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Investigation of Friction Stir Spot-Welded Dissimilar Aluminum and Steel Metallic Lap Joints through Experimental Approaches

Rasha M. Afify[*]

Department of Mechanical Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo 11629, Egypt
***Correspondence:** rash.ali@feng.bu.edu.eg

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ABSTRACT

This work aims to investigate the feasibility of joining two dissimilar metals, aluminum 7075 and low-carbon steel SAE1006 plates, with a high-quality weld. The processing parameters were different design of Tungsten carbide tool steel (WC) tools, three dwell times of 15, 17 and 20 sec, and a constant rotational speed of 1250rpm. The effect of processing parameters on the microstructure and mechanical behavior was investigated. Results showed that long tool pins increased the microhardness of the upper aluminum plate significantly. Long pins had greater tensile shear strengths than short ones because they were influenced by the tool shoulder. Among all factors, tool pin length had a more noticeable beneficial impact on properties obtained compared to dwell time. At a high pin length and a 17sec dwell duration, the highest temperature attained was 487°C. The joint interface area was observed using an optical electron microscope. Mechanical strength tests (lap shear test and micro hardness test) were carried out to see changes in grain properties through analysis of weld zone’s microstructure. The tensile shear strength for tools with long pin exceeded that for short ones due to effect from the tool shoulder region. Brittle mode of fracture was exhibited by both short and high pins under all conditions used for this research study. At those conditions which involved a long dwell time under higher pin length, maximum tensile shear strength recorded was found to be 82.4 MPa. The maximum micro hardness was 205 HV and was achieved at 20 sec dwell time and using the tool with longest pin.

KEYWORDS: Joining dissimilar alloys; friction stir spot welding; microstructural analysis; mechanical characteristics

دراسة الوصلات المعدنية المتباينة الملحومة لحام البقعة الأحتكاكي من الألومنيوم والصلب من خلال الطرق التجريبية

رشا محمد عفيفى*

قسم الهندسة الميكانيكية - كلية الهندسة بشبرا، جامعة بنها، القاهرة ، مصر

***البريد الاليكتروني للباحث الرئيسي : rasha.ali@feng.bu.edu.eg**

الملخص

يهدف هذا العمل إلى دراسة جدوى ربط معدنين مختلفين، الألمنيوم 7075 وصفائح الفولاذ منخفض الكربونSAE1006 ، بلحام عالي الجودة. كانت ظروف التشغيل عبارة عن تصميم مختلف لأدوات فولاذ كربيد التنغستن(WC) ، وثلاثة أوقات توقف لحام 15 و17 و20 ثانية، وسرعة دوران ثابتة تبلغ 1250 دورة في الدقيقة. تم التحقيق في تأثير ظروف التشغيل على البنية الدقيقة والسلوك الميكانيكي. أظهرت النتائج أن دبابيس الأداة الطويلة زادت من صلابة الصفيحة العلوية من الألمنيوم بشكل ملحوظ. كان للدبابيس الطويلة قوى قص شد أكبر من القصيرة لأنها تأثرت بكتف الأداة. من بين جميع العوامل، كان لطول دبوس الأداة تأثير مفيد أكثر وضوحًا على الخصائص التي تم الحصول عليها مقارنة بفترة التوقف الحام. عند طول دبوس مرتفع ومدة توقف 17 ثانية، كانت أعلى درجة حرارة تم الوصول إليها 487 درجة مئوية. تمت ملاحظة منطقة واجهة المفصل باستخدام المجهر الإلكتروني الضوئي. تم إجراء اختبارات القوة الميكانيكية (اختبار القص اللفة واختبار الصلابة الدقيقة) لمعرفة التغيرات في خصائص الحبوب من خلال تحليل البنية الدقيقة لمنطقة اللحام. تجاوزت قوة القص الشد للأدوات ذات الدبوس الطويل تلك الخاصة بالأدوات القصيرة بسبب تأثير منطقة كتف الأداة. أظهر كل من الدبابيس القصيرة والعالية نمط كسر هش في جميع الظروف المستخدمة في هذه الدراسة البحثية. في تلك الظروف التي تنطوي على وقت انتظار طويل تحت طول دبوس أعلى، وجد أن أقصى قوة قص شد مسجلة كانت 82.4 ميجا باسكال. كانت أقصى صلابة دقيقة HV 205 وتم تحقيقها عند وقت انتظار 20 ثانية واستخدام الأداة ذات أطول دبوس.

الكلمات المفتاحية: ربط السبائك غير المتشابهة، اللحام النقطي بالاحتكاك والتحريك، التحليل البنيوي الدقيق، الخصائص الميكانيكية.

1. Introduction

Aim at reducing fuel consumption and minimizing emissions in the automotive industry, often involves replacing some of the weighty steel components with lighter materials such as magnesium and aluminum. Efforts to lower the weight of vehicles in the automotive sector frequently entail substitution of specific steel parts with lighter substances like aluminum or magnesium [1-4]. This is because solid-state welding makes it easier for dissimilar metals to be joined together; this is why the welding of dissimilar metals has received considerable attention lately as it is important in various industrial applications [5-6]. Conversely, using screws or rivets to join different materials can result in an unattractive structure and increased component weight. Also, these materials have different mechanical properties and high melting temperatures that make conventional fusion welding processes difficult hence leading to numerous defects [7-9].

Another challenge for design and welding engineers during construction is metallurgical mismatching caused by dissimilar welds. Despite this, it offers advantages such as a power-to-corrosion ratio comparable to friction stir spot welding (FSSW) [10]. a new joining technology developed for aircraft and transportation based on the principles of friction stir welding (FSW). To join similar/ dissimilar materials cost-effectively with FSSW main structural elements including are recommended [11-15]. As a result, this type of welding is expected to pose strong competition among certain spot joining technologies [16-17].

The underlying principle behind FSSP involves inserting a non-consumable rotating tool into the assembly of workpieces under control [18]. The downward axial force applied on the tool causes it to rotate thus facilitating its rotation. This rotational motion generates rubbing between its tip and contact surface with experience resulting from frictional heating at their interface[19, 20]. In general, plate characteristics significantly affect joint quality along with factors like tool material, rotational speed, dwell time, penetration depth shoulder diameter pin geometry etc. [21-23].

Thimmaraju et al. [24] analyzed the effects of different tool pin shapes (square, cylindrical, and taper) on dissimilar joints made of AA 6061 and AA 6082, using constant operating velocities (1400 rpm and 60 mm/min). Based on both numerical and experimental data, they concluded that a cylindrical tool pin gave high-quality joints with outstanding hardness and ultimate tensile strength (UTS). Lastly, Ravikumar et al. [25] used square, taper cylinder, and taper square thread tool pins to investigate connections between AA6061-T652 and AA7075-T651 where taper cylindrical threaded tool pin showed the topmost tensile strength as well as hardness due to its effective metal stirring. Piccin’s study examined how altering the pin length can affect friction stir spot welding of galvanized low-carbon steel with AA6063 by varying the pin lengths at intervals of 0.65-1.5 mm while changing the depth of penetration into welded joints by means of tools. The shorter welding needles made aluminum overlay steel more compressive [26]. Conversely, Muna and Kareem [27] investigated lengths of pins composed from different materials (AA1100 & AA6061-T6) with a diameter equaling to 3mm in friction stir lap process under cylindrical-threaded pin profile having 2.8 mm; 5.4 mm; and 5.7 mm long pins respectively.

The study was conducted by Roberson et al. [28] to evaluate the effect of plunge duration, spindle speed and pin geometries on AA 5754-H114 / pure copper joints. They revealed that under ideal welding settings, highest shear pressures were obtained when using a straight cylindrical pin profile with a rotational speed of 1000 rpm and plunging duration of 90 seconds. The tensile strength of FSW joints in AA2024 and AA7075 improved with increasing rotational speeds as observed by Ismael [29]. In addition to this issue, other important factors also affect such a relationship depending on the weld joint. Raising dwell time from 10 to 15 sec increased heat input levels to their maxima hence complete dynamic recrystallization & grain refining while very long hold periods did not cause any noticeable change [30].

the present work aims to weld two different materials with a large difference in melting points using the friction stir spot welding method, Alluminum alloy 7075 and low carbon steel AIS1006. and to study the effect of different welding conditions on the quality of the weld. It has been established from previous studies that there have been extensive investigations into process parameters affecting mechanical and metallurgical properties. Nevertheless, one can point out some gaps in terms of the influence of dwell period or pin length on fracture load predictions [32]. Therefore, it is necessary to conduct an in-depth study on the effect of tool pin length and dwell time on shear fracture stresses during friction stir spot welding (FSSW) of varying materials including low carbon steel with AA7075 being one such material.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The investigation was performed on the AA 7075 alluminum and low carbon steel (SAE 1006) plates with thickness of 4 mm and 3 mm, respectively. Table 1 and 2 illustrate the chemical composition of the used aluminum and steel alloys sheets. The chemical composition have been done in Tabbin Institute for Mineralogical Studies. Fig. 1 shows the design of the used WC tool in this investigation. The WC tool was manufacturing using KEllENBERGER W57 with electroplated diamond wheel. The measured shoulder diameter was approximately ∼ 20 mm with cone angles of 15° as shown in **Fig.** 1 (a) and (b). Lap-jointed samples for tensile testing were laser-cut into sizes of aluminum alloy sheets measuring ∼100 × ∼30 mm long. Similarly, before welding, steel plates were cut into similar shapes. Their surfaces were cleaned by means of grinding with SiC papers with different grit followed by polishing with alumina suspension. The welding experiments were executed using vertical loads from a manual milling machine. Then these parts were confined into a specific arrangement that held them together allowing them to be securely fastened into a milling setup. This jointing style involved overlapping each plate to create a joint region. **Fig. 2** (a) and (b) depict square diameters which demonstrate the weld dimensions in contact with tool. The overlapping region has squared dimensions coinciding at this point where attached plates meet tools. The tool pin length, dwell time was taken into account at different levels. The welding period (dwell time) for this process took not less than 15 seconds as well as 17 seconds above 20 seconds. Rotary tool speed remained constant at 1250 RPM throughout all FSSW conditions. Conducting several experiments helped determine operational parameter ranges along with their allowable limits.

experiments were repeated three times and average values calculated. Weld temperature was measured during the FSSW using a thermal camera Fluke 32 with a resolution of 0.05°C at 30°C, logging the temperature changes. A tensile shear test was performed on lap joint samples using a universal testing machine of maximum load capacity of 300 Kg and accuracy ±1%. To understand completely stress-strain curves from tensile shear experiments were analyzed. Samples for microhardness and metallography tests were cut 300 μm away from the center of the button weld. Polishing was done by use of SiC papers having different grades from rough (200) to smooth (2000), then alumina suspension. The Hardness Tester LM700 with an applied force of 100g for ten seconds was used for microhardness testing. As such, two etching steps were involved in metallography test whereby Nital solution (5% nitric acid +98% alcohol) was used to immerse steel part for ten seconds revealing its internal structures examined under LECO LX31 light optical microscope; while Keller solution (1% hydrofluoric acid) that lasted for ten seconds etched off aluminum part. Fracture specimens were observed using scanning electron microscopy.

Table 1: Chemical Composition of AA7075

Elements	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ti**	**Ca**	**Pb**	**Sn**	**V**	**Zr**	**Al**
Wt%	0.067	0. 27	1.56	0.04	2.566	0.213	0.001	5.532	0.024	0.0019	0.001	.001	0.007	0.016	89.69

Table 2: Chemical composition of low-carbon steel based on SAE 1006 standard

Elements	**C**	**Si**	**Mn**	**p**	**S**	**Cu**	**Cr**	**Mo**	**Ni**	Fe
Wt%	0.04	0.001	0.03	0.003	0.009	0.002	0.02	0.001	0.001	99.45

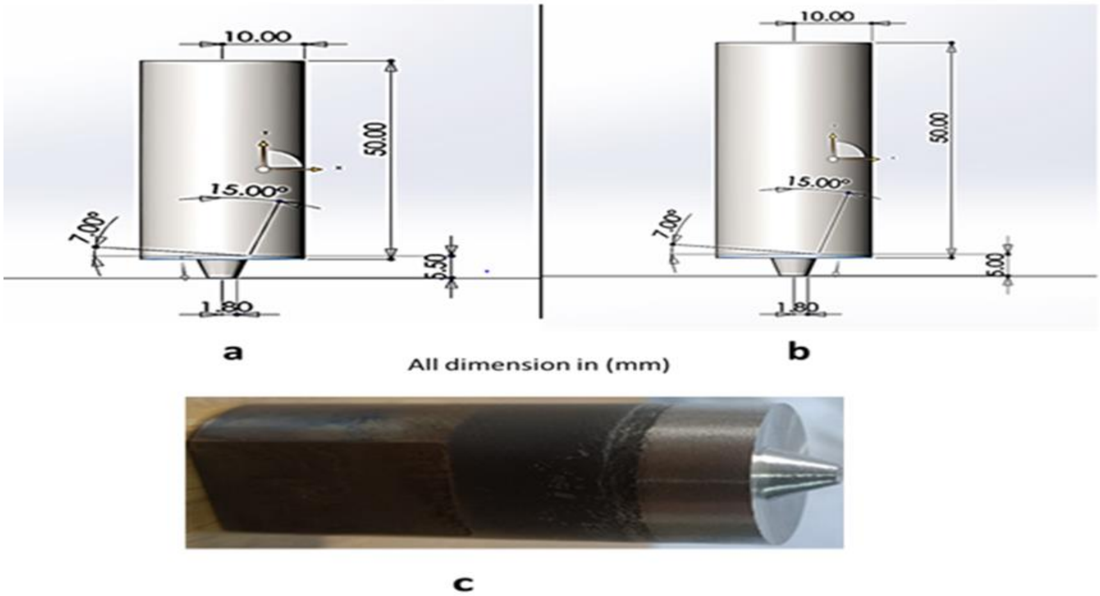

Fig. 1 schematic drawing of tool design a) short pin length 5 mm and b) long pin length 5.5 mm, c) designed tool

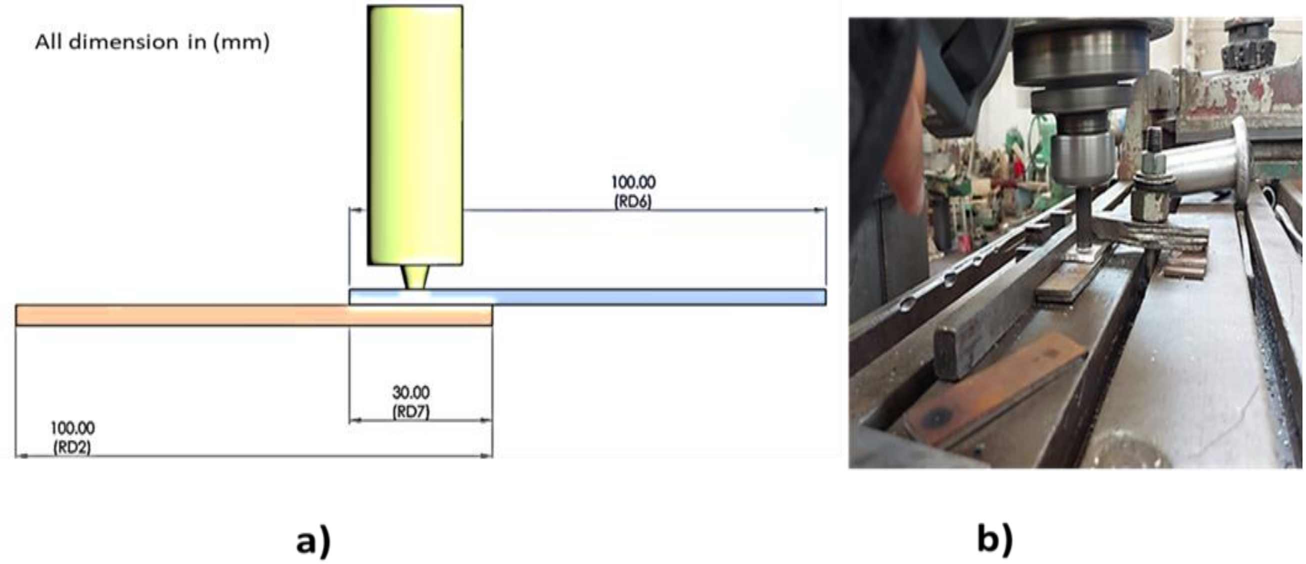

Fig. 2. a) Schematic design of the plate layouts, b) Welding setting

3. Result and Discussion

3.1 Temperature Distribution

The applied pressure also cause plastic deformation in the form of heat generation brought about by friction between the workpiece and tool. Welding time and tool pin length have a very clear effect on the microstructure of the FSSW [6, 8]. **Fig. 3** shows the macrostructure of FSSW, base material (BM) maintains its original microstructure features, Heat affected zone (HAZs) in this region, there are microstructural variations as a result of changes due to heat input and plasticity.It is also possible for TMAZ to suffer some amount of plastic deformation through slight thermal actions. Microstructural features within Stir Zone have become finer relative to that existing at other corresponding parts.

Fig. 4a shows temperature distribution measurements were made during welding at dwell time 15 sec and long pin Length 5.5 mm,. These numbers increased up to some point whereupon they decreased again [9]. The highest surface temperature was observed on weld specimen with dwell duration at 15 seconds and high tool pin length **Fig. 4b**. Weld nuggets show circumferential ejected flashes.

Fig. 5 presents peak temperature measurements when friction stir spot welding (FSSW) is conducted under different conditions. Temperature values peak when dwell time increases during welding and long pin length used. Through our study of the effect of dwell time on the generated temperature, it becomes clear that increasing the dwell time increases the generated peak temperature as a result of increasing the friction between the tool pin and the sheets [37- 42], Therefore, we find that when using dwell time 15 sec and a tool pin length of 5 mm, the peek temperature was 415°C, and when using 17 seconds, the temperature became 441°C, while when using 20 seconds it was 457°C. The peak temperature generated when using a tool pin length of 5.5 mm and a dwell time of 15 seconds was 427 °C, while when using a welding time of 17 seconds it was 459°C, and when using 20 sec it became 487°C. Significant friction between the stir pin's subface and the Al plate's upper surface resulted in a significant quantity of friction heat generation, which may have caused the initial sharp spike. But once the temperature rose above a certain point, the materials softened and started to flow around the stir pin [43]. This reduced the resistance to friction between the metals and the pin tool, which in turn slowed the pace at which the temperature rose. The pin tool's shoulder made contact with the plates as it continuously sank into them, increasing the frictional area significantly and causing the temperature to rise sharply for the second time.

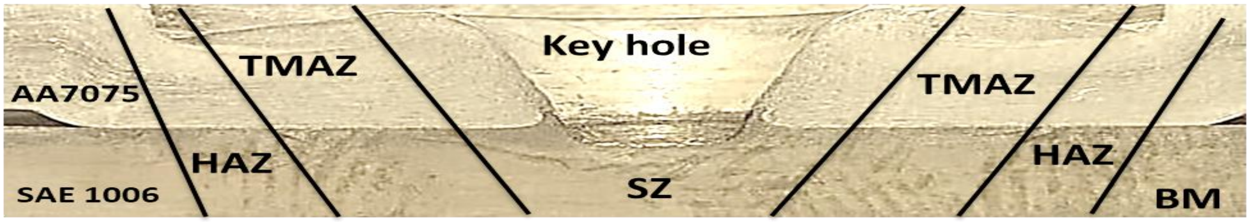

Fig. 3. Zones in FSSW composed of the Stir Zone (SZ), Thermo-mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ) and Base Metal BM) at 17 sec and short pin length.

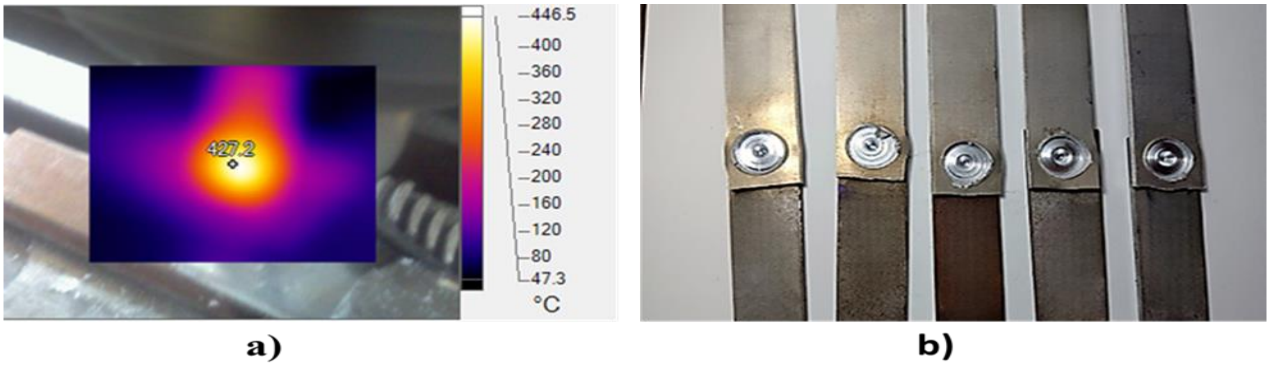

Fig.4. (a) Temperture Destrbusion During FSSW, and (b) welded specmen at dwell time 15 sec and tool pin length 5.5 mm,

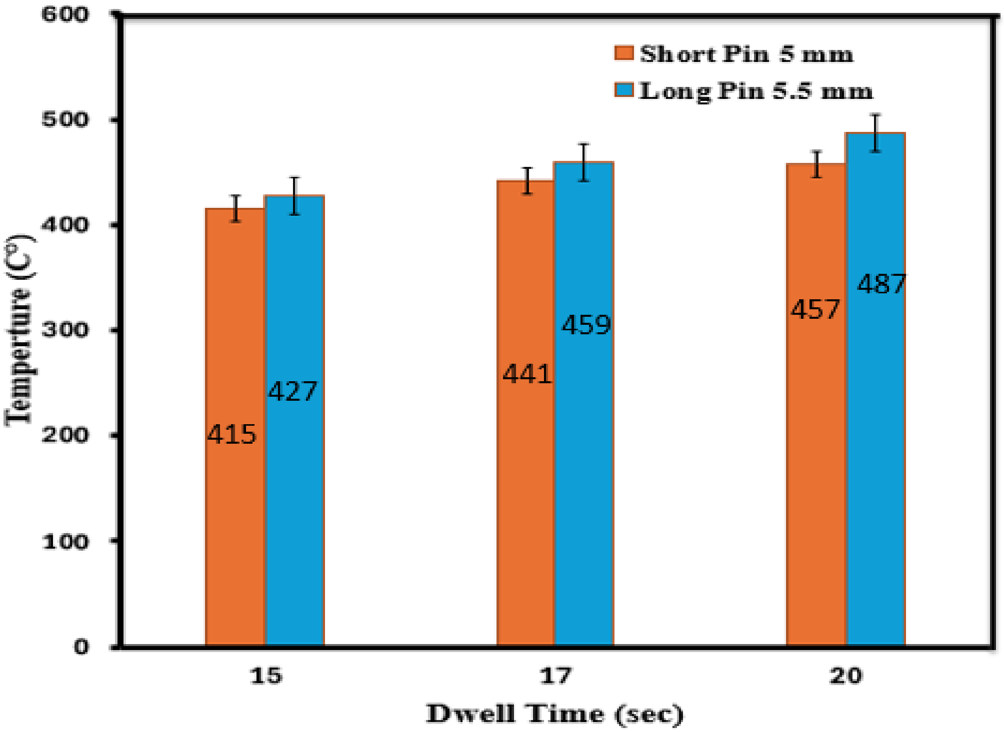

Fig. 5. Effect of dwell time on measuring temperature during FSSW at short and long pin length.

3.2. Metallography and Microstructural Analysis

To examine the weld microstructure, specimens were taken from the periphery of the weld button. The electron microscope for optical purposes was used to obtain images of different zones in aluminum after samples had been prepared. A similar pattern of changing microstructures is noticeable through various locations on plates of steel and others made from aluminum that are depicted here. This reduction occurs in grain size within the center of the weld. It is thus clear that, this area undergoes refinement since as it approaches central welding zone (CWZ), particles sizes tend to decrease due to mechanical pressure caused by tool shoulder. Microstructure for different weld regions can be observed in **Fig. 6**, which consists of **Fig.6a and h** display the base metal zones of alluminum 7075 and steel SAE 1006. For instance, Zones (b) and (c) represent heat-affected zone (HAZ) and stir zone (SZ) respectively.Fig.6 e and g display the Center Weld Zone (CWZ) while there are other weld regions too. This effect is felt across all these areas due to thermal energy from the process itself. In a tightly packed relatively dense region stirred by mechanical force imposed by tool shoulder creates the stir zone. Microstructure develops farther from the central weld region because tool shoulder decreases its impact and transmits more frictional heat resulting into increased particle size surrounding microstructure formation. Dynamic recrystallization may result when particles cool at a lower rate leading to faster cooling rate with higher temperature conditions [25]. The weld metal exhibits greater uniformity, regularity and less porosity than any other zone of the joint, usually known as micro structure area [31-34]. As we move closer to the weld center, the grain size is reduced due to the high mechanical pressure transferred during the process as shown in Fig. 6 b and c.

Fig.7 a illustrate the microstructure of stir zone at dwell time 15 sec and tool pin length 5mm,the base metal 7075 illustrated in Fig .7b. The grain structure of steel plates remains relatively unchanged with decreasing distance to central weld zone as in Fig. 7c and d. This information is thus indicative of unchanged grain structure during process causing heat generation. The welding process involved diffusion bonding— joining together of these aluminum and steel plates, which were facilitated by mechanical pressure and frictional heat generation that increased the bonding.

Also, when making friction stir spot welds between aluminum and steel in overlapping areas, at 17 sec dwell time and such as the regions in **Fig 8**; their strength is raised significantly by its low melting point. With long pin length there will be more compression in the SZ i.e., it gets smaller, see image (**b)** as compared to **(a).** As a result, this parameter has greater significance due to internal connections within materials than time spent in agitation area.

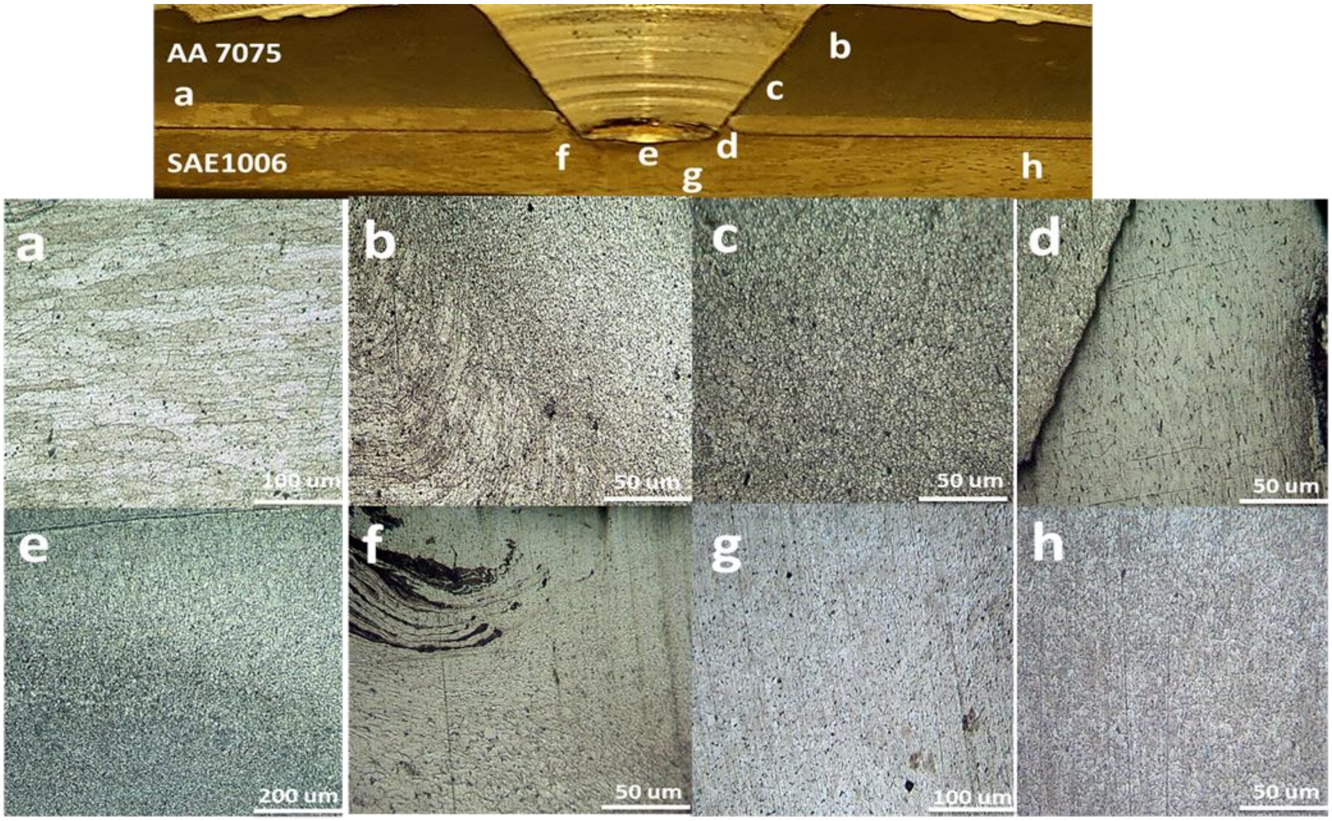

Fig.6. Microstructural at different weld region at dwell time 17sec and long pin length: a) base metal (BM) of AA 7075, b) stir zone (SZ) and HAZ zone, c) Stir zone, d) Right to Center Weld Zone (RCWZ), e. Center weld zone (CWZ), f. Left to the Center weld zone (LCWZ), g) and h) the base metal ASI 1006

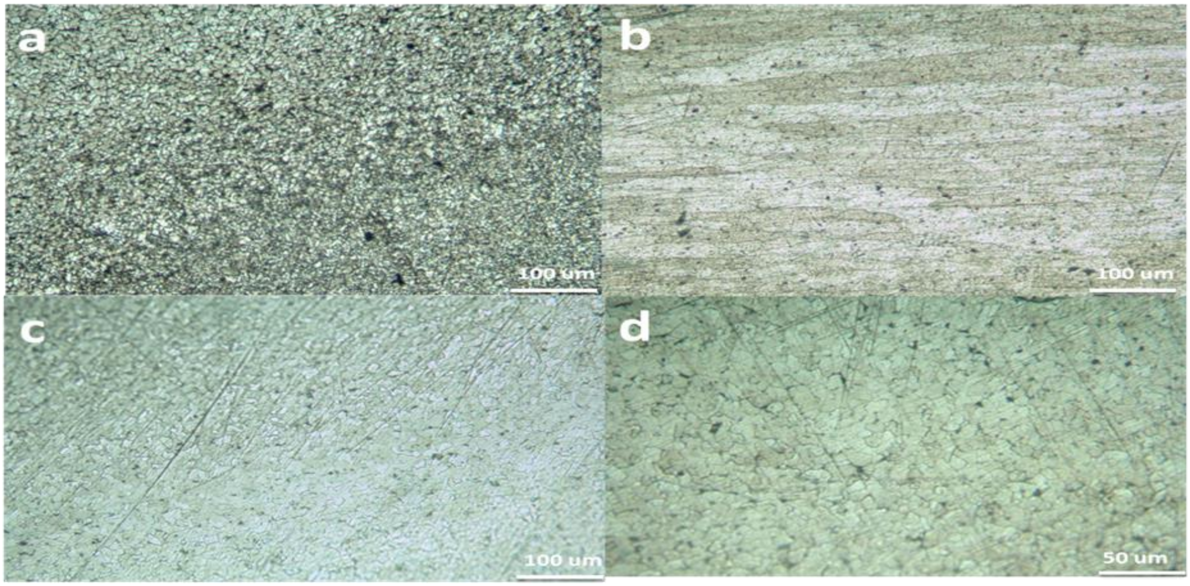

Fig 7. Microstructure at different weld zones: a) stir zone , b) base metal (AA7075), c) Center Weld Zone (CWZ), and d) base metal (AIS 1006) at 15 sec and short pin length

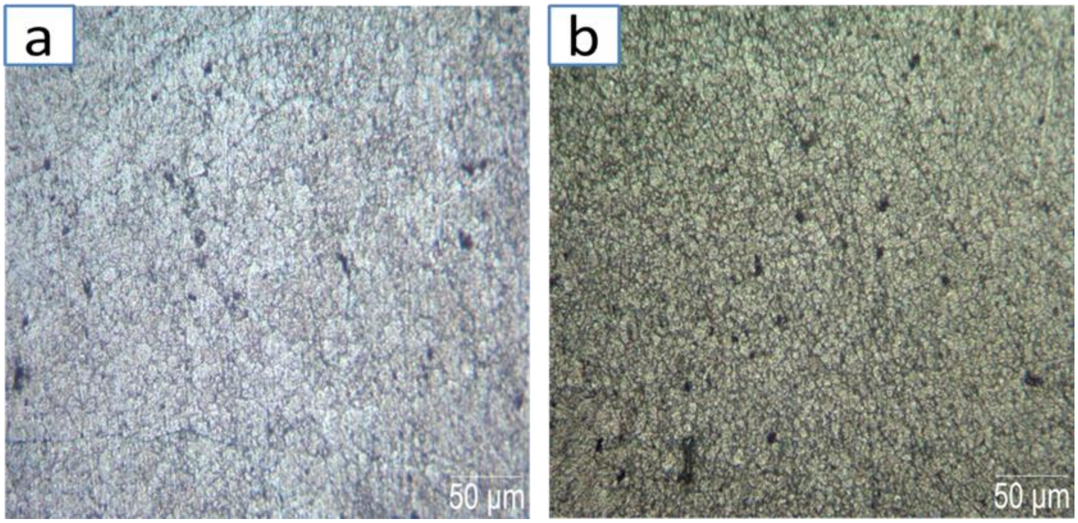

Fig 8. Microstructure at different weld zones: a) at dwell time 17 sec and short pin length and b) dwell time 17 sec and long pin length.

3.3 Mechanical Behavior

3.3.1 Tensile Shear Testing and Fracture Behavior

Tensile shear performance of spot-welded connections is considered by designers when designing new car models. The tensile shear test was carried out on each of the FSSWed joints.

Fig 9 illustrates a bar chart which shows differences in tensile strengths between two pin lengths (5 mm and 5.5 mm) and three dwell times (15, 17, and 20 seconds). The longer is the pin length, the stronger is its tensile shear strength (TSS) due to longer dwell time. As evidenced by the lowest tensile strength of 41 MPa at a 15-second dwell time and a short pin length of 5mm while highest being at about 82.4 MPa for a dwell time of 20 sec with high pin length as the. The findings of this investigation are consistent with the findings reported in the references [23, 35]. Friction caused by short pins leads to lesser heat than that produced by long pins. Nevertheless, pressure applied on the tool shoulder greatly affects tensile shear strength. Similarly, thermomechanical properties of tool shoulders also significantly affect weld contacts which play a role in determining weld strength. When using short pins their influence reduces the tensile shear loadings upon them. On the other hand, having higher contact surfaces created with higher pins produces more frictional heat resulting into greater shearing stress.

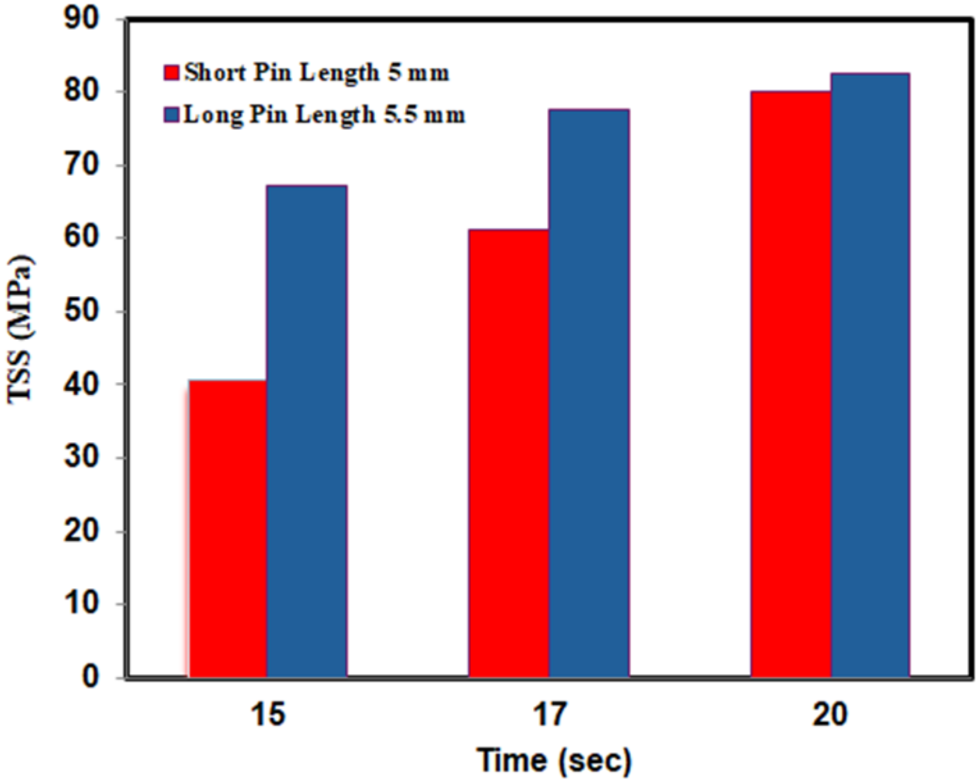

Fig.9. Effect of Dwell Time on Tensile Shear Strength at short and long pin length

The fracture mode observed in short and high pins is an interfacial fracture, which switches to pull-out nugget fracture mode as the length of the pin rises. The pull-out nugget weld type is the mode of fracture observed in the high pins for all parameter values. The use of electron scanning microscope (SEM) imaging is an additional method applied to assess the failure mode. The scanning electron microscope (SEM) image shown in **Fig. 10** demonstrates that short pins with a dwell period of 15 mm exhibit a brittle fracture mode. The SEM picture in **Fig. 11** depicts a high pin length and a dwell period of 20 seconds. As the length of the pin increases, the fracture mode transitions to a brittle state. The main reason for the failure of the samples during the shear tensile test [36] was brittle fracture.

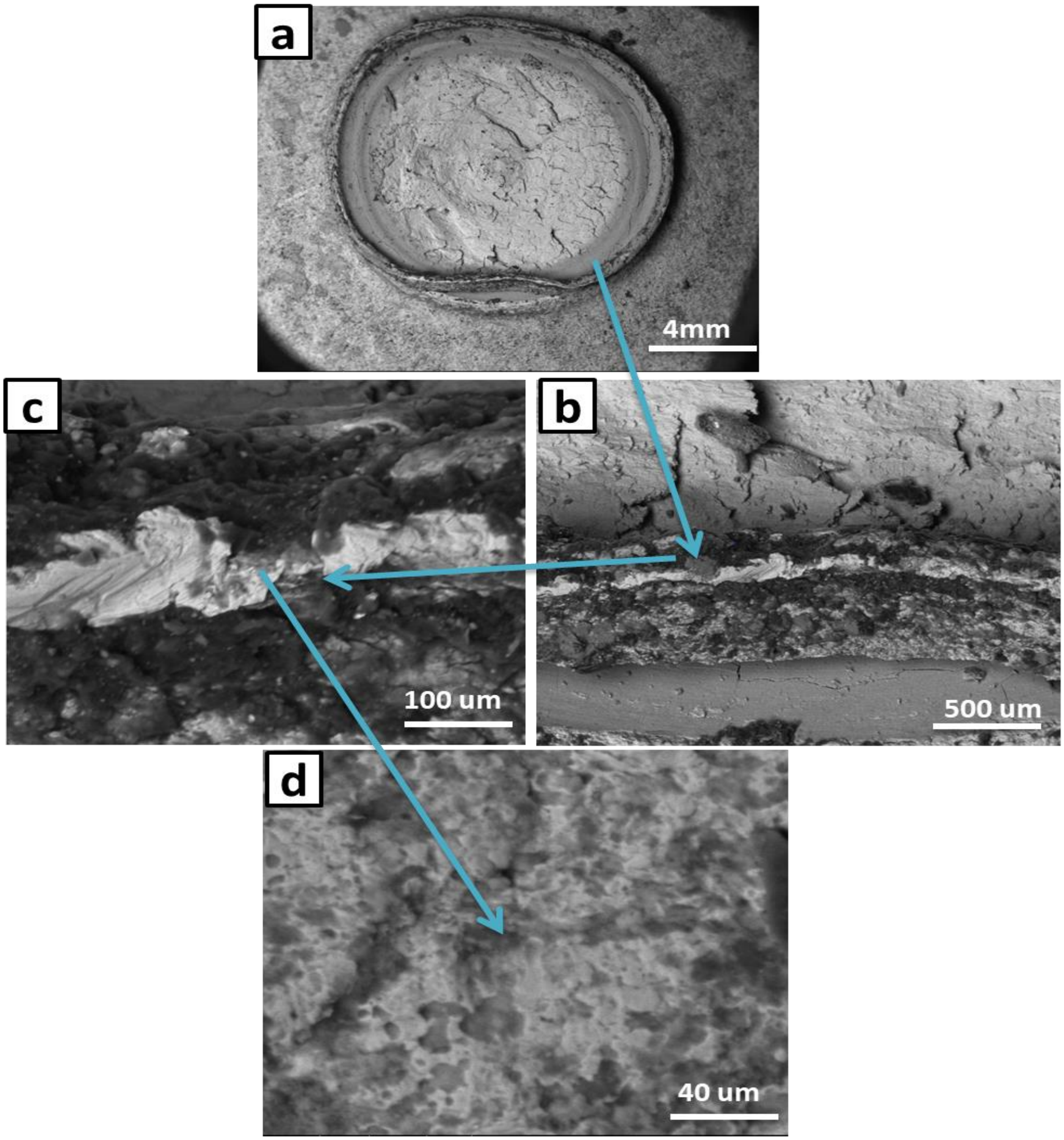

Fig. 10. Fracture morphology of brittle fracture at 15 sec dwell time and 5 mm pin length. (a) top view of lower sheet, b: region pointed in a, c and d magnification the region pointed in b.

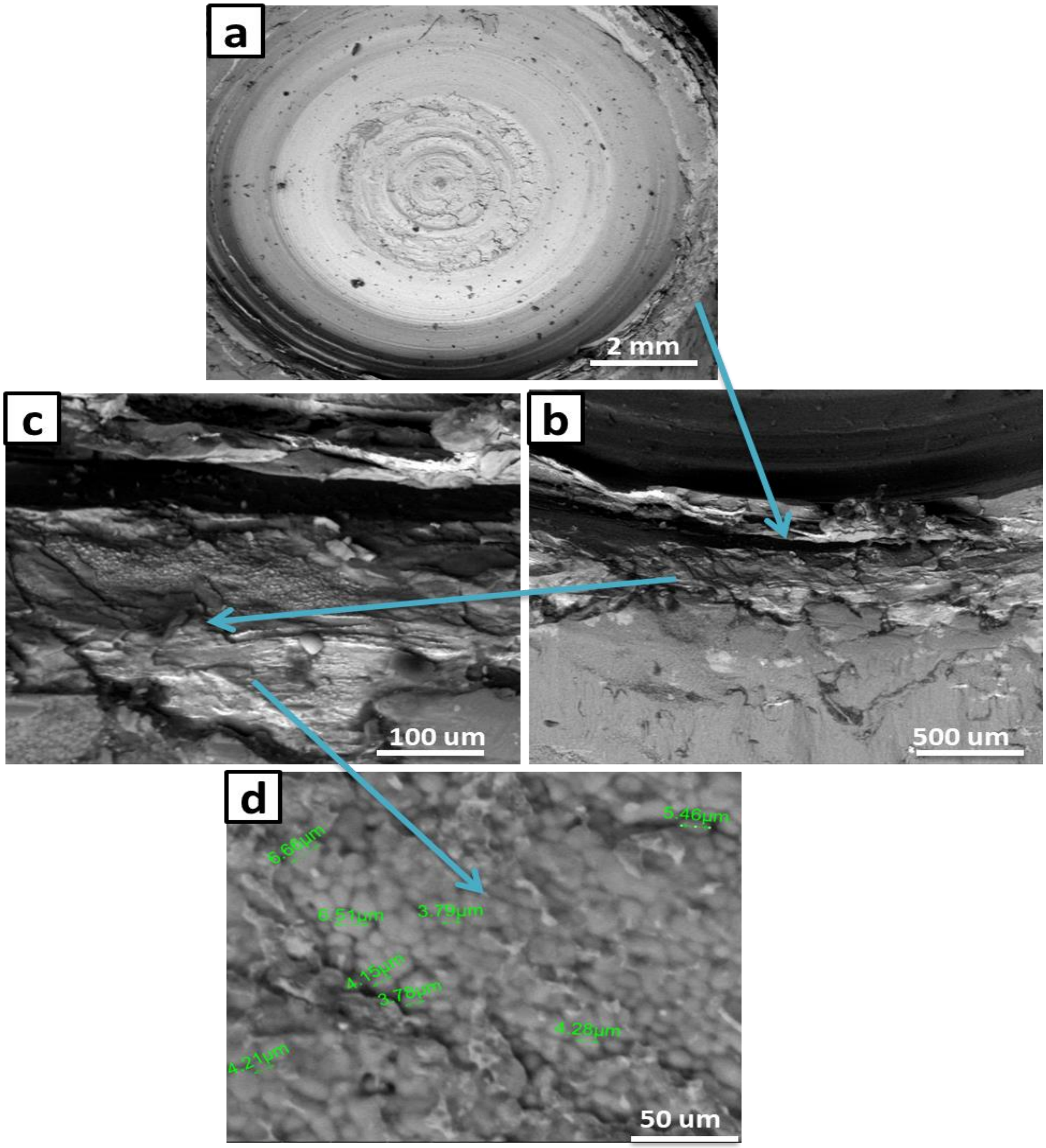

Fig. 11. Fracture morphology of brittle fracture at 20 sec dwell time and 5.5 mm pin length. (a) top view of lower sheet, b: region pointed in a, c and d magnification the region pointed in b.

3.3.2 Hardness Test

Within the central thickness of the welded joint, the hardness profiles shown in Figs. 12 and 13 provide an example of varying types, taking into account three different dwell times and two pin lengths. All joints demonstrate a skewed pattern of hardness. Due to the presence of a narrow zone with intensive deformation, microhardness values in the stir zone underwent change. The observed differences in dwell time and microhardness evidence that longer dwell times are positively correlated with higher microhardness. In the stir zone (SZ) of AA7075 alloy at a pin length of 5.5 mm and at a dwell time of 20 seconds, HV measured as high as 205 was recorded for the highest value obtained on SZ weld metal region investigated in this work. However, during welding with shorter tool (at a pin length 5 mm), it registered a lower value than all other DW 17 sec, 149.3 HV.

The Microhardness test was carried out on the 7075 aluminum upper sheet not low carbon steel, at a distance of 1 mm from the upper surface, on both sides, on the right side of the key hole formed as a result of the position of the tool pin, from 0 to 6 mm, and on the left side of the tool pin, from 0 to - 6 mm. Rotating the tool pin clockwise from the right, we find that the hardness values increase towards the right, reaching 205 HV.

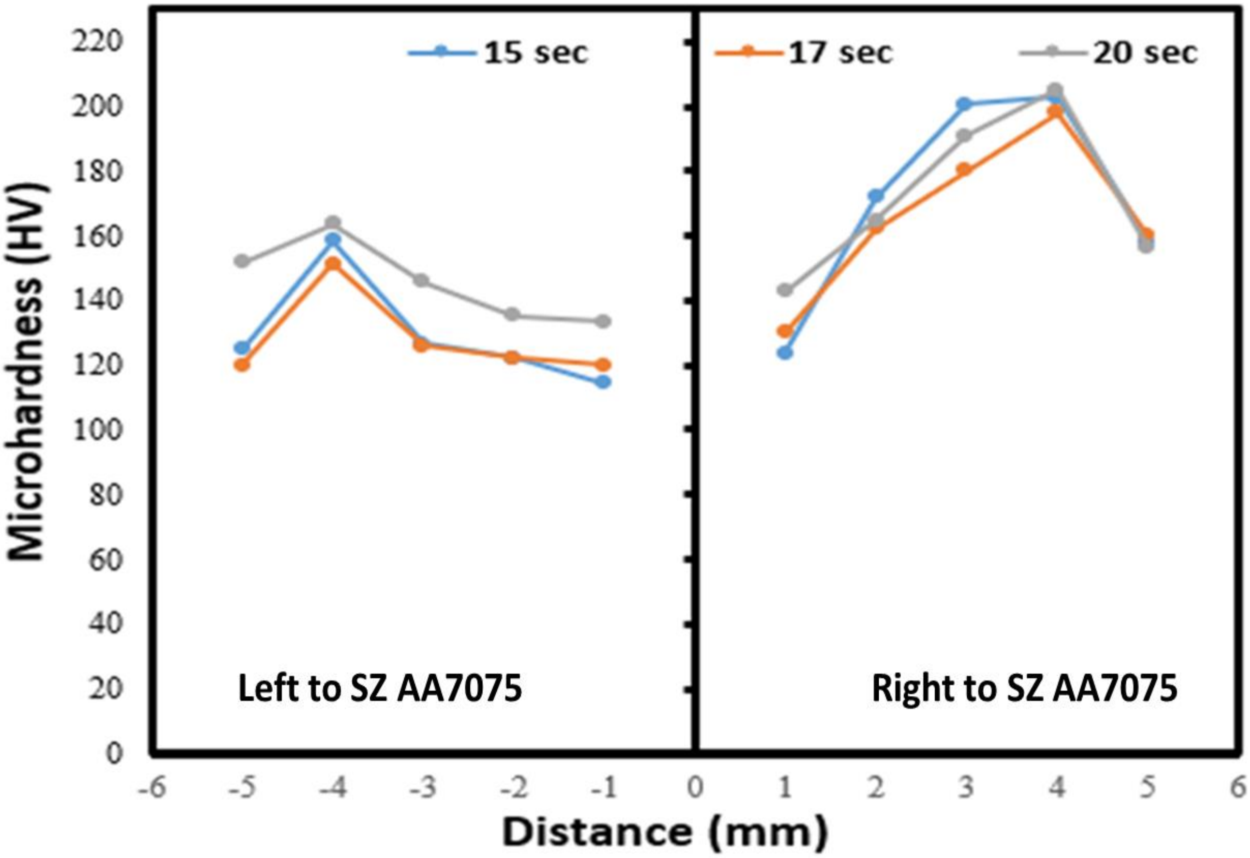

Fig. 12. Microhardness measured in the stir zone (SZ) in the upper plate AA7075 from 0 to 6 on the right side and from 0 to - 6 on the left side by changing the dwell time at long pin length 5.5 mm.

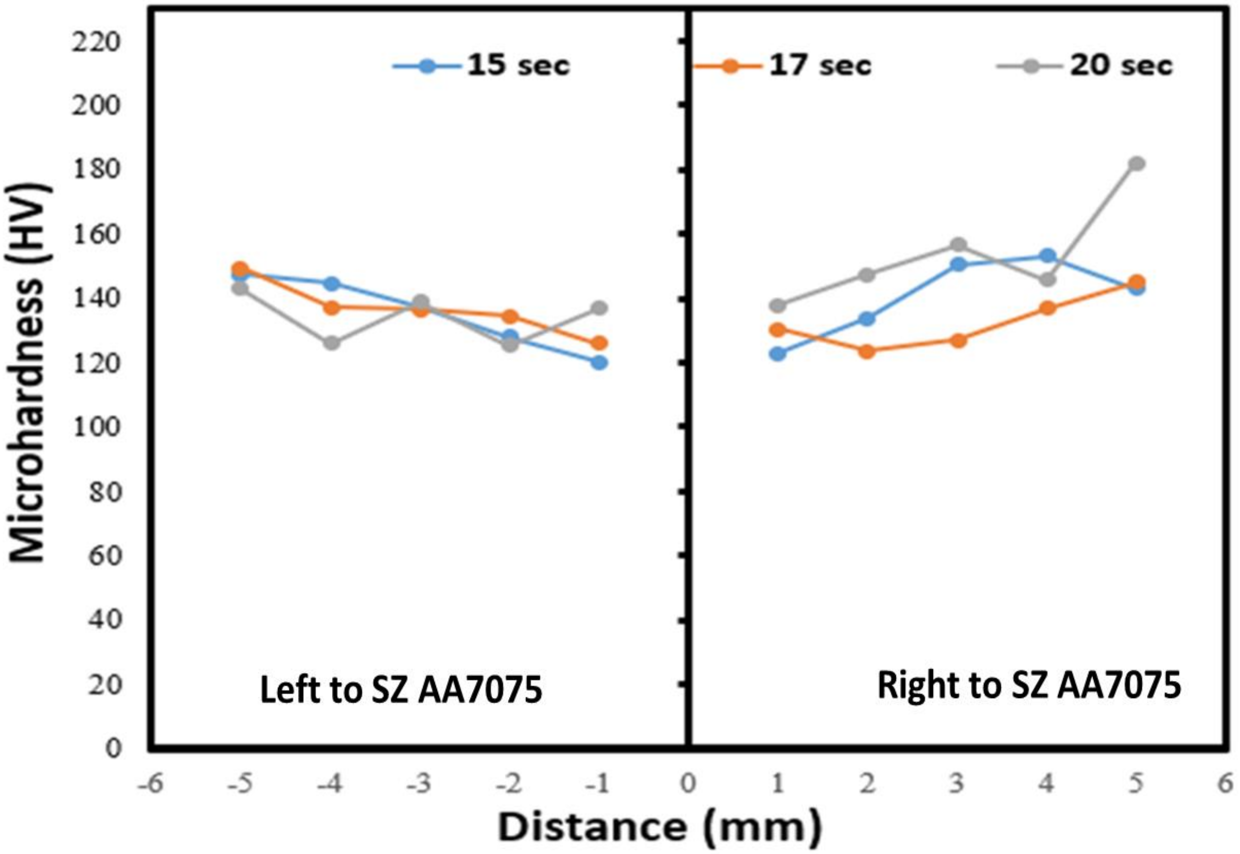

Fig. 13. Microhardness measured in the stir zone (SZ) at the upper plate AA7075 from 0 to 6 on the right side and from 0 to - 6 on the left side by changing the dwell time at short pin length 5 mm.

CONCLUSIONS

Secure joints properties were identified in this investigation. The friction stir welding process involved adequate heat and pressure such that the aluminum plate was welded onto the steel plate with no big deformation into plastic form. The following findings were obtained:

- With a long tool pin length and a 17 sec dwell period, the temperature reached its high at 487°C.
- The Stir zone (SZ) area was determined to have a fine microstructure through the use of microstructure analysis. Similarly, increasing tool pin lengths and dwell led to higher friction heat. However, there was no sufficient evidence to prove any substantial change of steel plate's microstructure due to small friction heat generated by welding process.
- Low ultimate tensile strength (UTS) was 41 MPa at short tool pin length of 5 mm and dwell time of 15 seconds. A high tensile strength was 82.4 MPa at longer tool pin length of 5.5mm and a dwell duration of 20 seconds.
- The maximum microhardness value was 205 HV at 20 sec dwell time and a 5.5 mm tool pin length while the lowest microhardness resulted at 5 mm short tool pin lengths for 17sec was 149.3 HV.

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CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

REFERENCES

1. Feizollahi, Vahid, and Ali Heidary Moghadam. "Effect of pin geometry, rotational speed, and dwell time of tool in dissimilar joints of low-carbon galvanized steel and aluminum 6061-T6 by friction stir spot welding." Results in Materials 20 (2023): 100483.
2. Piccini, Joaquin M., and Hernan G. Svoboda. "Effect of pin length on Friction Stir Spot Welding (FSSW) of dissimilar Aluminum-Steel joints." Procedia Materials Science 9 (2015): 504-513.
3. Suryanarayanan, R., and V. G. Sridhar. "Studies on the influence of process parameters in friction stir spot welded joints–A review." Materials Today: Proceedings 37 (2021): 2695-2702.
4. Piccini, Joaquín M., and Hernán G. Svoboda. "Effect of the tool penetration depth in Friction Stir Spot Welding (FSSW) of dissimilar aluminum alloys." Procedia Materials Science 8 (2015): 868-877.
5. Joshi, Gaurang R., et al. "The joining of copper to stainless steel by solid-state welding processes: a review." Materials 15.20 (2022): 7234.
6. Isa, Mohammad Syahid Mohd, et al. "Recent research progress in friction stir welding of aluminium and copper dissimilar joint: a review." Journal of Materials Research and Technology 15 (2021): 2735-2780.
7. Liu, Zepeng, et al. "Microstructural origins of mechanical and electrochemical heterogeneities of friction stir welded heat-treatable aluminum alloy." Materials Today Communications 24 (2020): 101229.
8. Hirsch, Jürgen. "Recent development in aluminium for automotive applications." Transactions of Nonferrous Metals Society of China 24.7 (2014): 1995-2002.
9. Mishra, Rajiv S., and Z. Y. Ma. "Friction stir welding and processing." Materials science and engineering: R: reports 50.1-2 (2005): 1-78.
10. Heidarzadeh, Akbar, et al. "Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution." Progress in Materials Science 117 (2021): 100752.
11. Tunçel, Oğuz, Mümin Tutar, and Ali Bayram. "Effect of tool pin profile on the hook geometry and mechanical properties of a friction stir spot welded AA6082-T6 aluminum alloy." Transactions of the Canadian Society for Mechanical Engineering 45.2 (2020): 233-248.
12. Ahmed, Mohamed MZ, et al. "Bobbin tool friction stir welding of aluminum using different tool pin geometries: Mathematical models for the heat generation." Metals 11.3 (2021): 438.
13. Ravikumar, S., V. Seshagiri Rao, and R. V. Pranesh. "Effect of process parameters on mechanical properties of friction stir welded dissimilar materials between AA6061-T651 and AA7075-T651 alloys." Int. J. Adv. Mech. Eng 4.1 (2014): 101-114.

14. Li, Peng, et al. "Interfacial microstructure and mechanical properties of dissimilar aluminum/steel joint fabricated via refilled friction stir spot welding." Journal of Manufacturing Processes 49 (2020): 385-396.
15. Tabasi, M., et al. "Dissimilar friction stir welding of 7075 aluminum alloy to AZ31 magnesium alloy using SiC nanoparticles." The International Journal of Advanced Manufacturing Technology 86 (2016): 705-715.
16. Gao, Zeng, et al. "Dislocation density-based modeling of dynamic recrystallized microstructure and process in friction stir spot welding of AA6082." Metals 9.6 (2019): 672.
17. Haghshenas, M., and A. P. Gerlich. "Joining of automotive sheet materials by friction-based welding methods: A review." Engineering science and technology, an international journal 21.1 (2018): 130-148.
18. Mubiayi, Mukuna P., and Esther T. Akinlabi. "Friction stir spot welding of dissimilar materials: an overview." Proceedings of the world congress on engineering and computer science. Vol. 2. 2014.
19. Chen, Yingchun, Haddadi Farid, and P. B. Prangnell. "Feasibility study of short cycle time friction stir spot welding thin sheet Al to un-galvanised and galvanized steel." 8th International Friction Stir Welding Symposium, Timmendorfer Strand, Germany. 2010.
20. Qiu, Ranfeng, Chihiro Iwamoto, and Shinobu Satonaka. "Interfacial microstructure and strength of steel/aluminum alloy joints welded by resistance spot welding with cover plate." Journal of Materials processing technology 209.8 (2009): 4186-4193.
21. Tashkandi, Mohammad A., Jawdat A. Al-Jarrah, and Masoud Ibrahim. "Spot welding of 6061 Aluminum alloy by friction stir spot welding process." Engineering, Technology & Applied Science Research 7.3 (2017): 1629-1632.
22. Kumar, C. Labesh, and G. Bharathiraja. "An Assessment of Non Consumable Welded Joint-Friction Stir Spot Welding." (2020): 1581-1585.
23. Lakshminarayanan, A. K., V. E. Annamalai, and K. Elangovan. "Identification of optimum friction stir spot welding process parameters controlling the properties of low carbon automotive steel joints." Journal of Materials Research and Technology 4.3 (2015): 262-272.
24. Ismael, Qays Hazim, Mohmmed Shaalan Fathi, and Zenaa Moyaser Abid. "Effect of friction stir welding parameters on welding joint characteristics: A review." SVU-International Journal of Engineering Sciences and Applications 4.2 (2023): 90-97.
25. Ravikumar, S., V. Seshagiri Rao, and R. V. Pranesh. "Effect of process parameters on mechanical properties of friction stir welded dissimilar materials between AA6061-T651 and AA7075-T651 alloys." Int. J. Adv. Mech. Eng 4.1 (2014): 101-114.
26. Piccini, Joaquin M., and Hernan G. Svoboda. "Effect of pin length on Friction Stir Spot Welding (FSSW) of dissimilar Aluminum-Steel joints." Procedia Materials Science 9 (2015): 504-513.
27. Abbass, Muna K., and Kareem M. Raheef. "Evaluation of the mechanical properties of friction stir lap welded joints for dissimilar aluminum alloys (AA1100 to AA6061)." 2018 1st International Scientific Conference of Engineering Sciences-3rd Scientific Conference of Engineering Science (ISCES). IEEE, 2018.
28. Abbass, Muna Khethier, Sabah Kh Hussein, and Ahmed Adnan Kudair. "Optimization and Characterization of Friction Stir Spot Welding of Aluminum Alloy (AA 5754-H114) with Pure Copper Sheet." IOP Conference Series: Materials Science and Engineering. Vol. 1094. No. 1. IOP Publishing, 2021.

29. Ismael, Qays Hazim, Mohmmed Shaalan Fathi, and Zenaa Moyaser Abid. "Effect of friction stir welding parameters on welding joint characteristics: A review." SVU-International Journal of Engineering Sciences and Applications 4.2 (2023): 90-97.
30. Alkhafaji, Amir, and Daniel Camas. "Effect of Tool Rotational Speed and Dwell Time on the Joint Strength of Friction Stir Spot Welded AA6061-T6 Sheets." Engineering Proceedings 56.1 (2023): 215.
31. Ahmed, M. M. Z., et al. "Effect of tool geometry and heat input on the hardness, grain structure, and crystallographic texture of thick-section friction stir-welded aluminium." Metallurgical and Materials Transactions A 50 (2019): 271-284.
32. Ahmed, Mohamed Zaky, et al. "Crystallographic texture investigation of thick section friction stir welded AA6082 and AA5083 using EBSD." Key Engineering Materials 786 (2018): 44-51.
33. Ahmed, Mohamed MZ, et al. "The development of wc-based composite tools for friction stir welding of high-softening-temperature materials." Metals 11.2 (2021): 285.
34. Ahmed, Mohamed MZ, et al. "Microstructure and mechanical properties of dissimilar friction stir welded AA2024-T4/AA7075-T6 T-butt joints." Metals 11.1 (2021): 128.
35. Tozaki, Yasunari, Yoshihiko Uematsu, and Keiro Tokaji. "Effect of tool geometry on microstructure and static strength in friction stir spot welded aluminium alloys." International Journal of Machine Tools and Manufacture 47.15 (2007): 2230-2236.
36. Dong, Honggang, et al. "Refilled friction stir spot welding of aluminum alloy to galvanized steel sheets." Materials & Design 94 (2016): 457-466.
37. Shete, Manish, et al. "Improving friction stir spot welding of high-density polyethylene sheets for welding parameters and its optimization." International Journal on Interactive Design and Manufacturing (IJIDeM) (2024): 1-13.
38. Li, Gaohui, et al. "Influence of dwell time on microstructure evolution and mechanical properties of dissimilar friction stir spot welded aluminum–copper metals." Journal of Materials Research and Technology 8.3 (2019): 2613-2624.
39. Nipen M Khirsaria, et al. “Effect of Tool Pin Profile and Dwell Time on Friction Stir Spot Welding of Similar AA5083 -T6 Sheets.” International Conference on Advances in Engineering and Technology (RTET-2018): Jan. 1-3.
40. Ahmed, Mohamed MZ, et al. "Friction Stir-Spot Welding of AA5052-H32 Alloy Sheets: Effects of Dwell Time on Mechanical Properties and Microstructural Evolution." Materials 16.7 (2023): 2818.
41. Mohammed, R. K., S. S. Mohammed, and T. S. Mahmoud. "Study of peak temperatures in friction stir spot welding of AA2024-Al/polycarbonate and AA2024-Al/polypropylene systems." The International Conference on Applied Mechanics and Mechanical Engineering. Vol. 19. No. 19th International Conference on Applied Mechanics and Mechanical Engineering.. Military Technical College, 2020.
42. Fereiduni, Eskandar, et al. "Effect of dwell time on joint interface microstructure and strength of dissimilar friction stir spot-welded Al-5083 and St-12 alloy sheets." Metallurgical and Materials Transactions A 48 (2017): 1744-1758.
43. Su, P., et al. "Material flow during friction stir spot welding." Science and Technology of Welding and Joining 11.1 (2006): 61-71.