Local melting and cracking in Al 7075-T6 and Al 2024-T3 friction stir spot welds

A. Gerlich*[1], M. Yamamoto[2] and T. H. North[3]

Local melting of eutectic films and cracking is found in Al 2024 and Al 7075 alloy friction stir spot welds. Dissolution of melted films removes all evidence melted film formation in spot welds made using typical welding parameter settings. For this reason friction stir spot welding is carried out at a rapid plunge rate of 10 mm s^{-1} and an extremely short dwell time of 0·05 s and after tool retraction, the welded samples are rapidly quenched using a mixture of methanol and liquid nitrogen at a temperature of $-80^{\circ}C$. Eutectic films rich in Zn and Cu are formed in Al 7075 spot welds while melted Al_2CuMg particles promote the formation of α-Al + Al_2CuMg eutectic films in Al 2024 spot welds. Melted eutectic formation and cracking is also observed beneath the tip of the rotating pin during Al 7075 friction stir spot welding and is consistent with the occurrence of melt wear in this location.

Keywords: Friction Stir Spot Welding, Melting, Cracking, Al2024, Al7075

Introduction

It is generally presumed that local melting and cracking does not occur in Al alloy friction stir seam welds since the highest temperatures produced within the stir zone are less than those required for local melting. Support for this proposition is provided by the fact that cracking is not observed in the stir zone, TMAZ or HAZ regions of friction stir seam and friction stir spot welds when joining Al alloy base materials known to be crack sensitive when they are fabricated using fusion welding. In addition, detailed metallographic examination of friction stir seam welds has provided only limited evidence indicating local melting and in situations where the seam welds were produced using high tool rotational speed settings. For example, Hassan *et al.*[1] and Yan *et al.*[2] found evidence of eutectic melting when they examined Al 7010 and Al 2524 friction stir seam welds made using tool rotational speeds of 660 and 600 rev min^{-1}. However, there was no evidence of local melting in Al 7010 and Al 2524 friction stir seam welds when lower tool rotational speed settings were employed. These test results suggest that local melting might only occur when abnormally high (some believe unacceptably high) tool rotational speed settings are used during friction stir seam welding operations.

North *et al.*[3] proposed that local melting and tool slippage could account for the low travel speeds that are obtainable during friction stir seam welding of Al 2024 and Al 7075 sheets. Gerlich *et al.*[4,5] provided support for this proposal in detailed investigations of Al 2024 and Al 7075 friction stir spot welds. The remarkable decrease in estimated strain rate values in friction stir spot welds made using high tool rotational speed settings was associated with spontaneous melting of second phase particles (η, S and T phases), which promoted tool slippage at the contact interface between the periphery of the rotating tool and adjacent material in the stir zone. Metallographic evidence confirming local melted film formation has been reported by numerous investigators when examining Al 7010, Al 2524 and Al 2024-T3 friction stir seam welds,[1,2,6] dissimilar Al 1050-AZ31 and Al 2024-Al 2014/Al_2O_3 friction stir seam welds,[7,8] Al 6061/Al_2O_3 plunge tests,[9] AZ31 and AZ91 friction stir spot welds[10,11] and dissimilar Al 6111/AZ91 friction stir spot welds.[12]

It is difficult to reconcile the apparent contradictions in the published literature regarding measured stir zone temperature values, local melting and the absence of cracking in completed friction stir seam and friction stir spot welds. For example, why is the stir zone temperature in Al 7075 friction stir spot welds high enough to promote local melting of second phase particles and tool slippage and yet completed friction stir spot welds are crack free? These apparent contradictions readily explain why transient local melting during friction stir welding is such a controversial and contentious issue.

Background

The friction stir spot welding process initiates when the rotating pin moving downwards at a selected plunge rate contacts the surface of the upper sheet and the axial force and the torque values begin to increase. The initial stage in tool penetration involves mild wear, which is characterised by plastic shearing and the nucleation and propagation of subsurface cracks which reach the surface, creating wear debris.[13,14] As tool penetration continues there is a transition from mild to severe wear.

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Severe wear occurs when thermally activated deformation processes promote softening of material immediately beside the contact interface[13] so that the bottom of the rotating pin is coated with an adhering layer of Al alloy base material. There is a sudden decrease in the axial force when melt wear becomes the dominant wear mechanism.[13,14] Melt wear involves local melting of thin (10–20 μm thick) layers, which dramatically lower the viscosity of material at the contact interface.[13–17] Low viscosity material is displaced to cooler regions where the local melted films solidify; after their displacement viscous dissipation increases the temperature once more and local melted films reform. Gerlich *et al.*[13] suggested that the transition from severe wear to melt wear explained the marked decrease in axial force and the levelling off in measured torque values observed during the tool penetration stage in friction stir spot welding. Melt wear formation was also confirmed in material immediately beneath the tool shoulder during friction stir spot welding trials using a particularly low plunge rate.

The highest temperature attained in the stir zones of Al alloy and Mg alloy friction stir spot welds is ultimately limited by either the solidus temperature of the alloy in question or the spontaneous melting temperatures of second phase particles, which are contained in the as received base material. For example, the highest temperatures found in the stir zones of Al 7075, Al 2024, Al 6111, Al 6061, Al 5754, AZ31, AZ91 and AM50 friction stir spot welds correspond with homologous temperatures ranging from 0·94 to 0·99.[4,5,10–14,18–21]

The heating rate during the tool penetration stage in friction stir spot welding is determined by the tool rotational speed setting and ranges from 210 to 400°C s^{-1}.[21] The high heating rate during friction stir spot welding of Al alloy sections has important consequences. η, S and T particles in as received Al 7075-T6 base material, for example, have insufficient time to dissolve[4] and melt spontaneously when the stir zone temperature reaches 475 (η), 480 (S) and 490°C (T).[22–24] Although similar behaviour is exhibited in Al 2024-T3 friction stir spot welds[5] this is not the case when Al 5754 and Al 6061-T6 are spot welded. Local melting and tool slippage are precluded when Al 5754 and Al 6061-T6 are welded since they do not contain second phase particles having melting points less than their solidus temperatures.[20]

When AZ91 base material is spot welded, the temperature in the stir zone at the end of the 4 s long dwell period (438°C) is remarkably close to the (α-Mg+$Mg_{17}Al_{12}$) eutectic temperature in the Al–Mg binary equilibrium diagram (437°C).[25] Much higher temperatures (500 and 550°C) are found in AM60 and AZ31 friction stir spot welds.[11] Melted eutectic film formation and cracking has been observed in the TMAZ region early in the dwell period in AZ91, AM60 and AZ31 friction stir spot welding. Also, liquid penetration induced (LPI) cracking has been observed in the stir zones of AZ91 friction stir spot welds close to their extremities.[26] Both LPI cracking in the stir zone and melted eutectic formation at the root of the pin thread have been observed in AZ91 friction stir spot welds.

It has been suggested that the different cracking behaviours found during AZ91, AM60 and AZ31 spot welding are due to the dramatic increase in the dissolution rate of melted eutectic films when the stir zone temperature is much higher than the α-Mg+$Mg_{17}Al_{12}$ eutectic temperature (437°C). Higher stir zone temperatures are produced during AM60 and AZ31 spot welding and therefore melted eutectic films are rapidly dissolved after their formation.[11]

With this in mind, it is proposed that local melting and cracking occur very early in the dwell period during Al 7075 and Al 2024 friction stir spot welding and that subsequent dissolution of melted eutectic films removes all evidence of their occurrence. This proposition is examined in Al 7075 and Al 2024 friction stir spot welds produced with the precise objective of limiting the dissolution of melted eutectic films in the high temperature stir zone and when the spot welds cool to room temperature after the spot welding operation. This objective is accomplished by making spot welds using a rapid plunge rate of 10 mm s^{-1} and an extremely short dwell time of 0·05 s. Also, rapid cooling after spot welding is facilitated by plunging the spot welded test sections into a mixture of methanol and liquid nitrogen at a temperature of −80°C immediately after tool retraction. Al 7075 and Al 2024 base materials are employed during this investigation since spontaneous melting of second phase particles (η, S and T phases) and tool slippage has been confirmed during friction stir spot welding operations.[4,5]

Evidence is presented confirming melted eutectic film formation and cracking very early in the dwell period in Al 7075 and Al 2024 friction stir spot welding. The implications of these results and their relation vis-à-vis friction stir seam welding are discussed.

Experimental

Base materials

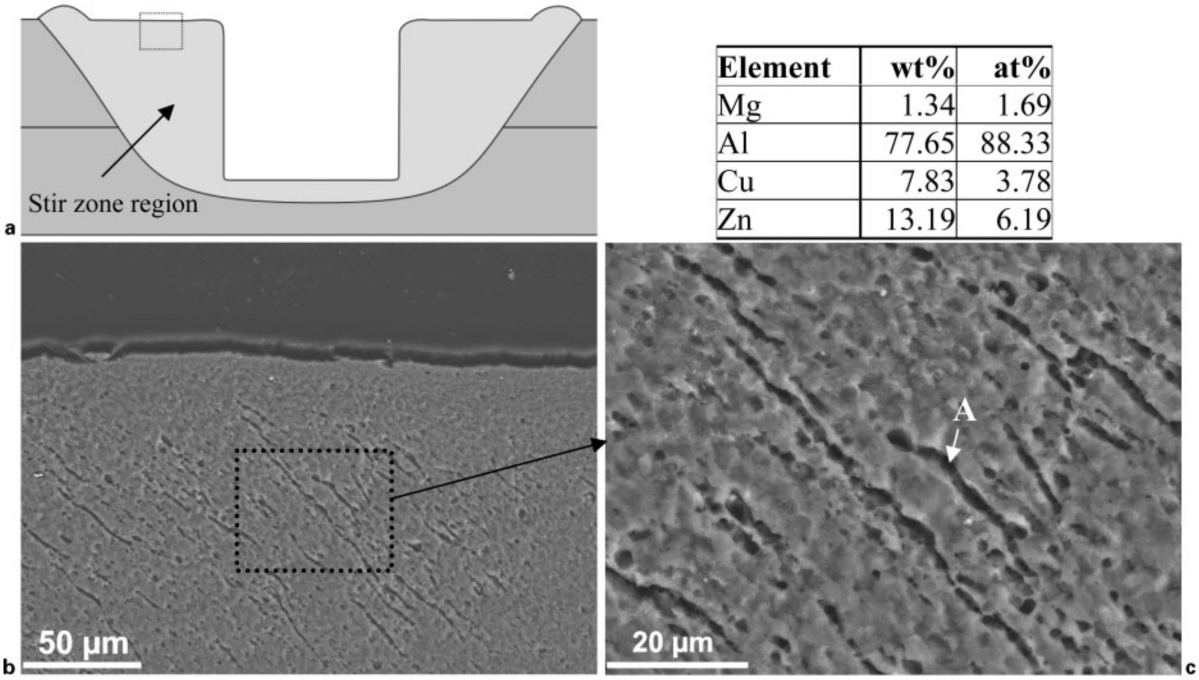
The chemical compositions of the aluminium alloy sheet materials are summarised in Table 1. Joints between 1·5 mm thick overlapping sheets of Al 7075 are examined, as well as spot welds made in monolithic 6·3 mm thick plates of Al 2024 and Al 7075.

Equipment

The friction stir spot welding equipment provided rotational speeds of 3000 rev min^{-1} and a torque capability of up to 28 N m and axial loads up to 15 kN via a displacement controlled servomotor. The plunge rate during friction stir spot welding was 10 mm s^{-1} with the penetration depth being controllable to ±0·1 mm. A six axis load cell was configured with the Z axis parallel to the axial direction of the tool to measure the axial force and the torque values during spot welding; the X and Y axes of the load cell measured side loads on the welded test specimen. Tool displacement (penetration depth) was measured using a linear transducer, which had an accuracy of ±0·01 mm while the tool rotation speed was measured using a shaft encoder with an accuracy of ±30 rev min^{-1}. A data acquisition system was used and

Table 1 Base material compositions, wt-%

Alloy	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Al 2024-T3	Bal.	<0·01	4·30	0·15	1·42	0·62	0·07	0·03	0·07
Al 7075-T6	Bal.	0·21	1·27	0·12	2·34	<0·01	0·07	<0·01	5·41



Element	wt%	at%
Mg	1.34	1.69
Al	77.65	88.33
Cu	7.83	3.78
Zn	13.19	6.19

a schematic of location in Al 7075 spot weld stir zone; *b* SEM image of melted films; *c* detail of melted film and EDX chemical analysis at location A

1 Melted films observed in Al 7075 friction stir spot weld made using plunge rate of 10 mm s^{-1}, dwell time of 0·05 s and tool rotation speed of 3000 rev min^{-1}

enabled simultaneous recording of axial force, torque and penetration depth during spot welding operations.

Spot welding was carried out using a 0·35 wt-%C, 5 wt-%Cr, 1·5 wt-%Mo, 1 wt-%V steel tool having a hardness of 46–48 HRC. The shoulder diameter was 10 mm, the pin diameter was 4 mm and the pin length was 2·2 mm. The pin had a threaded geometry corresponding with an M4 metric screw profile and during the spot welding operation the tool rotated in a counterclockwise direction. The specified pin penetration depth was 2·2 mm and corresponded with the point when the tool shoulder just contacted the upper surface of the sheet being spot welded. The spot welding cycle was extended by incorporating a dwell time of 0·05 s when the rotating pin was fully penetrated, during which time the tool rotation speed remained constant.

All Al 2024 and Al 7075 friction stir spot welds were produced using a plunge rate of 10 mm s^{-1} and an extremely short dwell time of 0·05 s. All spot welded test sections were immersed in a mixture of methanol and liquid nitrogen at a temperature of -80°C immediately after tool withdrawal.

The Al 7075 spot weld sections were etched using Keller's reagent, while the Al 2024 spot welds observed in the SEM were etched using 10% phosphoric acid. This particular etchant prevented excessive removal of intermetallic phases. A Hitachi S-4500 field emission scanning electron microscope was used during SEM examination and EDX chemical analysis.

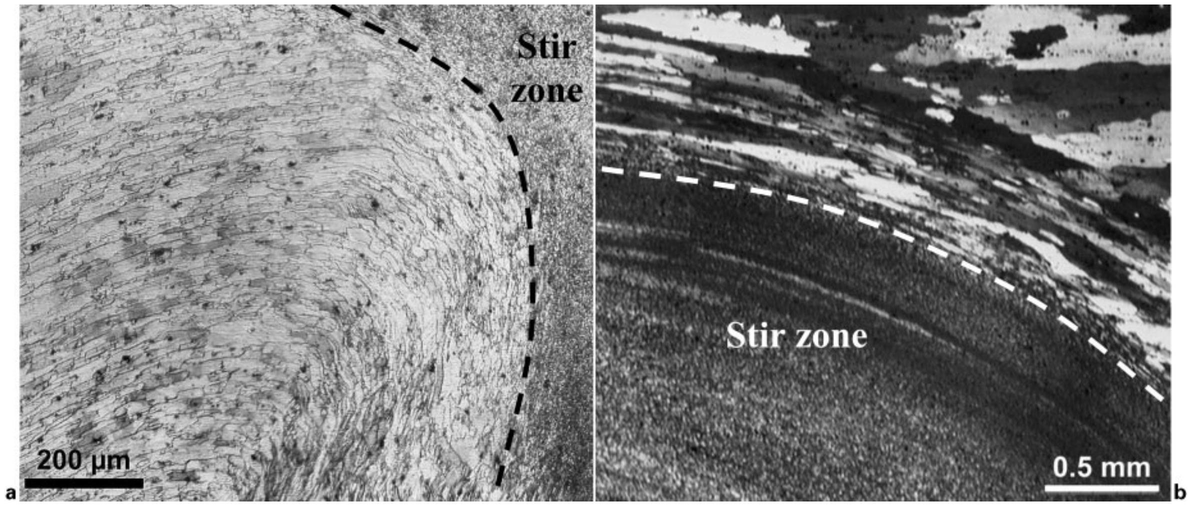
Results and discussion

Al 7075 spot welds

Figure 1 shows the evidence of eutectic film formation in the stir zone of an Al 7075 friction stir spot weld made using a plunge rate of 10 mm s^{-1} and a dwell time of 0·05 s. The eutectic films are rich in Zn and Cu. Gerlich *et al.*[4] confirmed that the temperature in the stir zone during Al 7075 friction stir spot welding exceeds the spontaneous melting temperatures of second phase particles 475 (η), 480 (S) and 490°C (T) contained in the as received base material.[21,24] The temperature also exceeds 475°C at the end of the tool penetration stage in Al 7075 spot welds made using a tool rotational speed of 3000 rev min^{-1}. In this connection Bjørnklett *et al.*[23] suggested that spontaneous melting of η particles located at grain boundary regions produces melted eutectic films rich in Zn while Hassan *et al.*[1] associated Cu rich films at grain boundary regions in Al 7010 friction stir seam welds with the formation of an α-Al+S+η ternary eutectic.

The eutectic films observed in the stir zones of Al 7075 spot welds are ~50 μm long and 2 μm wide (*see* Fig. 1). In direct contrast, second phase particles in the as received Al 7075 base material are typically 100 nm long and 80 nm wide.[4] This difference in dimension can be explained as follows. Figure 2 shows that α-Al grains in the TMAZ regions are elongated in the direction parallel to the stir zone boundary and second phase particles (η, S and T phases) located at grain boundary regions are aligned during the tool penetration stage in spot welding. At the end of the tool penetration stage recrystallisation occurs and second phase particles, which are aligned along grain boundaries, are incorporated into the stir zone. When spontaneous melting occurs the resulting eutectic films are much larger than the dimensions of second phase particles contained in as received Al 7075 base material. The location where local melted films form is heated

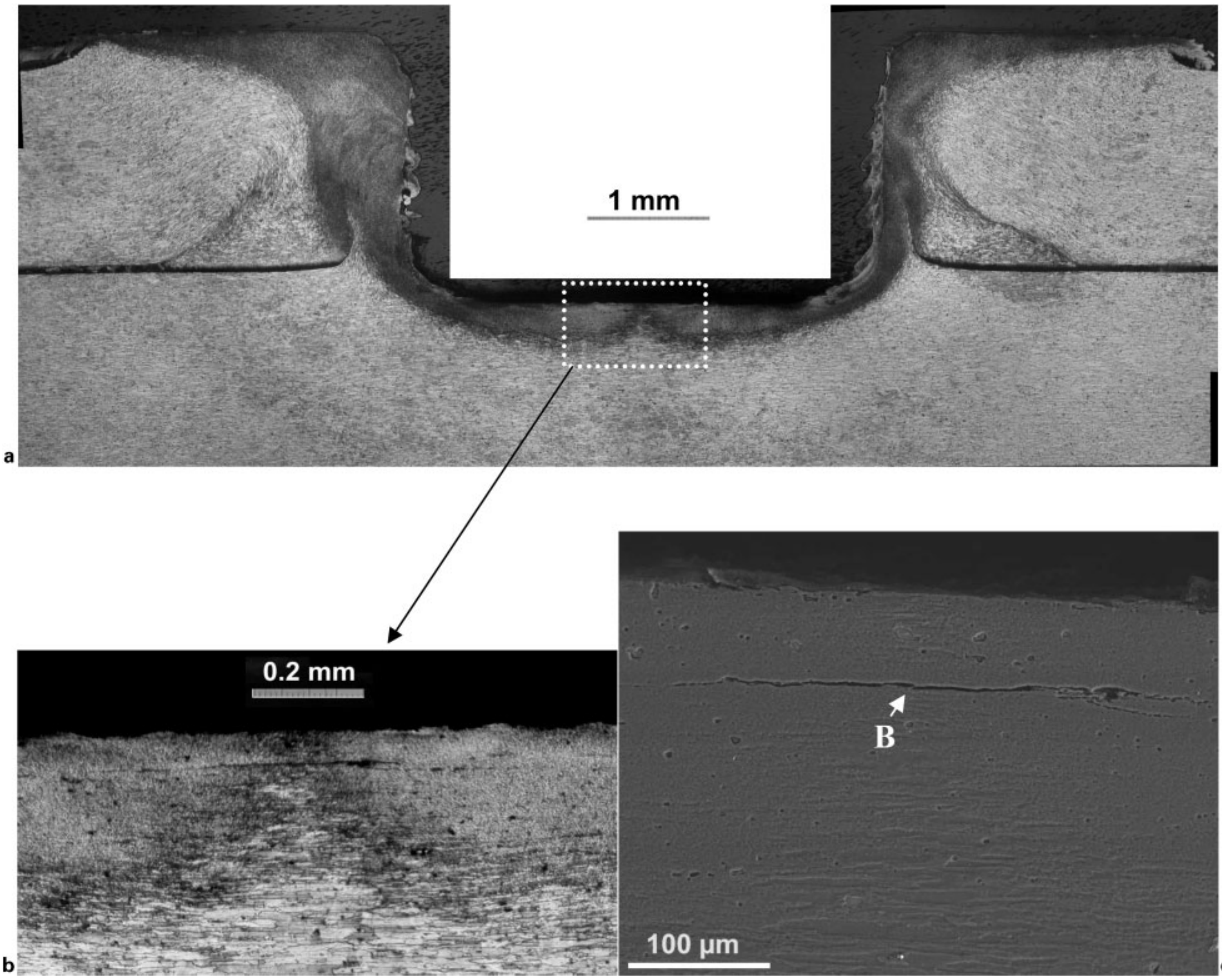
(i) during the tool penetration stage in spot welding
(ii) when material is displaced upwards during tool penetration
(iii) when the tool shoulder contacts with the surface of the upper sheet.[26]



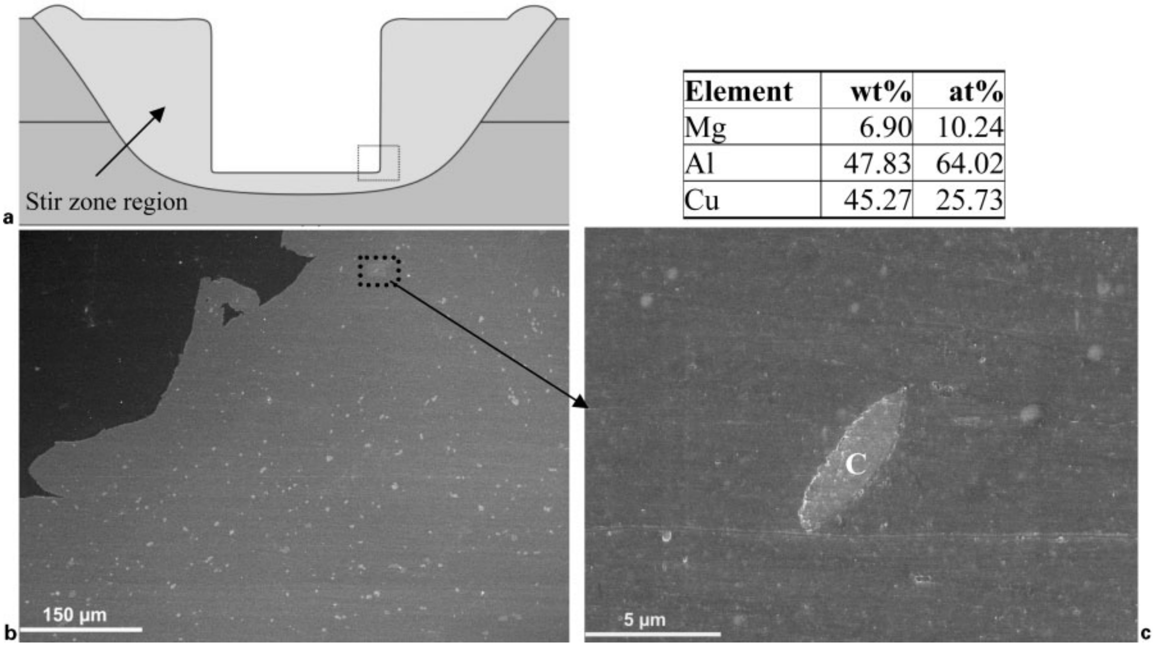
2 ***a*** **optical micrograph showing transverse section through Al 7075 spot weld with grains in TMAZ elongated parallel to stir zone boundary (see dashed line) and** ***b*** **polarised light micrograph showing grains elongated parallel to shoulder periphery in TMAZ region (see dashed line) in horizontal cross-section through Al 7075 spot weld**

It is worth noting here that heat generation is generated during tool rotation much earlier than expected in the spot welding cycle, when material expelled during pin penetration is trapped beneath the tool shoulder and the surface of the upper sheet.[13]

Cracking in the location immediately beneath the tip of the rotating pin is associated with Zn and Cu rich material (*see* Fig. 3). Cracking is apparent in the TMAZ region at the extremity of the dynamically quiescent region and within the dynamically quiescent region itself



3 ***a*** **optical micrograph of location, which exhibits cracking (in location beneath tip of rotating pin in rapidly quenched Al 7075 spot weld produced using plunge rate of 10 mm s^{-1} and dwell time of 0·05 s,** ***b*** **optical micrograph of crack location and** ***c*** **SEM image of crack in detail: EDX analysis at location B was 73·1 wt-%Al, 20·2 wt-%Zn, 6·6 wt-%Cu**



Element	wt%	at%
Mg	6.90	10.24
Al	47.83	64.02
Cu	45.27	25.73

a **schematic of location in stir zone of Al 2024 spot weld;** ***b*** **SEM image of location of melted S phase particle;** ***c*** **detail of melted S phase particle and EDX chemical analysis at location C**

4 Melted S phase (Al_2CuMg) particle observed in stir zone of Al 2024 friction stir spot weld made using plunge rate of 10 mm s^{-1}, dwell time of 0·05 s and tool rotation speed of 3000 rev min^{-1}

(*see* Fig. 3*b* and *c*). The dynamically quiescent region is formed beneath the tip of the rotating pin immediately after contact between the rotating tool and the surface of the upper sheet.[27] This particular terminology is employed since material flow within this region is only of the order of micrometers per second.[28] Consequently, material contained within the dynamically quiescent region is retained in this location during the whole of spot welding operation.[27,29]

Gerlich *et al.*[13] formulated an argument based on sliding wear and wear mechanism maps and suggested that the decrease in axial force and the levelling out of torque values during the tool penetration stage in spot welding was associated with melt wear formation in material immediately beneath the tip of the rotating pin. However, no metallographic evidence supporting the melt wear proposal was presented. Since cracking is observed at the extremity and within the dynamically quiescent itself (Fig. 3), the temperature beneath the tip of the rotating pin during spot welding must be high enough to promote eutectic melting. As a result, Fig. 3 provides strong support for melt wear proposal made by Gerlich *et al.*[13]

Finally, since cracking is observed in the location beneath the tip of the rotating pin close to the centreline of the rotating tool, negligible torque is imposed when the rotating tool rotates. Since it has been confirmed that stir zone material adheres to the bottom of the rotating pin,[13,30] it is suggested that crack propagation is caused by tensile straining during retraction of the rotating tool.

Al 2024 spot welds

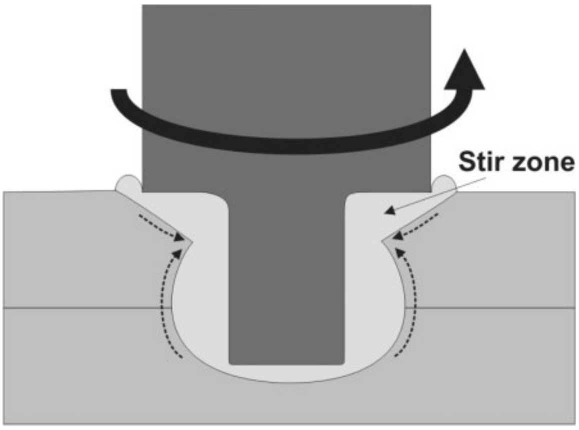
Figure 4 shows S phase (Al_2CuMg) particles in the stir zone of an Al 2024 spot weld in the location close to the periphery of the rotating pin. Melting of S phase particles has already been associated with the formation of Cu rich films observed at grain boundaries in the nugget region of an Al 2524 friction stir seam welds.[2] Also, melted α-Al + Al_2Cu eutectic films resulted from spontaneous melting of Al_2Cu particles during upquenching of Al–4·2Cu. In a similar manner to the melted eutectic films formed during upquenching, the S phase particles found in the stir zones of rapidly quenched Al 2024 spot welds exhibited pores (Fig. 4). In direct contrast, S phase particles observed in as received Al 2024 base material did not exhibit pores.

During the dwell period in spot welding material from the locations beneath the tool shoulder and the bottom of the rotating pin is incorporated at the top of the thread on the rotating pin and is discharged from the bottom of the thread on the rotating pin.[27,29] A helical vertical rotational flow of material is created within the stir zone formed beside the periphery of the rotating pin, which facilitates heat transfer and the development of a uniform temperature across the width of the stir zone.[21,25,29] The downward transfer of Al_2O_3 tracer material via the pin thread has been confirmed during Al 2024 friction stir spot welding.[5] With this in mind, it is suggested that the melted S phase particles observed in the stir zone (in the location close to the periphery of the rotating pin) result from the incorporation of material during the dwell period in spot welding. S phase particles contained in the as received base material are incorporated into the stir zone, moved downwards via the pin threads and discharge at the bottom of the thread on the rotating pin (Fig. 5).

Figure 6 shows melted eutectic films rich in Cu and Mg in the stir zone of an Al 2024 spot weld. It is suggested that these melted eutectic films form in a similar manner to those found in Al 7075 spot welds (Fig. 2).

Dissolution of melted eutectic films

Although melted eutectic film formation and cracking are apparent in rapidly quenched Al 2024 and Al 7075 friction stir spot welds made using a high plunge rate of 10 mm s^{-1} and an extremely short dwell time of 0·05 s, this is not the case in spot welds made using a longer



5 Schematic representation showing material flow during friction stir spot welding, based on combination of particle tracer studies and numerical modelling:[5] flow of material causes S phase particles from as received Al 2024 material to be incorporated in stir zone

dwell time settings. Al 7075 and Al 2024 friction stir spot welds are crack free since melted eutectic films dissolve in the high temperature stir zone when the dwell period is extended and when the spot welds cool to room temperature after tool retraction. The dissolution kinetics of melted eutectic films has been evaluated by Reiso *et al.*[31] during upquenching of Al alloy sections and by Gerlich *et al.*[4,5] and Yamamoto *et al.*[11,25] during friction stir spot welding of Al 7075, Al 2024, AZ91, AM60 and AZ31 base materials. They are determined by the following factors:

(i) the solidus temperature of the base material or the spontaneous melting temperatures of second phase particles contained in the as received base material
(ii) the diffusion coefficients of solute atoms at high temperature
(iii) the thermodynamic driving force for diffusion and dissolution
(iv) the shape and dimensions of the liquid droplets, which depend on the dimensions and particle size distribution of second phase particles in the as received material
(v) the time available for dissolution during the dwell period in spot welding and as the spot weld cools to room temperature.

Dissolution of spherical droplets is determined by the relation[31]

$$\left(\frac{R}{R_\mathrm{o}}\right)^2 = 1 - \frac{kD}{R_\mathrm{o}^2}t \tag{1}$$

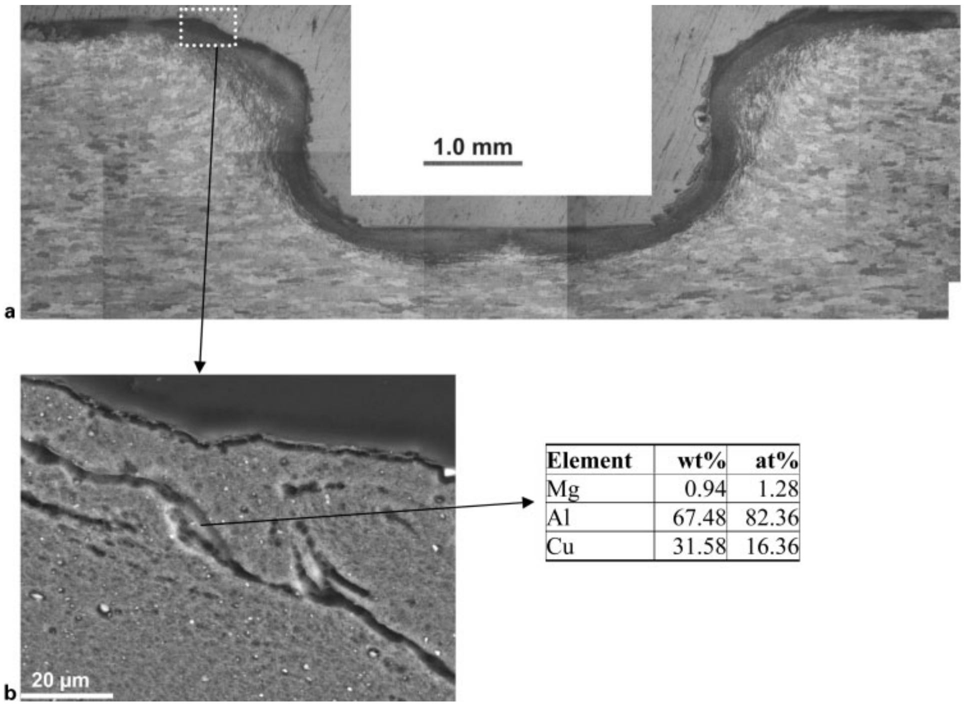
where R is the radius of the spherical droplet, R_o is the initial radius, D is the diffusion rate of the rate controlling element, t is the time in seconds and k is the driving force for solute diffusion given by[31]

$$k = 2\left[\frac{C_{\mathrm{T}_2}^{\alpha/\mathrm{liq}} - C_{\mathrm{T}_1}^{\alpha/\beta}}{C_{\mathrm{T}_2}^{\mathrm{liq}/\alpha} - C_{\mathrm{T}_2}^{\alpha/\mathrm{liq}}}\right] \tag{2}$$

where $C_{\mathrm{T}_2}^{\alpha/\mathrm{liq}}$ is the solid solubility limit at the eutectic temperature (corresponding with α-Al+Al_2CuMg eutectic formation in Al 2024, α-Al+$MgZn_2$ eutectic formation in Al 7075 and α-Mg+$Mg_{17}Al_{12}$ eutectic formation AZ91) at the eutectic temperature T_2, $C_{\mathrm{T}_2}^{\mathrm{liq}/\alpha}$ is the chemical composition of the α+intermetallic pseudobinary eutectic and $C_{\mathrm{T}_1}^{\alpha/\beta}$ is the effective concentration of the solute elements in the as received base material at room temperature T_1, which correspond with the composition values as shown in Fig. 7*a*.

The dissolution time is calculated using the relation

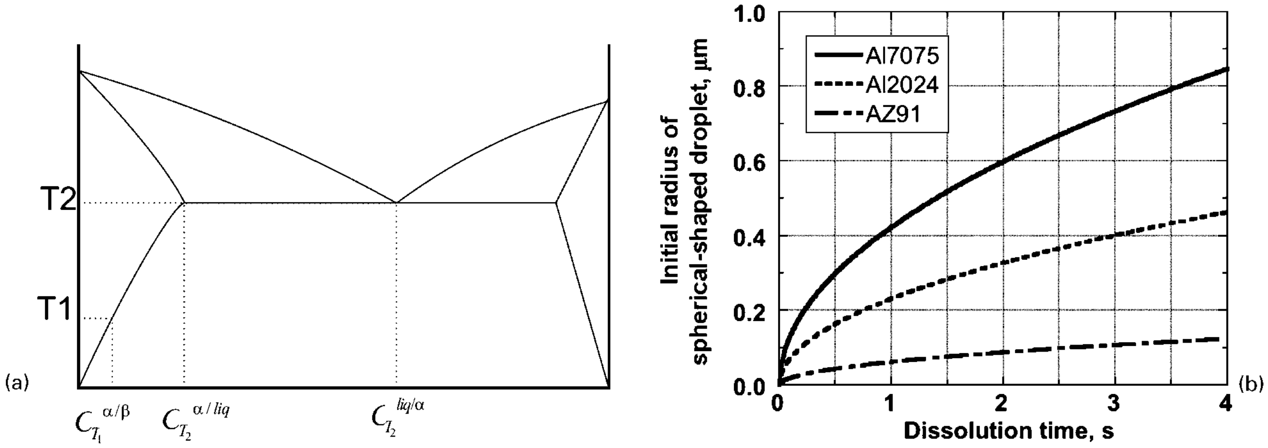
$$t = \frac{R_0^2}{kD} \tag{3}$$



Element	wt%	at%
Mg	0.94	1.28
Al	67.48	82.36
Cu	31.58	16.36

a optical micrograph of location in stir zone of Al 2024 spot weld; *b* SEM image of cracking

6 Cracking observed in Al 2024 friction stir spot weld made using plunge rate of 10 mm s^{-1}, dwell time of 0·05 s and tool rotational speed of 3000 rev min^{-1}



7 ***a*** **phase diagram for pseudobinary showing locations of composition values used in equation (2) and** ***b*** **dissolution rate of melted eutectic films in stir zone region during 4 s long dwell period in Al 2024, Al 7075 and AZ91 friction stir spot welding**

In the case of plate shaped liquid films, the dissolution rate is determined using the relations[31]

$$B = B_0 - \frac{k}{\pi^{1/2}}(Dt)^{1/2} \tag{4}$$

$$t = \frac{\pi B_0^2}{Dk^2} \tag{5}$$

where B is half the thickness of the liquid film and B_0 is half the initial film thickness. The constants in equations (1)–(5) for Al 2024, Al 7075 and AZ91 base materials are shown in Table 2.

Figure 7*b* indicates that melted droplets dissolve at a much higher rate in Al 7075 friction stir spot welds since the thermodynamic driving force for dissolution is much higher. Melted α-Mg$+$Mg$_{17}$Al$_{12}$ eutectic films formed in the stir zone of AZ91 friction stir spot dissolve less rapidly than melted eutectic films in Al 7075 and Al 2024 spot welds and this readily explains why cracking is observed in AZ91 spot welds made using a dwell time of 4 s.[25]

Gerlich *et al.*[4,5] examined the dissolution kinetics of spontaneously melted η and S phase particles in the stir zone during Al 2024 and Al 7075 spot welding and found that melted droplets having radii ranging from 0·45 to 0·85 μm dissolve during the 4 s dwell period in spot welding. Since η and S phase particles in as received Al 2024 and Al 7075 base materials have dimensions <0·5 μm, an extremely short dwell time of 0·05 s and a high plunge rate during spot welding are essential requirements if evidence of melted eutectic formation and cracking is to be retained in Al 7075 and Al 2024 friction stir spot welds. Unless such steps are taken dissolution of melted eutectic films in the high temperature stir zone and as the spot weld cools to room temperature will remove all evidence of local melting during friction stir spot welding. It follows directly from the results found during this investigation, there is no need to assume that the temperature attained within the stir zone during friction stir spot welding is less than that required for melted eutectic film formation and cracking. Also, dissolution of melted eutectic films during the friction stir spot welding can readily account for the production of crack free Al alloy friction stir spot welds produced using dwell times >0·05 s.

Local melting and tool slippage during friction stir seam welding

It might be argued that the evidence confirming eutectic melting and cracking is directly associated with the use of an excessively high tool rotational speed of 3000 rev min^{-1} during Al 2024 and Al 7075 friction stir spot welding. However, tool rotational speeds from 2000 to 3000 rev min^{-1} are required during Al alloy friction stir spot welding to provide sufficient heat input in a short spot welding cycle and achieve acceptable joint strength properties.[32] When a tool rotation speed of 1000 rev min^{-1} is used during Al 7075 friction stir spot welding, for example, the width of the stir zone formed beside the periphery of the rotating pin is <100 μm.[4] In this connection, high tool rotational speeds are also employed during friction stir spot welding of steel, e.g. tool rotational speeds as high as 6000 rev min^{-1} have been reported.[33]

Although lower tool rotational speed settings are generally employed during friction stir seam welding, it cannot be assumed that the peak temperature in the stir zone is lower than that measured during friction stir spot welding. For example, Song and Kovacevic[34] reported temperatures ranging from 515 to 565°C when examining Al 6061-T6 friction stir seam produced using a rotational speed of 914 rev min^{-1}. The temperature in the stir zone of Al 6061-T6 friction stir spot welds made using a tool rotational speed of 3000 rev min^{-1} was

Table 2 Constants used when calculating dissolution rate of eutectic films

Alloy	k	$C_{T_2}^{\alpha/\text{liq}}$, wt-%	$C_{T_2}^{\text{liq}/\alpha}$, wt-%	$C_{T_1}^{\alpha/\beta}$, wt-%	T_1, K	T_2, K	D at T_2, 10^{-15} m^2 s^{-1}	Reference
Al 2024-T3	0·0119	5·9	39·4	5·7	273	763	240	5
Al 7075-T6	1·42	17	30	7·75	273	748	123	4
AZ91	0·4	13	33	9·0	273	710	3·89	11 and 25

548°C.[20] Also, Colegrove *et al.*[35] reported temperatures from 520 to 550°C during Al 7075 friction stir seam welding using a rotational speed of 394 rev min^{-1} and in follow-up research assumed a temperature of 527°C during the development of a numerical model for Al 7075-T6 friction stir seam welding.[36] This particular temperature value is remarkably close to the highest temperature measured by Gerlich *et al.*[4] during Al 7075 friction stir spot welding using a tool rotational speed of 3000 rev min^{-1}.

A dwell period of several seconds is typically applied during friction stir seam welding once the rotating tool has been plunged into the Al alloy component. The initial tool penetration phase in friction stir seam welding is therefore quite similar to a friction stir spot welding operation when a longer than normal dwell time is applied. It has been shown that the solidus temperatures of Al 2024 and Al 7075 are approached when the temperatures measured in the stir zone during friction stir spot welding are extrapolated to dwell time of 10 s.[37] The solidus temperatures of these base materials are reached no matter the rotational speed used during welding. Similar output is produced when Al 5754 and Al 6061 friction stir spot welds are examined.[21,37]

Su *et al.*[19] confirmed that the energy required for stir zone formation during friction stir spot welding using a smooth pinned tool comprises only a small percentage of the total energy, which is generated during tool rotation. The low efficiency of utilisation of energy values (1·6 to 4%) in Al 6061 and AM50 spot welds are indicative of the fact that once the energy generation requirements for stir zone formation have been met, continued tool rotation simply maintains the temperature in the stir zone and excess energy is transferred into the available heat sinks (into the tool assembly, holding clamp, the support anvil and the sheets being fabricated). Bearing this in mind, consider the situation when the stir zone temperature is 525°C immediately before the movement of the rotating tool during Al 7075 friction stir seam welding. Since the energy requirement for stir zone formation is only a small fraction of the energy generated during tool rotation and energy transfer into heat sinks is a consequence of and not a determining factor in stir zone formation and maintenance, the temperature in the stir zone will remain at 525°C as the tool traverses the component. Experimental support for this proposal has been provided by Song and Kovacevic.[34] These investigators reported that the temperature at the contact surface between the tool shoulder and material in the stir zone is negligibly affected when higher travel speed settings are applied during friction stir seam welding.

Spontaneous melting of second phase particles in as received Al 7075 base material only occurs when the heating rate is rapid enough to prevent dissolution before their melting temperatures are reached. For example, Bjørneklett *et al.*[23] found metallographic evidence confirming spontaneous melting of η particles at grain boundary regions when Al 7030 test samples were heated at 330°C s^{-1} to the eutectic temperature (475°C). Colegrove *et al.*[35] reported that the heating rate during Al 7075 friction stir seam welding exceeds 200°C s^{-1}. Heating rates from 210 to 440°C s^{-1} are produced during friction stir spot welding of Al 2024 and Al 7075.[21]

Based on the above commentary, it would be expected that spontaneous melting of second phase particles and tool slippage may occur during friction stir seam welding of Al 7075 and Al 2024 base materials. There is experimental support for this proposition. For example, the power input is significantly overestimated and different tool geometries cannot be discriminated in terms of their measured forces and torque values when a no slip condition is assumed at the contact interface during friction stir seam welding of Al 7075.[38] Frigaard *et al.*[39] also suggested that the low strain rate values (from 1·6 to 17 s^{-1}) found during Al 7108 friction stir seam welding resulted from local melting and tool slippage at the contact interface between the periphery of the rotating tool and adjacent material in the stir zone. These estimated strain rate values are remarkably similar to those found when investigating Al 7075 friction stir spot welds.[4]

Conclusions

The proposal that local melting and cracking occur very early in the dwell period during Al 2024 and Al 7075 friction stir spot welding and that subsequent dissolution of melted films removes all evidence of their occurrence is examined in the present paper. Al 2024 and Al 7075 friction stir spot welds were produced with the precise objective of limiting dissolution of melted eutectic films in the high temperature stir zone and as the spot welds cool to room temperature after welding. Spot welds were produced using a rapid plunge rate of 10 mm s^{-1} and an extremely short dwell time of 0·05 s and were rapidly cooled after spot welding by immersing the spot welded samples into a mixture of methanol and liquid nitrogen at a temperature of −80°C. It has been confirmed that:

1. Melted eutectic film formation and cracking occur very early in the dwell period during Al 2024 and Al 7075 friction stir spot welding. Eutectic films rich in Zn and Cu form in Al 7075 spot welds while melted Al_2CuMg particles promote the formation of an α-Al+Al_2CuMg eutectic film in Al 2024 spot welds.
2. Melted S phase particles observed in the stir zone in the location close to the periphery of the rotating pin are formed when eutectic material is incorporated at the top of the pin thread and is subsequently discharged at the bottom of the thread on the rotating pin.
3. Melted eutectic formation and cracking are observed at the extremity of and within the dynamically quiescent region formed beneath the tip of the rotating pin during Al 7075 friction stir spot welding. These results provide strong support for the melt wear proposal made by Gerlich *et al.*[16]
4. It is suggested that local melting and tool slippage may occur during Al 2024 and Al 7075 friction stir seam welding operations.

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