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Development of High Welding speed in Friction Stir Welded 5182-H111, and the Resulting Influence on Down Force

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Abstract. In this manuscript the development of the process parameters to friction stir weld 5.15mm thick AA5182-H111 at a feed rate of 1500mm/min is discussed. Compared to a weld made at 200mm/min the weld-pitch had to be reduced from 2.0rev/mm to 0.3rev/mm and down force increased from 27kN to 59kN to create a weld with tensile-and yield strength exceeding that of the parent material, whilst elongation was only marginally reduced. The low weld pitch coupled with the high feed rate resulted in a reduction in the weld temperature and an increase in the process reaction forces. A lower down force was sufficient to consolidate the stir zone and result in ultimate tensile strength yield strength exceeding that of the parent material. However, elongation was reduced since the low weld pitch also reduced the effectiveness of the flutes on the pin to break up and disperse the oxide layer, rendering a pseudo bond along the 'Lazy S'. This pseudo bond was eliminated through an increase in the down force.

Introduction

Over the past two decades friction stir welding has been developed to the point where it can successfully be applied in the production industry [1]; however, friction stir welding of 5xxx aluminium alloys tends to be carried out at weld speeds below 500mm/min [2], While feed rates of up 6000mm/min has been reported in 6xxx series aluminium alloys with a plate thickness of 4mm (scaled from macrograph) [3]. Although joints made in aluminium through FSW generally have superior properties over fusion welding methods, the low welding speeds accompanied by the increased preparation time means that FS welding mainly applied in critical, high value, low production volume components. Rao et al. [4] welded 3mm thick cold rolled AA5083 with a feed rate and spindle rotational speed of 1000mm/min and 1800rpm respectively. They removed micro-tensile samples longitudinally to the weld direction, and their results indicated an average longitudinal yield strength in the stir zone of 160MPa. Deplus et al. [5] reported on the residual stresses in friction stir welded joints of 4mm thick AA5754-H111 made with a spindle speed of 1000rev/min and a feed rate of 1100mm/min. They did, however, not report on the macrostructure or tensile properties of the joints. Up to date no other work has been found where 5mm thick 5xxx series aluminium alloy have been welded above 1100mm/min.

Conventionally, weld pitch (spindle speed / feed rate) is above 1rev/mm. Lakshminarayanan et al. [6] investigated a process window with spindle speed and feed rate ranging from 500rpm to 1500rpm, and 30mm/min to 150mm/min respectively (weld pitch between 3.33rev/mm and 36.7rev/mm). They concluded that the spindle speed should be sufficiently high such that the material moves around the pin fast enough to fill the cavity behind the tool. In AA2219, weld quality was dependent on both weld pitch and specific energy input, since this is heat treatable alloy. They stated that hot processing with sticking conditions will result in excessive material flow leading to (amongst others) nugget collapse, while cold processing with slip conditions will result in insufficient material flow causing wormholes or lack of consolidation. Some studies have, however, shown that it is possible to carry out a friction stir weld with a pitch below 1rev/mm; the parameters reported by Deplus [5], as stated earlier, equated to a weld-pitch of 0.91rev/mm. Commin et al. [7] found that at a weld speed of 2000mm/min, and a rotational speed of 600rpm (0.3rev/mm) was sufficient to create a weld with similar properties to weld made with weld pitch above 2rev/mm in 2mm thick strain hardening AZ31-O magnesium alloy. Similar weld pitch have been reported in FSW of 1.6mm thick stainless steel by Ishikawa et al. [8]. They achieved tensile failure in the parent material with welds made at 1200mm/min and 600rpm, relating to a weld-pitch of 0.5rev/mm. These last two examples are, however, in plates with a thickness below 2mm. In the current paper, the process parameter development is presented were a conventional tool that was developed for weld speeds of 200mm/min was used to reach a weld speed of 1500mm/min, in 5.15mm thick AA5182-H111 plate.

Experimental set-up

Material. This study was performed on aluminium alloy 5182-H111 (T500) with a thickness of 5.15mm which is used to manufacturing of road tankers, of which the chemical composition is shown in Table 1.

Table 1. Chemical composition (in wt. %) of AA5182-H111 (T500).

Si	Fe	Cu	Mn	Mg	Cr	Ti	Al
0.103	0.223	0.089	0.456	4.89	0.039	0.008	94.2

Weld preparation. The friction stir weld coupons was made on a 4-axis MTS friction stir welding platform at the Nelson Mandela Metropolitan University. The welding tool had a shoulder diameter of 22mm, and a threaded conical pin, with a major diameter of 10mm and a minor diameter of 8mm. The pin also contained 3 equally spaced flutes, as illustrated in Fig. 1. The temperature in the pin was measured during welding by means of a K-type thermocouple imbedded inside it, roughly 0.5mm from the side-wall and at mid weld depth.

Fig. 1. Friction stir welding tool features

Methodology. It was investigated whether a FS weld could be made at 1500mm/min with a tool which was initially developed for a feed rate of 200mm/min, accompanied by a spindle speed of 500rpm and a down force of 27kN (This weld will be referred to as the "slow weld", and will be presented as "W10" in this manuscript). Process development to achieve the "fast weld" was approached in three stages; *Stage I* and *II* was performed by making bead on plate welds of 200mm in length, and the down force on the tool was controlled at 39kN throughout both stages. Since there was no clear indication which parameters would be necessary to create a high speed weld, the process parameters for *Stage I (W1 – W2)* was selected by first adopting a conventional weld pitch (spindle speed / feed rate [rev/mm]) greater than one. Hereafter spindle speed was reduced for the same feed rates, *(W3 – W4)*, resulting in a minimum weld pitch of 0.7rev/mm. In *Stage II* the most promising weld from *Stage I* was selected, and the feed rate was increased to 1500mm/min while keeping the spindle speed constant (*W5)*. Hereafter the spindle speed was further reduced *(W6 – W7)*. In *Stage III* the parameters from "W7" was transferred to butt welds *(W8 – W9)* and only the down force on the tool was increased. The force was initially increased to eliminate voids, after which it was increased based on the performance of a longitudinal (all-weld) tensile samples.

Results

A summary of the process parameters that was investigated during this study is presented in Table 2. Macro and micrographs from *Stage I* is shown in Figs. 2 and 3 respectively. In both these figures, (a) and (b) presents two welds which was made with a spindle speed of 1500rev/min, and a feed rate of 700mm/min and 1000mm/min respectively. For both welds the stir zone was broader at the bottom than at the top, as seen in Fig. 2, which is indicative of high downward material flow. However, as seen from Fig. 3, neither stir zones was sufficiently plasticized. Leitão et al. [9] presented similar stir zone structures from welds made at 1000rpm and 200mm/min. They found that a reduction in tool rotation at a constant feed rate resulted in better material flow. The subsequent two welds was made at 700rpm, again with feed rates of 700mm/min (weld pitch = 1 rev/mm) and 1000mm/min (weld pitch = 0.7 rev/mm), and are presented in Figs. 2 and 3 as (c) and (d) respectively. The stir zones of the welds with the reduced weld pitch had a different shape to the high pitch welds, having a similar diameter at the top and at the bottom of the weld. With a high weld pitch a higher volume of material is forced downward, resulting in a wider base. The stir zone of both these welds were completely plasticized, and no voids were visible in either welds. The weld pitch of 0.7rev/mm and 1.0rev/mm for welds "W3" and "W4" is similar to that reported by Deplus et al. [4].

Table 2. Process Parameters investigated during this study.

Stage	Weld #	Down force [kN]	Feed rate [mm/min]	Spindle Speed [rev/min]	Weld pitch [rev/mm]	Pin Temp. [°C]	Comments
Stage I (Bead on Plate)	W1	39	700	1500	2.14	574	Insufficient Plasticization
	W2	39	1000	1500	1.50	566	Insufficient Plasticization
	W3	39	700	700	1.00	548	Complete consolidation
	W4	39	1000	700	0.70	536	Complete consolidation
Stage II (Bead on Pate)	W5	39	1500	700	0.47	-	Evidence of plasticization, Incomplete consolidation
	W6	39	1500	600	0.40	-	Good consolidation, Void (483μm x 370μm)
	W7	39	1500	500	0.30	-	Good consolidation, Void (438μm x 21μm) & (63μm x 79μm)
Stage III (Butt-Weld)	W8	52	1500	500	0.30	-	Complete consolidation, Void (28μm x 57μm)
	W9	59	1500	500	0.30	505	Complete consolidation
"Slow Weld" (Butt-Weld)	W10	27	200	500	2.50	543	Complete consolidation

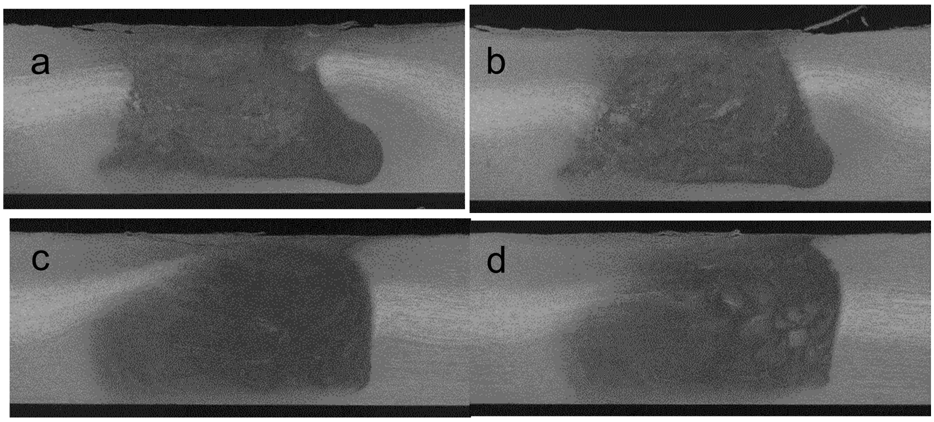

Fig. 2. Macrographs of the stir zone of (a) “W1”, (b) “W2”, (c) “W3” and (d) “W4”.

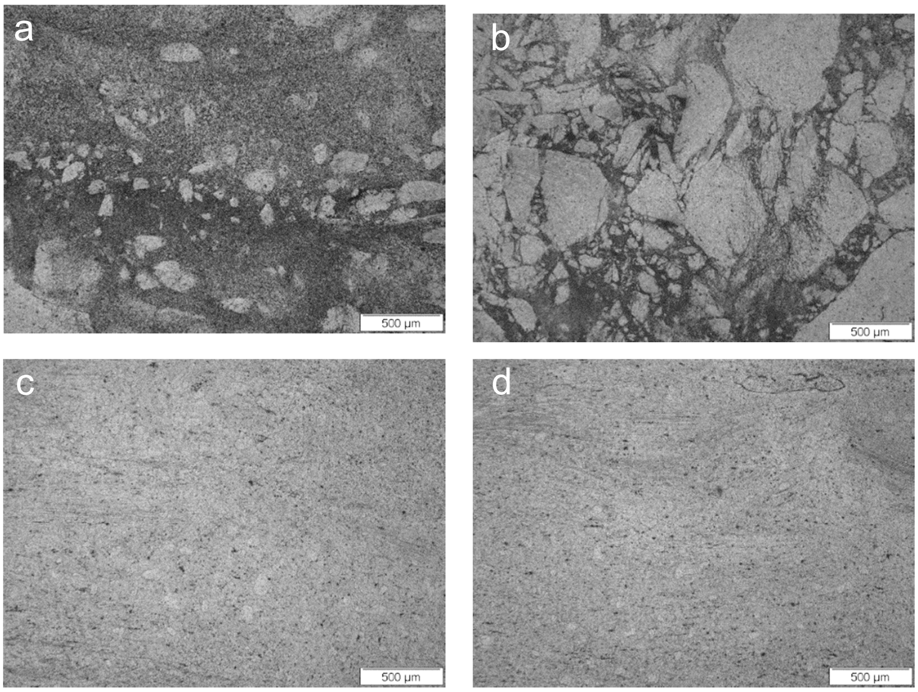

Fig. 3. Micrographs of the stir zone of (a) “W1”, (b) “W2”, (c) “W3” and (d) “W4”.

Stage II was initiated with by increasing the weld speed for “W5” to 1500mm/min while maintaining a spindle speed of 700 rev/min and a down force on the tool at 39kN. The appearance of the stir zone for “W5” is shown in Fig. 4 (a). Although the stir zone was not completely consolidated, there was sufficient evidence of plasticization with an increased feed rate and decreased weld pitch. For welds “W6” and “W7”, of which the micrographs are shown in Fig. 4 (b) and (c), the rotational speed was reduced to 600rev/min and 500rev/min respectively, while the feed rate and down force remained at 1500mm/min and 39kN. Reducing the spindle speed to 500rev/min improved plasticisation and consolidation, and reduced the void significantly.

During *Stage III* the parameters was transferred to butt welds. The void was reduced to a size of 28µm x 57µm in “W8”, as indicated by the white arrow in Fig. 5, by increasing the down force to 52kN. A longitudinal (all-weld) tensile sample from “W8” reached an ultimate tensile strength (UTS) of 314.0MPa and an elongation of 21.6%. The fracture surface, however, displayed evidence of a forging defect, or pseudo bond. The forging defect was eliminated by increasing the down force to 59kN for weld “W9”. Fig. 6 presents the tensile curves for “W8”, “W9” and the parent material (perpendicular to the rolling direction), while Table 3 presents a summary of the results.

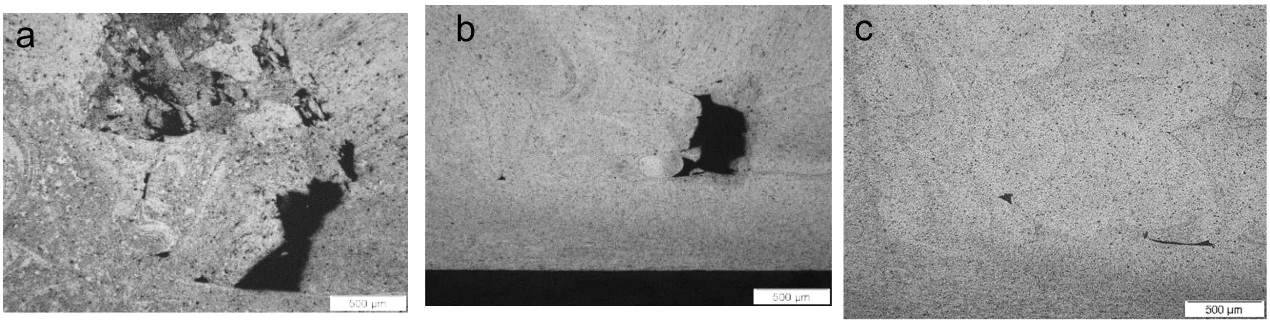

Fig. 4. Micrographs showing the influence of reducing the spindle speed at a constant feed rate and down force of 1500mm/min and 39kN respectively (a) “W5” [700rev/min] (b) “W6” [600rev/min], and (b) “W7” [500rev/min].

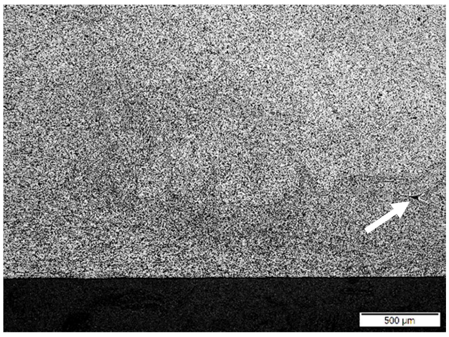

Fig. 5. Micrograph of weld “W8” made at 1500mm/min, 500rev/min and 52kN.

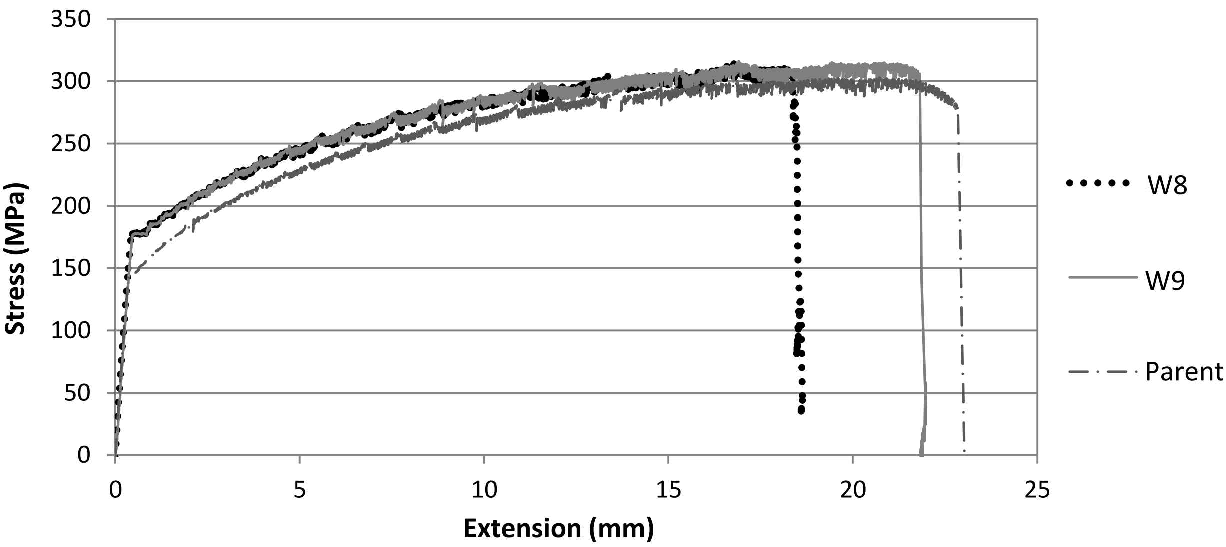

Fig. 6. Tensile flow curves for the parent material and welds “W8” [52kN] and “W9” [59kN].

No change in UTS or yield strength was observed with an increase in the down force, however elongation increased from 21.6% to 25.4% since the forging defect was eliminated. The UTS and yield strength for “W9” was 4.6% and 22.5% higher than the parent material respectively. The fracture surfaces of “W8” and “W9” is shown in Fig. 7 (a) and (b). The forging defect in “W8” is indicated by red arrows, while “W9” displayed no indication of a forging defect. With a weld pitch of 0.3rev/mm the tool completes one rotation every 3mm which seems to reduce the effectiveness of the flutes in breaking up and dispersing the oxide layer. These continuous oxide bands therefore creates a boundary within the plasticized material which resists forging, creating a weak or “pseudo bond” [10, 11]. It is believed that the increased down force allowed this boundary to be overcome, allowing the material to be forged. The yield strength of 177.7MPa is marginally higher than the average yield strength of the stir zone in the work by Rao et al. [4] of 160MPa, which was made in a cold rolled AA5083 (AA5083 has a similar chemical composition to AA5182).

Table 3. Tensile properties of the parent material and welds “W8” [52kN] and “W9” [59kN]

Weld #	Down force [kN]	UTS [MPa]	Yield Strength [MPa]	Elong-gation [%]
W8	52	314.0	177.9	21.6
W9	59	316.0	177.7	25.4
Parent	-	302.2	145.1	27.8

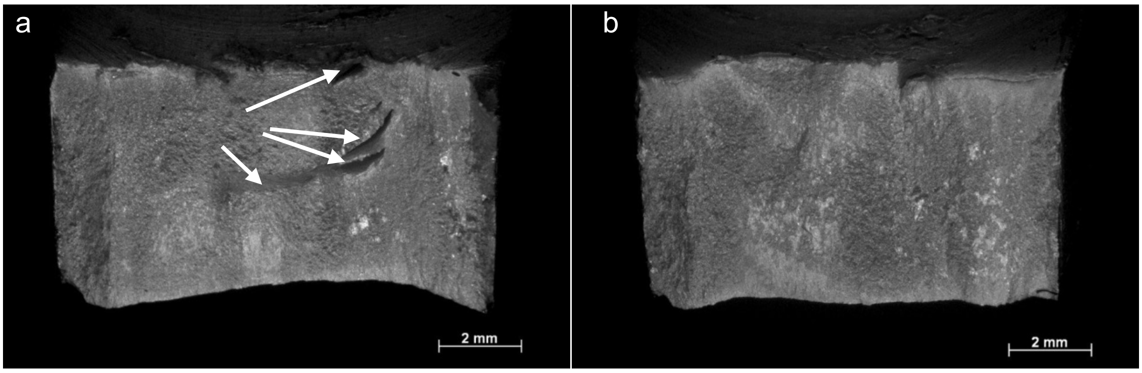

Fig. 7. Fracture surface appearance of tensile samples for welds made at 500rev/min and 1500mm/min, with a down force of (a) “W8” [52kN] and (b) “W9” [59kN].

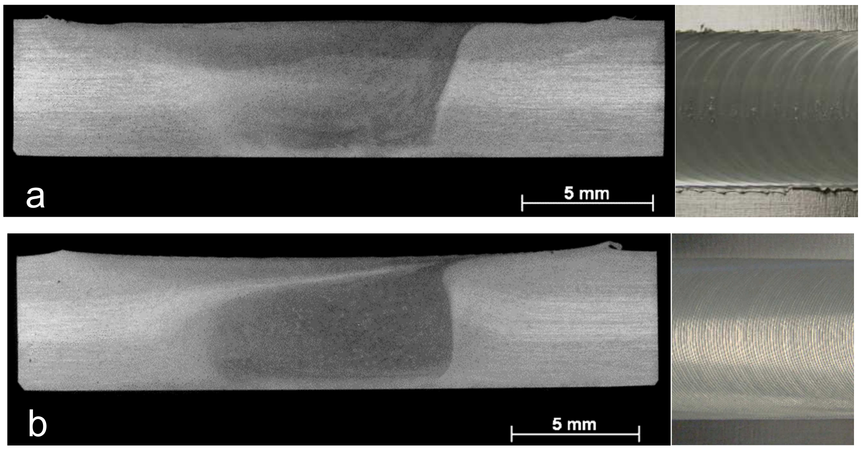

Fig. 8. Macrograph and surface appearance of the fast and slow welds, both made with a spindle speed of 500rev/min (a) “W9” [1500mm/min] (b) “W10” [200mm/min].

Fig. 8 presents the macrographs and surface appearance for the 1500mm/min weld (“W9”) and 200mm/min weld (“W10”). Both these weds were made at a spindle speed of 500rpm, however the down force was increased from 27kN for a feed rate of 200mm/min (“W10”), to 59kN to achieve adequate properties for a feed rate of 1500mm/min (“W9”). Irrespective of these vast differences in weld speed and down force, both welds had a fully consolidated stir zone and good surface appearance. It is well documented that a decrease in feed for a constant spindle speed reduces the peak temperature [12], and since both the fast and slow welds were made at 500rev/min, the pin temperature was reduced from 543°C (“W10”; weld pitch = 2.5rev/mm) to 505°C (“W9”; weld pitch = 0.3rev/mm). The cooler weld coupled with the increased material interaction resulting from the reduced weld pitch also resulted in an increase in down force, drag force and spindle torque. “W1” and “W2”, made at high feed rate as well as high weld pitch, resulted in pin temperatures of

574°C (weld pitch = 2.14rev/mm) and 566°C (weld pitch = 1.5rev/mm) respectively; which approaches the melting point of the material. “W3” and “W4”, both made with a spindle speed of 700rev/min and feed rates of 700mm/min (weld pitch = 1rev/mm) and 1000mm/min (weld pitch = 0.7rev/mm) respectively, resulted in peak temperatures of 549°C and 536°C. The two welds in which the pin temperature exceeded 560°C was not adequately plasticized, while all the welds with temperatures below 550°C displayed sufficient plasticization.

Conclusions

In this paper the process development for high feed rates in friction stir welded AA5182-H111 was discussed for a tool that was initially designed for low weld speeds. It was found that, in order to make a fast weld with a UTS and yield strength exceeding that of the parent material, the rotational speed of the tool was the same for a feed rate of 200mm/min as well as for 1500mm/min. The following conclusions can be deduced from this study:

The welds made at 1500rev/min (“W1”; 700mm/min and “W2”; 1000mm/min), which had a weld-pitch of 2.14 rev/mm and 1.5rev/mm respectively, did not contain a sufficiently plasticised stir zone; yet, at low feed rates of 200mm/min, a weld-pitch of 2.5rev/mm is adequate to form a weld. Reducing the weld pitch proved to be advantageous at high welding speeds, with a spindle of 500rev/min being sufficient to create a fully consolidated weld at a feed rate of 1500mm/min; equating to a weld-pitch of 0.3rev/mm. The nature of the plasticization in the stir zone may be related to the weld temperature, since the pin temperature in “W1” and “W2” exceeded 560°C, while those welds where the temperature was below 550°C (the lowest temperature measured in this study was 505°C) resulted in an adequately plasticized stir zone.

The all-weld longitudinal tensile sample comprising mostly of the dynamically recrystallized stir zone had a yield strength of 177MPa compared to 145MPa of the parent material, while the UTS was slightly increased from 302MPa to 316MPa. Creating a weld at 1500mm/min was achievable, however, it is associated with a large increase in all process forces. The down force on the tool was increased from 27kN (200mm/min) to 59kN (1500mm/min) in order to achieve a weld which displayed no evidence of pseudo bonds on the fracture surface of a longitudinal tensile sample, thereby achieving the maximum elongation. While a lower down force (52kN) may be adequate to consolidate the weld and achieve a UTS and yield strength exceeding that of the parent material, the oxide layer results in a “pseudo bond” which reduced elongation from 25.4% to 21.6%. The oxide layer seems to arise since the low weld pitch reduces the effectiveness of the flutes in dispersing the oxide layer from the original faying surfaces.

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