A WELD MARKER TECHNIQUE FOR FLOW VISUALIZATION IN FRICTION STIR WELDING

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ABSTRACT

Experimental techniques have been developed to allow the investigation of metal flows during friction stir welding. The techniques are based on the use of a marker material that is re-distributed during welding. In the examples shown, copper strips (0.1mm thick) were used as markers. After welding various methods were used to investigate the marker movement including; radiography, tomography and metallurgical sectioning.

Examples of the material distortions are shown. The advantages and disadvantages of the methods are discussed. Particular attention is paid to the validity of the data. Finally, variations to the techniques are proposed that may improve the validity of the results.

1. INTRODUCTION

One of the earliest investigations into the material movements in friction stir welds was carried out by Colligan[1], who used a stop-action technique to freeze-in the flow. Although some of his general observations are useful, it is difficult to track material movements in his work. Subsequently Colligan[2] used steel balls as tracer particles; the ∅0.38mm balls were embedded into slots at different positions relative to the joint line; after welding the balls were highlighted using radiography. The general flow could be traced in this later work but there is some concern that the detail of the flow will not be properly represented because the balls were of similar size to the probe threads. Reynolds et al[3,4] used dissimilar aluminium alloy marker materials and an ingenious experimental procedure, produced spatially wider ranging, but less detailed study of material flows. Their experiments did show significant differences between welds made with different welding parameters and illustrated that this could influence the material flow and mixing. However, Reynolds' results were for sections of completed weld and did not show the material movements as the weld progressed. Russell[5]

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also showed, in a qualitative sense, the disruption of the material near the joint line by welding through copper marker pins set into the parent plates; the marker material movements were highlighted using radiography. Guerra et al[6] used a marker technique similar to that used for the work in this paper; it consisted of placing a copper strip in the original joint-line prior to welding. London et al[7] have shown some useful flow visualization techniques and data from experiments using these techniques. Finally Ouyang et al[8] describe experiments using dissimilar aluminium alloys to highlight flow patterns. Although some of the above authors give warnings about the generality of the results, little attention seems to have been paid to the influence of any marker material on the flow within the welds and hence the validity of the results.

This paper will describe marker material experiments and focus on the validity of the results. The aim is to concentrate on the experimental techniques rather than the results from specific welds. The techniques include stop-action welding similar to that used by Colligan[1] to "freeze in" the flow pattern around the tool. Conventional radiography and X-ray tomography were used to examine the gross flows at the weld and traditional metallographic sectioning methods were used to interrogate the detailed flow.

2. WELDING EXPERIMENTS

A series of instrumented welds in aluminium alloys were carried out using an adapted milling machine located in the German Aerospace Research (DLR) facility near Cologne. The milling head was of the cantilever variety, which gave good access but lacked the stiffness of portal machines. The tool was driven through a dynamometer which gave dynamic readings of forces and torques. Other instrumentation on the machine included three-axis tool position measurements. A data acquisition system was used to collect and store the welding data; this system was also used to collect temperature data via thermocouples. The torque data was used to calculate the total heat generation, which was factored for heat loss into the tool[9]; hence the weld heat inputs were calculated as a function of time and tool position in the weld. Figure1 shows the sizes and layout of the welds; the thickness of the weld panels was either 3mm or 5.8mm.

Annealed copper sheet 0.1mm thick was used as a marker material in some welds. The copper was placed in three positions and two orientations as shown in Fig.1. The copper sheets in the two orientations were in different welds.

A number of variations of a welding tool were used but all had an Ø18mm shoulder with a length adjustable probe of Ø6mm, other details will be given with the results.

A variety of welding parameters were used but no systematic study is reported here. Where they are of importance the appropriate parameters will be quoted with the results. At the end of each of the weld the traverse motion was stopped and almost simultaneously the tool was extracted at the same rate as the downward velocity of the thread profile. The aim was to extract the threaded probe by unscrewing and hence with minimum disturbance to the flow profile.

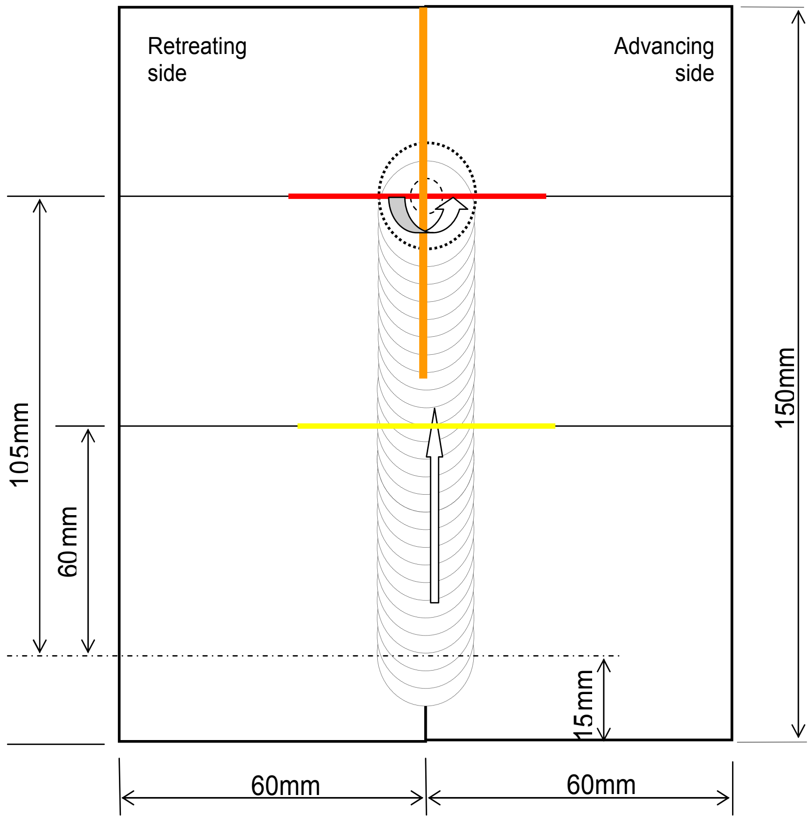


Figure 1 The layout and sizes of the welded panels used in this work. The coloured lines represent placement of copper marker material: orange= longitudinal, red= transverse at exit hole, yellow= transverse at weld centre.

To enable cross reference of the different data in this paper, the welds are identified by the names DMC-py or FSW-Ty, where p is the weld series letter and y is the weld number within the series.

3. RESULTS

The results are presented in sub-sections below by the analysis method used. Much of the analysis of the data will be biased towards the validity, advantages and limitations of the techniques used. By validity we mean the influence of the marker and other experimental methods on the welding inputs and material flow and hence on weld properties. High validity means the methods had little effect on the welding compared to a weld without the techniques applied.

3.1 WELDING

If the inclusion of the copper marker material influences the global inputs into the welds, for instance if the torque or forces change, the weld is likely to be affected and the validity of the marker technique will be reduced.

Figure 2 shows the weld heat input for two pairs of weld; all had copper in the joint-line (longitudinal marker) from about 65mm to past the weld end at 105mm. Although welds the 2024-T3 to 2024-T3 show a systematic decline in the weld heat input as the welds progress, there is little change in the heat input when the tool enters the marker material region. A similar lack of influence of the copper marker has been seen for other 2024-T3 in other welds in the same series and in other welds[10]. Although for the 6082-T6 to 2024-T3 welds in Fig.2 the heat input behaviour is more erratic, there is a clear drop in the heat input of about 20% once the tool enters the copper region of the joint line. In 7075 welds an increase in the heat input has been reported[11] as the tool enters the copper region.

Colligan[1] put considerable emphasis on the dynamics of the welding machine and its ability to change from welding to tool extraction with minimal interruption. Similarly the tool he used was specially made to enhance extraction. The control system on the machine tool used in this

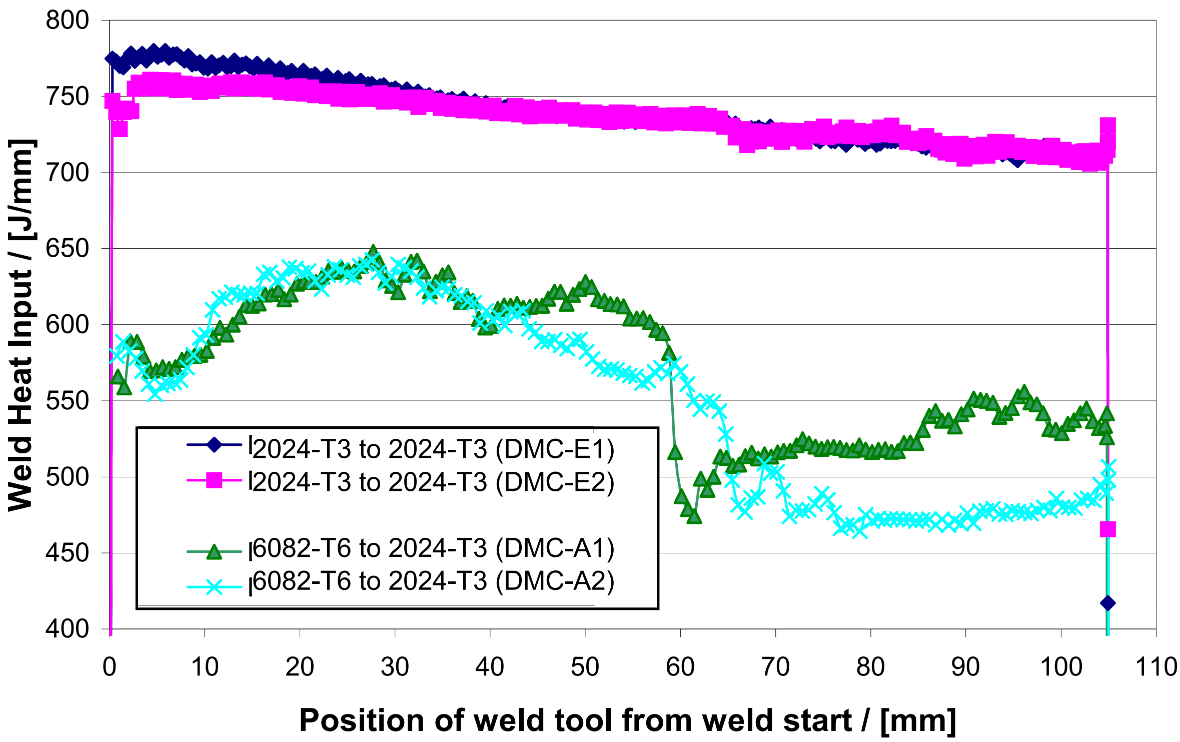


Figure 2 Comparison of the weld power inputs for four 3mm thick welds. All welds had copper marker material from 65mm to the weld end at 105mm.

Figure 3 Exit hole damage in a 5.8mm thick 2024-T3 alloy weld (FSW-T1). The copper marker can be seen in the joint line on the lower left. From reference [10]

work was not as sophisticated as that used by Colligan and so care is needed in validating that the tool extraction could be made with minimal disturbance to the flow patterns. Standard welding tools were also used in this work; they were not specifically designed for easy or clean extraction. The welding machine had had a sequential controller, which meant that the traverse had to completely stop before the tool could be extracted. The dwell between these two actions was estimated at about 50-100ms, which enables up to one complete rotation of the tool to be made between the traverse stopping and the tool extraction. This rotation had the potential to destroy or modify the detail of the material flow patterns. However, the tool forces and torque did not change significantly during the unwanted dwell; small rises of typically 5% in the torques indicated in Fig.2 at the end of the weld, a similar small fall in the forces also occurred. The lack of change in the torques and forces are attributed to elasticity of the machine tool. Effectively, this meant that the tool carried on welding until and during its extraction.

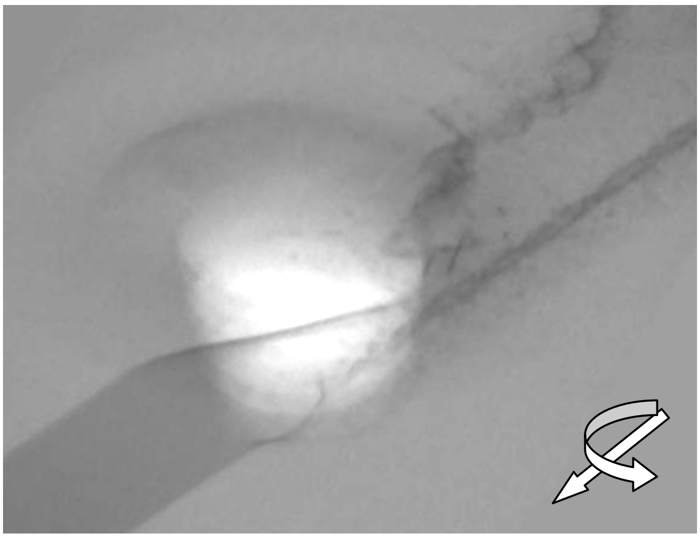


Figure 4 X-ray radiographic image of a weld FSW-T1. This is the same weld as seen in Fig.30 and is approximately the same scale and view angle. The darker grey is the copper and the light patch the tool exit hole. From reference [10]

The exit holes in some of the welds were damaged during tool extraction. This damage is attributed to the weld material sticking to the tool; the bond has to be broken to remove the tool. The damage occurred in welds with and without the marker material in the joint. This sticking was exacerbated with the tool used because the adjustable length probe has re-entrant features. Welds in some materials allowed damage free extraction of the tool, 5083 and 6082 were particularly good examples. Unfortunately 2024 was the worst example encountered and some damage always occurred. Figure 3 shows relatively severe damage caused at the exit hole in a 2024-T3 weld during tool extraction. Mostly the damage was at the weld top surface and the threads formed deeper in the welds were unaffected. For the 2024-T3 welds the damage reduced the usefulness of the subsequent work but in most cases it was not catastrophic to the investigations.

3.2 RADIOGRAPHY

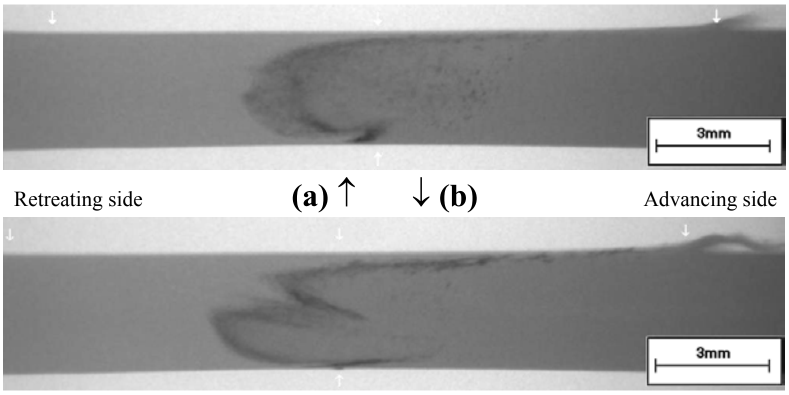


Figure 5 X-ray radiographic images of sections of two welds taken in the direction of weld traverse. The two welds were both made in 2024-T3 to 2024-T3 and with the same welding conditions: (a) using a tool with threaded probe (DMC-A1) and (b) using a tool with threaded probe and 3 straight flutes (DMC-A9).

An X-Tek HMX160 real time X-ray machine[12,13] was used to take digital X-ray images. A typical image can be seen in Fig.4, to help interpretation it is of the same weld as Fig.3 and viewed from a similar position. In general it is difficult to interpret these generalized views except when viewed in real time because of the loss of the depth dimension. The tomography described later improves on this 2-dimensional (2D) approach. However, this 2D radiography has an interesting use in determining the distribution of the marker material in the completed weld where the process is in a steady-state condition. As will be seen later, conventional metallographic sectioning allows only a planar view of the distribution of the marker material. Often what is needed is a more general assessment of the marker distribution so, for instance, the final placement of the joint line can be tracked. An X-ray image of a transverse section of a weld with longitudinal marker, looking along the weld axis will enable the marker distribution to be integrated over a length. Two such images can be seen in Fig.5 where welds using two slightly different welding tools were used. In the figures the position and distributions of the marker, which is effectively where the original joint-line is deposited, can be easily assessed. There is concern that the weld made with the fluted probe has not broken the joint-line up enough at the weld root and just under the weld cap.

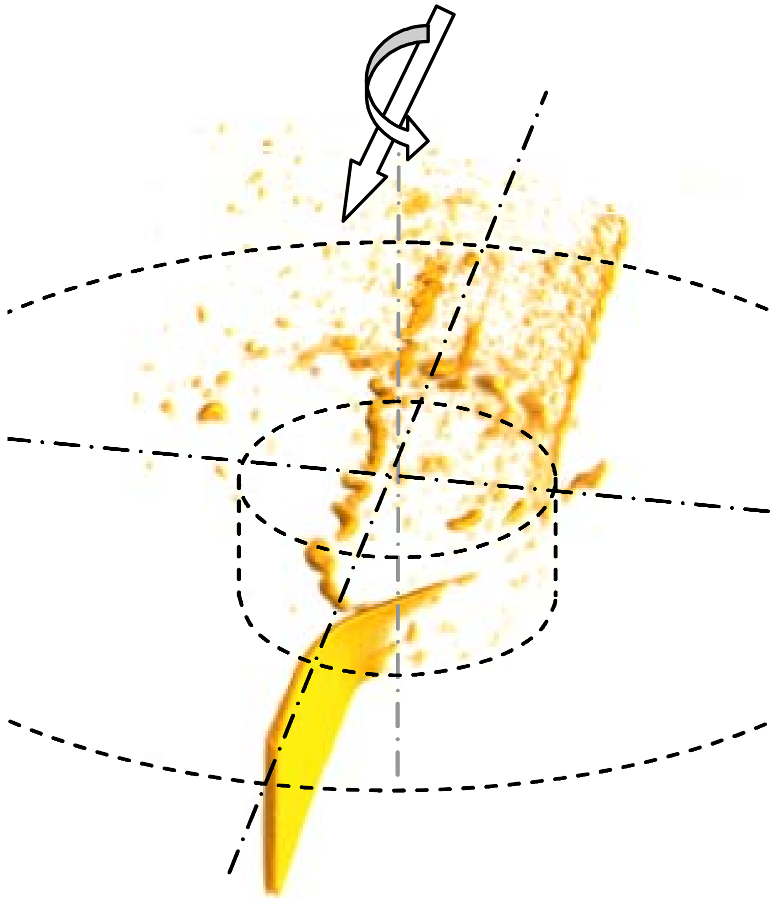
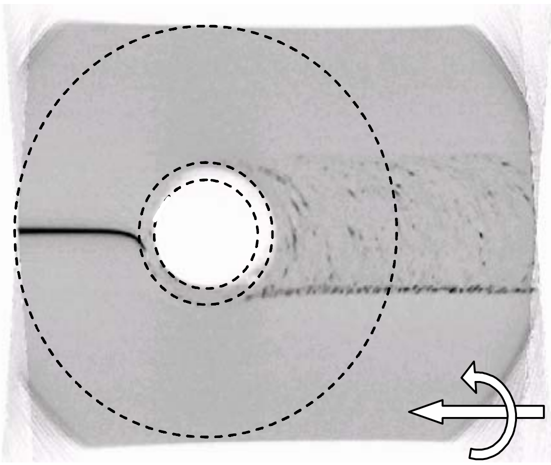


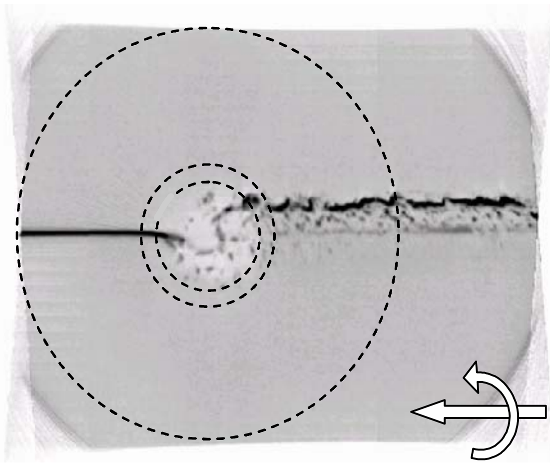
Figure 6 The tomographic model of weld in 2024-T3 to 2024-T3 (DMC-E1), highlighting only the copper marker material at the exit hole. The tool shoulder and probe positions are also illustrated.

3.3 X-Ray Tomography

The same X-Tek X-ray machine was used to make tomographic models as for the 2D radiographic imaging. For the tomography a series of 2D digital X-ray images was made, each taken from a different angle. A total of 360 images were taken at 1° intervals about a rotation axis. These images were then processed into a 3-dimensional model of density variation from which the different materials could be digitally extracted, coloured etc. The models can be viewed as 3-dimensional (3D) images or planar slices



(a) Mid-plane, z=1.50 mm



(b) Weld root, z=2.75 mm

Figure 7 CT slices through the tomographic model of the exit hole of a 2024-T3 to 2024-T3 weld (DMC-E1). Black=copper, grey=aluminium alloy and white(ish)=air. Figure (a) is at the mid-plane of the 3mm thick weld and (b) is near the weld root. The dotted circles represent the tool shoulder and probe positions.

through the model can be made. The 3D images can be manipulated on computer screen and can give an excellent impression of the marker material movements; however they do not transfer so well to 2-dimensional media such as this paper. However the slices through the model, which are termed CT slices, do transfer well to this media.

Figure 60 shows a typical view of a tomographic model of a 2024-T3 weld; only the marker material is highlighted. Despite the image manipulation that can be carried out such as the light shading shown in Fig.60, the model is still difficult to interpret due to the loss of the depth dimension. Live images on the computer screen are much more impressive and the model can be further manipulated in real time. Using red/green glasses it is also possible to view the model in 'true' 3D. The 3D images are a useful way of interrogating and understanding the flow phenomena, yet despite the clever manipulation that can be carried out simpler images such as the CT slices are needed for comparison of welds and modelling data.

Examples of CT slice data are shown in Fig.7; in this case slices in the plane of the weld panels are shown but any arbitrary section can be made. It can be seen that specific parts of the weld can be investigated, for instance in Fig.7(b) the root is shown. In this case the root shows a relatively high concentration of copper; the path that the original joint-line takes under the probe can be traced. Obvious examples of how this could be used would be to investigate the influence of the probe length or a disruptive profile on the probe end.

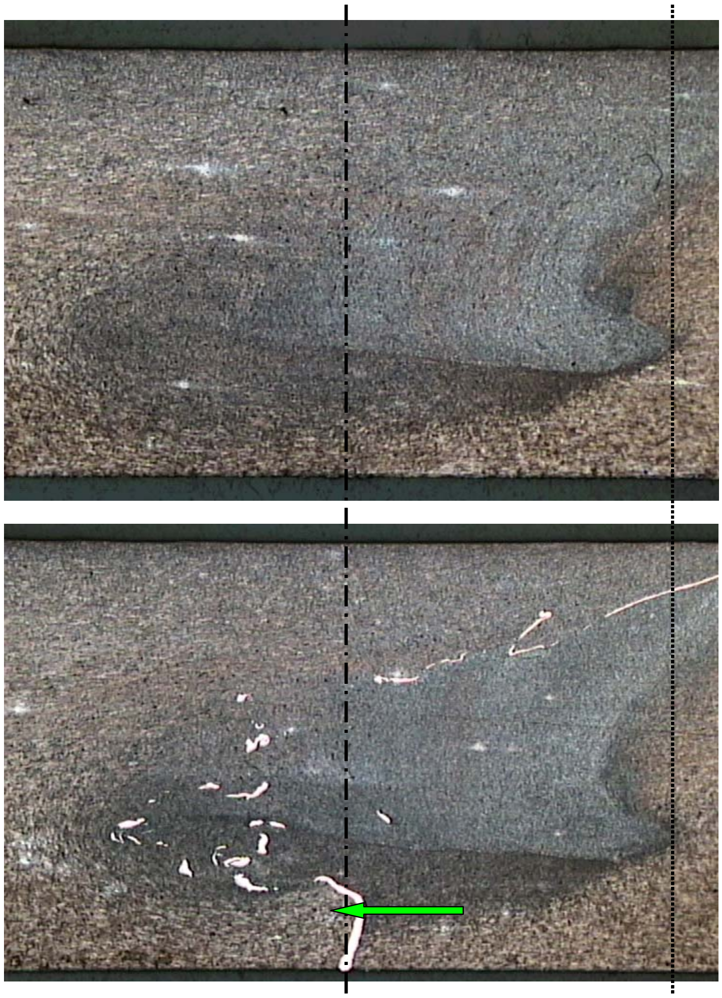


Figure 8 Transverse section of a weld in 2024-T3 to 2024-T3 (DMC-E0) taken from positions (a) without marker and (b) with copper marker. Only the nugget region is shown; the dotted line is the weld centre-line

Despite the usefulness of the

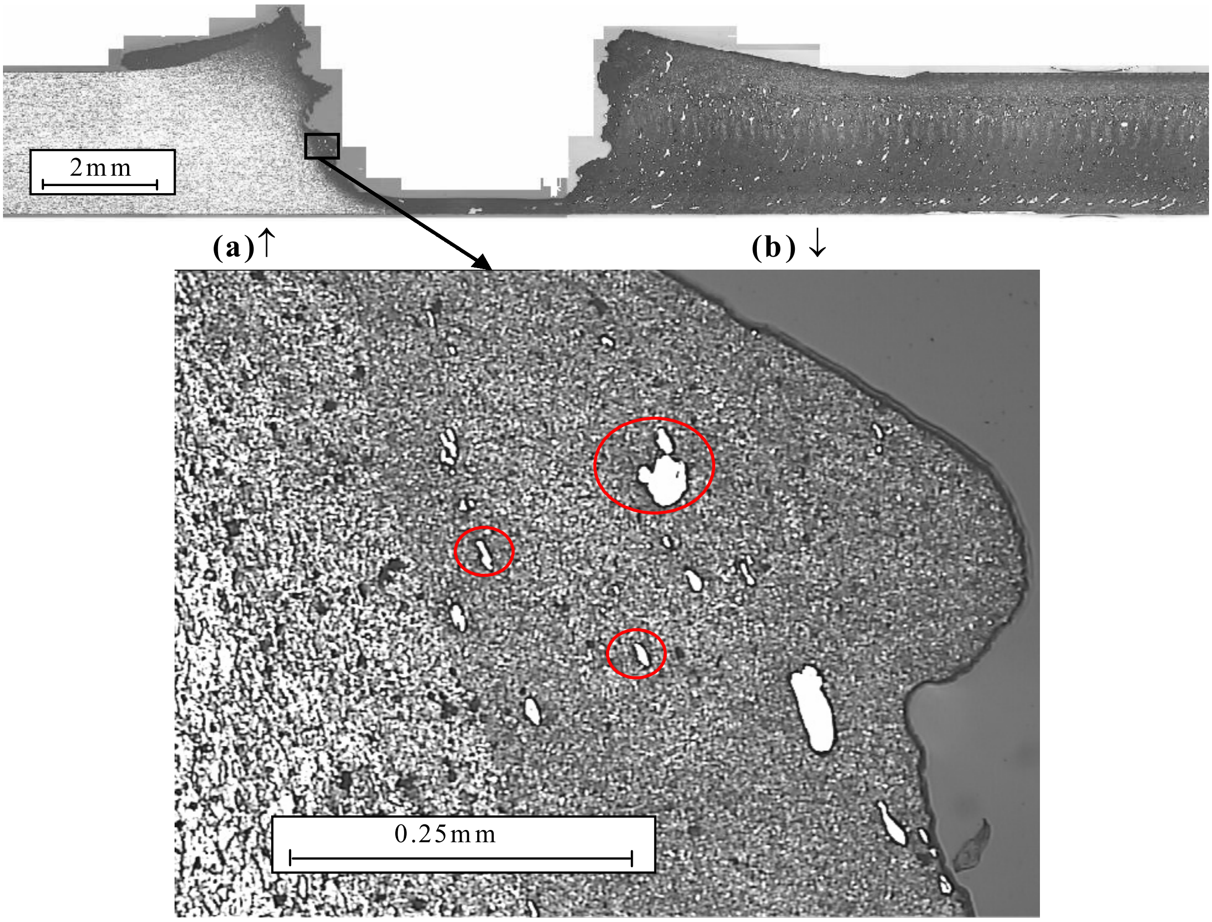


Figure 9 Longitudinal section through a 2024-T3 to 2024-T3 weld (DMC-E1): (a) macrosection on the weld axis centre-line and (b) detail in the thread region. Examples of the resulting copper flecks (bright patches) have been ringed.

radiography and tomographic modelling techniques described the detail of the flow can some times get lost because of the resolution of the equipment. For instance, close to the probe the copper may be broken into very fine particles which the X-ray methods miss or smear. Traditional metallographic sectioning has proven to be complementary to the X-ray techniques.

3.4 METALLOGRAPHIC SECTIONING

Sections of the welds in a number of orientations can be made. After etching with Kellar's reagent the microstructure can be interrogated to give clues to the material flows; however, the distribution of the copper gives useful additional information. The copper is not etched by the Kellar's solution and remains as bright patches.

Examples of sections can be seen in Fig.8, these again are from welds in 2024-T3. In the sections the copper can be clearly seen and at higher magnifications greater and greater levels

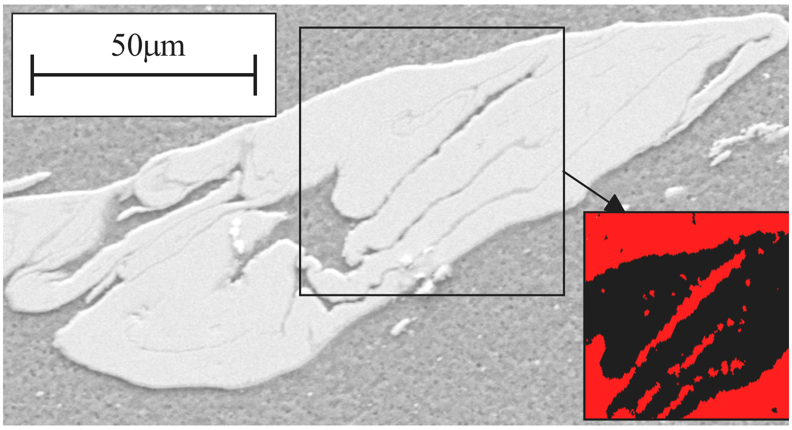


Figure 10 A copper fleck in a 2024-T3 to 2024-T3 weld (DMC-E1), inset is an elemental scan for aluminium, red=aluminium, black=copper.

of detail are revealed. Importantly the shape and size of the weld nugget is unaffected by the presence of the copper indicating in this case that the welds with the marker have high validity. Only at the weld root, indicated by the green arrow, is there a difference between the two sections in Fig.8. In this weld the probe length was too short which explains why the copper at the weld root is not disrupted.

A longitudinal section through the exit hole of a weld can be seen in Fig.9. As can be seen the copper is broken-up into small pieces and may track into the flow deformation. Some of the pieces of copper are smaller than 10µm. The size and shape of the copper marker will also indicate the intensity and type of deformations that have been produced by the welding process. Figure 10 illustrates this by showing a copper particle that had been deposited in the wake of the tool. The particle has a layered structure which indicates it has been folded on itself and squeezed; this is good as it indicates the original joint-line has had significant work carried out on it which will disrupt the oxides and consolidate the joint.

4. DISCUSSION

The use of any marker must be used with care as it may influence the welding characteristics and hence invalidate the results. As seen in Fig.2 the copper did influence some welds in some materials. Although not tried in this work, there are ways that any influence of the marker material could be (further) reduced:

- Copper sheet thinner than the 0.1mm thick used for this work could be used. The analysis techniques used could easily detect copper from the 0.1mm thick sheet and so thinner marker is unlikely to reduce the effectiveness of the analysis.
- Place the marker in parts of the weld only and not through the entire weld thickness (as in this work). If a strip of copper were placed in the top third of the joint-line, for

instance, a further benefit would be that information about the through-thickness flow deformations would be generated.

- An alternative marker material to copper could be used. Work would be needed to determine what marker materials would be compatible with which alloys. Deformable materials like the copper used here are likely to provide local deformation information similar to that shown in Fig.10. Unless heavy metals like gold or platinum are used the imaging quality of the X-ray techniques used here are unlikely to be improved on.
- Finally the marker material could be pre-broken into small particles so the welding process does not have to do this. For instance copper powder could be used, although a suitable method of application and retention into the weld joint-line would need to be developed. Other power or granular materials could also be used as long as they have sufficient X-ray definition.

Despite the above suggestions it was found that copper sheet embedded into the aluminium alloy 2024-T3 had a minimum disruption on the welding and could be usefully used as a marker material. Importantly, the method is easy to incorporate into welds and could, for example, be used in production equipment as a periodic check on weld quality. Copper was also favoured for the work because it was amenable to analysis using a number of techniques.

5. ACKNOWLEDGEMENTS

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