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INTEGRITY AND FSSW PERFORMANCE OF Al AND Mg SHEETS FOR NEXT-GENERATION AEROSPACE AND AUTOMOTIVE APPLICATIONS

KARAKTERISTIKE TAČKASTOG ZAVARIVANJA TRENJEM SA MEŠANJEM (FSSW) I INTEGRITET Al I Mg TRAKA U AEROKOSMIČKOJ I AUTOMOBILSKOJ PRIMENI NOVE GENERACIJE

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Keywords
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- Friction Stir Spot Welding (FSSW)
- tensile strength
- next-generation aerospace technology

Ključne reči
- integritet zavarenog spoja
- tačkasto zavarivanje trenjem sa mešanjem (FSSW)
- zatezna čvrstoća
- aerokosmička tehnologija nove generacije

Abstract

Welding lightweight materials such as aluminium and magnesium ensures optimal structural integrity in welded joints; this is essential for applications that require high strength and durability, as improper welding conditions can lead to defects and reduced load-bearing capacity. Friction stir spot welding (FSSW) is an effective method for joining similar and dissimilar lightweight metals, even with differences in their densities and melting points. The structural integrity of FSSW joints depends on factors such as material properties, process parameters, and tool design, which affect the mechanical performance of the joint and its fatigue resistance. This study investigates the mechanical properties of aluminium alloy EN AW 2024-T4 and magnesium alloy AZ31B, as well as their joint performance with FSSW. The study focuses on the structural integrity of welded joints through three scenarios. The first is by conducting a tensile test for the base metal of both metals to show that they are qualified in yield strength and ultimate tensile strength values. The second scenario the study includes the effect of sheet thickness on the tensile shear force of the welded joint by taking three thicknesses. The last scenario represents the effect of the shoulder-face configuration on the tensile shear force. The results show that the smaller the sheet thickness, the weaker is the weld joint. Also, a zigzag configuration for shoulder-face configuration can give the highest structural integrity, and a configuration consisting of concentric circles can lead to the worst structural integrity of the joint.

Izvod

Zavarivanje lakih materijala kao što su aluminijum i magnezijum obezbeđuje optimalan integritet konstrukcije zavarenog spoja; a to je veoma bitno za primene gde se zahteva visoka čvrstoća i trajnost, jer nepravilni uslovi zavarivanja mogu dovesti do grešaka i smanjenja kapaciteta nosivosti. Tačkasto zavarivanje trenjem sa mešanjem (FSSW) je efikasna metoda za spajanje sličnih i različitih lakih metala, čak i sa različitim gustinama i temperaturama topljenja. Integritet konstrukcija FSSW spojeva zavisi od faktora kao što su: osobine materijala, parametri procesa, konstrukcije alata, a koji utiču na mehaničke karakteristike spoja i na otpornost prema zamoru. U radu se istražuju mehaničke karakteristike legure aluminijuma EN AW 2024-T4 i legure magnezijuma AZ31B, kao i karakteristike njihovih FSSW spojeva. Rad se fokusira na integritet zavarenih spojeva u tri scenarija istraživanja. U prvom se zatezanjem ispituje osnovni materijal za oba metala, kako bi se pokazali zadovoljavajući napon tečenja i zatezna čvrstoća. U drugom scenariju se istražuje uticaj debljine traka na silu smicanja pri zatezanju zavarenog spoja, razmatranjem tri debljine. U poslednjem scenariju je predstavljen uticaj profila čela alata na silu smicanja pri zatezanju. Rezultati pokazuju da sa smanjenjem debljine traka zavareni spoj sve više slabi. Takođe, cik-cak profilom čela alata dostiže se najveći integritet konstrukcije, dok se sa profilom čela oblika koncentričnih krugova postiže najlošiji integritet konstrukcije zavarenog spoja.

INTRODUCTION

The transportation sector, including space transportation, is one that has witnessed the most technological leaps during the past three decades. Significant investments in this sector are one of the main reasons for the clear research trend, especially in the US, China, and Europe /1-2/. The next-generation applications in this field are advanced technologies that can make a prominent difference in performance and reduce costs /3-4/. Manufacturing lighter and better-performing materials is today the primary concern of most industries, including automobiles, aircraft, space vehicles, and even military aspects. Reducing weight and improving performance has led to a considerable increase in the production of drones and a significant development in the production of hypersonic missiles in addition to the traditional transportation industries mentioned previously, /5/.

Aluminium and magnesium alloys are among the most sought-after alloys when the target is less weight and better performance. Aluminium is one of the most used elements in the industry, and its alloys can be of two types: cast and wrought alloys, both of which are divided into heat-treatable and non-heat-treatable categories /6-7/. Cast aluminium alloys produce cost-effective products due to their low melting point despite generally having lower tensile strength than wrought alloys. Since the introduction of metal-shell aircraft, aluminium has been essential in the aerospace industry because if left unprotected by oxidation and proper coating procedures, aluminium alloy surfaces form a protective white layer of aluminium oxide. On the other hand, magnesium has good tensile strength and low density, enabling it to play an essential role in many applications, /8/. Its high strength/density ratios compared to other metals make it more suitable for automotive and aerospace equipment applications.

Welded joints in engineering metal structures often compromise structural integrity, serving as common points for crack initiation due to inherent metallurgical flaws, geometric irregularities, mechanical property inconsistencies, and residual stresses /9/. The structural integrity of components with flaws can be evaluated to achieve specific objectives /10/. The study of the integrity of welded structures focuses on three axes: process, property, and performance joints. It attempts to understand their relationship and their impact on the structure's integrity in real applications, as shown in Fig. 1.

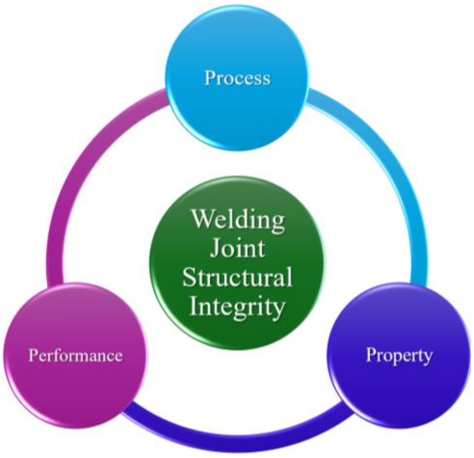


Figure 1. Structural integrity of welded joint structures.

One thing to consider when determining structural integrity for welded joints is the type of welding process. In some welds, such as laser beam welding, FSW, and FSSW, the joint strength is much lower than that of the base metal.

Due to the relatively low melting points of both aluminium and magnesium, their welding capabilities by conventional welding methods (fusion welding) have remained limited which has affected the spread of industrial applications based on aluminium and magnesium, /11, 12/. However, a breakthrough occurred in the early 1990s when researchers at The Welding Institute (TWI) were able to develop a solid-state welding technique called friction stir welding (FSW) /13, 14/. FSW is a revolutionary technology that has given great potential for welding low-alloy metals, as well as for joining dissimilar metals such as Mg and Al. Moreover, it has even been remarkably successful in fusing dissimilar metals that have a significant difference between their melting points, such as Cu and Al, steel and Mg /15, 16/. FSW technology has recently found more comprehensive and unconventional applications, such as its ability to join polymers and composite materials /17, 18/. In FSW, two workpieces are close together and fixed well. Then, a non-consumable rotating tool (consisting of a shoulder and a pin) is plunged down until the shoulder contacts the workpieces. The tool continues to rotate in the same place until sufficient friction heat is generated to soften the workpieces. Later, the tool moves in a transverse motion along the weld line in addition to its rotational motion. The transverse speed contributes to the merging of the two pieces, creating a highly efficient welded joint, /19, 20/.

Over the last decade, many techniques have branched off from FSW. Friction stir spot welding (FSSW) is the most popular and advanced improvement, as it has become a fierce competitor to resistance spot welding. In FSSW, the transverse movement is eliminated as the tool presses on specific points, often automatically, to join two or more plates /21, 22/. The rotating tool is pushed down until the pin contacts the upper plate, followed by penetration of the plate until the shoulder contacts the plate (plunging stage), /23/. The tool continues to rotate until the two plates soften and the metal flows (bonding stage). The tool is pulled up after the two plates are spot-welded (drawing out stage), /24-25/. FSSW stages are shown in Fig. 2.

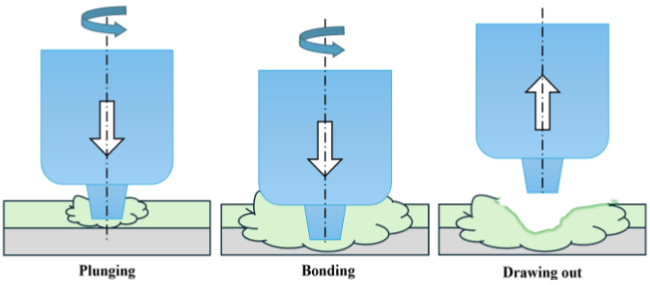


Figure 2. FSSW schematic illustration.

In FSW and FSSW, weld defects include voids, kissing bonds, lack of penetration, and tool wear-induced defects. Any type of these defects can reduce load-bearing capacity performance, reduce joint integrity, and can be considered a main source of stress concentration, /26-27/. These effects ultimately influence mechanical properties, such as tensile strength and hardness which can reduce fatigue life and initiate fracture in many applications, /28/.

The characteristics of FSSW welded joints are said to be a function of the material properties, process parameters, as well as tool design that contribute to mechanical strength and fatigue resistance of the joint. This is of great concern, especially for applications that require FSSW joint performance, where several loads bear members since FSSW joints are defined to have good structural integrity. In summary, there are discrepancies between strength and the parameters of the process.

Although studies are available on friction stir welding, in-depth research is still needed on FSSW, especially regarding the structural integrity of joints and their relationship to next-generation aerospace and automotive applications. The effect of sheet thickness on welding joint integrity still needs to be better understood, and shoulder face configuration and its effects on the welded joint are interesting topics.

MATERIALS AND METHODS

An essential part of the study focuses on the effect of shoulder shape on joint performance and structural integrity. An austenitic stainless steel (X6CrNiTi18-10) pinless FSSW tool of 50 mm length and 8 mm shoulder is used. Five types of shoulders are used in this study, as shown in Fig. 3, where the letter S and the number that follows it indicate the shape (S01-S05) for use in the following parts of the article.

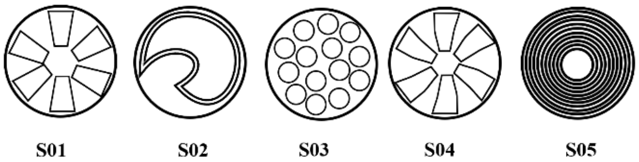


Figure 3. Shoulder configurations used in this study.

Tensile tests are performed on FSSW welded specimens with the INSTRON 3369 machine, while a five-axis CNC machine HAITIAN-HISION-VMC1000II is used as FSSW machine, as shown in Fig. 4.

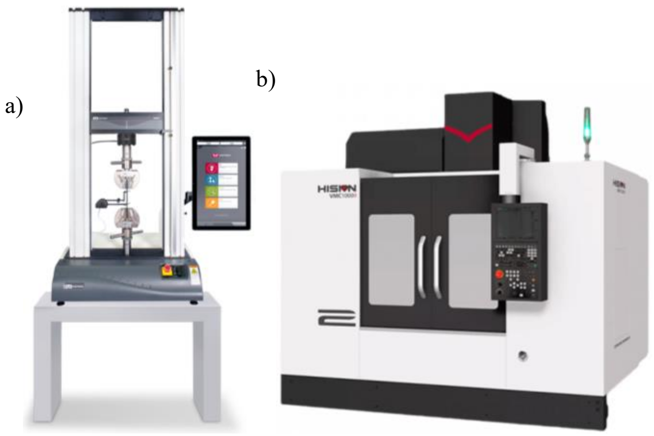


Figure 4. a) Universal tensile test machine, b) FSSW machine (CNC).

Tensile test specimens are prepared according to ISO 6892-1/29/. Figure 5 shows specimen dimensions. Three specimens are taken for each case, and the average values are adopted. In contrast, samples for tensile-shear and three-point bending tests are prepared according to ISO 14273, /30/, as shown in Fig. 6.

Tables 1 and 2 show the chemical composition of AZ31B magnesium alloy and EN AW 2024-T4 aluminium alloy, in respect, while Table 3 shows the mechanical properties of both alloys. Since the material's modulus of elasticity is less than 150000 MPa, the tensile speed used is 1 mm/min, corresponding to 18 MPa/s in accordance with ISO 6892-1.

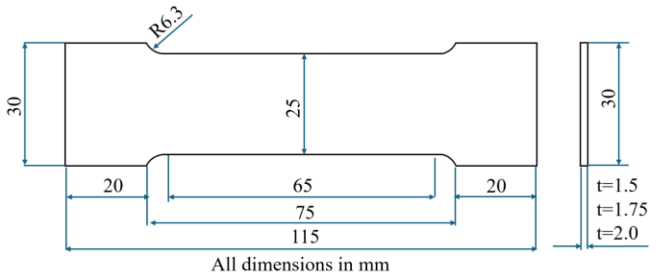


Figure 5. Tensile test specimen according to ISO 6892-1.

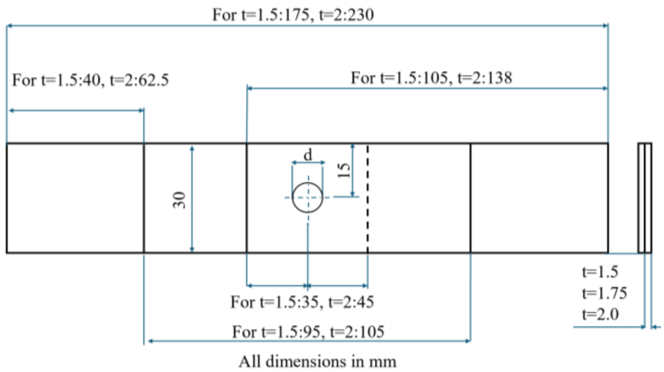


Figure 6. Tensile-shear test specimens according to ISO 14273.

Table 1. Chemical composition (wt.%) of AZ31B /31/.

Al	Ca	Cu	Fe	Mn	Ni	Si	Zn	Mg
2.5-3.5	0.04	0.05	0.005	0.2-1.0	0.005	0.1	0.6-1.4	bal.

Table 2. Chemical composition (wt.%) of EN AW 2024-T4 /32/.

Cu	Mg	Mn	Fe	Cr	Ti	Zn	Si	Al
3.8-4.9	1.2-1.8	0.3-0.9	0.5	0.1	0.15	0.25	0.5	bal.

Table 3. Mechanical properties of AZ31B and EN AW 2024-T4 /31-32/.

Material	AZ31B	EN AW 2024-T4
Tensile strength (MPa)	240	≥ 425
Yield stress (MPa)	145	≥ 275
Elongation (%)	≥ 7	≥ 12

For better sample qualification, semi-automatic grinding and polishing Laboforce-100 equipment is used (25 N of force at 300 rpm for 2.30 min). For welding the AZ31B Mg alloy, three different thicknesses (1.5, 1.75, and 2.0 mm) and three plunge depths (0.87, 1.02, 1.16 mm) were used, and the tool rotational speed was fixed at 1800 rpm. In contrast, EN AW 2024-T4 Al sheets of 1.2 mm thickness, a plunge depth

a)

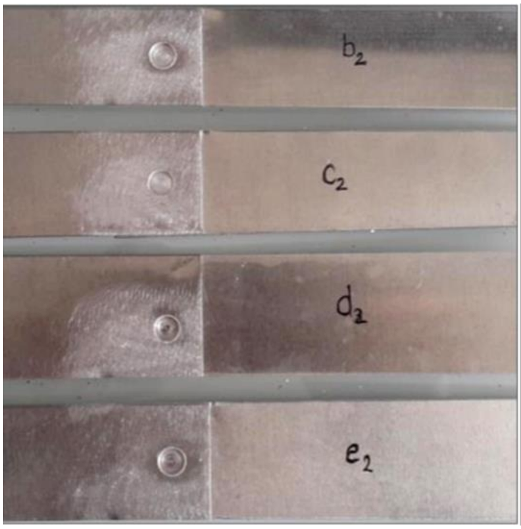
b)


Figure 7. FSSW lap joint specimens: a) EN AW 2024-T4 ; b) AZ31B.

of 0.7 mm, and tool rotational speed 2500 rpm were used. Figure 7 shows examples of FSSW-welded specimens of AZ31B Mg alloy and EN AW 2024-T4 Al alloy.

RESULTS AND DISCUSSION

The structural integrity of welded joints is of great importance in all types of welding, whether fusion or solid-state welding. In FSSW, the structural integrity of welded joints is of greater importance because they are limited to specific points and not to the rest of the parts. On the other hand, the sensitive nature of FSSW applications, often in the aerospace industry, renders compromising structural integrity unacceptable. FSSW produces distinctive microstructural properties by mechanically mixing the metals at the joint line without melting them. The evaluation of the tensile strength in FSSW directly affects the reliability and durability of the joint under mechanical loads in various applications. This section studies and compares the effect of tensile strength on welded joints in both EN AW 2024-T4 and AZ31B with the tensile strength obtained for the base metal of both materials without welding.

Tensile strength in the base metal

In tensile testing, an INSTRON 3369 machine is used, and three samples of each metal are selected based on their availability in the laboratory. A thickness of 1.5 mm is selected in tensile tests for AZ31B Mg alloy, while a thickness of 1.2 mm is selected for EN AW 2024-T4 Al alloy for base metal testing. The samples were arranged according to the criteria mentioned above. Since the strain rate can affect the properties /33-34/, 1 mm/min is chosen as an average value in these tests. Slower strain rates typically allow the material more time to undergo plastic deformation, resulting in higher elongation and ductility, while faster strain rates can lead to lower ductility as the material needs more time to adapt to the applied stress before fracturing, /35-36/. The results are recorded for each yield stress, maximal ultimate tensile strength, and elongation for three samples for each metal, and the average values are taken for comparison purposes in subsequent parts of this study. Tables 4 and 5 indicate the tensile test for base metal of AZ31B and EN AW 2024-T4 alloys and the average values (AVG).

Table 4. Base metal tensile test for AZ31B.

Exp. no.	Magnesium alloy AZ31B		
	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (A%)
1	252.6	156	21.8
2	253.5	147	21.3
3	253.2	153	21.4
AVG	253.1	152	21.5

Table 5. Base metal tensile test for EN AW 2024-T4.

Exp. no.	Aluminium alloy EN AW 2024-T4		
	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (A%)
1	455.5	301	25.1
2	452.3	323	25.7
3	455.1	315	22.7
AVG	454.3	313	24.5

The yield strength and ultimate tensile strength results obtained from Tables 4 and 5 compared with Table 2 show that they are higher, which means that the samples to be adopted in the study of the structural integrity of the welded joints achieve reliability and can be relied upon.

Effect of sheet thickness on structural integrity

In real applications, such as aircraft, automobile, and ship structures, where structural integrity is an important criterion, the tensile shear strength test is essential to determine how much shear force the FSSW-welded joint can withstand before failure /37-38/. With this test, the stress distribution is found and is linked to the outside load applied on the cross-linked shear and cross-linked tensile test specimens which is done by looking at the specific way the material fails. The tensile shear strength test can evaluate the quality of the weld, including whether the bonding between the materials in the stir zone and adjacent heat-affected zones is strong and uniform, /39-40/.

Three sheet thicknesses are adopted for the Mg AZ31B alloy: 1.5, 1.75, and 2 mm, while for Al EN AW 2024-T4 alloy, 1.2 mm is adopted as a uniform thickness for all sheets due to the availability of more studies that discuss the effect of thickness in this type of alloy. In the tensile-shear test for AZ31B alloy, the thickness of the sheet is 2.0 mm, the plunge depth is 1.4 mm, the plunge rate is 0.1 mm/s, the dwelling time is 15 s, the holding time is 25 s, and the tool rotational speed is 1800 rpm. Moreover, the tool shoulder diameter and length are 8 and 50 mm, respectively. The tensile shear test was carried out on five specimens to enhance the reliability of the alloy integrity. The maximum tensile shear force values achieved were 1902 N and the minimum 1593 N, as shown in Fig. 8. The average value for the selected specimens was 1770 N.

Table 6 summarizes the tensile shear test of the FSSW welded specimens when the thickness of AZ31B samples is 2.0, 1.75, and 1.5 mm. Table 6 displays the highest shear force each specimen experiences at various sheet thicknesses, arranged in order of average.

These results highlight several exciting points, such as achieving a maximum average value of 1769 N when the sheet thickness was 2 mm. The obtained result indicates that the increased thickness contributes to greater joint strength and structural integrity. The maximum shear force observed for this thickness was 1902 N (specimen M3), suggesting a robust joint performance in certain specimens. The average shear force for the 1.75 mm sheet was 1626 N which reduces compared to the 2.0 mm thickness but maintains a reasonable structural performance. The 1.5 mm sheet, with an average shear force of 1437 N, demonstrated the lowest joint strength, reflecting the influence of thinner material on joint shear capacity.

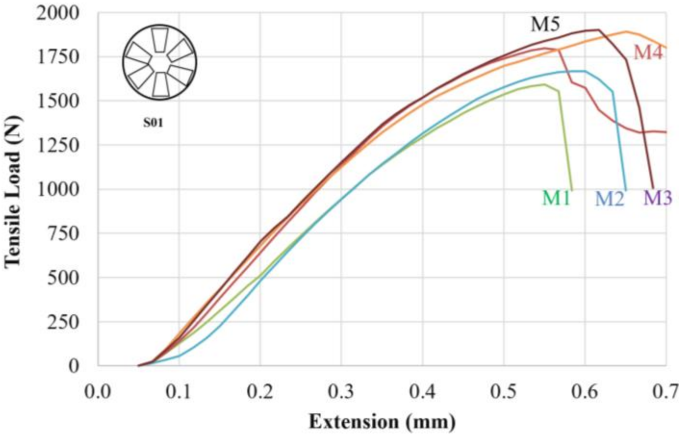


Figure 8. Tensile load-extension curve for AZ31B base metal.

Table 6. Max. and average shear force for EN AW 2024-T4 specimens.

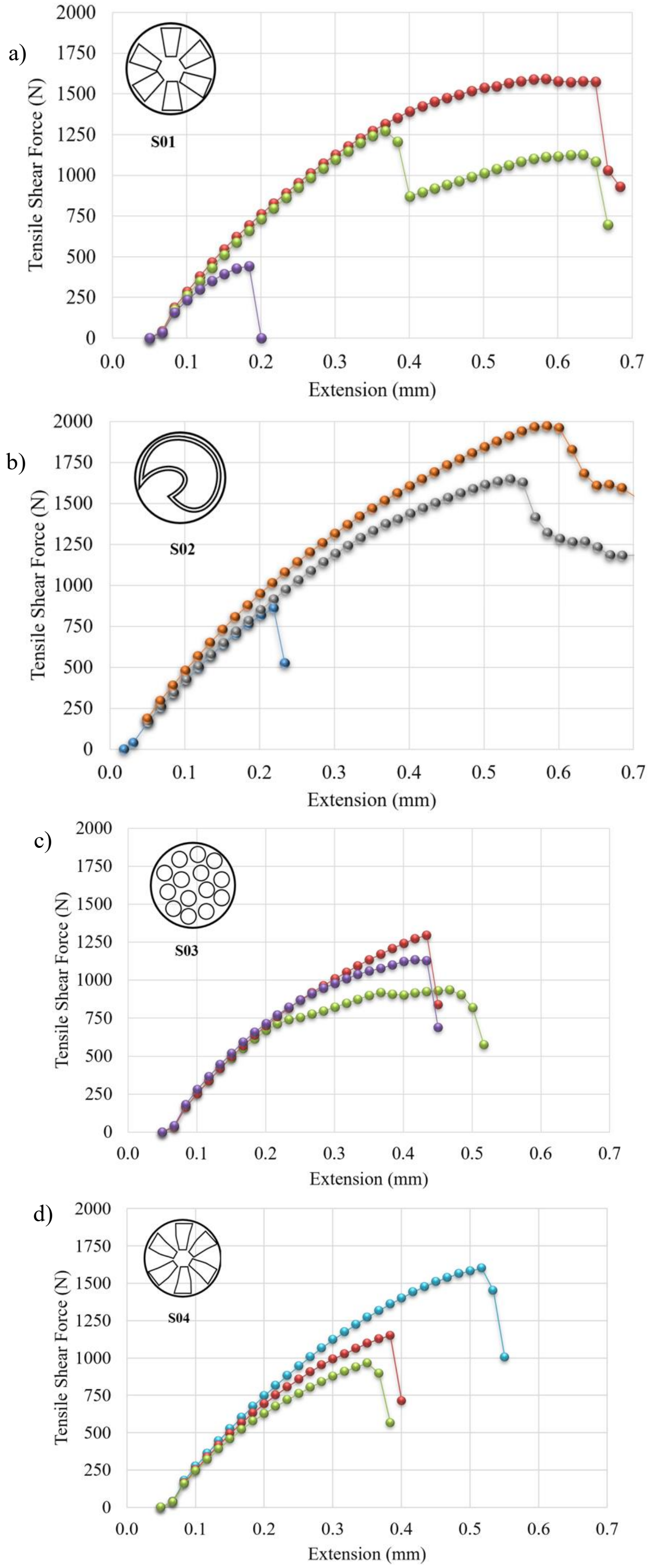
Specimen thickness	Maximum shear tensile force (N)					Average force
	M1	M2	M3	M4	M5	
1.2 mm	2200	2967	2296	2506	2510	2495

The different test results, especially for the 1.5 mm thick specimens (M3 1253 N and M4 1730 N), show that the quality of the joints can vary depending on the welding method and the materials used. However, a wider gap exists between the lowest and highest values of thinner sheets.

Effect of shoulder configuration on structural integrity

As previously mentioned, the effect of shoulder configuration on the weld joint's structural integrity during FSSW operations is investigated. Test sections of three or sometimes more specimens are made for each of the five shoulder shapes shown in Fig. 3. Configurations (S01-S05) refer to the shoulder face arrangement. To investigate the shear tensile strength of the AZ31B Mg alloy, a high rotational speed of 3500 rpm and sheet thickness of 1.5 mm are used. The rationale behind selecting a high rotational tool speed and a smaller thickness in the test stems from the increased risk of welded joints failing at high speeds, /41-42/. In addition, the previous section proves that samples with a thickness of 1.5 mm are more prone to failure than the rest of the samples with larger thicknesses (2 mm and 1.75 mm). Therefore, studying the failure of joints under these conditions will be more convincing in understanding the structural integrity of the resulting joint /43-44/.

Figure 10 indicates the effect of a shoulder profile on the tensile shear force. Evaluation of the tensile-shear test results reveal that shoulder profile types S02 (Fig. 10b) and S04 (Fig. 10d) reach the maximal failure force of 1500 N. In the S01 type (Fig. 9a), values around 1300 N, both high and low amplitude (stable, repeatable), are obtained. By performing subsequent joints and tests with optimal parameters, we achieve a tensile-shear force of approximately 1750 N, significantly exceeding this value. However, only two samples of type S02 (Fig. 10b) exhibited this situation, while others yielded values below 500 N. For the S03 (Fig. 10c) and S04 (Fig. 10d) types, all connections yield values that remain relatively stable around 1000 N. Consequently, the evaluation of the shear test reveals the optimal joints.



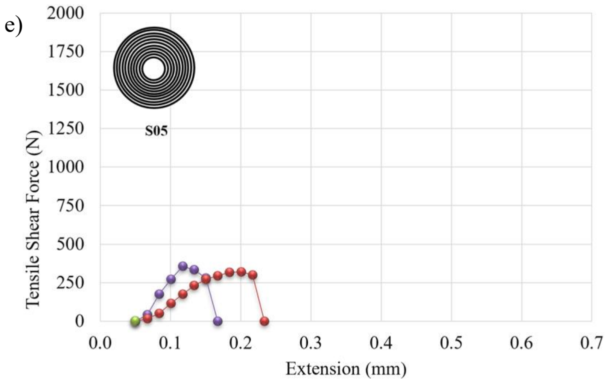


Figure 9. Effect of shoulder face profiles on tensile shear force.

CONCLUSIONS

This study focuses on the structural integrity of welded joints in FSSW welded specimens. The specimens were first tested before welding using a universal tensile test. After welding, the welded joints were qualified for tests that focus on tensile shear stress. All tests were conducted according to the standards adopted in structural safety studies. The following points are the most important conclusions.

- Structural integrity is greatly affected by sheet thickness, where a small thickness of about 1.5 mm can lead to joint failure under lower loads compared to a larger thickness, especially in magnesium alloys.
- The shoulder-face configuration has a significant effect on structural integrity, as the shoulder-face configuration is composed of concentric circles and can fail significantly compared to other types, especially the zigzag configuration or the opposite rectangular parallelepiped configuration.
- The load-bearing capacity of aluminium alloys is greater than that of magnesium alloys and can even reach double, especially when the sheet thickness is small.
- FSSW is a promising welding technique and can achieve adequate structural integrity when the welding parameters, weld thickness, and type of welding tool are well selected.
- FSSW's outstanding ability to join light metals, especially those with low melting points, such as aluminium and magnesium, can make it a promising welding technique for Next-Generation Aerospace and Automotive Applications.

REFERENCES

1. McGuire, S. (2007), *The United States, Japan and the aerospace industry: From capture to competitor?*, The Pacific Rev. 20(3): 329-350. doi: 10.1080/09512740701461439
2. Qu, H. (2023), *A literature review on the evaluation and improvement of the international competitiveness of China's aerospace manufacturing industry*, Front. Bus. Econ. Manag. 10(3): 147-152. doi: 10.54097/fbem.v10i3.11467
3. Mehmeti, F., La Porta, T.F. (2020), *Reducing the cost of consistency: Performance improvements in next generation cellular networks with optimal resource reallocation*, IEEE Trans. Mob. Comput. 21(7): 2546-2565. doi: 10.1109/TMC.2020.3039757
4. Gohardani, O., Elola, M.C., Elizetxea, C. (2014), *Potential and prospective implementation of carbon nanotubes on next generation aircraft and space vehicles: A review of current and expected applications in aerospace sciences*, Prog. Aerosp. Sci. 70: 42-68. doi: 10.1016/j.paerosci.2014.05.002
5. Shubov, M.V. (2020), *Drone launched short range rockets*, Aerospace, 7(6): 76. doi: 10.3390/AEROSPACE7060076
6. Kaufman, J.G., Ch.3: Understanding Wrought and Cast Aluminum Alloys Designations, In: J.G. Kaufman, Introduction to Aluminum Alloys and Tempers, ASM Int., 2000. doi: 10.1361/iaat 2000p023
7. Jassim, A.K., Al-Subar, R.K. (2017), *Studying the possibility to weld AA1100 aluminum alloy by friction stir spot welding*, Int. J Mater. Metall. Eng. 11(9): 645-651. doi: 10.5281/zenodo.1132 443
8. Khalaf, H.I., Al-Sabur, R., Derazkola, H.A. (2023), *Effect of number of tool shoulders on the quality of steel to magnesium alloy dissimilar friction stir welds*, Arch. Civ. Mech. Eng. 23 (2): 125. doi: 10.1007/s43452-023-00673-z
9. Koçak, M. (2010), *Structural integrity of welded structures: Process - Property - Performance (3P) relationship*, In: Proc. 63rd Annual Assembly & Int. Conf. on Advances in Welding Science and Technology for Construction, Energy and Transportation, AWST 2010, Istanbul, Turkey, 2010. 17 pages.
10. Koçak, M. (2007), *FITNET fitness-for-service procedure: An overview*, Weld. World, 51: 94-105. doi: 10.1007/BF03266577
11. Liu, L., Ren, D., Liu, F. (2014), *A review of dissimilar welding techniques for magnesium alloys to aluminum alloys*, Mater. 7(5): 3735-3757. doi: 10.3390/ma7053735
12. Ahmed, M., Javidani, M., Mirakhorli, F., et al. (2023), *Developing high-strength Al-Si-Mg filler metals for aluminum fusion welding*, J Mater. Eng. Perform. 32(5): 2218-2227. doi: 10.100 7/s11665-022-07286-2
13. Serier, M., Jassim, R.J., Al-Sabur, R., Siddiquee, A.N. (2024), *Thermal diffusivity modeling for aluminum AA6060 plates during friction stir welding*, In: AIP Conf. Proc. 3051(1): 070004. doi: 10.1063/5.0191742
14. Chikh, A., Serier, M., Al-Sabur, R., et al. (2022), *Thermal modeling of tool-work interface during friction stir welding process*, Rus. J Non-Ferrous Met. 63(6): 690-700. doi: 10.3103/S10678 21222060049
15. Al-Sabur, R.K. Jassim, A.K. (2018), *Friction stir spot welding applied to weld dissimilar metals of AA1100 Al-alloy and C11000 copper*, In: IOP Conf. Series: Mater. Sci. Eng. 455: 012087. doi: 10.1088/1757-899X/455/1/012087
16. Fu, B., Shen, J., Suhuddin, U.F.H.R., et al. (2021), *Revealing joining mechanism in refill friction stir spot welding of AZ31 magnesium alloy to galvanized DP600 steel*, Mater Des. 209: 109997. doi: 10.1016/j.matdes.2021.109997
17. Al-Sabur, R., Serier, M., Siddiquee, A.N. (2024), *Analysis and construction of a pneumatic-powered portable friction stir welding tool for polymer joining*, Adv. Mater. Process. Technol. 10 (2): 1052-1066. doi: 10.1080/2374068X.2023.2173769
18. Khalaf, H.I., Al-Sabur, R., Demiral, M., et al. (2022), *The effects of pin profile on HDPE thermomechanical phenomena during FSW*, Polymers, 14(21): 4632. doi: 10.3390/polym14214632
19. Al-Sabur, R. (2021), *Tensile strength prediction of aluminium alloys welded by FSW using response surface methodology - Comparative review*, Mater. Today: Proc. 45(6): 4504-4510. doi: 10.1016/j.matpr.2020.12.1001
20. Al-Sabur, R., Serier, M., Ch.7- Material Sustainability During Friction Stir Joining, In: S.T. Kumaran, T.J. Ko (Eds.), Sustainable Machining and Green Manufacturing, Scrivener Publ. LLC2024, 2024. doi: 10.1002/9781394197866.ch7
21. Al-Sabur, R., Jassim, A.K., Messele, E. (2021), *Real-time monitoring applied to optimize friction stir spot welding joint for AA1230 Al-alloys*, Mater Today: Proc, 42(Part 5): 2018-2024. doi: 10.1016/j.matpr.2020.12.253
22. Al-Sabur, R., Slobodyan, M., Chhalotre, S., Verma, M. (2021), *Contact resistance prediction of zirconium joints welded by small scale resistance spot welding using ANN and RSM models*, Mater. Today: Proc. 47(Part 17): 5907-5911. doi: 10.1016/j.matpr.202 1.04.431

23. Çam, G., Javaheri, V., Heidarzadeh, A. (2023), *Advances in FSW and FSSW of dissimilar Al-alloy plates*, J Adhes. Sci. Technol. 37(2): 162-194. doi: 10.1080/01694243.2022.2028073
24. Bagheri, B., Abbasi, M., Sharifi, F., Study on Microstructure Evolution and Mechanical Properties of Al5083 Joint Obtained from Friction Stir Spot Welding: Effect of Vibration and Plunge Depth, In: K.O. Cooke, R.C. Cozza (Eds.), Engineering Principles - Welding and Residual Stresses, IntechOpen, 2022. doi: 10.57 72/intechopen.102082
25. Adibeig, M.R., Vakili-Tahami, F., Saeimi-Sadigh, M.A., et al. (2021), *Polyethylene FSSW/adhesive hybrid single strap joints: Parametric optimization and FE simulation*, Int. J Adhes. Adhes. 111: 102984. doi: 10.1016/j.ijadhadh.2021.102984
26. Arandjelovic, M., Djordjevic, B., Sedmak, S., et al. (2024), *Failure analysis of welded joint with multiple defects by extended Finite Element Method and Engineering Critical Analysis*, Eng. Fail. Anal. 160: 108176. doi: 10.1016/j.engfailanal.2024.108176
27. Aranđelović, M., Petrović, A., Đorđević, B., et al. (2023), *Effects of multiple defects on welded joint behaviour under the uniaxial tensile loading: FEM and experimental approach*, Sustainability, 15(1): 761. doi: 10.3390/su15010761
28. Aranđelović, M., Sedmak, S., Jovičić, R., et al. (2021), *Numerical and experimental investigations of fracture behaviour of welded joints with multiple defects*, Materials, 14(17): 4832. doi: 10.3390/ma14174832
29. ISO 6892-1:2019 Metallic materials - Tensile testing. Part 1: Method of test at room temperature, 3rd Ed., 2019.
30. ISO 14273, Resistance welding - Destructive testing of welds - Specimen dimensions and procedure for tensile shear testing resistance spot and embossed projection welds, 2nd Ed., 2016.
31. Atak, A. (2020), *Impact of pinless stirring tools with different shoulder profile designs on friction stir spot welded joints*, J Mech. Sci. Technol. 34(9): 3735-3743. doi: 10.1007/s12206-02 0-0825-9
32. ASTM B107/B107M-13 (2021), Standard Specification for Magnesium-Alloy Extruded Bars, Rods, Profiles, Tubes, and Wire, 2021, ASTM Int. doi: doi: 10.1520/B0107_B0107M-13R21
33. Liu, Y., Dong, D., Wang, L., et al. (2015), *Strain rate dependent deformation and failure behavior of laser welded DP780 steel joint under dynamic tensile loading*, Mater. Sci. Eng.: A, 627: 296-305. doi: 10.1016/j.msea.2014.12.103
34. Zielinski, B., Sadat, T., Lukić, B., et al. (2023), *Characterization of local mechanical properties of Al/Cu Magnetic Pulse Welded joints under high strain rates using synchrotron X-ray imaging*, Mater. Lett, 337: 133943. doi: 10.1016/j.matlet.2023. 133943
35. Wakchaure, K., Chaudhari, R., Thakur, A., et al. (2023), *The effect of cooling temperature on microstructure and mechanical properties of Al 6061-T6 aluminum alloy during submerged friction stir welding*, Metals, 13(7): 1159. doi: 10.3390/met13071159
36. Jannotti, P., Hornbuckle, B.C., Lloyd, J.T., et al. (2024), *Characterizing stable nanocrystalline Cu-Ta behavior and failure dynamics under extremes of strain rate, strain, temperature and pressure by modified dynamic tensile extrusion*, Acta Mater, 263: 119476. doi: 10.1016/j.actamat.2023.119476
37. Ahola, A., Lipiäinen, K., Lindroos, J., et al. (2023), *On the fatigue strength of welded high-strength steel joints in the as-welded, post-weld-treated and repaired conditions in a typical ship structural detail*, J Mar. Sci. Eng. 11(3): 644. doi: 10.3390 /jmse11030644
38. Fakhri, M.S., Al-Mukhtar, A., Mahmood, I.A. (2024), *Effect of mechanical deformation on the electrical conductivity of resistance spot welding joints*, J Appl. Sci. Eng. 27(9): 3165-3173. doi: 10.6180/jase.202409_27(9).0007
39. Kim, D.-Y., Hwang, J.H., Kim, G.-G., et al. (2023), *Prediction of weld tensile-shear strength using ANN based on the weld shape in aluminum alloy GMAW*, J Weld. Join. 41(1): 17-27. doi: 10.5781/jwj.2023.41.1.2
40. Ganesan, R., Gurusami K. (2025), *Investigating the effect of tensile shear strength of resistance spot welding using a neuro fuzzy control system*, Int. J Interact. Des. Manuf. 19: 3267-3275. doi: 10.1007/s12008-024-01882-3
41. Feizollahi, V., Yousefi, M., Elahifar, A., et al. (2024), *Effect of shoulder diameter, tool rotation speed, and arrangement of plates on mechanical and metallurgical properties of dissimilar aluminum 2024-T3 and 7075-T6 friction stir spot welding (FSSW)*, Eng. Fail. Anal, 163(Part A): 108548, doi: 10.1016/j.engfailana l.2024.108548
42. Alkhafaji, A., Camas, D., Lopez-Crespo, P., Al-Asadi, H. (2023), *The influence of tool geometry on the mechanical properties and the microstructure of AA6061-T6 aluminum alloy friction stir spot welding*, Materials, 16(11): 4135. doi: 10.3390/ma16114135
43. Nelson, N.R., Prasad, N.S., Sekhar, A.S. (2023), *Structural integrity and sealing behaviour of bolted flange joint: A state of art review*, Int. J Pres. Ves. Pip. 204: 104975. doi: 10.1016/j.ijpvp. 2023.104975
44. Zhang, M., Cao, Z., Zheng, G., et al. (2024), *Quasi-static tensile failure mechanism analysis of CFRP/Al countersunk electromagnetic riveted joints with different rivet-hole clearances*, Eng. Fail. Anal. 155: 107759. doi: 10.1016/j.engfailanal.2023.107759