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A PROCESS MODELLING APPROACH TO THE DEVELOPMENT OF LAP WELDING PROCEDURES

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ABSTRACT

Process modelling (PM) is used in many industries to make considerable contributions to the development of safe and efficient engineering designs. The authors have experience of applying PM to a wide range of industries and applications; they are currently investigating the application of commercial CFD software to Friction Stir Welding (FSW). PM augments results generated by laboratory testing by providing full field and full duration predictions of important parameters such as material state. Analyses of engineering processes are increasingly conducted with commercial software, which attracts a significant license fee, but license fees may not be the only barrier to the utilisation of PM in engineering design. PM can be very complex and the requirements for an understanding of many advanced material behaviours may deter their use. It might fairly be expected that there could be a considerable investment needed before a desirable return is achieved. FSW has been the fastest growing joining technology over the last two decades and it now being used in many industries, including aerospace, automotive and shipping. The process has advantages over the more traditional techniques for joining metallic materials. Results show that FSW joints have a superior fatigue resistance when comparted to fusion joining, and the lower process temperature means that thinner sheet fabrications are less likely to suffer heat-related distortion. FSW procedure development is needed for each application to show that the proposed welding procedure for any application will robustly produce defect-free welds of suitable quality. The current paper extends a FSW PM technique which assumes that accuracy mostly depends upon the conditions that exist near the FSW tool plus some straightforward mechanics and thermodynamics remote from the tool. The technique can be used for a wide range of materials using properties that are generally available and easily understood by a process engineer. Comparisons are made here against test data of a series of lap welds for a range of conditions. Of particular interest is the effect of two different tool pin designs on the corresponding welds. The test data showed that welding parameters (rotation rate and welding speed) and tool pin design strongly affect the characteristics of the typical defect features (hooking and cold lap defects). The comparisons showed that the tool pin design including thread must be captured explicitly in the model, and that the relative position of the tool as it rotates must also be modelled. This results in quantitatively accurate predictions of torque and qualitatively realistic results for hooking and cold lap defects. The approach is based upon the use of general purpose CFD software combined with a set of easy to access materials data.

Keywords: (Process Modelling, CFD, Lap Welding, Hooking, Cold Lap Defects)

INTRODUCTION

Friction Stir Welding (FSW) tends to be a solid-state welding process because the input power would drop considerably if the material around the tool became molten. A schematic of this behaviour is shown in Fig. 1.

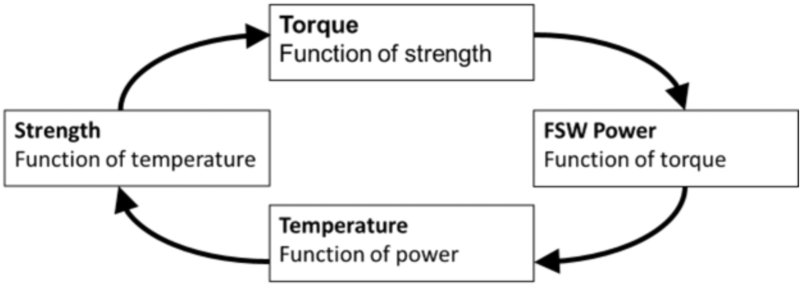


Fig. 1 Simple relationship between the main characteristics that determine the conditions that are generated during Friction Stir Welding

The current Process Modelling (PM) assumes that the material behaviour in the heavily straining region is dominated by an exponentially weakening trend of material strength as the material temperature approaches its melting point. A simple relationship between material strength at pseudo-static strain rates and temperature, T is assumed as described in reference [1]. A simple strain rate sensitivity was added to augment the pseudo-static strength behaviour.

Work with this model has previously analysed butt welds. The current paper presents its use on lap welds where hooking and cold laps can reduce weld strengths [2, 3].

MODEL DESCRIPTION

The current work was undertaken using the Computational Fluid Dynamics (CFD) code STAR-CCM+ [4] which provides user friendly and simple to learn facilities for the development of a FSW model. The CFD model approach is quite straight forward and has been outlined previously in [1].

Two regions are created representing the tool and the upper and lower work pieces. The travel of the tool is captured by “moving” the work piece, i.e. the upstream boundary condition is a fixed inlet velocity boundary condition and the work pieces move past the tool. The outlet boundary condition is a fixed pressure boundary condition. The Volume of Fluid method is used to separate the upper and lower work pieces, and to measure the mixing of the work pieces following welding. The tool is rotated at the given rotation rate, and the interface between the tool and the work piece experiences the shear stress associated with that. A predominantly hexahedral mesh consisting of approximately 18 million cells is used for all simulations.

All simulations are steady state, which implies an infinite weld. Subsequently, the far field temperature boundary conditions are adjusted to account for the short test section seen in the tests.

The derivation of viscosity is provided in [1]. It was assumed that the correct room temperature strength parameter was the Ultimate Tensile Strength, which was chosen to be 550MPa. The melting temperature assumed was 710°C [5].

The heat generation was assumed to be by adiabatic shearing alone. Many models of FSW adopt advanced friction characteristics that would be both expensive and laborious to develop on a bespoke basis for general analyses of FSW. The current work assumed that friction was caused by the shearing of the workpiece material in the small crevices that represent the surface of the tool, so, even at a microscopic level friction is really the adiabatic shearing of material.

ALDANONDO TESTS

Z shaped extrusions of aluminium alloy AA2099-T83 with a thickness of 2 mm (UTS about 560MPa [6]) and sheets of aluminium alloy AA2060-T8E30 with a thickness of 2.5 mm (UTS about 540MPa [7]) were used as base materials in this work. Both alloys were in a T8 hardened temper condition.

FSW joints were performed in overlap configuration where the alloy AA2099-T83 was used as a stringer and placed on top of the alloy AA2060-T8E30 which was used as a skin. An example of this lap joint is shown in Fig. 2a. 120mmlong joints were performed for each welding condition investigated.

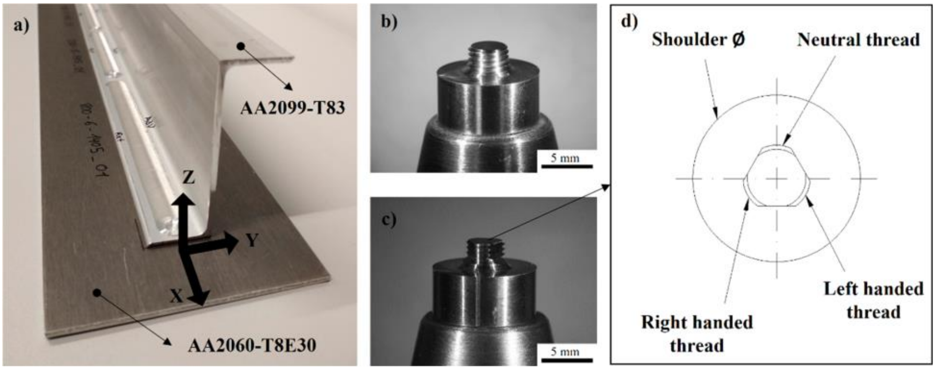


Fig. 2 a) Friction stir welding (FSW) lap joint between AA2099-T83 extrusion and AA2060-T8E30 sheet and FSW tools used to produce them; (b) conventional threaded tool; (c) 3 flats + mixed thread tool; and (d) sketch showing details of the top view of the 3 flats + mixed thread tool. Reproduced from [3]

Two types of FSW tools were employed to produce lap joints. Both FSW tools had a plane shoulder of 10 mm in diameter and a probe 4 mm in diameter and 2.5 mm in length. The difference between the tools was the probe design. One probe had a conventional right-handed thread cylindrical probe (Fig. 2b) while the other tool had a probe with 3 flats and 3 types of threads in the 3 cylindrical sections (Fig. 2c,d). The flats were used to divide the probe in three different threaded sections. All threads were produced with the same pitch and depth dimensions, but each had different thread orientations. One section had a right handed thread, another one a left handed thread and the other thread was neutral (no inclination). The main purpose of this probe design was to avoid any preferential vertical plasticized material flow to reduce the hook formation, while promoting sufficient flow at the faying surface to break the oxide layers and produce a mixing between the parts to be welded. All the welds were performed with a tool tilt angle of 1.5°.

Combinations of two rotational speeds and two welding speeds were investigated. The rotational speeds investigated were 800 rpm and 1200 rpm, and the welding speeds investigated were 150 mm/min and 250 mm/min.

FRICTION STIR WELDING PROCESS MODELLING OVERVIEW

The modelling approach developed using the CFD code is outlined in Lewis [1] with a few minor adjustments. Previously, it was noted that the torque was under-predicted, and subsequent analysis showed this was due to the simplified representation of the tool thread; so the tool thread has to be captured explicitly. Here the two Aldanondo tool types are investigated: a standard threaded tool and a mixed threaded tool (see Fig. 3).

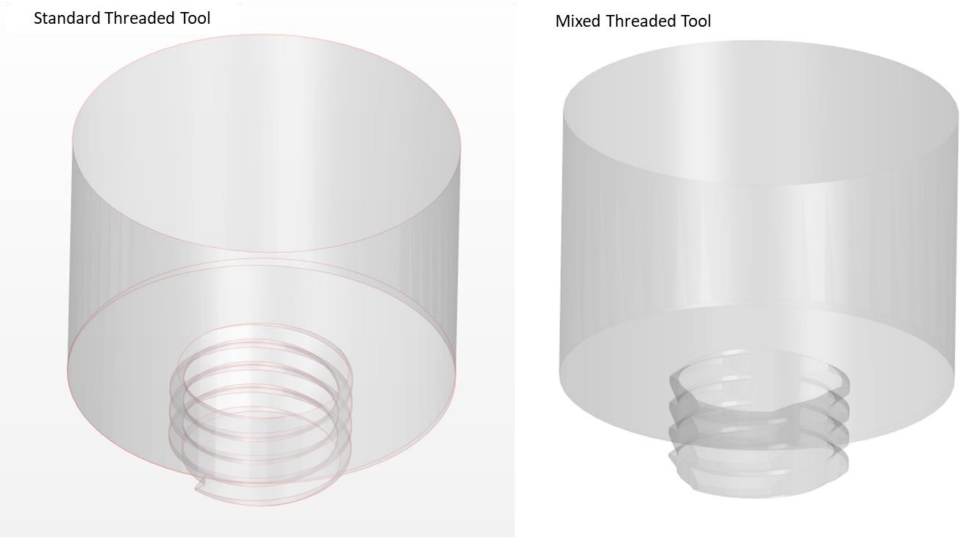


Fig. 3 Standard threaded tool and mixed threaded tool used in this study

The tool rotation can be captured explicitly using a transient analysis, but this is computationally expensive. Instead, the simulations are steady state and the tool rotation is captured using a rotating reference frame such that the shear stress of the movement is experienced by the material close to the tool. To study the effect of keeping the tool in one orientation, separate simulations were carried out with the tool at four different angles of rotation (see Fig. 4).

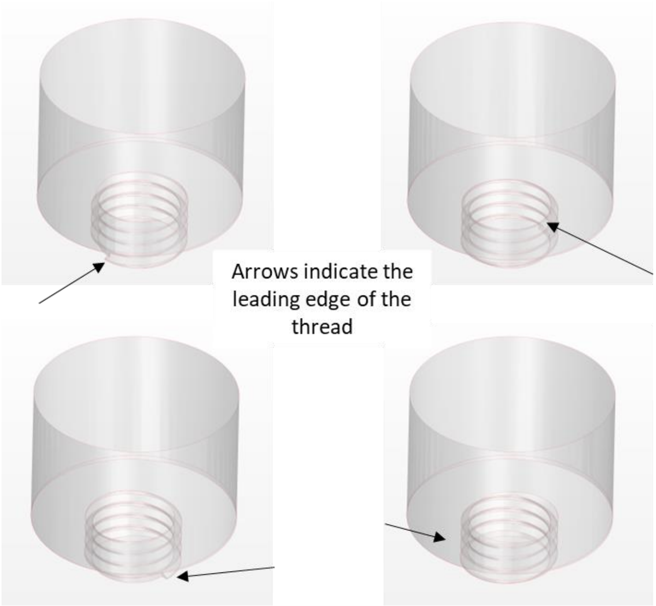
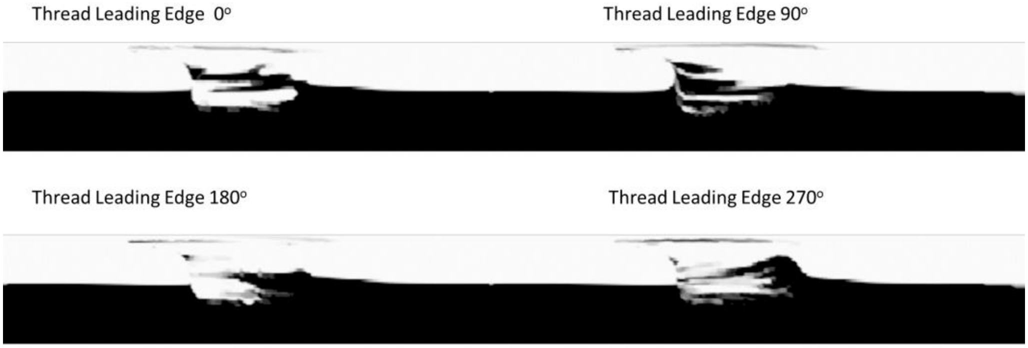


Fig. 4 Four orientations of the tool used in steady state analyses to accommodate the behaviour of real tool rotation

Each of these steady state simulations with different tool pin leading edge rotations produce slightly different results. This is clearly demonstrated in Fig. 5 for the conventional threaded tool at a rotational rate of 1200rpm and welding speed of 250mm/min. The contour plots show a transverse section post welding where the colours show the mixing of the top (white) and bottom (black) plates. Hooking is shown at 0^o and 90^o and a cold lap defect is shown at 270^o.



Thread Leading Edge 0°

Thread Leading Edge 90°

Thread Leading Edge 180°

Thread Leading Edge 270°

Fig. 5 A series of contour plots with the tool pin in a different rotational position, each contour plot is of a transverse section post welding; colours show the mixing of the top and bottom plates; for the conventional threaded tool at 1200rpm and 250mm/min

The results from each of these four simulations have then been averaged to get an overall behaviour. Fig. 6 shows the average behaviour via a contour plot of a transverse section post welding where the colours show the mixing of the top and bottom plates for conventional threaded tool at a rotational rate of 1200rpm and welding speed of 250mm/min.

Fig. 6 Contour plot of a transverse section post welding; colours show the mixing of the top and bottom plates; for the conventional threaded tool at 1200rpm and 250mm/min

Fig. 7 shows the Aldanondo [3] cross section for a weld made with the conditions used to create the CFD result shown in Fig. 6. The hooking and cold lap defects that are clear from the measurements can be inferred from the CFD simulation results.

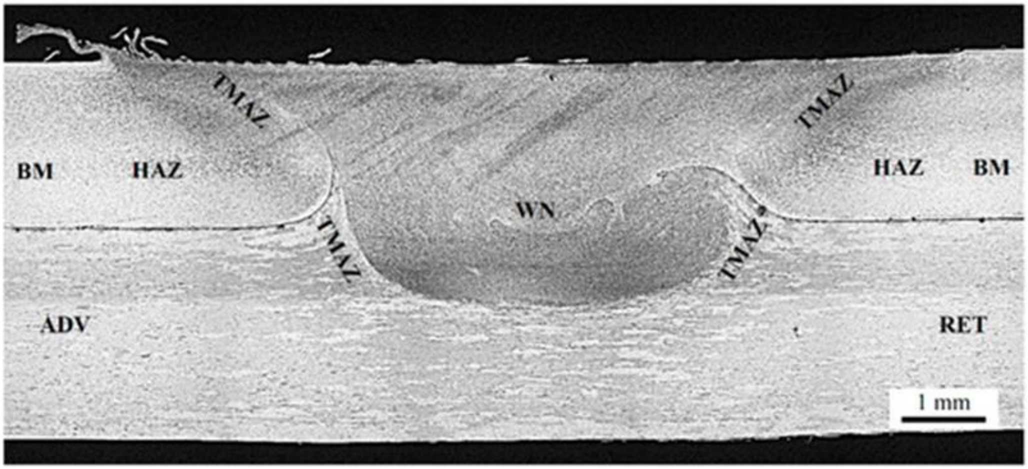


Fig. 7 Cross-section and microstructural zones of a FSW lap joint produced using a conventional threaded tool at 1200 rpm and 250 mm/min (Reproduced from [3])

Fig. 8 shows contour plots from the CFD which show the mixing of the weld for the conventionally threaded tool at a range of rotational rates and welding speeds. Fig.9 shows transverse macro sections from the equivalent welds from [3]. Comparing these two figures it can be seen that the hooking and cold lap defects, clear from the actual welds, can be inferred from the edge of the mixing zone in the CFD results.

Fig. 8 Contour plot of a transverse section post welding; the grey scale shows the mixing of the top and bottom plates; for the conventional threaded tool

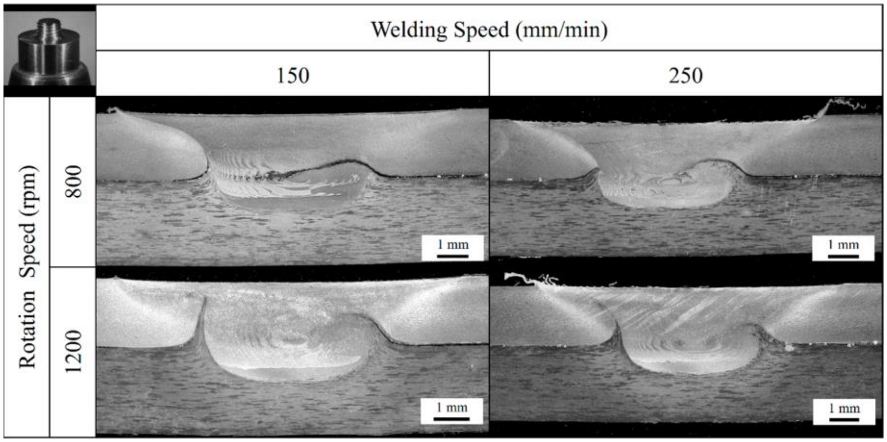


Fig. 9 Cross-section and microstructural zones of a friction stir welding (FSW) lap joint produced using a conventional threaded tool (Reproduced from [3])

Fig. 10 shows contour plots from the CFD which show the mixing of the weld for the mixed threaded tool at a range of rotational rates and welding speeds. Fig. 11 shows transverse macro sections from the equivalent welds from [3]. Comparing these two figures it can be seen that the reduction in the cold lap defects seen in the test sections for the mixed threaded tool is reproduced in the CFD simulations.

Fig. 10 Contour plot of a transverse section post welding; grey scale shows the mixing of the top and bottom plates; for the mixed threaded tool

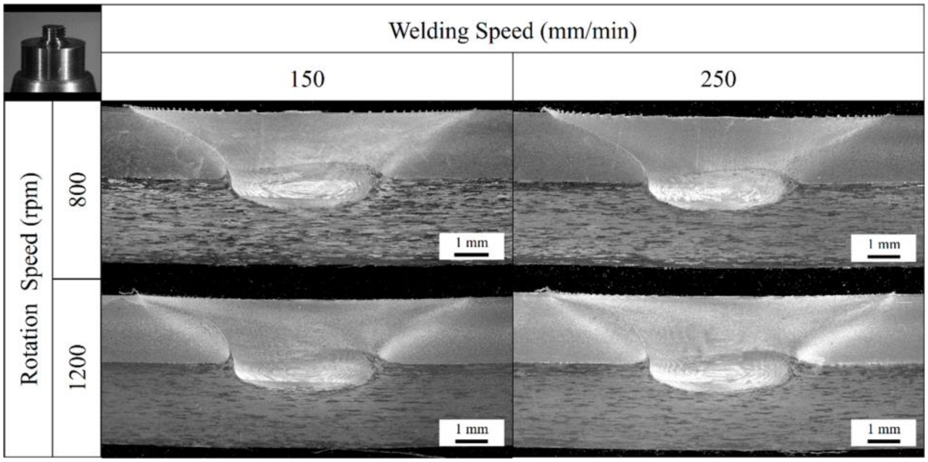


Fig. 11 Cross-section and microstructural zones of a friction stir welding (FSW) lap joint produced using a mixed threaded tool (Reproduced from [3])

Fig. 12 shows comparisons of measured and predicted torques for the mixed threaded tool; the trends are captured quantitively as are the individual values of torque.

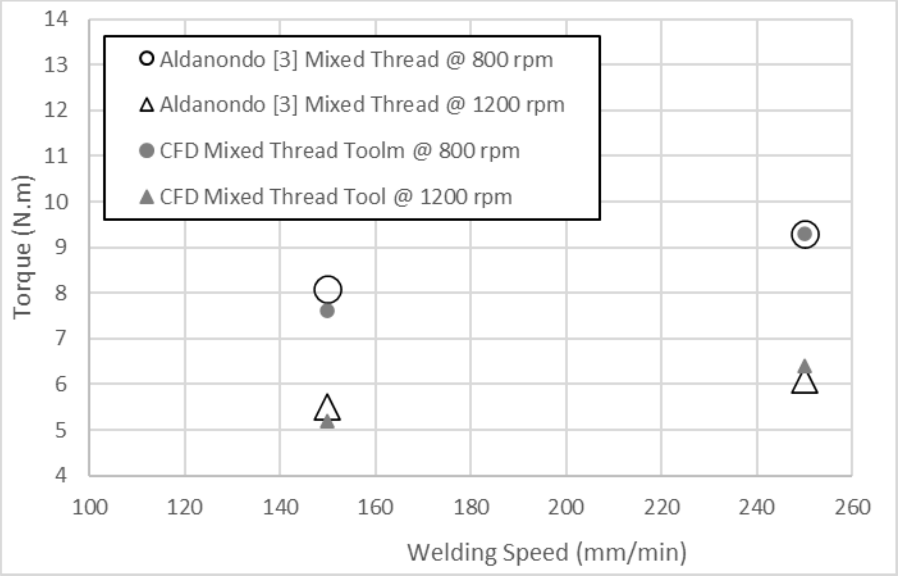


Fig. 12 Torque predictions and measurements for the Mixed Thread tool

DISCUSSION AND CONCLUSIONS

The comparisons showed that the tool pin design including thread must be captured explicitly in the model. However, the simulations are steady state and the relative position of the tool as it rotates influences the results. A series of simulations for a range of tool angular orientations has been modelled and then the results averaged. The method produces quantitatively accurate predictions for torque and qualitatively realistic results for hooking and cold lap defects. The approach is based upon the use of general purpose CFD software combined with a set of easy to access materials data.

PM can be applied to lap welds and is now available for use by welding engineers to provide a detailed understanding of FSWs based upon an extension the CAD/CAM tools that they are currently familiar with.

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