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ENHANCEMENT MECHANICAL PROPERTIES OF VERTICAL COMPENSATION FRICTION STIR WELDED JOINTS, THROUGH CHANGING POST-WELD HEAT-TREATMENT CONDITIONS

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ABSTRACT

Frictional stir welding (FSW) technology is increasingly used to weld various alloys, especially aluminum alloys, which are used in the manufacture of aircraft, ships, trains, etc. One of the most common techniques used to improve the mechanical properties of welded joints made of different alloy aluminum is the Vertical Compensation Friction Stir Welding (VCFSW) technique. Moreover, the use of different conditions of post-weld heat treatment of VCFSWed joints has a major impact on the mechanical properties of welded joints.

Therefore, in the present work, different conditions of post-weld heat treatments were carried out on the VCFSW joints in order to improve the mechanical properties. Specifically, this paper focused on the effect of aging conditions (artificial aging at 120°C, 140°C, and 160°C) and 3 mm wide VCFSW static tape on mechanical properties such as fine hardness and tensile stress.

Overall, the results indicated improvement in mechanical properties after using post-weld heat treatment. Specifically, the highest values of exact hardness and tensile strength were obtained at 140 °C, which is due to the change of the microstructure of the welded area by post-weld heat treatment conditions.

KEYWORDS: Friction stir welding (FSW), post weld heat treatment, strengthening mechanisms.

تحسين الخصائص الميكانيكية للوصلات الملحومة بالاحتكاك والتعويض العمودي من خلال تغيير ظروف المعالجة الحرارية بعد اللحام

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الملخص

تُستخدم تقنية لحام المزج الاحتكاكي (FSW) بشكل متزايد في لحام السبائك المتشابهة و غير المتشابهة وخاصة سبائك الألومنيوم التي تُستخدم في تصنيع الطائرات والسفن والقطارات وما إلى ذلك. ومن أكثر تقنيات التحسين الواعدة في FSW إدخال شريط من سبائك الألومنيوم بين جانبي اللحام (لحام المزج الاحتكاكي بالتعويض الرأسي VCFSW) التي تنتج تقاطعًا مركبًا بين السبائك غير المتشابهة. ومع ذلك ، فإن معظم هذه المفاصل تنكسر عند واجهة اللحام لأنها أظهرت سلوكًا هشًا. علاوة على ذلك ، فإن استخدام الظروف المختلفة للمعالجة الحرارية بعد اللحام لمفاصل FSWed له تأثير كبير على الخواص الميكانيكية للوصلات الملحومة.

في هذا العمل ، تمت دراسة تأثير ظروف المعالجة الحرارية المختلفة على اللحام المزج الاحتكاكي بالتعويضي الرأسي لسبائك الألومنيوم. على وجه التحديد ، تم التركيز على تأثير ظروف الشيخوخة لوصلات AA2024-O الملحومة بالاحتكاك والتي تحتوي على طبقة تعويض عمودية من سبائك الألومنيوم AA7075-O. تم إخضاع الوصلات الملحومة لمعاملة المحلول متبوعة بظروف تقادم مختلفة عند ١٢٠ درجة مئوية ، ١٤٠ درجة مئوية ، ١٦٠ درجة مئوية.

بشكل عام ، أشارت النتائج إلى تحسن في الخواص الميكانيكية بعد استخدام المعالجة الحرارية بعد اللحام. وعلى وجه التحديد ، تم الحصول على أعلى قيم للصلابة الدقيقة وقوة الشد عند ١٤٠ درجة مئوية ، ويرجع ذلك إلى تغيير البنية المجهرية للمنطقة الملحومة عن طريق ظروف المعالجة الحرارية بعد اللحام.

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الكلمات المفتاحية: لحام الدمج الاحتكاكي (FSW)، المعالجة الحرارية بعد اللحام ، آليات التقوية.

- List of Abbreviations

Abbreviations	*Meaning*
AS	Advancing Side
BM	Base material
CM	Compensation Material
EDAX	Energy dispersion x-ray analysis
FSW	Friction stir welding
FSWed	Friction stir welded
HAZ	Heat affected zone
hr	Hour
hrs	Hours
HV	Vickers microhardness
IM	Interlayer Material

NZ	Nugget Zone
OM	Optical microscope
PWHT	Post weld heat treatment
PWHTed	Post weld heat treated
RS	Retreating Side
SEM	Scanning electron microscopy
SZ	Stir zone
TMAZ	Thermo-mechanically affected zone
TWBs	Tailor-welded blanks
UTS	Ultimate Tensile Strength
VCFSW	Vertical Compensation Friction Stir Welding
VCFSWed	Vertical Compensation Friction Stir Welded
WM	Welding metal

1. INTRODUCTION

Friction stir welding is an excellent welding technique especially for aluminum alloys, which are used in many industries that required lightweight material and complex structural designs like automotive, aerospace industries, and military applications [1, 2]. These applications require special methods to joint different aluminum alloys parts with different melting points to fulfill the design requirements of their structural designs [3,4]. Joining these alloys during the manufacturing process required special welding requirements, especially for different alloys junctions because of the difference in melting points and high oxidization tendency of the aluminum alloys at elevated temperatures. Friction stir welding technology satisfies such requirements largely however, other defects hinder the full usage of such technology like brittleness and void formations during welding. Because of this the enhancing the stir welding microstructural characterization and mechanical properties of aluminum alloys junction become an important research area. Many proposed methods are under research to solve stir welding defects including using heat treatment techniques or trying to enhance the weak welding zone by strengthening it with a vertical compensation layer (VCFSW)[5,6,7,8]. In this work the improvement of a stir welding joint mechanical properties by using a combination of two techniques, heat treatment with vertical compensation layer was been investigated. The AA2024-O aluminum alloy used as base metal and the compensation layer from aluminum alloy AA7075-O.Many researchers have been studied the effects heat treatment on the properties of stir welded joints [2, 9, 10, 11, and 12]. For example, M Abu-Okail et al [5] used interlayer compensation strips made from AA7075 with different widths as reinforcements to improve ductility and strength of the stir weld junction. They found that the ultimate strength of the joint improved by 18% and the failure strain improved by 54% compared to welded joint without compensation interlayer. Shude Ji et, X Meng [6] added interlayer strip of AA2024-T4 alloy between two blanks of AA6061 during friction stir welding to strength the weld zone (WZ) of VCFSW joint. A high-quality VCFSW joints were obtained, indicating that VCFSW was an effective technique to eliminate the welding defects, which were produced by a regular stir welding junction without compensation strip (big gap). S. D. Ji and X. C. Meng [7] used an interlayer strip made from AA2024 to improve the mechanical properties of 7N01-T4 aluminum alloy and they found that the welding speed has a large effect on the microstructures and mechanical properties of the joint. The strength and elongation of the VCFSW joint enhanced compared to the Bass Metal, respectively. Shude Jia, et X Menga [8] study a joint of 4 mm thick aluminum alloy 6061-T6 with VCFSW using a compensation strip of 1 mm between blanks. Their result showed enhancement elongation and tensile strength of the joint by 58.8% and 75.1% respectively of the base material. In another study by M Abu-Okail et al [9] try to understand the improving technique of welding properties when using vertical compensation friction stir welding. They concluded that improvement of the strength of the weld junction is a result of the reduction in the grain size and the precipitation of Al2Cu (as filler metal) and Mg2Zn (base metal) intermetallic phases on the grain boundaries of aluminum during the FSW process. Their results showed improve in junction ductility mainly caused by the presence of Mg.P. Sivaraj et D. Kanarajan [10] used AA2024-T4 aluminum alloy as the compensation material, the proved obtaining a high-quality VCFSW joints which indicates that VCFSW is effective to eliminate the adverse effect produced by a big gap between the blanks during the welding. Meanwhile, they also found that offset of the tool pin is beneficial to reduce or even eliminate the cavity defect on the advanced side of the joint. They also find the technique produces a defect-free joint while the microhardness distribution corresponds to the generation of the boundaries and the mixture of two materials, which are influenced by welding process conditions. They also found that the technique results in a weld joint that is free from defects and has an improvement in hardness. The improvement is consistent with the distribution of the hardness on the welding line, because of generating the boundaries that are a mixture of two materials and this is affecte by the conditions of the welding process. It was also found that the effects of artificial aging (the heat treatment cycle of aging after solution treating) slightly improve the tensile properties. M Momeni et M and Guillot's [11] work on welding dissimilar joints made from AA2024-T351 to AA7075-T651 prepared by friction stir welding and examined the microstructure and mechanical properties post welding heat treatment. They found that the efficiency of a joint subject to post welding heat treatment does not improve due to a weak phenomenon of no penetration between two base metals in the lower region of the joint. A.Kannusamy et R Ramasamy [12] study friction stir welded joint made from aluminum alloy AA2014-T6 and subjected to heat treatment involving solution treatment and artificial aging. The as-welded and heat-treated samples were tested for their mechanical and corrosion characteristics. They found that the tensile strength of the heat-treated samples is higher when compared to the as-welded samples and the samples subjected to aging treatment have higher Corrosion resistivity than the as-welded samples.

Based on a previous literature survey[13-17], this paper focuses on the effecting of aging conditions such as 120 °C, 140 °C, and 160 °C at constant strip width 3 mm on mechanical properties such as microhardness and tensile of VCFSW in order to improve mechanical properties and joints efficiency.

2. EXPERIMENTAL WORK

The specimen used in the test consists of two pieced of AA2024-O with dimensions of 300x100x3.2 mm rigidly clamped together with a thin strip of AA-7075-O in between. The specimen was installed on vertical milling machine. A compensation layer was used from 7075-O alloy with dimensions 300x3x3 mm. The chemical compositions of AA2024-O and 7075-O aluminum alloys used in the study are given in Table 1 and the blank & compensation strep dimensions are shown in figure 1.

Table (1): Chemical composition (% weight) of the used aluminum alloys [5]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA2024	0.1	0.15	3.8	0.75	1.35	0.006	0.02	0.06	Balance
AA7075	0.1	0.15	1.5	0.01	2.6	0.22	5.63	0.12	Balance

The tool axis is inclined by tilt angle 2° to the direction of the machine table movement. The FSW tool used is a thread pin with a shoulder diameter of 30 mm; the pin is 3 mm in diameter and 5 mm as shown in figure2. Figure 3 shows the stir welding process detail and installation process. Using the optimal welding parameters selected from previous studies, the rotation speed of the instrument is 2000 rpm and welding speed 20 mm/min [5]. All samples subjected to solution treatment at 480 ºC for one hour and then quenching in the air. The samples divided into three equal groups. Each group was followed a different artificial aging methods [2]. The first group was aged at 120 ºC for a period of 24 hours (A120), the second group was aged at 140 ºC for a period of 10 hours (A140), and the third and last group was aged at 160 ºC for a period of 8 hours (A160) as shown in Table 2. The post-heating cycles (time and temperature) of different conditions are schemed in figure 4. These conditions were selected to understand which conditions are best of heat treatment for the friction-welding junction produced in the study. According to that, the mechanical properties including tensile strength, and hardness were tested and the microstructure of the segments was analyzed for each condition. Tensile test was performed on a universal testing machine at room temperature according to the standard recommendations ASTM-E8M-04 figure (5). The crosshead speed during tensile tests was kept 2 mm/min for all the tests. Two samples were tested for each condition, and the average obtained.

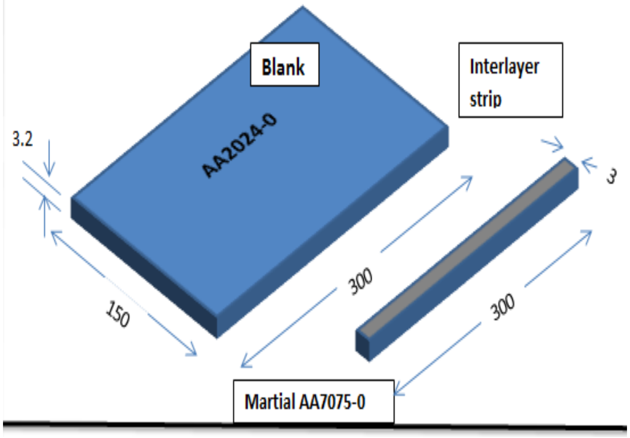


Figure 1. Blank of AA2024-O and interlayer AA7075-0 dimensions.

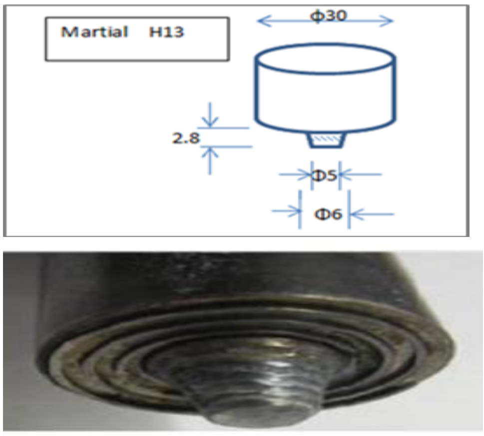


Figure 2. Friction stir welding tool.

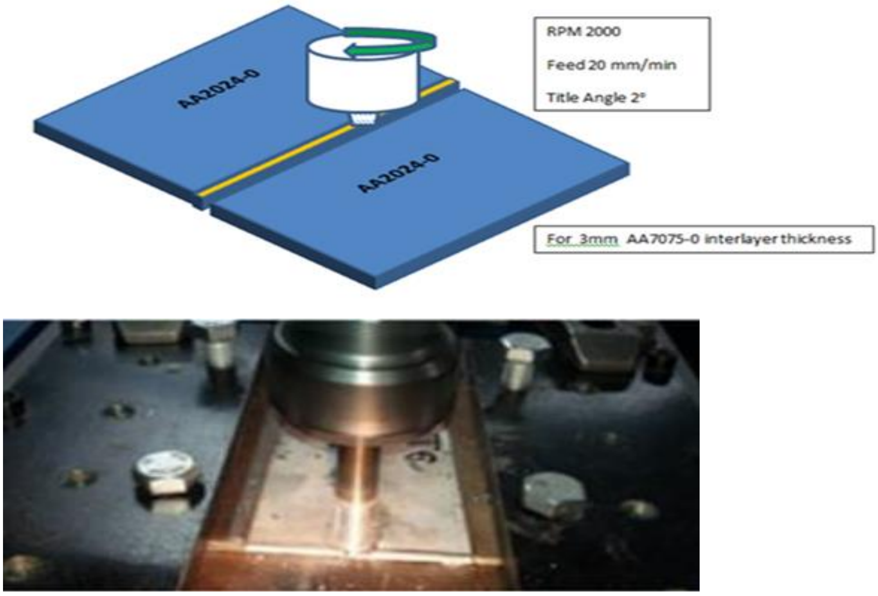


Figure 3.[*] schematic diagram of VCFSW process

Table (2): Post heating samples groups' according to heat treatment conditions

	Solution treatment			Artifial Aging	
	°C	Period	Quenching media	oC	Period
A120	480	1hr	Air	120	24hrs
A140	480	1hr	Air	140	10hrs
A140	480	1hr	Air	160	8hrs
AW	As weld without PWHT				

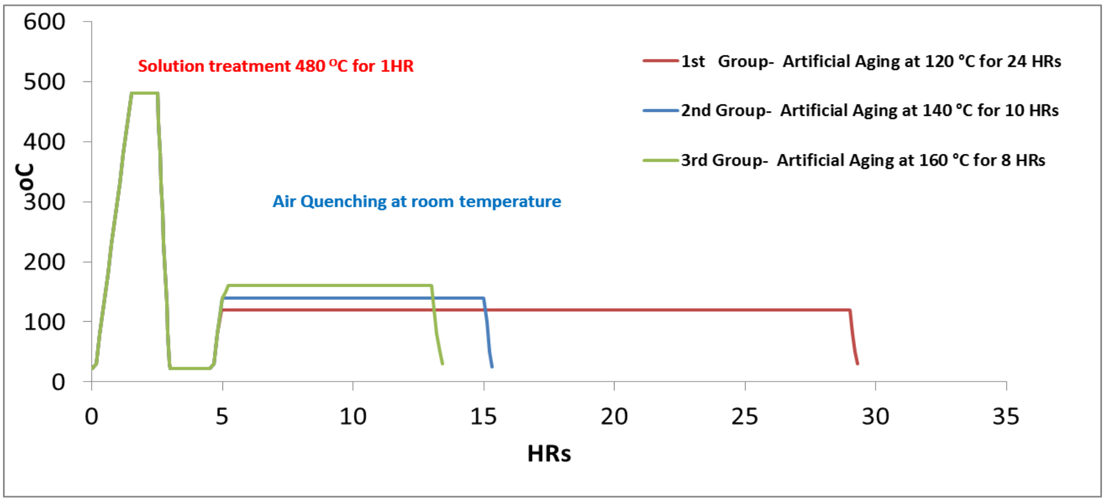


Figure 4. Post Heating process

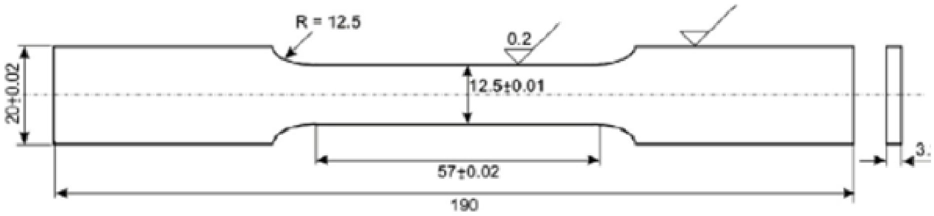


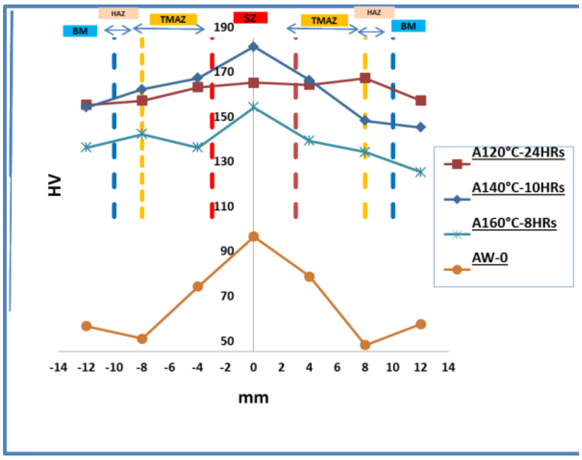
Figure 5 Tensile test specimen

3. RESULTS AND DISCUSSION

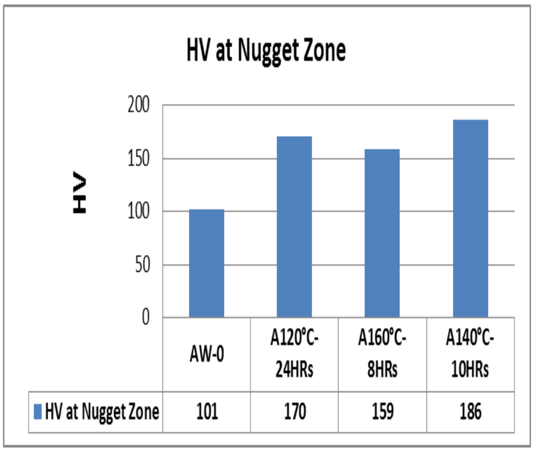
3.1 Hardness

The actual hardness values were been measured on the cross-section of the nugget zone as shown in Figure 6. The microhardness values were covered in different zones such as the nugget zone, Thermo-mechanical affective zone (TMAZ), and heat affective zone (HAZ) of both welding sides, Advanced

Side (AS) and Retreating Side (RS). For the post-weld heat-treated sample made at A120, the maximum value of the microhardness in the nugget region (NZ) was 170 HV and the minimum hardness value was 160 HV, which is a good improvement of the hardness at the weld joint. For samples of A160 condition, hardness was 159 HV at the nugget zone as a maximum value and minimum is 139 HV at the heat-affected zone. Similarly, the recommended condition sample A140, showed the highest hardness result in this work where the hardness reading was a maximum value is 186 HV and a minimum value 150 HV. Finally, we can conclude that the highest hardness value was obtained because of the use of the procedure of post-weld treatment.



.**Figure 6.a**. Hardness distribution along the centerline of the cross-section of the joints for different Aging conditions: (a)AW (b) A20 (c) A140 (d) A160



	AW-0	A120°C-24HRs	A160°C-8HRs	A140°C-10HRs
HV at Nugget Zone	101	170	159	186

Figure 6.b. Hardness value at Nugget Z0ne for different Aging conditions: (a) AW (b) A120 (c) A140 (d) A160.

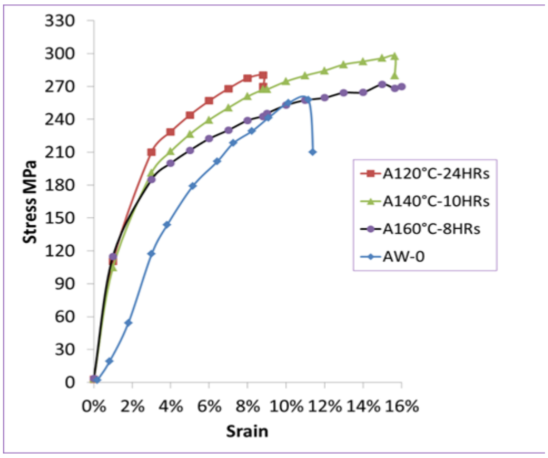
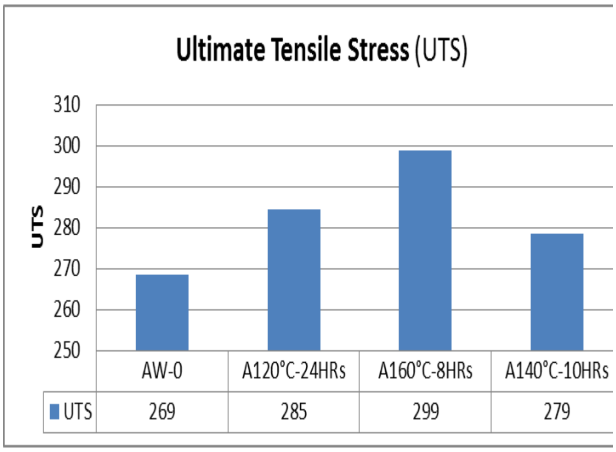


Figure 7.a. Stress-Strain Diagram for different Aging conditions: (a) AW (b) Aging at A120(c) A140 (d) A160.



	AW-0	A120°C-24HRs	A160°C-8HRs	A140°C-10HRs
UTS	269	285	299	279

Figure 7.b. Ultimate tensile stress for different Aging conditions: (a)AW (b) A120 (c) A140 (d) A160

3.2. Tensile properties

The results of the tensile test performed for VCFSW joints under conditions A120, A140 and A160 are shown in Figure 7. An improvement in weld joints were been observed over the treatment of artificial aging of the VCFSW joint. This improvement has a tensile stress range between 280 MPa and 299 MPa.

Generally the ultimate tensile strength for AW (as weld) joint showed the lowest value 269 MPa. Specifically, the ultimate tensile strength of the post-heat joint at A140 was obtained the highest value 299MPa which increased by 11.2%, compared to AW joint. Also The PWHT at `A120, A160 obtained the values of UTS (285),(279) which increased by 5.9%, and 3.7% compared to AW joint respectively. However, the elongation results of the AW joint were 11.8%, and the PWHT at A120, reduce the elongation to 8.9% but the PWHT at A160 and A140 have improved the elongation to 15.7%, 17.3% respectively.

Finally, it can be concluded that the improvement in weld joints were been observed when using the treatment of artificial aging of the VCFSW joint.

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3.3. Microstructural observations

An overall macroscopic cross-sectional image of the weld zones of the FSWed (Friction Stir Welded) AA 2024-O joint can be seen in Figure8.

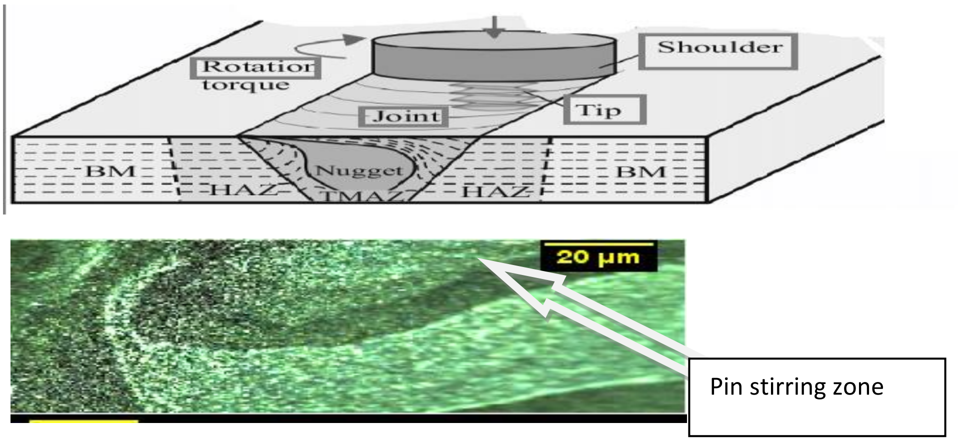

Figure 8.[*] weld zone 0f AA2024 with vertical compensation AA7075 strip

In figure 8, the weld zones are clearly visible because of their different contrasts after etching. Boundaries generation due to heat generation and deformation in the different zones and widens near the top surface due to the close contact between the shoulder of the tool and the upper surface during FSW. The microstructure of The PWHT joints can be seen in Figures 9, 10. Eevery figure represents one case of Aging conditions after solution heat treatment. It appears that grain sizes in the stir zones approach several hundred microns. There is also a noticeable difference in the grain sizes in the stir zones of all PWHT joints was observed. It became clear to us after analyzing the microscopic results that when PWHT aging at A120 and A160, (figures9 a, c and figuers10 a, c) a discrepancy in the size of the particles appears in the different stirring zones where the grains transform in size into fine coherent and semi-coherent .

While at A140, (Figures9.a, 10.a) is more fine grains and little voids than the other types of other conditions. Therefore, the highest microhardness and strength values have been obtained at the A140 aging joints.

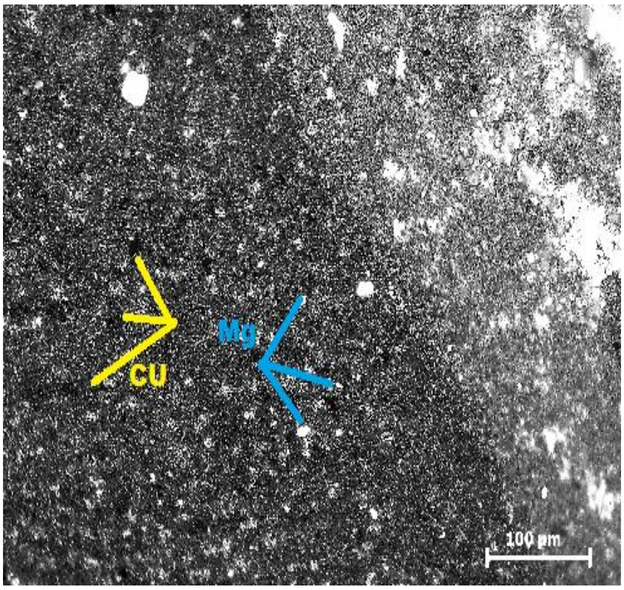

Figure 9.a Microstructural of A120

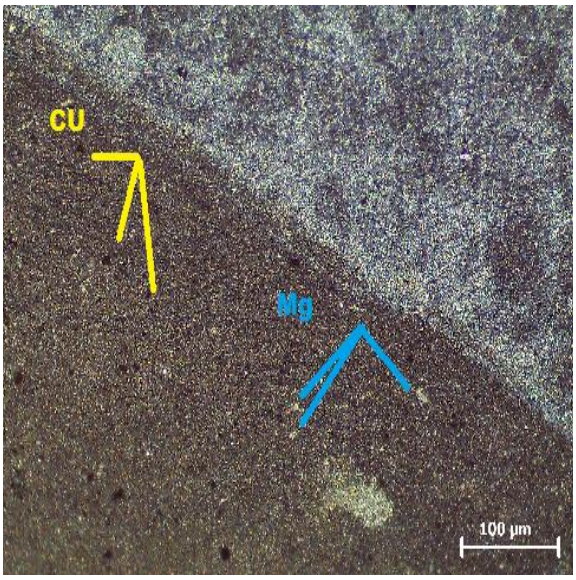

Figure9.b Microstructural of A140

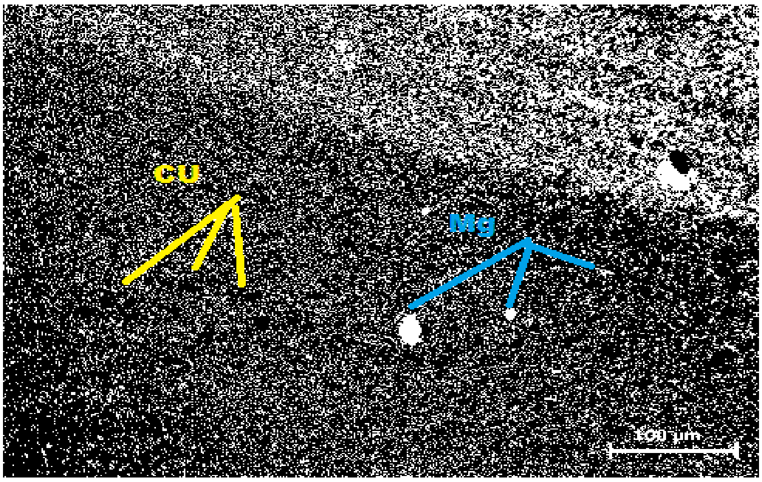

Figure 9.c Microstructural of A160

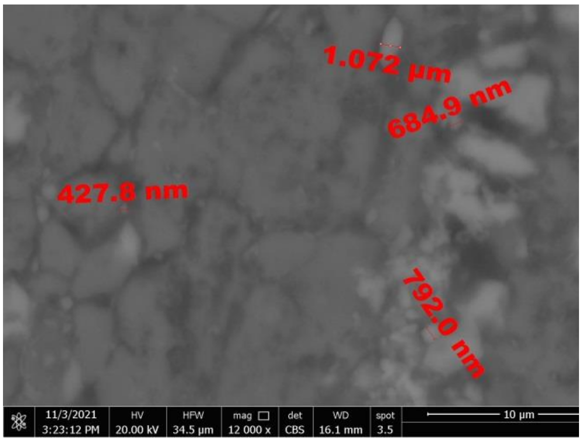

Figure 10.a SEM of A120 at Nugget zone (NZ)

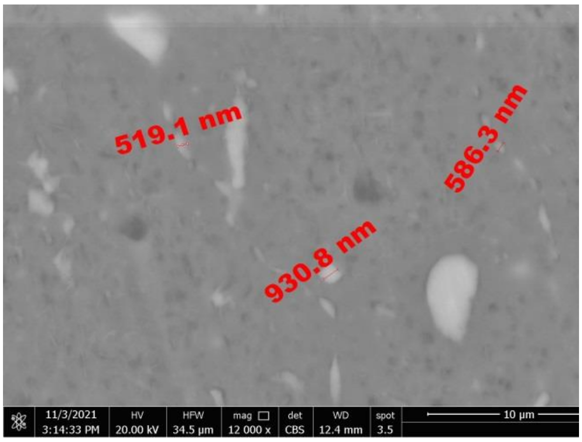

Figure 10.b SEM of A140 at Nugget zone (NZ)

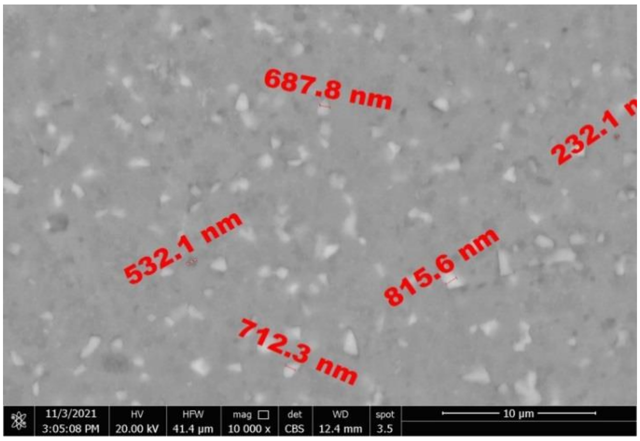

Figure 10.c SEM of A160 at Nugget zone (NZ)

SUMMARY AND CONCLUSIONS

This paper focuses on the effect of post-heating of VCFSW by solution treatment at 480 °C and aged at three different temperatures as120, 140, and 160°C for 24 hr, 10 hours, and 8 hours periods. The effects of these post-weld heat treatments were investigated and analyzed. The conclusions obtained are summarized in the following items

(1)The tensile properties of VCFSW of AA2024 with filler AA7075 alloy were increased due to post- heating.

(2) Increasing the aging period may not effect on the hardness values, and tensile stress but it is an important factor, when the aging temperature associated with its time

(3) The hardness values of PWHT samples at all conditions of interlayer widths were a maximum of 186 HV and a minimum of 150 HV

(4) The grain size in TMAZ is considerably larger than that of the SZ for all conditions.

(5) The micro hardness test and microstructure analysis observed that the aging period would cause the reduction of internal defects due to relaxation of internal residual stresses.

(6) The micro hardness values are also confirming to these that the maximum hardness values attained at NZ for all conditions.

(7) The aging temperature at 140 °C with a 10hr period represents the ideal condition in this research.

REFERENCES

1. Çam, G., & Mistikoglu, S. (2014). Recent Developments in Friction Stir Welding of Al-alloys. Journal of Materials Engineering and Performance, 23(June), 1936–1953. https://doi.org/10.1007/s11665-014-0968-x
2. Zhang, C., Huang, G., Zhang, D., Sun, Z., & Liu, Q. (2020). Microstructure and mechanical properties in dissimilar friction stir welded AA2024/7075 joints at high heat input: effect of post-weld heat treatment. Journal of Materials Research and Technology, 9(6), 14771–14782. https://doi.org/10.1016/j.jmrt.2020.10.053
3. Wang, G., Zhao, Y., & Hao, Y. (2018). Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing. Journal of Materials Science & Technology, 34(1), 73–91. https://doi.org/10.1016/j.jmst.2017.11.041
4. Azarniya, A., Taheri, A. K., & Taheri, K. K. (2019). Recent advances in ageing of 7xxx series aluminum alloys: A physical metallurgy perspective. Journal of Alloys and Compounds, 781, 945–983. https://doi.org/10.1016/j.jallcom.2018.11.286
5. Abu-Okail, M., Mahmoud, T. S., & Abu-Oqail, A. (2020). Improving Microstructural and Mechanical Properties of AA2024 Base Metal by Adding Reinforced Strip Width of AA7075 via Vertical Compensation Friction Stir Welding Technique. Journal of Failure Analysis and Prevention, 20(1), 184–196. https://doi.org/10.1007/s11668-020-00814-z
6. Ji, S., Meng, X., Xing, J., Ma, L., & Gao, S. (2016). Vertical Compensation Friction Stir Welding of 6061-T6 Aluminum Alloy. High Temperature Materials and Processes, 35(8), 843–851. https://doi.org/10.1515/htmp-2015-0063
7. Ji, S. D., Meng, X. C., Li, Z. W., Ma, L., & Gao, S. S. (2015). Investigation of vertical compensation friction stir-welded 7N01-T4 aluminum alloy. The International Journal of Advanced Manufacturing Technology, 84(9–12), 2391–2399. https://doi.org/10.1007/s00170-015-7904-6
8. Ji, S., Meng, X., Ma, L., Lu, H., & Gao, S. (2015). Vertical compensation friction stir welding assisted by external stationary shoulder. Materials & Design, 68, 72–79. https://doi.org/10.1016/j.matdes.2014.12.009
9. Abu-Okail, M., Sabry, I., Abu-Oqail, A., & Shewakh, W. M. (2020). Effect of Changing Heat Treatment Conditions on Microstructural and Mechanical Properties of Friction Stir Welded Sheets of AA2024 with Interlayer Strip Width AA7075. Journal of Failure Analysis and Prevention, 20(3), 701–722. https://doi.org/10.1007/s11668-020-00868-z
10. ivaraj, P., Kanagarajan, D., & Balasubramanian, V. (2014). Effect of post weld heat treatment on tensile properties and microstructure characteristics of friction stir welded armour grade AA7075-T651 aluminium alloy. Defence Technology, 10(1), 1–8. https://doi.org/10.1016/j.dt.2014.01.004
11. Momeni, M., & Guillot, M. (2019). Post-Weld Heat Treatment Effects on Mechanical Properties and Microstructure of AA6061-T6 Butt Joints Made by Friction Stir Welding at Right Angle (RAFSW). Journal of Manufacturing and Materials Processing, 3(2), 42. https://doi.org/10.3390/jmmp3020042
12. Kannusamy, A. S., & Ramasamy, R. (2019). Effect of post weld heat treatment and welding parameters on mechanical and corrosion characteristics of friction stir welded aluminum alloy AA2014-T6. Transactions of the Canadian Society for Mechanical Engineering, 43(2), 230–236. https://doi.org/10.1139/tcsme-2018-0185

13. M., Ata M.H., Abu-Oqail A., 2019. Effect of friction stir welding process parameters with interlayer strip on microstructural characterization and mechanical properties. *J. Fail. Anal. Prev*. **20**(1), 173–183.

14. Abu-Okail M., Mahmoud T.S., Abu-Oqail A., 2019. Improving microstructural and mechanical properties of AA2024 base metal by adding reinforced strip width of AA7075 via vertical compensation friction stir welding technique. *J. Fail. Anal. Prev.* **20**(1), 184–196.

15. Abu-Okail M., Ata M.H., Abu-Oqail A. et al. 2018. Production of tailor-welded blanks by vertical compensation friction stir welding technique. *Mater. Sci. Technol.* **34**(16), 2030–2041.

16. Abu-Okail M., Ata M. H., 2019. Enhancement ductility of friction stir welded aluminum blanks AA2024 via adding interlayer strip width of AA7075, J Mater Research Express; https://doi.org/10.1088/2053-1591/ab448c.

17. Abdelfatah A., Abu-Okail M., Zaki L., 2021. Corrosion behavior of the pre-heated friction stir welded AA2024 alloy reinforced with AA7075 in 3.5% NaCl solution*, Int. J. Electrochem. Sci.,* **16**, 151001, doi: 10.20964/2021.01.44.