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Effect of the combination of aluminum plate thickness 2024 T42 on hardness, tensile strength, and photo micro in the process of resistance spot welding part cover side L aircraft

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Abstract

The automotive industry, particularly the aerospace industry, frequently uses resistance spot welding. Connection failure is often caused by several things, namely the plate thickness factor. For this test, a combination of two kinds of plate thickness mixtures was used, namely 0.8 + 0.6 mm and 0.8 + 0.8 mm. Through several tests, the quality of the welding results will be compared using the same welding parameters. Tensile test testing cannot be used to see welding results. However, additional testing, including macrographic and hardness tests, is required. The tensile test of the two combinations gave higher results than the previous industry standards, namely 383.60 lbf and 344.27 lbf respectively. For the macrographic test results, the penetration value for variations with a thickness of 0.8 + 0.6 mm corresponds to the minimum and maximum standard values of (20.00 ÷ 80.00), more specifically 37.2% ÷ 74.6%. As for the thickness variation of 0.8 + 0.8 mm, it is standard but very close to the maximum value of 45% ÷ 79.2%. For the size of a nugget or spot weld the two mixtures are very good and go beyond current principles. Furthermore, for the final results of the hardness test with the Vickers Microhardness technique, the hardness value of the weld piece from the weld point area to the parent metal increases due to the effect of using welding which will cause softening of the 2024 T-42 aluminum material. In the end, the hardness value of each thickness variation will be different due to different parameters.

Keywords: aluminum 2024, macrography, micro hardness, resistance spot welding, tensile-shear test

1. Introduction

Welding the connection of materials (welding) is a form of metallurgical combination of metal or metal alloy bonds made in a molten or liquid state [1]. Welding is commonly applied in industry and construction, especially in the automotive industry and building construction. Apart from being used in connections, material splicing is also used for improvements or repairs [2]. This repair is used to increase the strength value of an object (engineering) through the surface covering process and can also be applied to repair damaged parts such as holes, rust, and porousness [3].

Spot welding is commonly referred to as Opposition Spot Welding (RSW), which is a welding technique when the surfaces of the plates are joined together and electrified so that the surfaces will become hot and dissolve due to the excessive force of the electric current [4][5][6]. There are many advantages of this kind of welding, including fast and functional circulation, low manufacturing costs, good joint quality, and can be applied through stable results continuously [7][8]. This welding technique is often preferred in the aviation industry [9]. This welding technique was chosen because of the benefits provided by this welding procedure. In fact, even in the automobile business, for example in vehicle body parts, this welding is applied up to 90% in the connection cycle between components [10].

In spot welding, there are three basic parameters, specifically the weld joining rate, weld joining power, and weld joining time [11]. The parameters used for each plate thickness will be different. The reason is because each thickness has different mechanical properties [12]. To measure the quality level of welded joints, one of the procedures that can be done is to conduct destructive testing (Destructive test) [13].

Until now, engineers in the automotive industry are still struggling with the problem of vehicle body weight, which engineers must consider [14]. The insistence of customer demand for safety and luxury makes thicker and lighter materials and various components for more careful development parts, for example, struts that must be applied [15]. That is why some body parts are being replaced with lightweight materials, for example, alumina and magnesium, which have comparative mechanical characteristics, or even exceed those of steel [16].

In contrast to metals of the same thickness level, joints of various thicknesses have more convoluted microstructure qualities and mechanical properties that affect the properties of the weld joint at the welding spot (Nugget) [17][18]. With destructive tests, the quality of spot welds is examined to decide whether subsequent welds are good, for example, semi-static flexure tests and dynamic cycle tests [19]. Macro properties of spot-welding joints can affect quality and performance. The macro characteristics of a welded joint are described by the melting rate, indentation rate, nugget diameter, and indentation diameter [20].

Company X, working in the aviation aspect, has built parts before applying them directly to its applications. This technique is aimed to obtain precise constraints. Company X, on the other hand, only used tensile test to determine the results. In addition, additional Micro Hardness and Macrographic test was used to conduct a review of the Aluminum 2024 T42 samples with two thickness variations - 0.8 + 0.6 mm and 0.8 + 0.8 mm - to obtain more precise results. With the same spot weld parameters, these thickness mix variations were chosen to investigate the effects of minute variations in the combination of metal thickness on mechanical properties and microstructure in more depth.

2. Methods

This research uses exploration techniques and literature review surveys from various sources. In this research and the test was conducted by using Aluminum 2024 T-42 material with thickness variations of 0.8 + 0.6 mm and 0.8 + 0.8 mm and involving fixed factors through welding parameters.

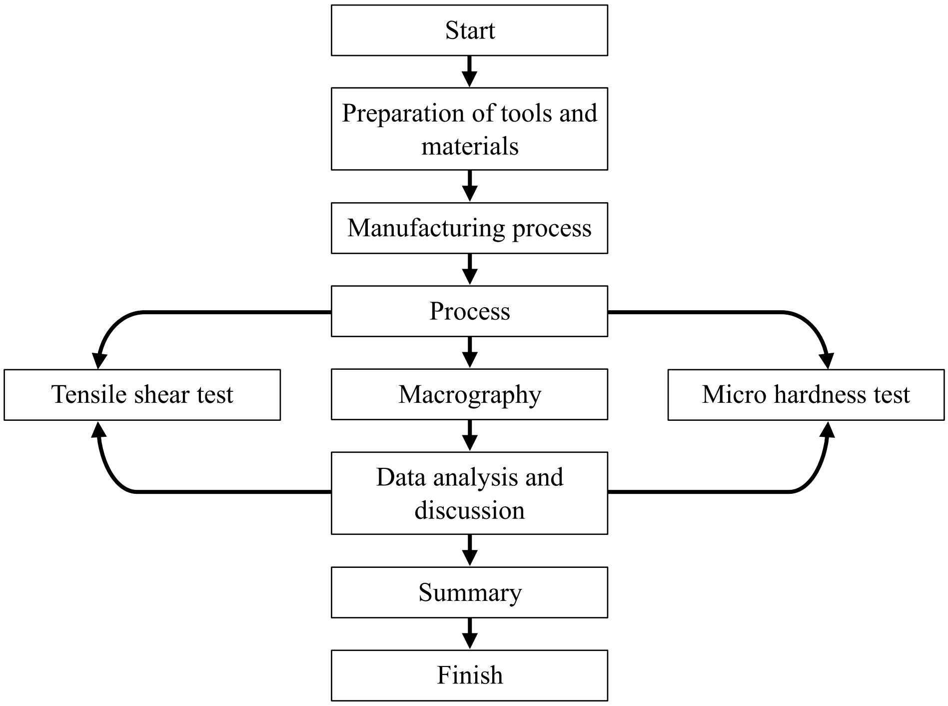


Figure 1. Research stages

The process of connecting specimens or welding by using tools is Resistance Spot Welding SCIAKY Type P272.

Figure 2. Welding machine

There are different standard welding parameters for two types of variations. For the welding parameters described in table 1 with the following specifications:

Table 1. Welding parameters

No.	Welding parameters	Aluminum 2024 T42	
		0.8 + 0.6 mm	**0.8 + 0.8 mm**
1	Electrode	CuAg / 16	CuAg / 16
2	*Radius Contact Upper*	100	150

No.	Welding parameters		Aluminum 2024 T42	
			0.8 + 0.6 mm	**0.8 + 0.8 mm**
	(mm)			
		Lower	100	150
3	*Contact Resistance* (µOhm)		15	8
4	*Weld Class*		2	2
5	*Pressure* (Psi)	*Upper Regulator* (PG2)	23	26
		Lower Regulator (PG1)	12	11
		Contact Gauge	20	20
6	*Pressure Program*		*Variable Press.*	*Variable Press.*
7	*Power*		*Low*	*Low*
8	*Phase*		3	3
9	*Pre-Compress* (*cycles*)		10	12
10	*Squeeze* (*cycles*)		10	10
11	*Quench* (*cycles*)		05	11
12	*Hold* (*cycles*)		20	22
13	*Welding* (*cycles*)		02	02
14	*Impulses CO* (*cycles*)		02	02
15	*Off (cycles)*		05	05
16	*HT* (*cycles*)		03	02
	Max. Current (%)		50%	62%
17	*CD* (*cycles*)		03	03
	Max. Current (%)		30	30

The purpose of tensile test is to ascertain the tensile strength of welded joints. Bluehill 3 software assists to execute the tests by following ASTM E8 testing standards. This product interprets the test results. The tensile test equipment with handling is UTM INSTRON 5982 which is seen in Figure 3.

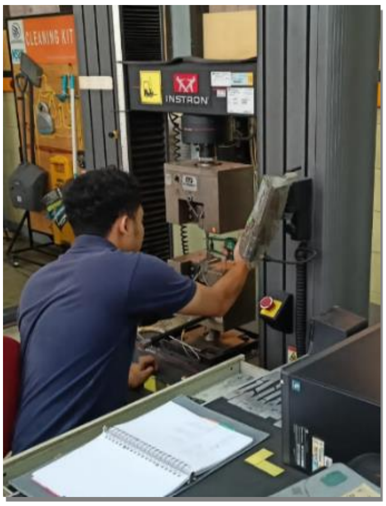


Figure 3. Tensile test machine

Figure 4. Microscope OLYMPUS SZX7

The Vickers Micro Hardness method is used for the final test, which measures hardness. The micro hardness test data will be presented automatically after the test is completed with the help of the Zwick/Roell HD Automatic Hardness Testing software. The Zwick Roell ZHV Micro Hardness Testing Machine is the tool used for this test, as depicted in Figure 5.

Figure 5. Machine Hardness test

The research and test data collection process were conducted at the Metallurgy and QA department of PT. Dirgantara Indonesia (Aerospace).

3. Result and Discussion

Result and Discussion of Tensile Test Data

The following is a table and the results of the Tensile test and is illustrated with a test graph in Figures 6 and 7.

Table 2. The results of the tensile test

No.	# 0.8 + 0.6 mm	# 0.8 + 0.8 mm
	Maximum Load [lbf]	**Maximum Load [lbf]**
1	350.24	416.10
2	364.95	455.99
3	337.25	376.13
4	328.62	376.05
5	342.16	360.20
6	353.33	368.96
7	366.45	368.74
8	320.60	380.07
9	323.64	375.01
10	355.45	358.74
Mean	344.27	383.60
Maximum	366.45	455.99
Minimum	320.60	358.74
DEV	**0.1331**	**0.2535**

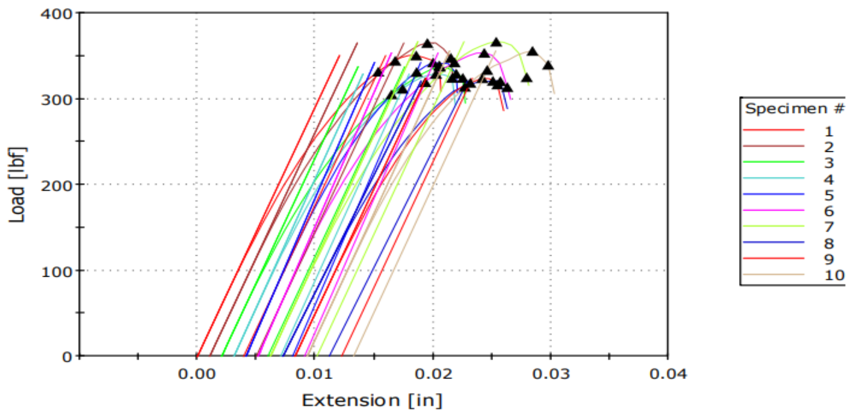


Figure 6. Graph of tensile test with 0.8 + 0.6 thickness

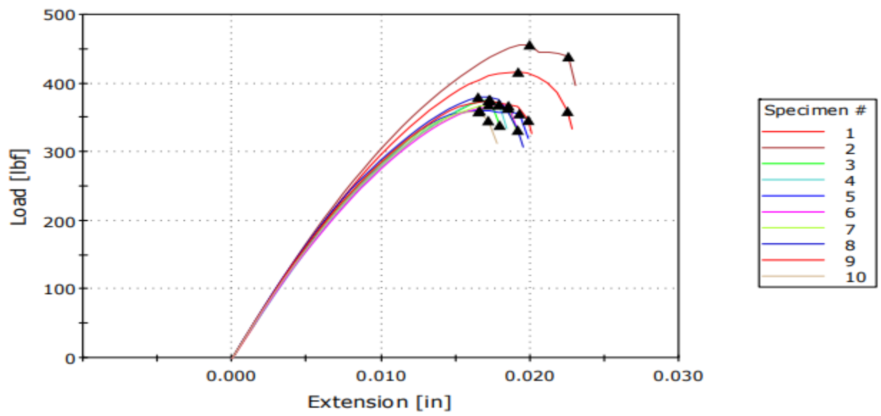


Figure 7. Graph of tensile test with 0.8 + 0.8 thickness

Determining the stiffness properties of each of the tested variations, it is important to survey the Standard Mechanical Properties of the specimens by referring to Table 3 for the dimensions of the smallest thickness variation to use as a reference in determining the standard values. In the two variations tried, the smallest thickness was 0.6 mm, or 0.023 inch. Then, the minimum tensile strength of the existing variations will be determined, as in Table 3.

Table 3. Standard Mechanical Properties Aluminium 2024 T42 Thickness 0.6 mm

Temper	Widths	Thickness	Tensile Strength minimum	Yield Strength at 0.2 percent Offset or at Extension Indicated		Elongation in 2 in. or 4 times D 1/, 2/, minimum
				Minimum	Extension under load	
	Inches	Inches	ksi	ksi	Inch/Inch	Percent
T42 8/	All	0.008 thru 0.009	55.0	34.0	0.0056	10
	All	0.010 thru 0.020	57.0	34.0	0.0056	12
	All	0.021 thru 0.062	57.0	34.0	0.0056	15
	All	0.063 thru 0.249	60.0	36.0	0.0056	15
	All	0.250 thru 0.499	60.0	36.0	0.0058	12
	All	0.500 thru 1.000 4/	61.0	38.0	0.0055	8
	All	1.001 thru 1.500 4/	60.0	38.0	0.0056	7
	All	1.501 thru 2.000 4/	60.0	38.0	0.0055	6
	All	2.001 thru 3.000 4/	58.0	38.0	0.0055	4

The Minimum Tensile Strength against a thickness of 0.6 mm is 57.0 ksi, when fully converted to psi it, becomes 57000 psi. Then, at that time, surveyed the Standard Mechanical Properties in table 3 and referred to the Ultimate Strength table for 57,000 psi and then matched it with the line for 0.6 mm thickness to find out the principles for Ultimate Strength Minimum and Ultimate Strength Average. It is shown in Table 4.

Table 4. Standard Nominal Thickness and Ultimate Strength Thickness 0.6 mm

Nominal Thickness of Thinner Sheet		Ultimate Strength[a]				Ultimate Strength[a]				Ultimate Strength[a]				Ultimate Strength[a]			
		56 000 psi and above lbf per Spot Weld		386 MPa and above N[b] per Spot Weld		35 000 psi to 55 999 psi lbf per Spot Weld		240 MPa to 385.9 MPa N[b] per Spot Weld		19 500 psi to 34 999 psi lbf per Spot Weld		135 MPa to 239.9 Mpa N[b] per Spot Weld		Below 19 500 psi lbf per Spot Weld		Below 135 MPa N[b] per Spot Weld	
in	mm	min.	min. avg	min.	min. avg	min.	min. avg	min.	min. avg	min.	min. avg	min.	min. avg	min.	min. avg	min.	min. avg
0.010	0.25	60	75	265	335	50	65	225	290	—	—	—	—	—	—	—	—
0.012	0.30	75	95	335	425	65	85	290	380	30	40	135	175	20	25	90	110
0.016	0.40	110	140	490	625	100	125	445	555	70	90	310	400	50	65	225	290
0.018	0.45	125	160	555	710	115	145	510	645	85	110	380	490	65	85	290	380
0.020	0.50	140	175	625	780	135	170	600	755	100	125	445	555	80	100	355	445
0.022	0.55	160	200	710	890	155	195	690	865	120	150	535	665	95	120	425	535
0.025	0.65	185	235	825	1045	175	200	780	890	145	185	645	825	110	140	490	625
0.028	0.70	215	270	995	1200	205	260	910	1155	175	220	780	980	135	170	600	755

The obtained standard variable for the strength of the tensile test is 160 lbf and the deviation is 200 lbf in minimum. Meanwhile, the following results were obtained from combination tests 1 and 2.

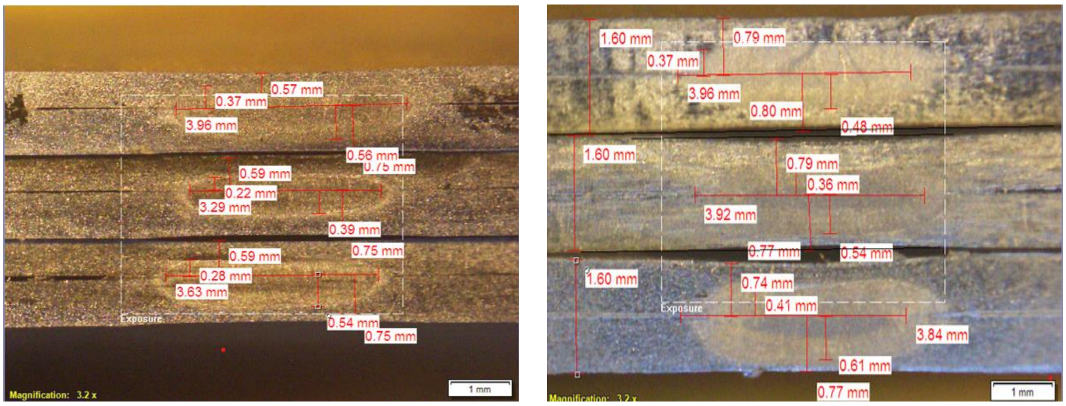
Table 5. Tensile strength values with comparison to standard

No.		Load Max (lbf)		Standard
		# 0.8 + 0.6 mm	# 0.8 + 0.8 mm	
1	Average	344.27	383.60	200
	Minimum	320.60	358.74	160

By looking at the tensile testing results of the 2 variations, it can be concluded that the strength value of the tensile testing of both thickness variations using parameters according to their respective specifications has exceeded the minimum standard. Low tensile test results are caused by excessive stress currents [21]. The large weld metal area and deep penetration caused by high weld circulation will cause small and brittle tensile test values [22].

The Discussion of Macrography Data

The Olympus Stream Basic software was used to make observations. It can be made directly by simply analyzing them through a computer screen. The obtained macrographic results are as follows:



(1) (2)

Figure 8. Diameter values of spot-welding specimens (1) 0.8 + 0.6 mm thickness, (2) 0.8 + 0.8 mm thickness

From these perceptions, the estimations were made, and the information obtained as shown in Table 6.

Table 6. Macrographic testing data

No.	.Ø SPOT. (mm)		Penetration (%)				Cacat
			# 0.8 + 0.6 mm		# 0.8 + 0.8 mm		
	# 0.8 + 0.6 mm	# 0.8 +0.8 mm	MIN.	MAKS.	MIN.	MAKS.	
1	3.96	3.96	65%	74.6%	46.8%	60%	-
2	3.29	3.92	37.2%	52%	45%	70%	-
3	3.63	3.84	47.4%	72%	55.4%	79.2%	-

In determining the spot-welding quality of the two examined specimens, it is important to first survey the nugget diameters of the test specimens by considering Table

6. The thickness of the smallest specimen is used as a perspective in determining the standard. The smallest thickness between the two tested combinations is 0.6 millimeters, or 0.023 inches. Then the Minimum Nugget Size of the current combination will be obtained. As it can be seen in table 7.

Table 7. Minimum Nugget Size (D) Aluminium 2024 T42 thickness 0.6 mm

Nominal Thickness of Thinner Sheet		Nugget Size (D_s)		Nominal Thickness of Thinner Sheet		Nugget Size (D_s)	
in	mm	in	mm	in	mm	in	mm
0.001	0.03	0.010	0.25	0.036	0.90	0.150	3.81
0.002	0.05	0.015	0.38	0.040	1.00	0.160	4.06
0.003	0.08	0.020	0.50	0.045	1.10	0.170	4.32
0.004	0.10	0.030	0.76	0.050	1.20	0.180	4.57
0.005	0.12	0.035	0.89	0.056	1.40	0.190	4.82
0.006	0.16	0.040	1.02	0.063	1.60	0.200	5.08
0.007	0.18	0.045	1.14	0.071	1.80	0.210	5.33
0.008	0.20	0.050	1.27	0.080	2.00	0.225	5.72
0.010	0.25	0.060	1.52	0.090	2.30	0.240	6.10
0.012	0.30	0.070	1.78	0.100	2.50	0.250	6.35
0.016	0.40	0.085	2.16	0.112	2.80	0.260	6.60
0.018	0.45	0.090	2.29	0.125	3.20	0.280	7.11
0.020	0.50	0.100	2.54	0.140	3.60	0.300	7.62
0.022	0.55	0.105	2.68	0.160	4.10	0.320	8.13
0.025	0.65	0.120	3.05	0.180	4.60	0.340	8.64
0.028	0.70	0.130	3.30	0.190	4.80	0.350	8.89
0.032	0.80	0.140	3.56	—	—	—	—

Then the results obtained from the value of the standard nugget diameter (Ø SPOT) are 0.55 mm or 0.105 in. then for testing on thickness variations 1 and 2 the following results are obtained:

Table 8. Comparison of Ø SPOT and Minimum Penetration of Specimens with Standards

No.	Measurement	Combination		Standard (mm)
		# 0.8 + 0.6 mm	# 0.8+ 0.8 mm	
1.	Diameter SPOT (mm)	3.96 ÷ 3.29	3.84 ÷ 3.96	2.68
2.	penetration (%)	37.2 ÷ 74.6	45 ÷ 79.2	20.00 ÷ 80.00

By looking at the test results of the two variations, the stiffness of the two thickness mixtures using various limits has exceeded the minimum standard [22]. Too high a weld force can result in small penetration. If the weld force is too high, the contact area will expand, resulting in low contact resistance and low current flow, both of which will significantly reduce the amount of heat generated by the weld and affect the size of the weld nugget [23].

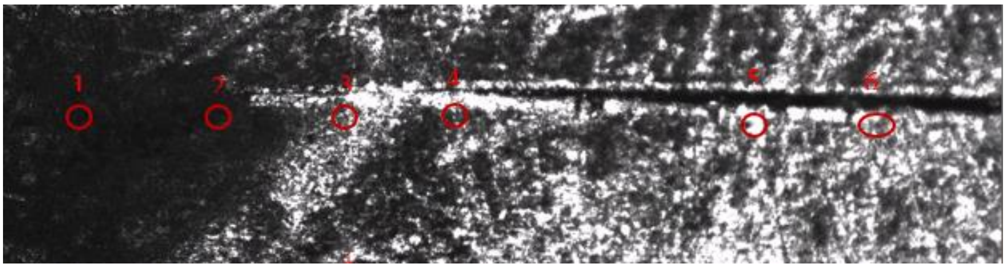
The Discussion of Micro Hardness Data

The strategy of joining specimens through welding is one of the methods to be maintained in this industry. Reduced strength (hardness) of the heat-treated part of the weld is one of the effects of welding on the mechanical properties of materials. This has been proven by hardness testing that explores various avenues regarding Microhardness strategies. From these results, the parts that were affected by the welding heat showed a decrease in hardness values, as shown in Table 9 for information on experimental results.

Table 9. Data on hardness test results

Indentation Point	# 0.8+0.6mm	# 0.8+0.8mm
	HV (µm)	HV (µm)
1	91.07	155.13
2	99.54	103.56
3	126.70	147.07
4	145.98	173.37
5	154.36	189.24
6	170.02	190.05

The following is a picture of the hardness test of Aluminum 20204 T-42 by pressing or indenting the specimen.



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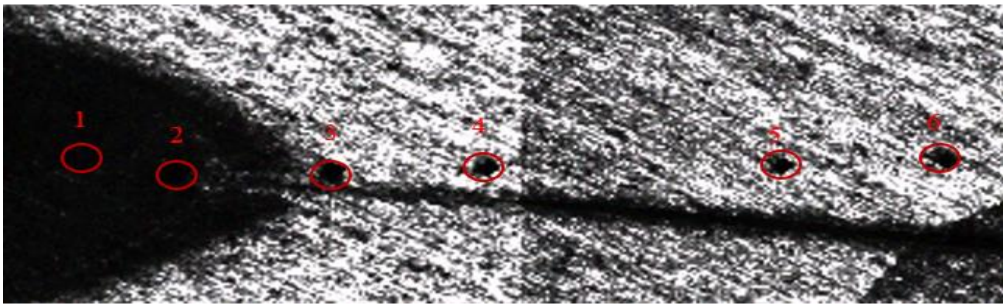

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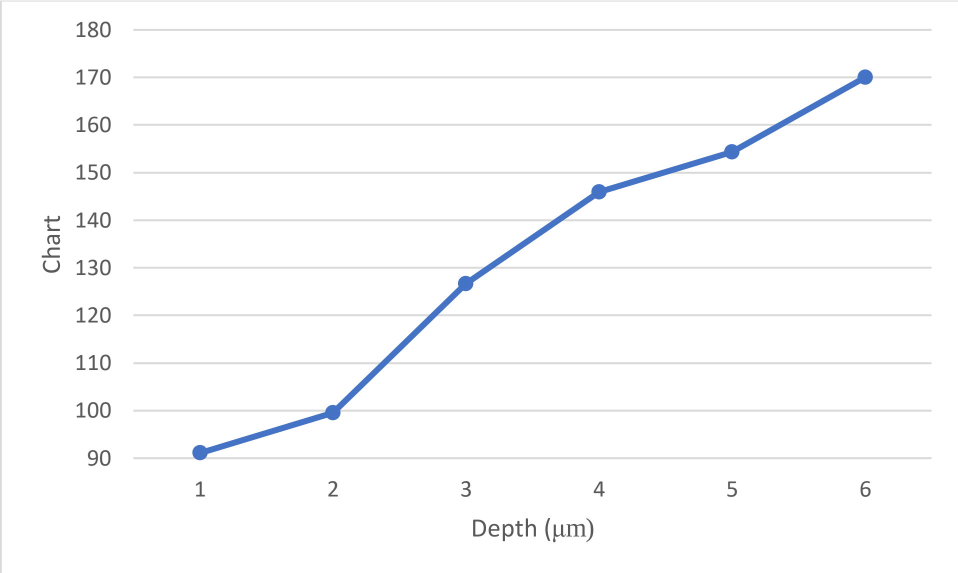
Figure 9. Points of Micro Hardness testing pressure
(1) Testing Specimen 0.8 + 0.6 mm and (2) Testing Specimen 0.8 + 0.8 mm

The graph of the test results is as follows.



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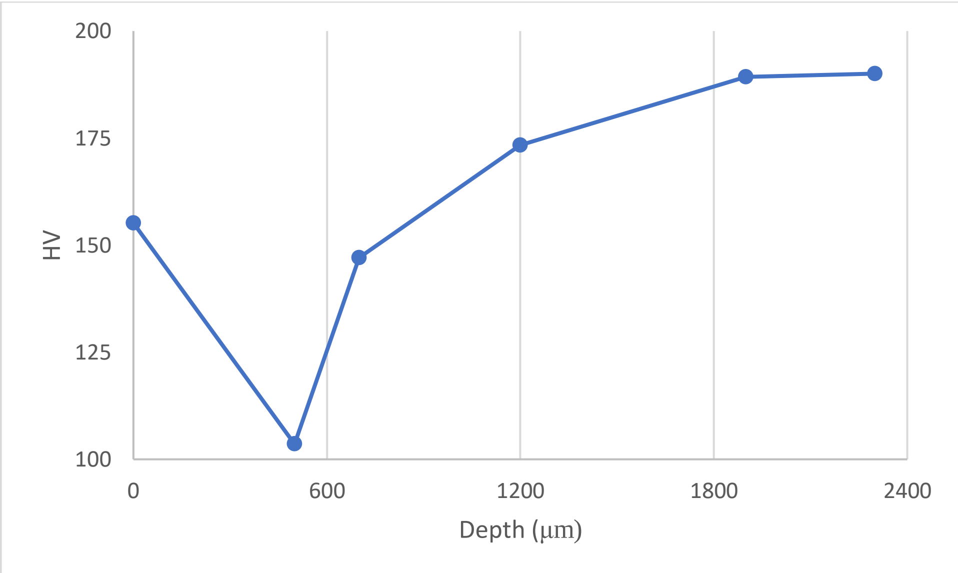

(2)

Figure 10. Graph of Results from Micro Hardness Testing
(1) Testing Specimen 0.8 + 0.6 and (2) Testing Specimen 0.8 + 0.8

In the test, the test data graph is shown in Figure 10 in the combination of 0.8 + 0.6 mm and 0.8 + 0.8 mm. both variations have different penetration or treatment, for hardness testing there are differences in hardness levels. In the diameter of the nugget shows low hardness results due to the main point exposed to heat [24]. For the heat affected zone (HAZ) shows an increase in hardness value which is increasing [25]. Then the base material hardness point is higher or harder because the base material is not affected by Spot Welding heating.

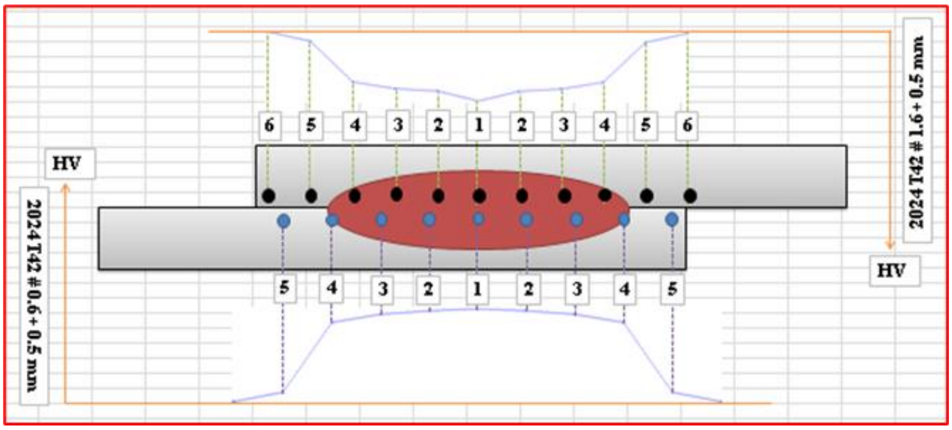

Figure 11. Hardness value distribution graph

4. Conclusion

From several tests on resistance spot welding, it can be summarized into several points as follows:

1. For tensile testing with a combination of 0.6 + 0.8 mm and 0.8 + 0.8 mm, the deviation results are 0.1331 and 0.2545. The test results of the two combinations already exceed the minimum standards of the Ultimate Srength Table.
2. The nugget diameters of the combinations 0.6 + 0.8 mm and 0.8 + 0.8 mm were found to be 3.29 ÷ 3.96 and 3.84 ÷ 3.96. For penetration, values of 37.2 ÷ 74.6 and 45 ÷ 79.2 were obtained. From these results, penetration with a thickness of 0.6+0.8 mm is in accordance with the specified standard value, but the value of the 0.8+0.8 mm variation is very close to the maximum value of the standard. It is also very influential because it can affect the application of parts on airplanes.
3. In the Micro Hardness test of the two combinations, the hardness value is stable starting from the spot point exposed to the solid to the point that is not exposed to heat. However, for the hardness value using a combination plate 0.6 + 0.8 mm is smaller than the combination of 0.8 + 0.8 mm, therefore the use of a combination of 0.6 + 0.8 mm is more recommended in the application of parts on the aircraft.

References

[1] B. Liu, A. Vivek, M. Presley, and G. S. Daehn, “Dissimilar Impact Welding of 6111-T4, 5052-H32 Aluminum Alloys to 22MnB5, DP980 Steels and the Structure–Property Relationship of a Strongly Bonded Interface,” Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 49, no. 3, pp. 899–907, 2018, doi: https://doi.org/10.1007/s11661-017-4429-7.

[2] O. M. Ikumapayi and E. T. Akinlabi, “Recent advances in keyhole defects repairs via refilling friction stir spot welding,” Mater. Today Proc., vol. 18, pp. 2201–2208, 2019, doi: https://doi.org/10.1016/j.matpr.2019.06.663.

[3] J. H. Lee, C. M. Lee, and D. H. Kim, “Repair of damaged parts using wire arc additive manufacturing in machine tools,” J. Mater. Res. Technol., vol. 16, pp. 13–24, 2022, doi: https://doi.org/10.1016/j.jmrt.2021.11.156.

[4] C. Summerville, P. Compston, and M. Doolan, “A comparison of resistance spot weld quality assessment techniques,” Procedia Manuf., vol. 29, pp. 305–312, 2019, doi: https://doi.org/10.1016/j.promfg.2019.02.142.

[5] M. Salem, "Control and Power Supply for Resistance Spot Welding (RSW)," no. April, pp. 1–121, 2011, [Online]. Available: http://ir.lib.uwo.ca/etd/130
[6] K. Zhou and P. Yao, "Overview of recent advances of process analysis and quality control in resistance spot welding," Mech. Syst. Signal Process., vol. 124, pp. 170–198, 2019, doi: https://doi.org/10.1016/j.ymssp.2019.01.041.
[7] J. Tomków, G. Rogalski, D. Fydrych, and J. Labanowski, "Advantages of the application of the temper bead welding technique during wet welding," Materials (Basel)., vol. 16, no. 6, 2019, doi: https://doi.org/10.3390/ma12060915.
[8] V. P. Singh, S. K. Patel, A. Ranjan, and B. Kuriachen, "Recent research progress in solid state friction-stir welding of aluminium–magnesium alloys: A critical review," J. Mater. Res. Technol., vol. 9, no. 3, pp. 6217–6256, 2020, doi: https://doi.org/10.1016/j.jmrt.2020.01.008.
[9] G. Wang, Y. Zhao, and Y. Hao, "Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing," J. Mater. Sci. Technol., vol. 34, no. 1, pp. 73–91, 2018, doi: https://doi.org/10.1016/j.jmst.2017.11.041.
[10] G. Liedl et al., "Joining of aluminum and steel in car body manufacturing," Phys. Procedia, vol. 12, no. PART 1, pp. 150–156, 2011, doi: https://doi.org/10.1016/j.phpro.2011.03.019.
[11] K. Zhou, T. Shi, and L. Cai, "Online measuring the electrical resistivity of molten nugget of stainless steel in resistance spot welding," J. Manuf. Process., vol. 28, pp. 109–115, 2017, doi: https://doi.org/10.1016/j.jmapro.2017.05.026.
[12] Syahri TP et al, "Optimasi Parameter Proses Resistance Spot Welding pada Pengabungan Material SECC-AF," SEMNASTERA (Seminar Nas. Teknol. dan Ris. Ter., no. September, pp. 125–131, 2019, [Online]. Available: http://semnastera.polteksmi.ac.id/index.php/semnastera/article/view/21
[13] B. Wang, S. Zhong, T. L. Lee, K. S. Fancey, and J. Mi, "Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review," Adv. Mech. Eng., vol. 12, no. 4, pp. 1–28, 2020, doi: https://doi.org/10.1177/1687814020913761.
[14] A. C. Serrenho, J. B. Norman, and J. M. Allwood, "The impact of reducing car weight on global emissions: The future fleet in Great Britain," Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., vol. 375, no. 2095, 2017, doi: 10.1098/rsta.2016.0364.
[15] M. Bolognesi, G. Farina, S. Alvisi, M. Franchini, A. Pellegrinelli, and P. Russo, "Measurement of surface velocity in open channels using a lightweight remotely piloted aircraft system," Geomatics, Nat. Hazards Risk, vol. 8, no. 1, pp. 73–86, 2017, doi: https://doi.org/10.1080/19475705.2016.1184717.
[16] D. Kumar, R. K. Phanden, and L. Thakur, "A review on environment friendly and lightweight Magnesium-Based metal matrix composites and alloys," Mater. Today Proc., vol. 38, no. August, pp. 359–364, 2020, doi: https://doi.org/10.1016/j.matpr.2020.07.424.
[17] B. Wang et al., "Microstructure and shearing strength of stainless steel/low carbon steel joints produced by resistance spot welding," J. Mater. Res. Technol., vol. 20, pp. 2668–2679, 2022, doi: https://doi.org/10.1016/j.jmrt.2022.08.041.
[18] D. Zhao, D. Ren, G. Song, K. Zhao, L. Liu, and Z. Zhang, "Comparison of mechanical properties and the nugget formation of composite ceramic-centered

annular welding and traditional resistance spot welding," Int. J. Mech. Sci., vol. 187, no. June, 2020, doi: https://doi.org/10.1016/j.ijmecsci.2020.105933.

[19] J. Zhang, H. Deng, A. Taheri, B. Ke, and C. Liu, "Deterioration and strain energy development of sandstones under quasi-static and dynamic loading after freeze-thaw cycles," Cold Reg. Sci. Technol., vol. 160, no. December 2018, pp. 252–264, 2019, doi: https://doi.org/10.1016/j.coldregions.2019.01.007.

[20] H. Zhang, X. Qiu, Y. Bai, F. Xing, H. Yu, and Y. Shi, "Resistance spot welding macro characteristics of the dissimilar thickness dual phase steels," Mater. Des., vol. 63, pp. 151–158, 2014, doi: https://doi.org/10.1016/j.matdes.2014.05.060.

[21] G. H. Farrahi, K. Reza Kashyzadeh, M. Minaei, A. Sharifpour, and S. Riazi, "Analysis of resistance spot welding process parameters effect on the weld quality of three-steel sheets used in automotive industry: Experimental and finite element simulation," Int. J. Eng. Trans. A Basics, vol. 33, no. 1, pp. 148–157, 2020, doi: 10.5829/IJE.2020.33.01A.17.

[22] C. Yuce, F. Karpat, and N. Yavuz, "Investigations on the microstructure and mechanical properties of laser welded dissimilar galvanized steel–aluminum joints," Int. J. Adv. Manuf. Technol., vol. 104, no. 5–8, pp. 2693–2704, 2019, doi: https://doi.org/10.1007/s00170-019-04154-7.

[23] G. Wiranto, S. Y. Lubis, and Rosehan, "Multiple linear regression analysis on effect of time variations and voltage variations on spot welding against shear strength of AA5083 material using IBM spss application," IOP Conf. Ser. Mater. Sci. Eng., vol. 1007, no. 1, 2020, doi: 10.1088/1757-899X/1007/1/012062.

[24] H. Aghajani and M. Pouranvari, "Influence of In Situ Thermal Processing Strategies on the Weldability of Martensitic Stainless Steel Resistance Spot Welds: Effect of Second Pulse Current on the Weld Microstructure and Mechanical Properties," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 50, no. 11, pp. 5191–5209, 2019, doi: 10.1007/s11661-019-05443-2.

[25] J. P. Oliveira, K. Ponder, E. Brizes, T. Abke, A. J. Ramirez, and P. Edwards, "Combining resistance spot welding and friction element welding for dissimilar joining of aluminum to high strength steels," J. Mater. Process. Technol., vol. 273, no. January, p. 116192, 2019, doi: https://doi.org/10.1016/j.jmatprotec.2019.04.018.