Relationships among FSW Process Parameters, Defects, Crack Paths and Fatigue Strength in 5083-H321 Aluminium Alloy

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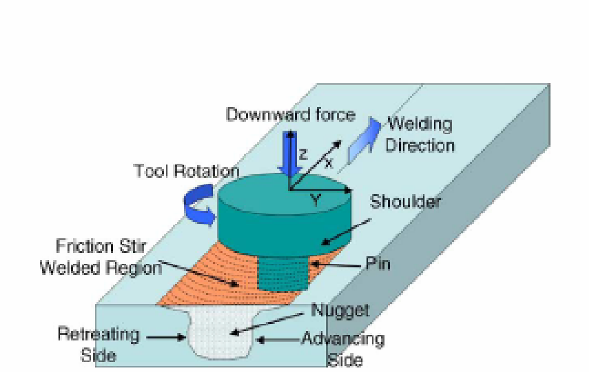
ABSTRACT. *This paper presents a brief outline of the complex relationships that exist between fatigue performance, mechanical properties, defects and crack paths in FS welded 5083-H321 alloy. These relationships are governed by frictional power input which affects plastic flow processes in the weld. Residual stresses are governed by heat input into the weld.*

INTRODUCTION

Friction stir welding (FSW) is a relatively new solid state joining process that offers the potential for joints with high fatigue strength, low preparation and little post-weld dressing. Other benefits include generally low defect populations (compared with fusion welding) and the ability to join dissimilar metals. The technique has hence attracted significant interest from the aerospace and transportation industries and an extensive literature exists on FSW. To date, however, there are few reported systematic studies of process optimisation in terms of the linkages among process parameters (primarily tool rotational speed and feed), defect population, residual stresses, mechanical properties and fatigue performance. In particular the use instrumented tools that can provide data on heat, power and energy input into the welds is in its infancy. Thus welding parameters (tool speed and feed, tool geometry, downwards tool force) are usually established empirically for individual cases. Fig. 1 illustrates the FSW process and defines force directions plus the advancing and retreating sides of the weld; because of the combination of tool rotation and forwards movement during welding, the material properties and residual stresses in the weld are slightly different on these two sides.

This paper builds on previously published work [1] that reported the potential use of data that could be obtained from an instrumented tool post (torque, temperature, forces on the tool). It considers a structural strain hardened aluminium alloy, 5083-H321, which has been previously reported [2] to show unusual pseudo-bond defects during FSW and demonstrates that clear linkages exist between fatigue performance, crack paths, defect type and process parameters. The influence of process parameters is characterised through power and heat input calculations. Data reported in this paper



offer the possibility of a predictive capability for structure-process-property relationships in FSW. The basic hypothesis of the work is schematically illustrated in Fig. 2.

Figure 1. Illustration of FSW process [3].

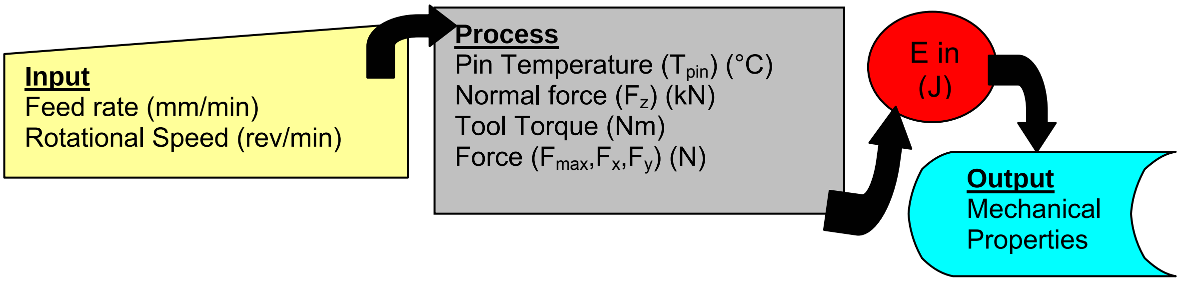


Figure 2. Schematic illustration of proposed linkages between input and output parameters in FSW.

OVERVIEW OF EXPERIMENTAL MATRIX

This work used 6 mm plates, 100 mm wide, joined by welds 750 mm long. Tensile and fatigue specimens were cut from the same positions towards the middle section of each weld where parameters like tool temperature, torque, and forces reach quasi-static values. The FS welding tool had a shoulder radius of 25 mm while the fluted and threaded pin was 10 mm in diameter and 5.7 mm long (see Fig. 3). The forging action of the tool was enhanced via a forwards tool tilt angle of 2.5 degrees. Table 1 gives the combinations of tool rotational speed and feed values chosen for this research. Tool speed and feed can be combined into a single characterising parameter giving tool pitch per revolution, and one aim of this work was to determine which parameter would provide the best predictor of weld performance. Tensile specimens were 12.5 mm across the gauge section and were not machined on the surfaces. Fatigue specimens were tested in tension at R = 0.1 and had a width of 18 mm across the gauge length. Their surfaces were machined smooth to avoid initiation at shoulder marks, as the intrinsic performance of the welded material was required.

Figure 3. Flute tool geometry used to make the FS welds.

Table 1. Tool rotational speed, feed and pitch values used in this work.

85 mm/min		135 mm/min		185 mm/min	
RPM	Pitch	RPM	Pitch	RPM	Pitch
400	0.21	635	0.21	870	0.21
266	0.32	423	0.32	617	0.3
201	0.42	318	0.42	436	0.42
		254	0.51	348	0.53

Fatigue performance was assessed by testing at a single stress level applied to all specimens. An initial estimate of an appropriate stress was obtained from the S-N curve for the parent plate, where a stress of 216 MPa corresponded with a mean life of 10^6 cycles and 242 MPa to a life of about $2x10^5$ cycles. Welded specimens were tested at 242 MPa because previous work on this alloy [2] had indicated that the pseudo-bond defects were activated at higher levels of plastic strain and their effects are therefore more likely to be an influence at shorter fatigue lives. S-N data for welded specimens often exhibits a cross-over in performance ranking between 10^5 and 10^6 cycles and future work will consider the longer life performance of the welds.

Extensive residual stress measurements were made on the welds using synchrotron X-ray diffraction beamline ID31 at the European Synchrotron Radiation Facility in Grenoble, France (experiment ME 992). These will not be covered in detail in this paper, but full experimental conditions are reported in reference 4.

Energy Calculations

In this work the energy input into the weld has been calculated using two routes; firstly using a heat input approach due to Khandkar et al [5] that is based on the tool torque and, secondly, a frictional power approach. Heat input correlates well with details of the residual stress distribution in the welds [4], in particular the maximum value of the longitudinal residual stress. The average heat input from the tool shoulder is given in Eq. 1:

$$Q_{in1} = \eta \frac{2\pi\omega Torque}{f} \qquad (1)$$

where η is the efficiency of heat transfer into the weld (typically about 0.9), ω is the tool speed in rev/min and f is the feed rate in mm/min. Fig. 4 demonstrates a good correlation between heat input and maximum longitudinal residual stress.

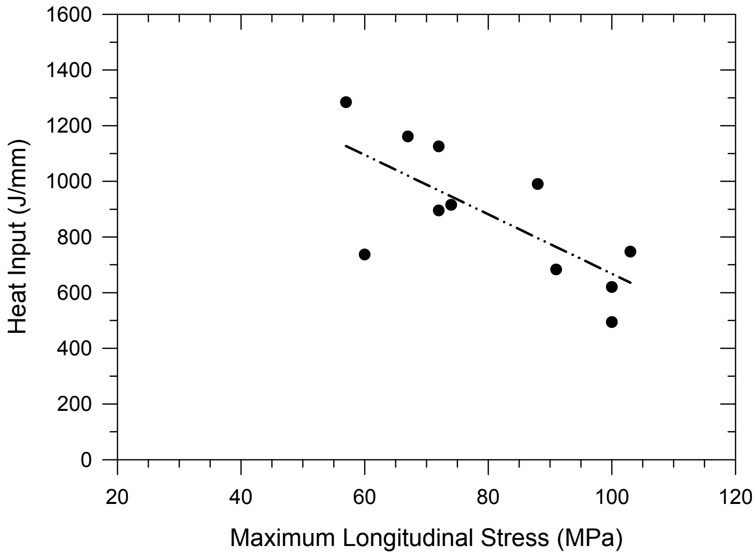
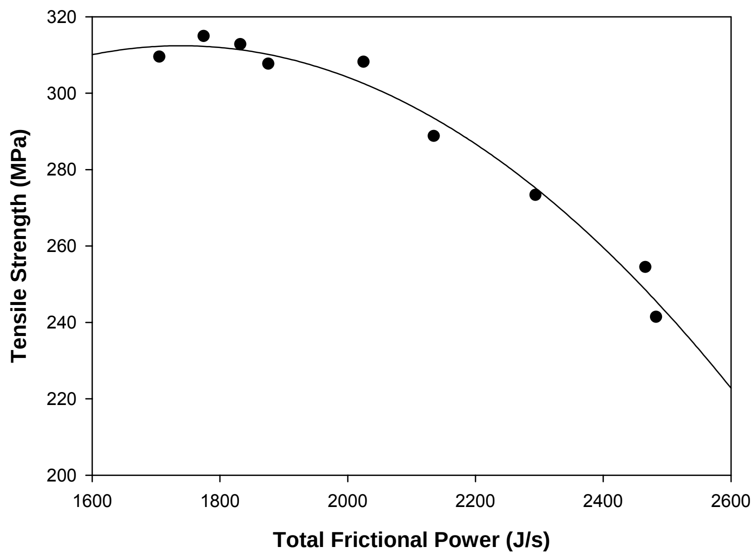


Figure 4. Correlation of maximum longitudinal residual stress by heat input.

The frictional power expression used in this work (Eq. 2) is due to Frigaard and Midling [6] and uses an effective coefficient of friction defined by Santella et al [7]:

$$P_{in1} = \frac{4}{3}\pi\mu F_z \omega r \qquad (2)$$

where μ is an effective coefficient of friction under the tool shoulder, F_z is the downwards force on the tool and r is the radius of the tool shoulder. Frictional power correlates well with tensile properties as is demonstrated in Fig. 5. Lower values of frictional power input provide higher tensile strengths and this can be related to the necessity of establishing high enough temperatures to ensure adequate plasticization of the alloy during the welding process; this in turn leads to a lower power requirement



during welding. Lower values of frictional power occur in two specific tool speed and feed regimes, as is shown in Fig. 6.

Figure 5. Frictional power input versus tensile strength.

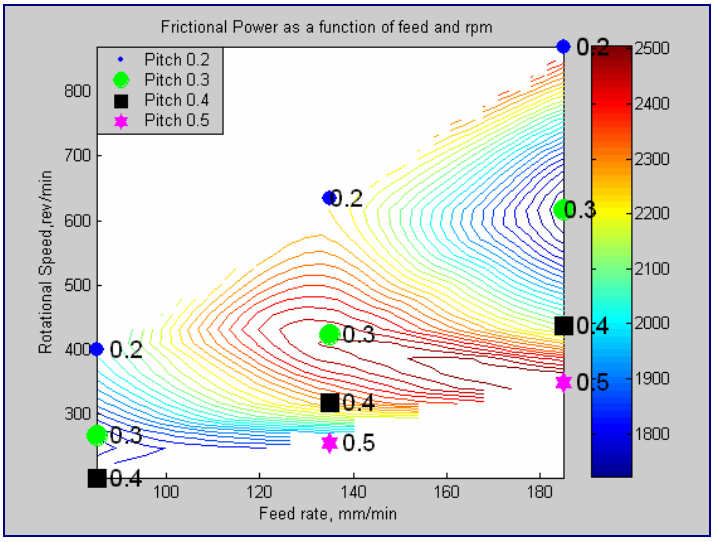


Figure 6. Frictional power as a function of tool rotational speed and feed rate.

The high speed and feed regime of low frictional power in Fig. 6 is centred around 600 rpm and 185 mm/min, while the low speed regime occurs below 300 rpm and 140 mm/min.

CRACK PATH EFFECTS

From the relationships shown already it would be expected that there would be a relationship between defects and tensile strength, and therefore between defects, frictional power and the process parameters of tool speed and feed. These welds do contain significant pseudo-bond defects in the form of planar regions on the fracture surface and in the form of so-called onion-skin defects. Both of the defect types are defined below fractographically and have been observed previously to affect crack paths and fatigue strength [2, 8]. Data presented in reference 8 indicated that tool feed and speed had an effect on the endurance limit in 5083-H321 alloy. Fig. 7 summarises the relationship between defects, tensile strength and tool speed and feed. As expected, the contour plot is the inverse of that seen in Fig. 6, and high tensile strengths correlate reasonably well with defect-free fracture surfaces.

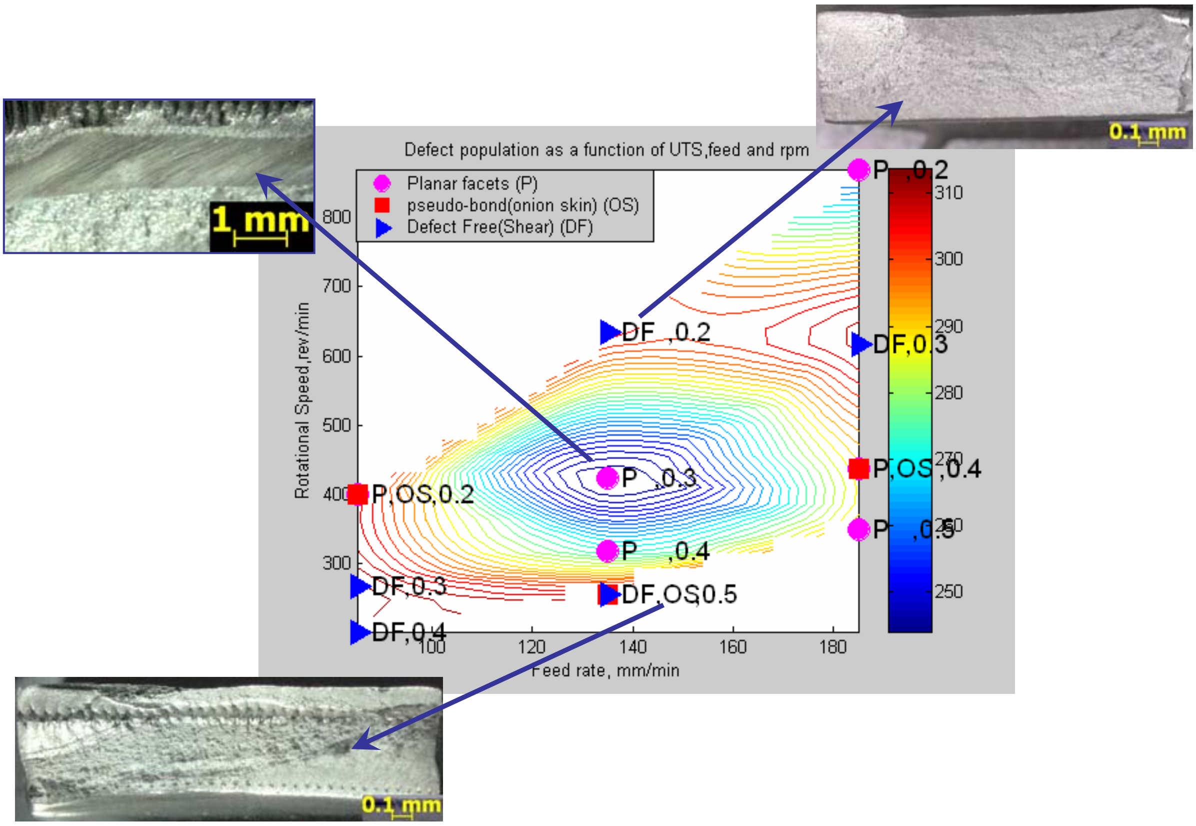


Figure 7. Defect type and occurrence as a function of tensile strength and tool speed.

Fig. 7 illustrates planar pseudo-bonds, sequences of onion-skin defects and a high strength defect free fracture surface. These defects can be very extensive and their effect on the tensile strength of the alloy ranges from 0.68-0.85 of the parent plate value (371 MPa), while the 0.2% proof strength ranges from 0.56-0.67 of the parent plate value (254 MPa). These strength ratios for FS welds in this strain-hardened alloy are typical, and similar values have been reported by Peel [9].

Fatigue Crack Paths

The paper thus far has provided a brief overview of the systematic manner in which the present research programme has attempted to analyse the relationships amongst weld input parameters (tool speed and feed), material-dependent process parameters like energy input, and the output parameters of interest to weld and static structural performance, i.e. residual stress, tensile strength and defects. This information is a necessary precursor to understanding the fatigue behaviour of a strain-hardened alloy like 5083-H321, which is subject to extensive recrystallisation in the weld nugget during FSW and where the defects that occur during welding are likely to be triggered by plastic strain [2]. In general, welds made under different process conditions often show a cross-over in dynamic performance in going from the high stress-short life regime (~$5x10^4$ cycles) to the low stress-long life regime (>10^6 cycles). This reflects their ability to reduce local strain concentrations through plastic flow and for the specific case of 5083-H321 alloy, the presence and triggering of pseudo-bond defects. The intention in this work was to examine the role of crack path defects and residual stress on the fatigue life and to relate these back to the process parameters. To date, a single value of applied stress has been considered which corresponds to a life of around $2x10^5$ cycles in the parent plate, and lives between 300-$1.5x10^5$ cycles in the welded specimens. Average fatigue lives recorded from 5 specimens are given in Table 2.

Table 2. Fatigue life for each combination of process parameters.

RPM	400	266	201	
Pitch (mm/rev)	0.21	0.32	0.42	
Feed (mm/min)	85	85	85	
Fatigue Life	21521	68798	50000	
RPM	635	423	318	254
Pitch (mm/rev)	0.21	0.32	0.42	0.51
Feed (mm/min)	135	135	135	135
Fatigue Life	74616	12746	14818	28624
RPM	870	617	436	348
Pitch (mm/rev)	0.21	0.30	0.42	0.53
Feed (mm/min)	185	185	185	185
Fatigue Life	32694	85897	16792	45021

Fatigue life does not correlate directly with frictional power or with tensile strength. However, relationships between defect type, fatigue life and frictional power do exist, as is demonstrated in Fig. 8. The fatigue life of specimens cut from defect-free regions of the welds is consistently higher across the range of frictional power input. Interestingly, in the relatively limited data available, the life of specimens containing onion-skin defects increases as frictional power increases, while those specimens containing planar defects show a bifurcation in behaviour as frictional power increases. These trends can be explained in terms of the relative sizes of the defects, and their extent across the weld, which reflect the plastic flow processes in the weld. These, in turn, reflect power input and process parameters, which affect tensile strength and residual stresses. Thus subtleties of crack path and process parameter interactions dominate the low cycle fatigue life in FS welds in this 5083-H321 alloy. Space precludes a full discussion of these effects in this paper.

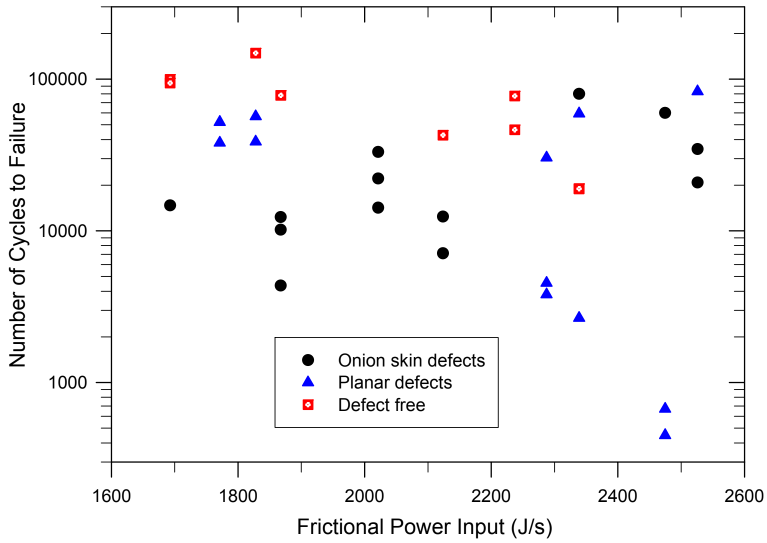


Figure 8. Fatigue life as a function of defect type and power input.

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