JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 14 No 6, 06008(5pp) (2022)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 14 № 6, 06008(5cc) (2022)

Effect of Heat Sink on Mechanical, Metallurgical and Microstructural Characteristics of Friction Stir Spot Welded Dissimilar Al6061 and Al5052 Joints

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(Received 14 October 2022; revised manuscript received 20 December 2022; published online 27 December 2022)

Friction stir spot welding is a well-known material joining technique for welding similar as well as dissimilar materials. In this welding technique, the operating temperature is retained below the melting point of the workpieces. As the temperature in the weld region is maintained above the recrystallization point and below the melting point, the joining takes place as a severe plastic deformation. It is advantageous as it joins dissimilar materials having unique and different properties as a single welded joint. In this paper, an attempt has been made to use copper material as heat sinks during spot joining of dissimilar Al6061 and Al5052 joints. The presence of Cu heat sinks ensured quick dissipation of frictional heat created in the nugget region. The spot welds cooled faster. When using Cu heat sinks, the cooling rates reduced by 32 %. Tensile properties of Al6061-Al5052 spot joints increased by 7.8 % and the joint microhardness improved by 12.3 %, compared to joints fabricated without heat sink attachment. Intermetallic compounds were not formed, and the grains were less deformed when using heat sinks. Faster cooling times ensured quick changeover of workpieces. The running duration of the welding equipment reduced by 19.3 %, as the joints were prepared faster. Hence the power consumption (energy savings) in a single shift was found to decrease by 11.35 %.

Keywords: Friction stir spot welding, Heat sink, Temperature dissipation, Microstructure, Microhardness.

DOI: 10.21272/jnep.14(6).06008 PACS numbers: 46.55. + d, 81.20.Vj

1. INTRODUCTION

In industrial sectors, the need for spot joining of similar and dissimilar materials has increased. This is due to complexity in shape and sizes of products in manufacturing industries, thermal power plants and automotive industries (Mahakur et al., 2021). The scope of fusion welding process is limited to similar material joining. Dissimilar materials have extremely different physical and chemical properties. It is difficult to control the welding parameters while joining dissimilar combinations. Friction stir welding can be used for such dissimilar material joining requirements (Yamamoto et al., 2009). Its linear variant such as friction stir spot welding (FSSW) is a successful method that can be used for spot joining. This FSSW method is highly efficient and consumable free (Feng et al., 2005). In FSSW joints, erratic temperature variations cause formation of intermetallics in the weld joint interfaces and sticking of the weld plates to the fixtures (Bozzi et al., 2010). The presence of heat in the joint region causes deterioration of weld quality. The presence of heat sinks ensures faster heat dissipation. Hence better joint quality is ensured (Guo et al., 2014). Many research investigations have showed that heat sinks are beneficial in improving the joint characteristics. The use of heat sink technology reduced residual stresses on stainless steel welds (Jiang et al., 2012). Reduction in residual stresses is very important for joints to withstand high temperatures and pressures when they are being used in pressure vessels. In multi pass welding, the presence of trailing heat sinks resulted in improving joint strength (Kala et al., 2014).

When joining titanium-based material, the presence of a heat sink near the nugget zone ensured better joint quality and reduction in welding defects (Li et al., 2004). While joining lap joints using dissimilar materials such as aluminum and copper, a considerable improvement in joint aspects was observed using heat sinks. Heat sinks near the weld region reduced angular distortion of welds. During low carbon steel welding, clamp and heat sinks improved the tensile characteristics of the joints (Okano et al., 2012).

Hence, in this investigation, an attempt has been made to incorporate copper heat sinks in the fixtures for increasing the quality of Al joints. The reduction in welding time and power savings was identified.

2. MATERIALS AND METHODS

2.1 Weld Setup and Evaluation of Base Materials

FSSW was used for spot joining. Computer numerically controlled vertical milling machine was used for conducting FSSW. Rolled 5 mm thick sheets of Al6061 and Al5052 were used as workpieces. The raw materials were thoroughly cleaned by using acetone to remove external impurities. Experiments were conducted with lap configuration, with Al 5052 in top and Al 6061 in bottom. The workpieces were 100 m long and 40 mm wide. The overlap of lap joint configuration was 30 mm. A spark spectrometer was used to identify the elemental composition of Al5052 and Al6061. Elements present in Al5052 and Al6061 are shown in Table 1.

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For grain surface evaluation, Al5052 and Al6061 were subjected to microscopic evaluation. Using standard specimen preparation techniques, the surfaces of Al5052 and Al6061 were prepared. In sequence, emery sheets were used to polish. Fine polishing was done on Al5052 and Al6061 surfaces using a disc polisher with diamond grit paste. Using an optical microscope, their surfaces were studied. Optical microscopic (OM) images of Al 5052 and Al 6061 are shown in Fig. 1. The surfaces of Al 5052 and Al 6061 were composed of finely equiaxed grain structure.

The chemical characteristics of as-received Al5052 and Al6061 specimens were investigated by using X-ray diffraction spectroscopy. Using (Rigaku-Make) XRD equipment, at a step size of 0.002, from 20 to 80 degree two theta, the scanning was done. The XRD spectra of Al5052 and Al6061 are shown in Fig. 2.

Table 1 – Elemental composition in wt. %

Alloy	Cu	Cr	Mg	Si	Mn	Fe	Al
Al5052	0.07	0.19	2.6	0.13	0.08	0.2	Bal
Al6061	0.28	0.22	0.8	0.6	0.001	0.001	Bal

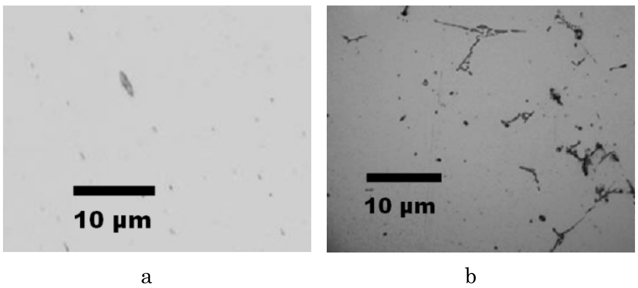


Fig. 1 – OM images of (a) Al6061, (b) Al5052

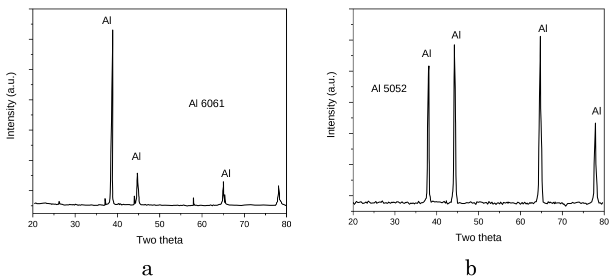


Fig. 2 – XRD spectra of (a) Al6061 and (b) Al5052

2.2 FSSW Setup with Copper Sinks

FSSW comprises of three steps, which are carried out in sequence. Initially, a high-speed tool is plunged through the workpieces. Then for certain duration, a plunged tool is retained for inducing friction stir of the material in the nugget zone to heat up. Thermomechanical stir ensures frictional heat, and the temperature increases beyond the recrystallization temperature. The region is made to soften. The final stage is retraction when the spot is allowed to cool down. This sequence is shown in Fig. 3.

During FSSW experiments, Cu plates were used as heat sinks. In the fixtures used in the FSSW apparatus, Cu plates were fixed close to the weld region. Using heavy type vertical milling CNC equipment, the FSSW experiments were performed. In the bed of the vertical milling machine, Cu heat sinks were placed adjacent to the weld region. FSSW tool was prepared using H13 tool steel. It was fabricated with 14 mm shoulder diameter, 6 mm pin diameter and 5 mm pin height.

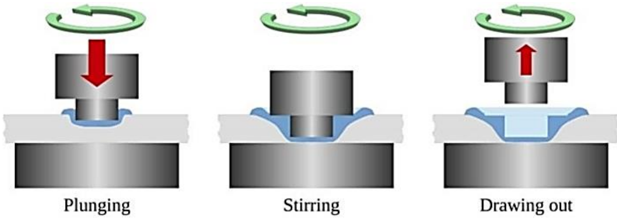


Fig. 3 – Three steps of the FSSW process

2.3 Spot Welding Experiments

FSSW experiments were conducted with process parameter values obtained from previous literatures (Bilici et al., 2011) and trial experiments. FSSW joints were made using tool rotational speed of 1200 rpm, dwell time of 13 s and shoulder plunge depth of 5 mm. A few of the fabricated FSSW joints are shown in Fig. 4.

Using a non-contact digital temperature sensor, the variations in temperature adjacent to the FSSW nugget zone was recorded. Three sets of Al5052-Al6061 joints were fabricated. The dissimilar joints of Al6061-Al5052 were compared with the similar joints of Al6061-Al6061 and Al5052-Al5052. Both similar and dissimilar joints were subjected to tensile testing using a universal testing machine. Tensile testing was conducted using ASTM E 08 standards. Since keyhole was evident in all Al5052-Al6061, Al5052-Al5052 and Al6061-Al6061 FSSW joints, the surface area was difficult to be identified. Hence, tensile shear failure load in N was observed. The joint microhardness of Al5052-Al6061, Al5052-Al5052 and Al6061-Al6061 FSSW joints was measured using Vickers microhardness testing equipment. On the joint surface, a load of 5 gf was placed for a dwell time of 15 s and the measurements were taken. XRD analysis of Al5052-Al6061, Al5052-Al5052, Al6061-Al6061 FSSW dissimilar joints was conducted, and microstructural evaluation was done using scanning electron microscopy (SEM).

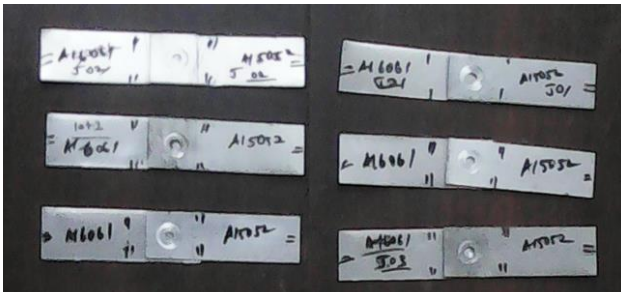


Fig. 4 – Photographs of the FSSW joints

3. RESULTS AND DISCUSSION

3.1 Tensile Test Evaluation

The variations in tensile shear failure loads were identified for similar and dissimilar joints with and without the presence of heat sinks. The variations are shown in Fig. 5.

From Fig. 5, a significant increase in tensile properties was observed when using heat sinks. For similar Al6061-Al6061 joints, the tensile shear failure loads increased from 16.8 to 21.3 N and for Al5052-Al5052 joints they increased from 17.6 to 19.25 N. The joint strength of Al6061-Al5052 dissimilar joints was comparatively lower than that of similar FSSW joints. Even in dissimilar joints, the presence of heat sinks considerably increased the joint strength.

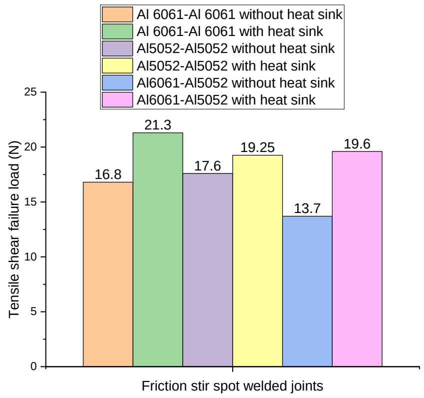


Fig. 5 – Variations in tensile shear failure loads

3.2 Microhardness Evaluation

The variations of microhardness were identified for similar and dissimilar joints with and without the presence of heat sinks. The variations are shown in Fig. 6. From Fig. 6., a significant reduction in the joint microhardness is observed when using heat sinks. For Al6061-Al6061 similar joints, the joint microhardness decreased from 68 to 64 HV when using heat sinks. Similarly, for Al5052-Al5052 joints, the joint microhardness reduced from 59 to 51 HV when using heat sinks. Compared to similar joints, the microhardness of dissimilar joints was high due to the formation of intermetallics. For dissimilar Al5052-Al6061 joints, the microhardness reduced from 74 to 67 HV when using heat sinks.

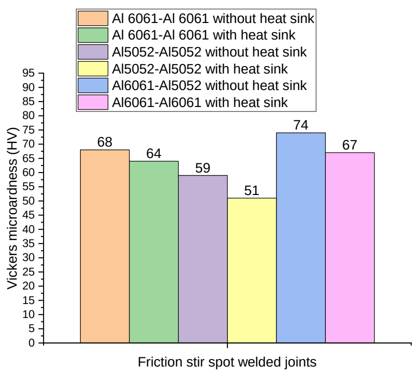


Fig. 6 – Variations in the joint microhardness

3.3 Temperature Studies

The peak temperatures reached during FSSW of similar and dissimilar joints with and without heat sinks were recorded and are shown in Fig. 7.

As seen from Fig. 7, a considerable decrease in peak temperatures was observed during the FSSW process.

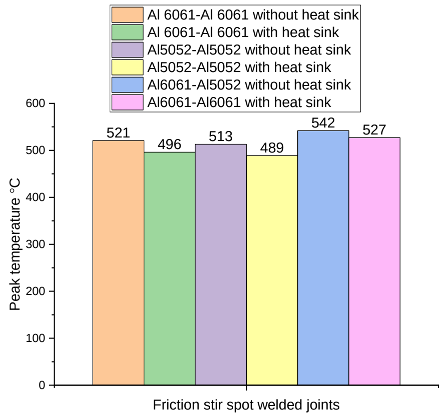


Fig. 7 – Peak temperatures reached during FSSW

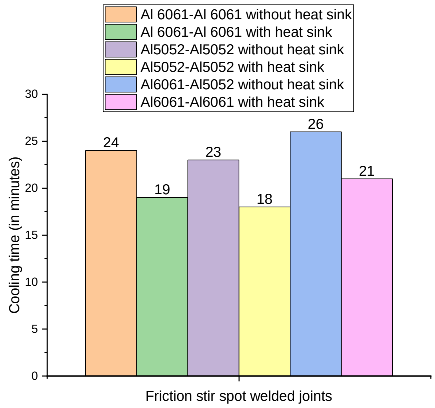


Fig. 8 – Time required for cooling, from peak temperature to room temperature

The time required for heat dissipation and the time required for cooling (from peak temperature to room temperature) are shown in Fig. 8. During frictional stirring, the thermomechanical heat generated in the weld zone was quickly dissipated through the heat sinks. Hence, it was found that the time duration required for joints to cool from peak temperature to room temperature also reduced. This is evident from Fig. 8.

3.4 XRD Studies

To identify the intermetallic compounds, present on the joint interface, the cross section of Al6061-Al5052 joints was evaluated by using XRD analysis. The XRD spectrum of Al5052-Al6061 joints prepared without heat sinks is shown in Fig. 9 and with heat sinks is shown in Fig. 10. The peaks from the XRD spectra of Al5052-Al6061 joint interfaces were compared with the JCPDS data and previous investigations to identify the intermetallics. From Fig. 9, intermetallics such as $Mg_{17}Al_{12}$, FeAl and Al_2O_3 were observed.

In Fig. 10, the presence of intermetallics was very low. The occurrence and formation of intermetallics in Al5052-Al6061 joints fabricated without heat sinks were due to the prolonged exposure of the weld region to heat. The presence of intermetallcs increased weld region microhardness. Intermetallics are brittle and cause reduction of tensile properties.

This was attributed to lower tensile strength of Al5052-Al6061 joints fabricated without heat sinks.

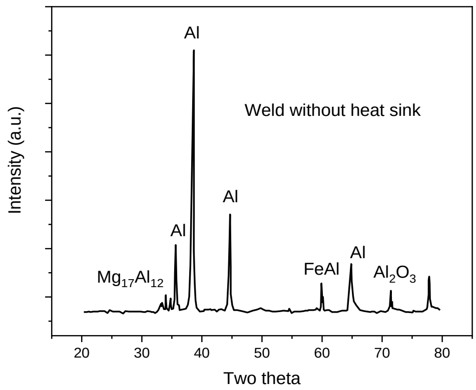


Fig. 9 – XRD spectra of Al5052-Al6061 joints fabricated without heat sinks

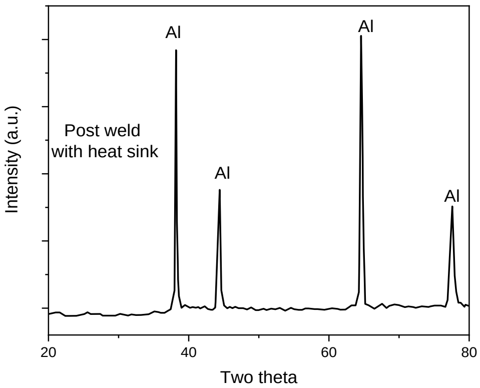


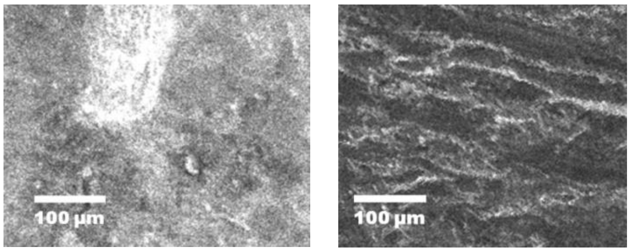
Fig. 10 – XRD spectra of Al5052-Al6061 joints fabricated with heat sinks

3.5 Microstructural Investigations

To identify the grain structure variations in the weld interface, the interface of Al5052-Al6061 joints was subjected to microstructural investigation using SEM. Thermomechanically affected zone (TMAZ) is the region of the weld adjacent to the central nugget stir zone. This TMAZ experiences high thermal fluctuations in addition to mechanical stirring of the sides of pin and shoulder. Stir zone (SZ) is the zone directly under the influence of the tool pin. This zone undergoes complete mix and fusion. These two regions were evaluated using SEM. SEM images of the Al5052-Al6061 joints without heat sinks are shown in Fig. 11 and in the presence of heat sinks are shown in Fig. 12.

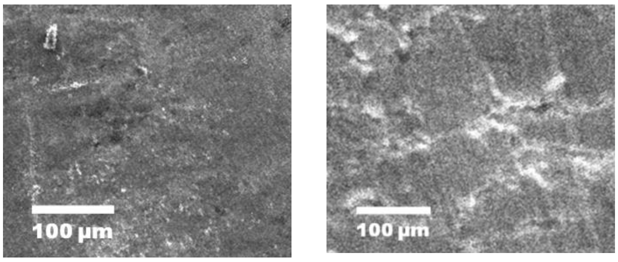
TMAZ region of Al5052-Al6061 joints without heat sinks (Fig. 11a) exhibited mechanical dents. It was partially fused and partially un-fused. SZ of Al5052-Al6061 joints fabricated without heat sinks (Fig. 11b) exhibited rough surface. Pits and wave type agglomerations were observed due to the presence of heat for a long time.

Fig. 12a shows TMAZ region of Al5052-Al6061 joints fabricated with heat sinks. The grains were relatively smooth and better mixed. Better mixing ensures better tensile strength. Fig. 12b shows SZ region of Al5052-Al6061 joints fabricated with heat sinks. This region was found to be completely mixed with very minimal surface defects. The re-crystallized grains were smooth. The presence of heat sinks helped to reduce grain surface deterioration and enhance the integrity of the joints.



(a) Thermomechanically affected zone (b) Stir zone

Fig. 11 – SEM images of Al5052-Al6061 joints fabricated without heat sinks



(a) Thermomechanically affected zone (b) Stir zone

Fig. 12 – SEM images of Al5052-Al6061 joints fabricated with heat sinks

3.6 Production Time Reduction and Power Savings

To observe the time saved by using heat sinks, the time required to make 60 spot joints was fabricated using Al5052-Al6061 combination. For a single lot, the running duration of modified FSSW apparatus was reduced by 19.3 %. This occurred as changeover time reduced. Quick production reduced the overall working time of the equipment. Power consumption reduced by 11.3 %. This reduction in power per shift can be extrapolated to annual savings. Hence, significant energy consumption can be obtained using Cu heat sinks in FSSW fabrication.

4. CONCLUSIONS

Dissimilar materials such as Al5052 and Al6061 were joined using friction stir spot welding. Using Cu heat sinks, the experiments were conducted. Heat sinks ensured better and quick heat transfer from the weld zone. For Al5052-Al6061 joints fabricated using heat sinks, mechanical and metallurgical properties increased. Quick heat dissipation ensured faster cooling time. Since more joints could be fabricated at the same time, equipment power and energy savings were obtained.

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Вплив тепловідводу на механічні, металургійні та мікроструктурні характеристики різнорідних з'єднань Al6061 та Al5052, виготовлених точковим зварюванням тертям із перемішуванням

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Точкове зварювання тертям із перемішуванням є добре відомим методом з'єднання матеріалів для зварювання подібних, а також різнорідних матеріалів. При цій технології зварювання робоча температура підтримується нижче температури плавлення заготовок. Оскільки температура в області зварювання підтримується вище точки рекристалізації та нижче точки плавлення, з'єднання відбувається як при сильній пластичній деформації. Це вигідно, оскільки поєднує різнорідні матеріали, що мають унікальні та різні властивості, як одне зварне з'єднання. У статті була зроблена спроба використати мідний матеріал як тепловідвід під час точкового з'єднання різнорідних з'єднань Al6061 та Al5052. Наявність мідних тепловідводів забезпечувала швидке розсіювання тепла від тертя, створюваного в області самородка. Точкове зварювання охолоджувалося швидше. При використанні мідних тепловідводів швидкість охолодження знижувалася на 32 %. Властивості на розтяг точкових з'єднань Al6061-Al5052 підвищилися на 7,8 %, а мікротвердість з'єднань покращилася на 12,3 % порівняно зі з'єднаннями, виготовленими без тепловідводів. Інтерметалічні сполуки не утворювалися, а зерна менш деформувалися при використанні тепловідводів. Швидший час охолодження забезпечив швидку заміну заготовок. Час роботи зварювального обладнання скоротився на 19,3 %, оскільки з'єднання готувалися швидше. Таким чином споживання електроенергії (енергозбереження) за одну зміну зменшилося на 11,35 %.

Ключові слова: Точкове зварювання тертям із перемішуванням, Тепловідвід, Розсіювання температури, Мікроструктура, Мікротвердість.