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Experimental investigation of longitudinal and transverse welds during sideways extrusion

To cite this article: X Lu *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1270** 012091

Experimental investigation of longitudinal and transverse welds during sideways extrusion

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Abstract. Differential velocity sideways extrusion (DVSE) is a novel process for fabricating curved profiles; welding quality during extrusion is an important issue for its industrial application. In this study, solid bars of aluminium alloy AA1070 were extruded from multiple billets at 500 °C using the novel process and the microstructure and mechanical properties of the extrudate were investigated. The weld formed between the billets includes longitudinal and transverse solid-state weld regions formed as the metal was extruded. The longitudinal welds have better mechanical properties than the transverse welds. Dynamic recrystallisation (DRX) occurred in areas with high dislocation density during the extrusion process and as a result, grains across the bonding interfaces of longitudinal welds have been formed, which improves the weld quality. In the areas with the transverse welds, macro weld defects can be observed at the weld front. With further progress of sideways extrusion, the defect density reduced and new grains formed at the bonding surface.
Keywords. differential velocity sideways extrusion; weld seam; welding quality; aluminium alloy

1. Introduction

Lightweighting for the reduction of energy consumption is one of the major issues facing industry today [1,2]. Aluminium alloys are some of the most widely used lightweight metallic structural materials with applications in the aerospace, automobile, shipping and chemical industries, thanks to their high strength-to-weight ratio and good corrosion resistance. Aluminium alloy profiles are attracting more and more attention today due to the urgent need for large-scale and complex cross-sections in many industrial applications. Extrusion is a commonly used method to form aluminium alloy profiles [3,4]. The shape, microstructure and mechanical properties of longitudinal and transverse welds are the key factors influencing the quality of aluminium alloy profiles. The transverse weld seam of extruded profiles produced using porthole dies usually has poor welding quality and mechanical properties [5]. Reggiani et al [6] predicted the shape evolution of transverse welds in extruded profiles using FEM simulations to predict the position of the transition zone and its extent in the profile and validated the simulation results experimentally. Lin et al [7] reported that with increasing extrusion temperature and ram speed, both the volume fraction of dynamical recrystallisation (DRX) and the dynamically recrystallised grain size increased. A physical simulation of a longitudinal seam weld in micro-channel tube extrusion showed that the higher the extrusion temperature, the better the quality of longitudinal seams [8]. Donati and Tomesani [9] found that although the weld seams had no unbonded macro-defects, they were still unsound due to the existence of micro-voids on the bonding interface.

Recently, a novel process, namely differential velocity sideways extrusion (DVSE) [10,11], was proposed for fabricating curved profiles; the welding quality during extrusion is an important issue for the industrial application of this process. The present study investigates the transverse and longitudinal

IOP Conf. Series: Materials Science and Engineering 1270 (2022) 012091 doi:10.1088/1757-899X/1270/1/012091

welds of profiles extruded using differential velocity sideways extrusion. The weld is characterised using optical microscopy (OM), electron backscatter diffraction (EBSD) and tensile testing, and the flow behaviour of deformed metal during sideways extrusion is analysed.

2. Experimental methods

The as-received material in the present study is a homogenised aluminium alloy AA1070 ingot. Its compositional specification is given in table 1. Cylindrical billets 40 mm in length and 12.5 mm in diameter were cut from the as-received ingot, and both ends of the billets were polished before extrusion to fit the die chamber dimensions. The average grain size *d* of the billet was determined to be ~500 μm and no significant texture was observed via EBSD.

Table.1 Composition specification for aluminium alloy AA1070.

Element	Al	Zn	V	Ti	Si	Mn	Mg	Fe	Cu
Content(wt.%)	≥99.7	≤0.04	≤0.05	≤0.03	≤0.2	≤0.03	≤0.03	≤0.25	≤0.04

Extrusion tests in this study were designed to extrude a solid profile containing both transverse (T-weld) and longitudinal (L-weld) welds. The novel energy-efficient DVSE forming procedure was employed in the study; with the opposing motion of upper and lower punches, the billets are extruded sideways together out of the exit. The extrusion tests were carried out using a 2500 kN Instron universal hydraulic press as the upper punch and a 500 kN Instron universal hydraulic press as the lower punch. Figure 1 shows schematically the tool set-up for this DVSE experiment. Four aluminium billets, each of which is 40 mm in length, were placed in the container for extrusion. The horizontal interface between Billets 2 and 3 was located at the same height as the centre of the exit. Before extrusion, the billets were heated to 500 °C and held at this temperature for 30 minutes. Following this, the upper and lower rams were moved to force the metal forward through the extrusion die exit. Both upper and lower ram velocities were set to 0.1 mm/s. The shape of the extruded profile is a solid cylinder of 10 mm in diameter.

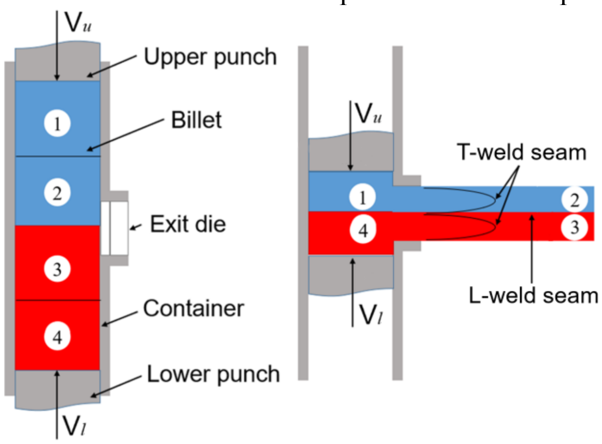


Figure 1. Schematic diagram showing the experimental set-up and the sideways extrusion process.

Sampling positions for microstructural examination and tensile testing are shown in figure 2. Subzones Z1 and Z2 are along the middle axis inside the die. Z3 is located at the longitudinal weld of the profile. Z4, Z5, and Z6 are at the beginning, middle, and end of the transverse weld of the profile, respectively. Three tensile test samples were cut from the profile in this study. T1 is close to the longitudinal weld zone and transverse weld seam; T2 is at the beginning of the transverse weld seam; T3 is the longitudinal weld zone. The uniaxial tensile tests were performed at room temperature at a fixed crosshead speed of 0.0067 mm s^{-1}.

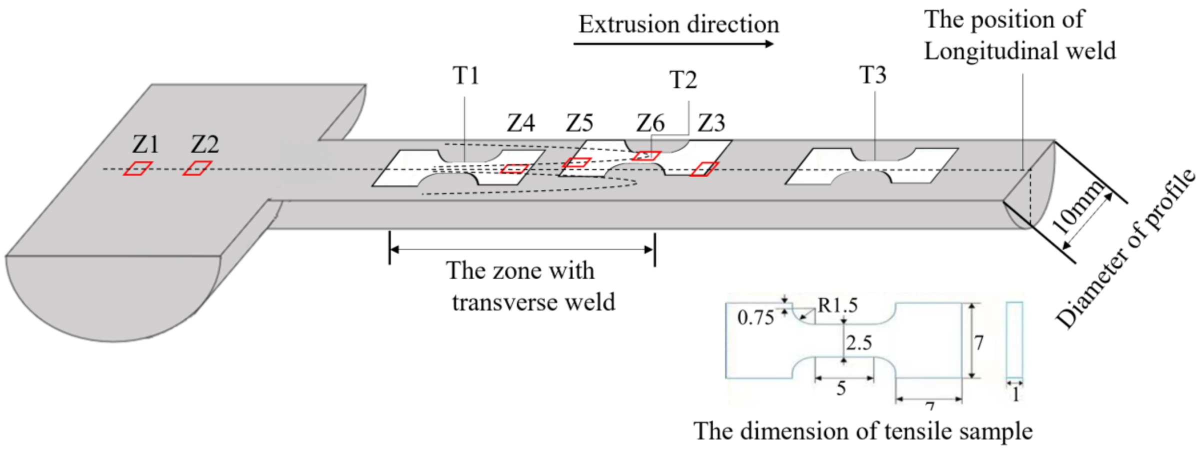
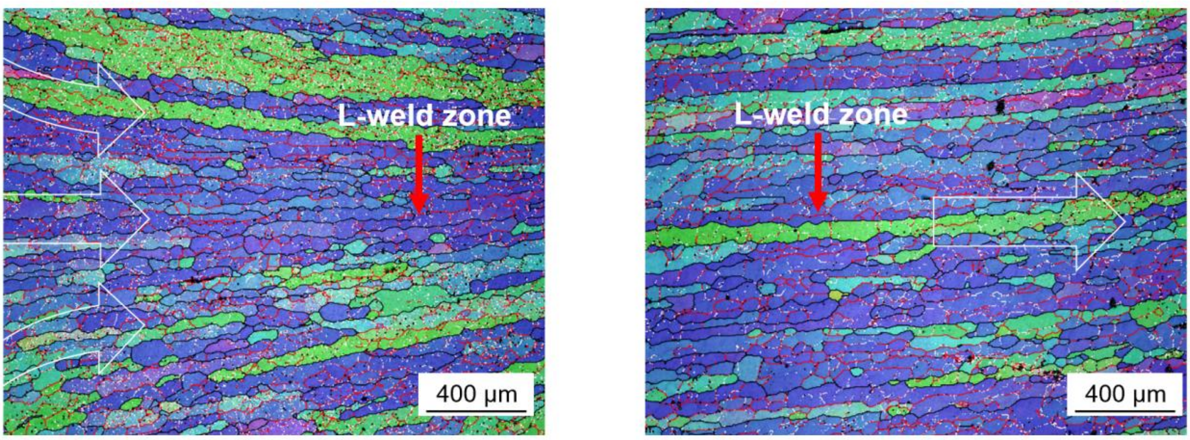


Figure 2. Sampling positions for microstructural examination and tensile testing. T1, T2, T3 are the specimens for the tensile tests, and Z1 to Z6 are subzones for microstructural examination.

3. Results and discussion

3.1. Welding in the container

The metal meeting at the centre of the container is subjected to a severe shearing action when it flows forward along the die exit, evidence of which can be seen in figure 3 in the form of directionality and preferred orientation in the microstructure. In this and figures 5 and 6, white lines represent low-angle grain boundaries (LAGBs) with $2° < \theta \leq 5°$, where θ is the misorientation angle, and red lines represent LAGBs with $5° < \theta \leq 15°$. Black lines indicate high-angle grain boundaries (HAGBs, $\theta > 15°$). The grains in subzone Z1 are elongated in the extrusion direction and this effect becomes more pronounced in Z2 where solid-state welding takes place. Long, strip-shaped grains can be seen along the welding line, and the grain boundaries appear serrated. Some serrated grains may be sheared off and transformed into similar size grains containing HAGBs; this behaviour is characteristic of geometric dynamic recrystallisation (GDRX). Some fine equiaxed grains are located on the boundaries of the large grains, indicating that continuous dynamic recrystallisation occurs during extrusion.



(a) (b)

Figure 3. Microstructure in subzones Z1 and Z2, showing grain boundaries: (a) Z1 and (b) Z2. The white arrows indicate the material flow direction.

3.2. Weld seam integrity

Transverse weld seams were formed between Billet 1 and Billet 2 as well as between Billet 3 and Billet 4 during extrusion. Figure 4 shows the typical microstructure of one of the transverse weld seams. This has an obvious bonding interface with grooves and holes clearly visible after etching. This means that there are impurities at the welding interface. Comparing the front (figure 4c) and the end (figure 4a) of the transverse weld seam, it can be seen that the density of welding defects on the transverse weld seam is reduced as extrusion progresses. In contrast to the transverse weld seam, the longitudinal weld zone has no visible defects, as can be seen in figure 4b.

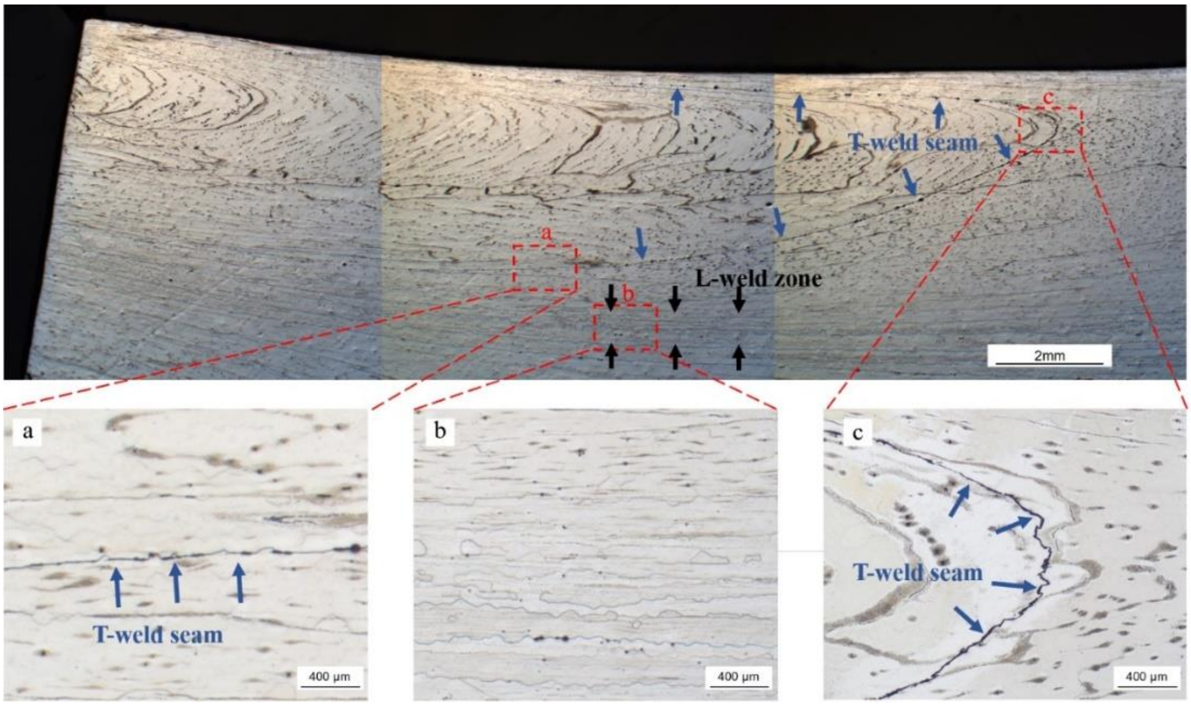


Figure 4. Morphologies observed by OM, showing the transverse weld seam after etching with Alpha Case reagent.

3.3. Grain microstructure of weld zones

Figure 5 shows the microstructure of the longitudinal weld in Z3. There are two kinds of morphology: elongated grains and small grains. Some grain boundaries are serrated and sheared off, indicating that geometric dynamic recrystallisation (GDRX) occurred during extrusion. Many substructures with LAGBs are formed in the interior of grains due to the occurrence of dynamic recovery during hot deformation and static recovery during subsequent cooling. Some large grains are divided into many small grains owing to DRX. New grain boundaries are often generated through the rotation of sub-grains due to large strains, and these grains are counted as DRX grains. The nucleation of these DRX grains in the AA1070 alloy is triggered by the high dislocation density accumulated during hot deformation; the strong shearing and deformation during extrusion cause many dislocations to quickly form clusters, allowing DRX to occur easily in the weld zone.

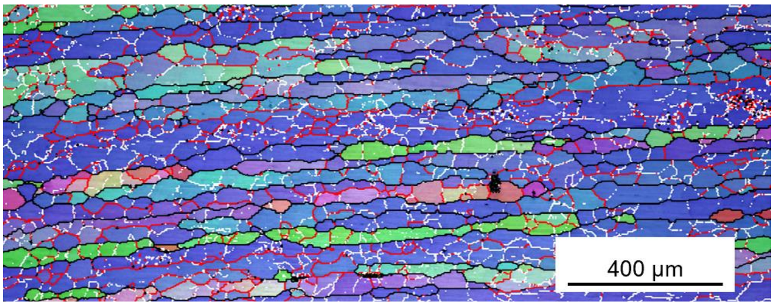


Figure 5. Grain boundaries in Z3.

Figure 6 shows the grain morphology and the distribution of low- and high-angle grain boundaries in the subzones Z4-Z6 along the transverse weld seam. In Z4, the transverse weld seam is almost parallel to the longitudinal weld zone. Z4 is around 10 mm back from the front of the 'tongue' (transverse weld seam). As shown in figure 6(a), the grains near the longitudinal weld zone formed between Billet 2 and Billet 3 are small, but the grains near the transverse weld seam formed between Billet 1 and Billet 2 are very large and elongated, especially those in Billet 1. Figure 6(b) shows the grains and bonding interface along the transverse weld seam. The bonding interface is clearly visible and separates the grains in the adjacent billets. The grains around the bonding interface are mostly very large, with a few fine recrystallised grains also present. The black features, consisting of points which the EBSD system fails to index as aluminium are voids, indicating an unsound weld. The 'tongue' of the transverse weld seam can be seen in figure 6(c); with some small new grains bounded by HAGBs present near the bonding interface. The holes and gaps are shown in black in figure 6(b) and (c) indicating that the welding quality of the transverse weld seam is very poor. By comparison with figure 6(a), it can be concluded that the bonding quality of the transverse welds is lower than that of the longitudinal weld.

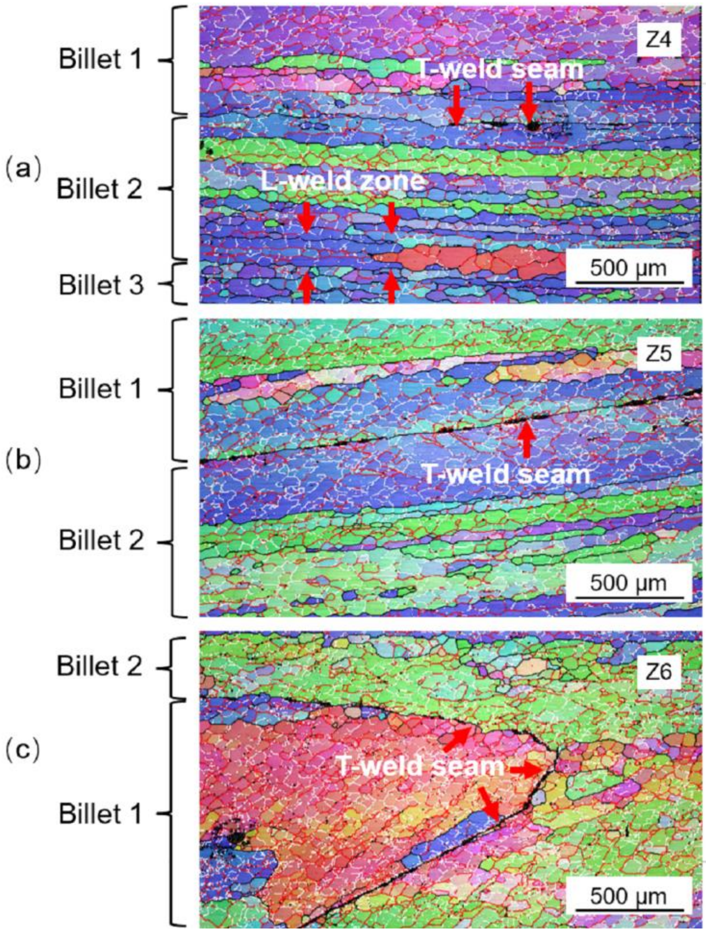


Figure 6. Grain boundaries in subzones: (a) Z4, (b) Z5 and (c) Z6.

3.4. Tensile properties

Table 2 shows the ultimate tensile strength (UTS) and total elongation to fracture (TE) of the specimens T1, T2, and T3. The specimen T2 has the lowest UTS, i.e., 53 MPa, and T1 and T3 have values of 61 and 80 MPa, respectively. The TE values of T1-T3 exhibit the same ranking as the UTS, with values of 64.2%, 48.4%, and 67.0%. The material at the front of the transverse weld (T2) has the lowest UTS and elongation, and the longitudinal weld (T3) has the highest UTS and elongation. The tensile test results from T2 indicate that the presence of the front of the transverse weld leads to a sharp decrease in the mechanical properties of the profile, and the material and bonding strength at the transverse weld is weaker than that at the longitudinal weld. The elongation at T1 is close to that at T3, indicating that the bonding quality of the transverse weld improves from the front to the end.

Table. 2 Ultimate tensile strength (UTS) and total elongation (TE) of T1-T3.

	Weld condition	UTS (MPa)	Elongation (%)
T1	T-weld seam (end)	61	64.2
T2	T-weld seam (front)	53	48.4
T3	L-weld	80	67.0

4. Summary

In this study, the microstructural variation and mechanical properties were studied for the longitudinal weld and different areas of the transverse weld of a profile manufactured using DVSE. Overall, the transverse weld had poor mechanical properties, especially at the front edge of the weld. Microstructural analysis showed that at these transverse welds, grains were not continuous across bonding interfaces, at which voids and gaps could be seen. However, with further extrusion processing, the degree of bonding at these interfaces increased, as evidenced by improved mechanical properties. By contrast, the longitudinal weld had a higher degree of recrystallisation during the extrusion process, and a continuous grain structure across the bonding interface could be seen, which leads to better mechanical properties.

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Acknowledgements

The strong support received from Beijing Institute of Aeronautical Materials (BIAM), China is gratefully acknowledged.