples following the ASTM E8 standard [13] Figure 1. This ensured consistency in gauge length, width, and gripping surfaces.

Figure 1. ASTM E8 standard specimen

2.2. Welding Electrode and Equipment

Welding was performed using a GOODWELD 315 MIG welding machine. The electrode used was ER70S-3 (Pinnacle Alloys SOWESCO AWS Class ER70S-3), whose chemical composition is listed in Table 3.

Table 3. Chemical composition ER70S-3 (SOWESCO AWS Class ER70S-3)

AWS	C	Mn	Si	S	P	Cu
ER70S-3	0.06-0.15	0.90-1.40	0.45-0.70	0.025	0.035	0.5

A shielding gas mixture of CO_2 was applied during welding [12]. All welds were made in the 1G horizontal position [14] detail for 1G position on Figure 2 with a single-pass bead layout except for thicker plates, where additional layers were used to ensure full penetration.

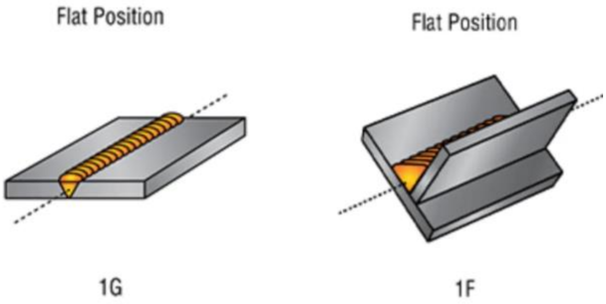

Figure 2. Welding 1G Position

Before welding, specimens were fixed using tack welds to prevent distortion explanation on the Figure 3.

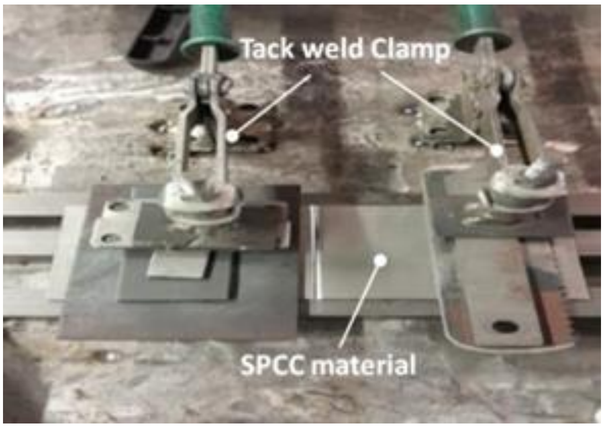

Figure 3. Welding position of specimens (SPCC)

2.3. Welding Parameters and Variable Control

In this study, welding parameters and control variables were determined to ensure the testing process was carried out systematically and measurably. The two main independent variables used were welding current and material thickness. The applied welding current variations consisted of 80 A, 90 A, and 100 A, while the material thickness variations used were 0.9 mm, 1.4 mm, and 2.0 mm. In addition, the welding speed was determined based on the travel time required for each welding path (bead). The welding time was used to calculate the resulting welding speed value. A summary of the recorded welding time, number of bead layers, and calculated welding speed is presented in detail in Table 4.

Table 4. Welding parameters and calculated travel speed

Welding length for plates 90 mm				
Current (A)	**Thickness (mm)**	**Layers (unit)**	**Time/ layers (second)**	**Welding speed (mm/s)**
80	0.9	1	1'30"	1
	1.4	2	1'55'	1.27
	2	3	2'	1.33
Total time & welding speed			5'25"	3.6
Average speed				1.2
90	0.9	1	1'20"	0.88
	1.4	2	1'34"	1.04
	2	3	1'50"	1.22
Total time & welding speed			4'44"	3.14
Average speed				1.04
100	0.9	1	1'15"	0.83
	1.4	2	1'27"	0.96
	2	3	1'45"	1.16
Total time & welding speed			4'27"	2.95
Average speed				0.98

Heat input in the welding process is calculated using an equation that relates welding voltage, welding current, welding speed, and process efficiency. This equation is generally expressed as:

$$HI = \frac{E.I.\eta}{\upsilon} \tag{1}$$

Where:

HI : heat input (J/mm)
E : represents the welding voltage, which was assumed to remain relatively constant during the welding process according to the machine operating settings (V)
I : welding current (A)
υ : welding speed (mm/s)
η : process efficiency (90%)

This equation is widely used in welding process analysis because heat input significantly influences the microstructure and mechanical properties of the weld zone and heat-affected zone (HAZ) [15].

The heat input values are shown in Table 5.

Table 5. Calculated heat input

Current (A)	**Heat Input (J/mm)**
80	900
90	1168.26
100	1377.55

2.4. Hardness Testing

Hardness was measured using a Portable Hardness Tester TH-160, applying the Leeb rebound method. Measurements were taken at four locations: HAZ 1, HAZ 2, Base Metal 1, and Base Metal 2, as illustrated in Figure 4. For each current–thickness combination, three specimens were tested, and average values were reported.

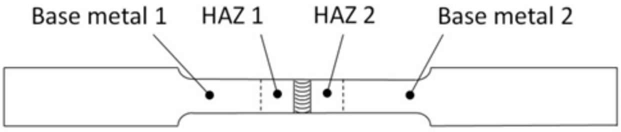

Figure 4. Hardness testing area

2.5. Tensile Testing

Tensile tests were performed using a HD-KB605S Tensile Tester with a capacity of 100 kg. The specimens were prepared in a dog-bone geometry following the standard specified in ASTM E8/E8M. During testing, each specimen was subjected to uniaxial tensile loading until fracture occurred.

The maximum load recorded during the test was used to calculate the tensile strength using Equation (2):

$$\sigma = \frac{F_{max}}{A} \tag{2}$$

Where:

σ : tensile strength (N/mm² or MPa)
Fmax : maximum applied force (N)
A : cross-sectional area of the reduced section of the specimen (mm²)

To ensure the reliability and repeatability of the experimental data, each combination of welding current and material thickness was tested in three repetitions (triplicate tests), and the average value was used for analysis.

3. Results and Discussion

3.1. Heat Input Characteristic

The experimental results indicate that welding current and material thickness significantly influence the mechanical properties of SPCC Steel welded using the Metal Inert Gas (MIG) Welding process. An increase in welding current resulted in higher heat input, which affected the microstructure and mechanical characteristics of the welded joints. The hardness values tended to increase with higher welding currents, particularly in the heat-affected zone (HAZ), where the highest hardness value of 672 HLD was recorded for the 0.9 mm specimen welded at 100 A. This condition is associated with higher thermal input followed by rapid cooling, which promotes localized hardening. However, the tensile strength exhibited a non-linear trend with respect to welding current. Although moderate welding current improved joint strength, excessive current led to a decrease in tensile strength due to overheating and grain coarsening within the weld region. The highest tensile strength of 340.56 N/mm² was obtained at a welding current of 90 A with a material thickness of 1.4 mm, indicating that moderate heat input provides a more balanced microstructure and improved mechanical performance. These findings demonstrate that both welding current and plate thickness play critical roles in determining the overall quality and mechanical behavior of MIG-welded SPCC steel joints.

3.1.1. Hardness Test Result

The hardness test was conducted to evaluate the effect of welding parameters on the hardness distribution of SPCC Steel welded using the Metal Inert Gas (MIG) Welding process. The measured hardness values provide an indication of the microstructural changes occurring in the weld metal and heat-affected zone for table 6 due to variations in welding current and material thickness.

Table 6. Average LEEB hardness values

Current (A)	Thickness (mm)	Hardness Test Areas				Average Hardness (HLD)
		HAZ 1 (HLD)	HAZ 2 (HLD)	Base Metal 1 (HLD)	Base Metal 2 (HLD)	
80	0.9	443	424	404	405	419
	1.4	422	433	310	315	370
80	2.0	308	346	260	232	287
90	0.9	515	590	300	240	412
	1.4	485	445	331	325	397
	2.0	402	407	390	305	376
100	0.9	583	672	458	461	544
	1.4	444	507	352	348	413
	2.0	353	415	255	269	323

3.1.2. Effect of Welding Current on Hardness

The results indicate a clear trend in which hardness increases with increasing welding current across all material thicknesses, suggesting that heat input plays a significant role in influencing the thermal cycle and resulting microstructural transformation within the HAZ. The highest hardness value, 672 HLD, was recorded in the Heat Affected Zone (HAZ) of a 0.9 mm thick specimen welded using a current of 100 A. This increase in hardness was influenced by several factors, including increased heat input during the welding process, relatively rapid cooling due to the thin material cross-section, and the formation of relatively harder microstructural constituents in the heat-affected zone due to rapid thermal cycling during welding [12]–[14].

Conversely, the lowest hardness value, 232 HLD, was obtained for a 2.0 mm thick material welded using a current of 80 A. Thicker materials have better heat absorption and distribution capabilities, resulting in slower cooling. This results in a relatively softer microstructure compared to thinner materials.

3.1.3. Effect of Material Thickness on Hardness

For all welding currents, hardness decreased with increasing thickness. Thin specimens (0.9 mm) cooled rapidly, producing a narrower but harder HAZ. Thicker specimens (2.0 mm) acted as heat sinks, reducing cooling rate and hardness.

3.2. Interpretation

The results of this study indicate that welding parameters, particularly welding current and material thickness, significantly influence the mechanical properties of MIG-welded SPCC steel joints. Welding current determines the magnitude of heat input applied during the welding process, which directly affects the melting behavior of both the base metal and the filler material, as well as the cooling rate during solidification. An appropriate level of heat input promotes proper fusion and adequate penetration, leading to a more homogeneous weld structure and improved mechanical properties. Conversely, insufficient welding current may result in incomplete fusion at the weld interface, while excessive current can generate excessive heat input that promotes grain coarsening in the heat-affected zone (HAZ). This microstructural coarsening can reduce the strength and hardness of the welded joint. Such behavior is consistent with established principles of welding metallurgy reported in previous studies [12], [13].

In addition to welding current, material thickness also plays a significant role in influencing the thermal behavior during the welding process. Thicker materials generally provide a higher heat absorption capacity, allowing heat to be distributed more uniformly and resulting in a more stable cooling process. In contrast, thinner materials tend to experience rapid heat accumulation and faster cooling rates, which may lead to localized microstructural transformations and greater variations in mechanical properties. The results further confirm that SPCC steel is sensitive to variations in heat input during MIG welding. In particular, the combination of higher welding current and thinner material tends to produce a harder heat-affected zone due to rapid thermal cycling and accelerated phase transformations. Therefore, the interaction between welding current and material thickness becomes a critical factor in determining the overall quality and performance of the welded joint, highlighting the importance of proper parameter selection in MIG welding applications involving thin sheet steels such as SPCC.

3.3. Tensile Test Result

The tensile test was conducted to evaluate the tensile properties of MIG-welded SPCC steel under different welding current and material thickness conditions. The obtained results provide information on the maximum force and elongation of the welded specimens, which are used to analyze the influence of welding parameters on the mechanical performance of the joints.

Table 7. Tensile test results

Current (A)	L_0 **(mm)**	**Variation**	**ΔL (mm)**	**A (mm ^{2})**	**Max Force (N)**
80	50	1	0.7	11.25	3180
			0.7	11.25	3520
80	50	1	0.6	11.25	3390
		2	1.3	17.5	5570
			1.1	17.5	5220
			1.1	17.5	5190

		3	1.19	25	6400
			1.55	25	7630
			1.3	25	6800
90	50	1	0.45	11.25	2980
			0.55	11.25	3660
			0.45	11.25	3000
		2	1.55	17.5	5480
			1.6	17.5	6190
			1.2	17.5	6210
		3	1.8	25	8840
			1.09	25	5830
			1.7	25	8160
100	50	1	0.55	11.25	2910
			0.65	11.25	3420
			0.7	11.25	3600
		2	0.75	17.5	2250
			1.2	17.5	5890
			1.8	17.5	5850
		3	1.5	25	7410
			1.1	25	4860
			1.4	25	7710

Table 8. Average tensile strengths

Current (A)	**Thickness (mm)**	**Specimens**	**Tensile strength (N/mm^2)**	**Avg. tensile strength (N/mm^2)**
80	0.9	I A	282.66	298.95
		II A	312.88	
		III A	301.33	
	1.4	I B	318.28	304.37
		II B	298.28	
		III B	296.57	
80	2.0	I C	256	277.73
		II C	305.2	
		III C	272	
90	0.9	I A	264.88	285.62
		II A	325.33	
90	0.9	III A	266.66	285.62
	1.4	I B	313.14	340.56
		II B	353.71	
		III B	354.85	

	2.0	I C	353.6	304.40
		II C	233.2	
		III C	326.4	
100	0.9	I A	258.66	294.22
		II A	304	
		III A	320	
	1.4	I B	128.57	266.47
		II B	336.57	
		III B	334.28	
	2.0	I C	296.4	266.4
		II C	194.4	
		III C	308.4	

A graphical summary based on Figure 5 shows the same trend: tensile strength varies with both current and material thickness.

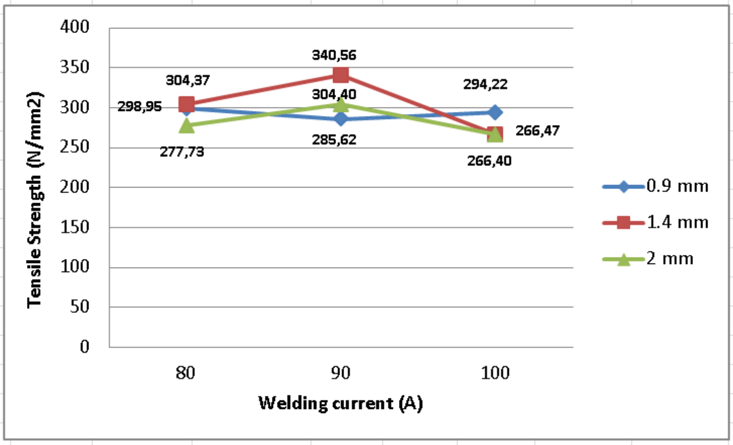

Figure 5. Tensile strength for each variation

3.4. Discussion of Tensile Strength Results

Based on the tensile test results, both welding current and material thickness significantly influence the tensile properties of SPCC Steel welded using the Metal Inert Gas (MIG) Welding process. The results indicate that tensile strength does not increase linearly with welding current. Instead, an intermediate welding current provides improved joint performance. Among the tested parameters, a welding current of 90 A produced the highest tensile strength, particularly for the 1.4 mm plate thickness. In contrast, a higher welding current of 100 A resulted in a reduction in tensile strength, which is attributed to excessive heat input leading to grain coarsening in the weld region [8], [14]. Meanwhile, a welding current of 80 A produced moderate tensile strength, which may be associated with insufficient penetration in some specimens.

Material thickness also played an important role in determining the tensile performance of the welded joints. The 1.4 mm plate thickness consistently demonstrated superior tensile strength compared with the 0.9 mm and 2.0 mm specimens. The thinner plates (0.9 mm) tended to exhibit lower tensile strength due to their higher susceptibility to overheating and distortion during welding, while the thicker plates (2.0 mm) showed moderate tensile performance but experienced a reduction in strength at higher welding currents due to excessive heat input. The optimal welding parameter combination was obtained at a welding current of 90 A with a plate thickness of 1.4 mm, producing the highest tensile strength of 340.56 N/mm². These findings indicate that an appropriate balance of welding current and material thickness is essential to achieve optimal tensile performance in MIG-welded SPCC steel joints. These findings are consistent with previous studies indicating that optimal heat input is critical in balancing hardness and tensile strength in MIG-welded low-carbon steels [13], [14].

4. Conclusion

The results demonstrate that welding current and material thickness significantly influence the hardness distribution and tensile performance of MIG-welded SPCC steel. Hardness increased with higher welding current and decreased with increasing material thickness, with the maximum hardness value of 672 HLD observed at 100 A for the 0.9 mm plate. Tensile strength exhibited a non-linear relationship with welding current, where the optimal performance was obtained at 90 A with a plate thickness of 1.4 mm, producing a tensile strength of 340.56 N/mm². These findings indicate that moderate welding current provides a balanced combination of hardness, penetration, and tensile strength for thin-gauge SPCC steel plates.

5. Recommendations for Future Work

Future research should further investigate several aspects to enhance the understanding of welding characteristics in SPCC Steel joined using the Metal Inert Gas (MIG) Welding process. Microstructural analysis using Optical Microscopy or Scanning Electron Microscopy (SEM) is recommended to verify the microstructural transformations occurring in the weld metal and heat-affected zone (HAZ). In addition, further evaluation of distortion and residual stresses in thin plates is necessary to better understand their influence on the structural integrity of welded joints. Future studies may also examine the effects of alternative shielding gases and variations in wire feed rate on weld quality and mechanical performance. Moreover, investigation of the fatigue behavior of welded joints under cyclic or dynamic loading conditions is recommended, particularly for applications in automotive or other structural components subjected to repeated loading.

References

[1] Akulwar S, Akela A, Satish Kumar D, Ranjan M. Resistance Spot Welding Behavior of Automotive Steels. Transactions of the Indian Institute of Metals 2021;74:601–9. https://doi.org/10.1007/s12666-020-02155-9.

[2] Handbook W. WFS. Welding Handbook vol. 3 - Welding Processes, Part 2 2007.

[3] Kearns WH. Welding Handbook Volume 3: Resistance and Solid-State Welding and Other Joining Processes. . vol. 3. John Wiley & Sons, Inc. J Polym Sci B; 1980.

[4] Wijoyo W, Mujahid M, Nurhidayat A, Surjadi E, Saefuloh I. The effect of current strength on tensile strength and impact toughness of cast iron welded joints. Teknika: Jurnal Sains Dan Teknologi 2021;17:125. https://doi.org/10.36055/tjst.v17i2.11216.

[5] Bhuyan P, Sahoo SS, Mahananda S, Bagal DK. Optimisation of resistance spot welding parameters using Taguchi’s orthogonal array. Mater Today Proc 2024. https://doi.org/10.1016/j.matpr.2024.01.052.

[6] Sukarman S, Abdulah A. Optimasi parameter resistance spot welding pada pengabungan baja electro-galvanized menggunakan metode Taguchi. Dinamika Teknik Mesin 2021;11:39. https://doi.org/10.29303/dtm.v11i1.372.

[7] Hapsari FK, Putra WS, Nugroho TA, Hutama AS, Kurniawan P. The effect analysis of wire speed, cycle and break time interval to tensile strength of SUS 304 and SPHC joint using cold metal transfer welding method on truarc weld 1000 machine, 2025, p. 020008. https://doi.org/10.1063/5.0227829.

[8] Ma Y, Takikawa A, Nakanishi J, Doira K, Shimizu T, Lu Y, Ma N. Measurement of local material properties and failure analysis of resistance spot welds of advanced high-strength steel sheets. Mater Des 2021;201:109505. https://doi.org/10.1016/j.matdes.2021.109505.

[9] Okayasu M, Ohkura Y, Sakamoto T, Takeuchi S, Ohfuji H, Shiraishi T. Mechanical properties of SPCC low carbon steel joints prepared by metal inert gas welding. Materials Science and Engineering: A 2013;560:643–52. https://doi.org/10.1016/j.msea.2012.10.008.

[10] ASTM International. Standard Test Methods for Tension Testing of Metallic Materials. West Conshohocken: n.d.

[11] Kang S-W, Park Y-M, Jang B-S, Jeon Y-C, Kim S-M. Study on fatigue experiment for transverse butt weldsunder 2G and 3G weld positions. International Journal of Naval Architecture and Ocean Engineering 2015;7:833–47. https://doi.org/10.1515/ijnaoe-2015-0059.

[12] Sindo Kou. Welding Engineering and Technology Welding Metallurgy. 2nd Edition. 2nd ed. New Jersey: John Wiley & Sons; 2003.

[13] M. Shafeek, S. S. Salins, D. Doreswamy, and H. K. Sachidananda, “Effect of welding parameters on microstructure and mechanical properties of GMAW welded steel,” *Discover Materials*, vol. 4, 2024

[14] H. Ko, H. J. Kim, D. Y. Kim, and J. Yu, “Improving the metal inert gas welding efficiency and microstructural stability in automotive components,” *Metals*, vol. 15, no. 1, 2025.

[15] S. Weis, R. Grunert, S. Brumm, and U. Prank, “Study on MIG–TIG hybrid brazing of galvanised thin sheet,” *Welding in the World*, vol. 67, pp. 1215–1221, 2023.