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A Physical Simulation Method for the Investigation of Weld Seam Formation during the Extrusion of Aluminum Alloys

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Extrusion through porthole die is a predominant forming process used in the production of hollow aluminum alloy profiles across the aluminum extrusion industry. Longitudinal weld seams formed during the process may negatively influence the quality of extruded profiles. It is therefore of great importance to understand the formation of weld seams inside the welding chamber during extrusion, as affected by extrusion process variables and die design. Previously developed physical simulation methods could not fully reproduce the thermomechanical conditions inside the welding chamber of porthole die. In this research, a novel physical simulation method for the investigation of weld seam formation during extrusion was developed. With a tailor-designed tooling set mounted on a universal testing machine, the effects of temperature, speed and strain on the weld seam quality of the 6063 alloy were investigated. The strains inside the welding chamber were found to be of paramount importance for the bonding of metal streams, accompanied by microstructural changes, i.e., recovery or recrystallization, depending on the local deformation condition. The method was shown to be able to provide guidelines for the design of porthole dies and choice of extrusion process variables, thereby reducing the scrap rate of aluminum extrusion operation.

Keywords: extrusion; aluminum; porthole die; weld seam; microstructure; physical simulation.

1 Introduction

Hot extrusion is a major forming process for aluminum alloys, during which a preheated billet in the container is compressed and then forced to flow through a die orifice that defines the geometry of the extruded profile. Hollow profiles are mostly extruded through porthole dies, bridge dies or spider dies with mandrels [1]. During the extrusion process to produce a hollow profile, a solid billet is forced to split into several metal streams and the latter become re-bonded in the welding chamber after flowing along the mandrel supports. Finally, the hollow profile with longitudinal weld seams are extruded through the die orifice. Pressure, strain rate and temperature are the main extrusion process parameters determining the quality of longitudinal weld seams [2]. Hollow profiles may suffer from premature fracture at or near longitudinal weld seams, especially under impact or cyclic loading conditions, when the combination of process parameters and die design is inadequate. Investigations into the effects of die design and process parameters on the weld seam quality are deemed important for avoiding non-compliance with extruded product specifications, e.g., ASTM B221–14.

To gain an improved understanding of weld seam formation inside the welding chamber during extrusion, as affected by extrusion process parameters and die design, numerical simulation would normally be considered to be a powerful tool. However, it is not really suitable for modeling the process involving bonding phenomena without invalid assumptions and simplifications. In other words, numerical simulation cannot serve the purpose of revealing the bonding of two metal streams during aluminum extrusion, although it can indeed reveal metal flow as affected by process parameters and die design [3]. In this case, physical simulation is the main experimental means to investigate weld seam formation during extrusion.

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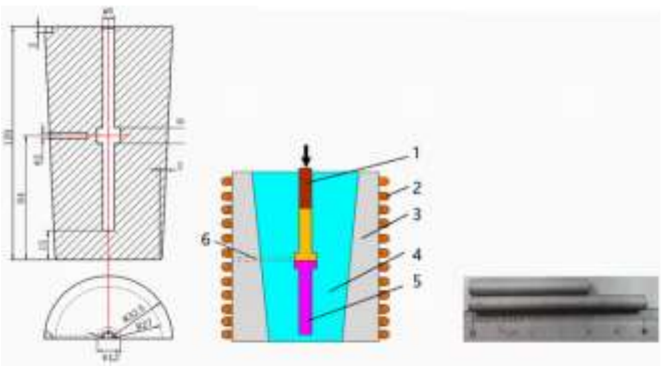

Fig. 1. Split die and its dimensions (a), cross section of the whole tooling set (b) (1 punch, 2 heating coil, 3 container, 4 die with a welding chamber, 5 billet, 6 thermocouple) and a two-half billet (c).

Edwards et al performed physical simulation to investigate the solid-state bonding of 6082 and 7020 aluminum alloys by pressing two bars face to face in a thermomechanical simulator [4-5]. Tang et al [6] used the same physical simulation method to study the solid-state bonding of another aluminum alloy 3003. In these investigations, deformation temperature and speed could be well controlled, but the local deformation condition at the contact interface was not exactly the same as that occurring inside the welding chamber where the billet material is deformed and bonded under high hydrostatic pressure. Bariani et al [7] developed another method of physical simulation with a prismatic specimen containing a steel pin and compressed the specimen in vacuum under a plane-strain condition so as to simulate the metal flow and bonding near the mandrel bridge inside the porthole die. With this method, the testing condition that the specimen was subjected to did not really represent the deformation and bonding conditions under hydrostatic confining pressure in real extrusion either. Khan et al [8] applied a special grid pattern technique to reveal the non-symmetric metal flow of the billet containing contrast material pins along the ports and welding chamber of a porthole die and showed the shifting of the weld seam after its formation while flowing through the die orifice. Donati et al [9, 10] designed special 'seam weld dies' to extrude I-shaped sections with a weld seam in the middle to facilitate subsequent mechanical testing. Den Bakker et al [11] investigated the flow-related defects in connection with different aluminum alloys and developed model dies for the investigation of weld seam formation during the extrusion of hollow profiles. With such model dies, however, the local thermomechanical condition occurring inside the welding chamber during extrusion could not be precisely set by varying extrusion process variables, i.e., billet temperature, extrusion ratio and extrusion speed. To gain a fundament understanding of solid-state bonding, Cooper et al [12] conducted a series of experiments of solid-state welding of aluminum alloys by stretching two aluminum strips and compressing them in the perpendicular direction in order to establish a basic relationship between deformation condition and weld strength. They found that a minimum strain was required for bonding. In their experiments, however, solid-state welding did not occur under hydrostatic confining pressure.

To achieve solid-state bonding under hydrostatic confining pressure, in this research, a novel physical simulation method was developed to reproduce the real thermomechanical condition occurring inside the welding chamber during aluminum extrusion. The main objective was to evaluate the effects of extrusion process parameters on the weld seam quality and ultimately to provide guidelines for the choice of extrusion process variables and improvement of die design.

2 Experimental details

2.1 Tailor-designed tooling set

To reproduce the deformation and bonding conditions under hydrostatic pressure resembling those inside the welding chamber during extrusion through porthole dies [7], a special welding chamber inside the die was designed, where two metal streams could be forced to join and flow in the radial direction. To allow the evaluation of the formed weld seam, the die could be longitudinally

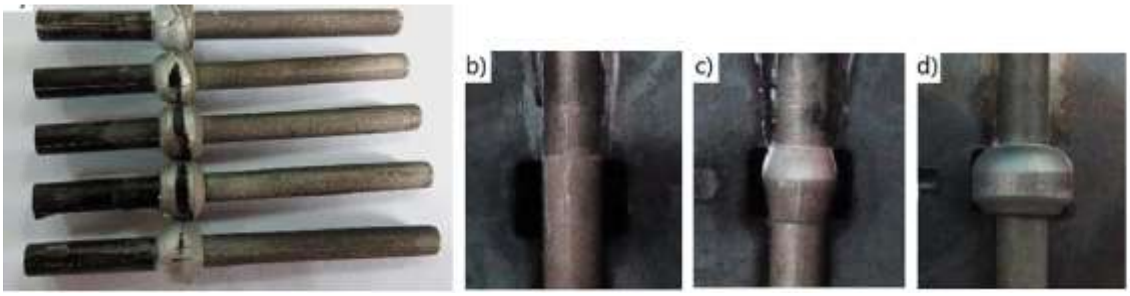

Fig. 2. Barreled samples (a) and deformation and bonding inside the welding chamber at punch displacements of 6 (b), 12 (c), and 24 mm (d)
(v = 0.8 mm/s; T = 440_C).

(a) (b)

Fig. 3. Fractured samples at punch displacements of (a) 24 mm and (b) 12 and 6 mm.

split into two halves. During the physical simulation experiment, they were clamped together by the container with a conical inner surface. When the experiment was completed, the split die was taken out of the container and separated into two halves and subsequently the bonded billet with a weld seam fell out the die. Fig. 1a illustrates the die with all the dimensions. The split die with a conical outer surface (a draft angle of 3°) was fitted into a container surrounded by heating coil with a power of 1500 W (Fig. 1b). A thermocouple was inserted into the die to measure and display real-time temperature. The measured temperature was fed into a closed-loop control system to maintain the pre-set temperature so as to ensure a stable temperature of the container and billet throughout the experiment.

2.2 Material

6063 aluminum alloy billets with a diameter of 6 mm were cut from extruded rods by means of wire electro discharge machining (WEDM). Every billet was composed of two halves. The lower half had a length of 60 mm and the upper half 40 mm (Fig. 1c), determined by means of finite element simulation in order to ensure the formation of the weld seam right in the middle of the welding chamber. Prior to the physical simulation experiments, the ends of the billet were ground to remove the oxide layer.

2.3 Physical simulation procedure

The tooling was mounted on a universal testing machine. The die and billet were heated to a pre-set temperature, followed by a holding time of 15 min. Another thermocouple was used to measure the temperature at the end of the upper half billet to ensure the attainment of the pre-set temperature. Three billet temperatures (namely, 400, 440 and 480 °C) and three punch speeds (namely, 0.2, 0.4 and 0.8 mm/s) were used in the experiments. During the experiment, the punch compressed the upper half billet inside the die and push it downwards, while the lower half billet was standing still. In other words, at a given moment, the upper and lower halves had dissimilar deformation states. Loads acting on the billet and varying with punch displacement were registered. After the experiment, the billet with a bonded weld seam was cooled and discharged from the split die. Then, pull tests of bonded billets were performed

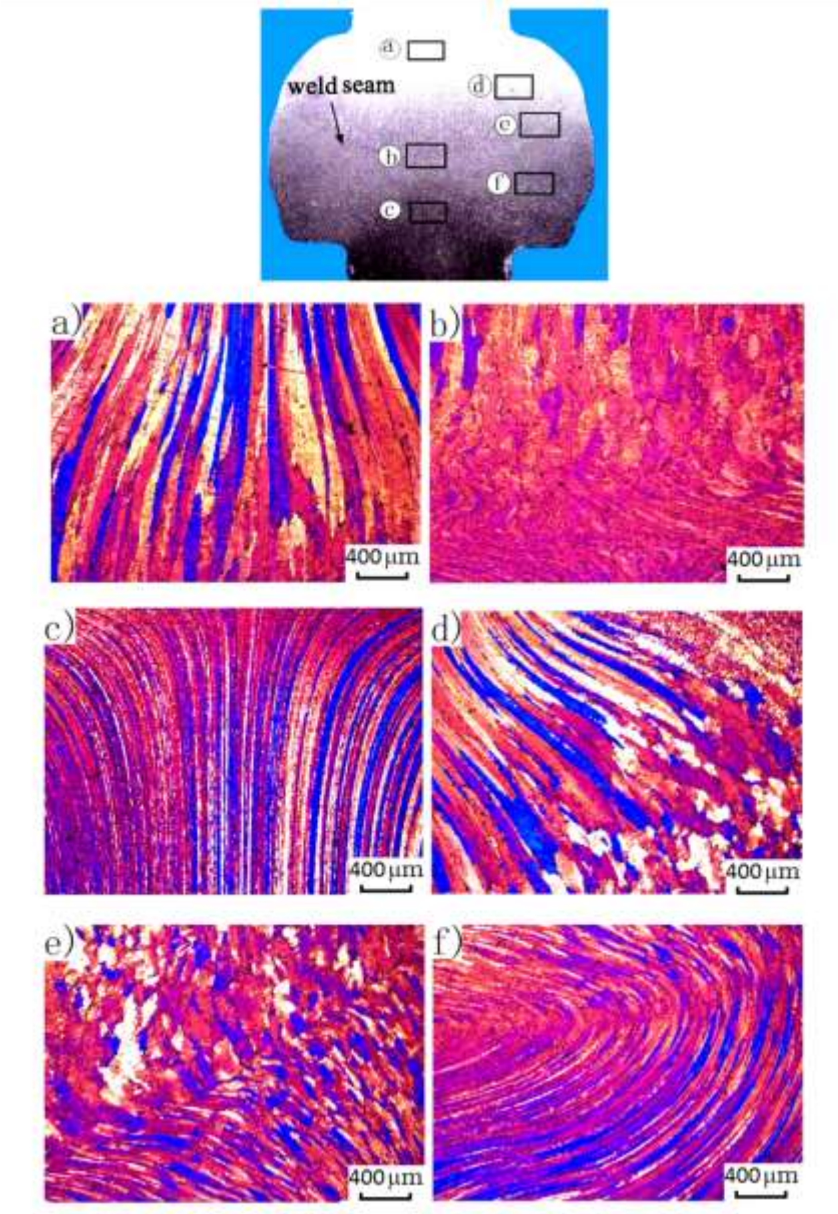

Fig. 4. Longitudinal section of the barreled region of a bonded billet (v = 0.8 mm/s, T = 480_C and punch displacement = 24 mm) and the
microstructures at spots (a)–(f).

and the microstructures around the weld seam were observed with a polarized light microscope. It is important to mention that the focus of the present study was placed on the physical simulation method and pull tests of welded samples, instead of tensile tests, were performed to simply the experiment procedure. If the tensile tests had been applied, the bulged welding area would have been machined off in order to obtain a uniform cross-section area of specimens.

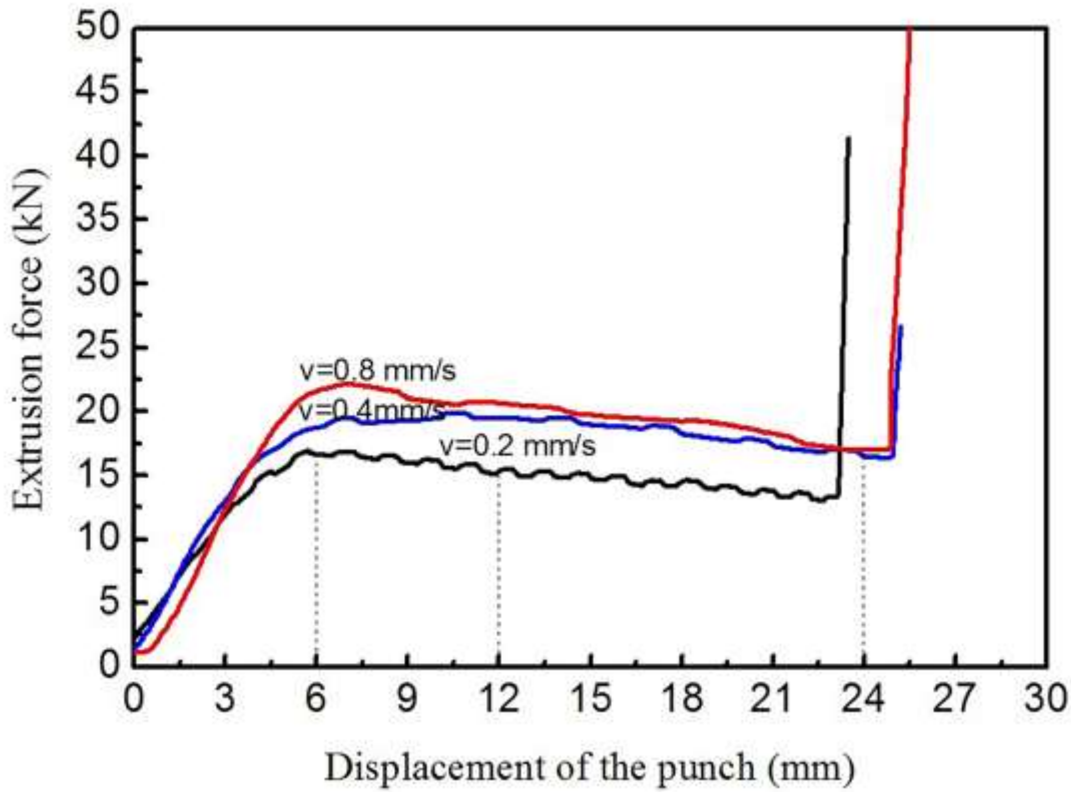

Fig. 5. Extrusion load variations with punch displacement at a temperature of 480_C and various punch speeds.

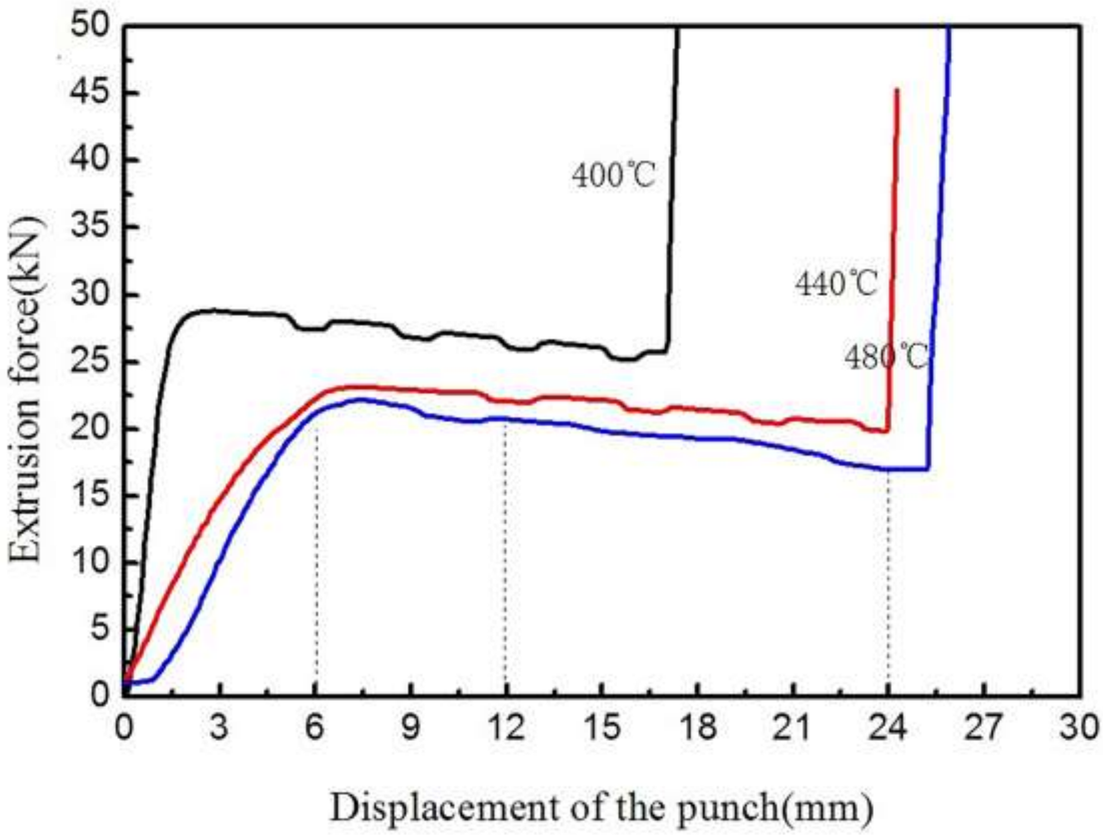

Fig. 6. Extrusion load variations with punch displacement at a punch speed of 0.8 mm/s and various temperatures.

3 Results and discussion

3.1 Deformation and bonding occurring during physical simulation

Fig. 2a shows that, with the tailor-designed tooling set, under compression, the billet became barreled around the weld seam. On the outer surface, no weld seam was visible to the naked eye. Fig. 2b-d shows the three stages of deformation and bonding inside the welding chamber along with punch displacement. At the initial stage of the experiment, the clearances between the billet and die cavity were filled and the billet was upset (Fig. 2b). Then, the billet around the contact interface became barreled and flowed radially to fill the welding chamber (Fig. 2c). Finally, at a punch displacement of 24 mm, the welding chamber was filled, while bonding took place under high hydrostatic pressure (Fig. 2d).

3.2 Fracture of bonded specimens during pull testing

When the punch displacement reached 24 mm, all the billets were well welded at 400 – 480 °C and 0.2 - 0.8 mm/s, as fracture during subsequent pull testing did not occur at or near the weld seam (Fig. 3a). However, at punch displacements of 6 and 12 mm, the samples went through 'kiss bonding' [2] only and fracture indeed occurred at or near the weld seam (Fig. 3b). Punch displacement corresponds to increasing strains inside the welding chamber. At a larger displacement, more material flows into the welding chamber and higher strains occur there. Numerical simulation by means of DEFORM-2D indicated the maximum effective strains of 0.32, 1.45 and 2.10 at punch displacements of 6, 12, and 24 mm, respectively. Thus, by using the present physical simulation method, a critical value of strain leading to sound solid-state bonding of a given aluminum alloy can be determined.

3.3 Microstructure changes during physical simulation

The barreled region of the bonded billet was split longitudinally to allow microstructural observation (Fig. 4). When the upper half billet was compressed, the flow of the material near the welding chamber walls was retarded due to friction at the die wall. Consequently, the material in the middle flowed radially faster than that near the ceiling and bottom of the welding chamber, resulting in a barreled shaped. A weld seam was discernible after the longitudinal section was etched. The weld seam exhibited a concave shape with its valley at the central axis and near the equator of the barreled region. Six representative spots were selected for microstructural analysis. At spots 'a' and 'c' on the central line of the barreled region, grains were elongated, showing a vertical flow pattern and a tendency towards the equator. The upper half billet had gone through severe deformation than the lower half billet and, as a result of high strains and strain rates, recrystallization and grain growth occurred. A similar observation was made by comparing the spots ‘d’ and ‘f’. At spot ‘d’, both elongated and newly recrystallized equiaxed grains were present. However, at spot ‘f’, the material flowed radially, leading to the formation of elongated grains. Recrystallization did not take place, indicating that local strains and strain rates in the lower half billet were insufficient to trigger recrystallization to take place. At spots ‘b’ and ‘e’ where the two halves were bonded, differences in grain size on the two sides of the weld seam could be seen, but the recrystallized grains at the interface were mingled. The weld seam at spot ‘e’ was more recognizable than at spot ‘b’, likely due to higher strains at the valley of the concave weld seam.

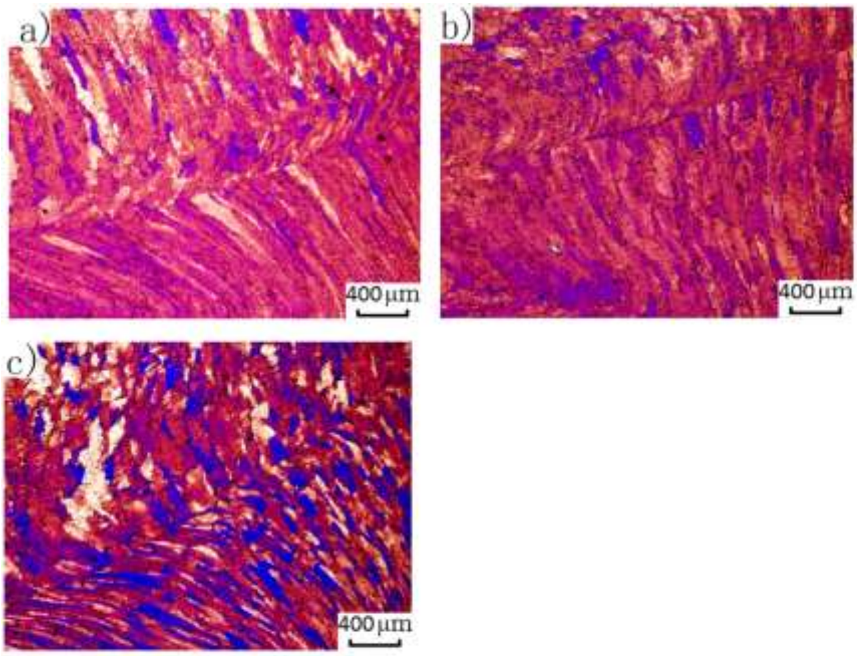

Fig. 7. Microstructures across the weld seams formed at a punch speed of 0.8 mm/s and temperatures of (a) 400, (b) 440, and (c) 480_C.

3.4 Solid-state bonding affected by deformation condition

The effects of deformation condition, namely temperature, strain and strain rate on the solid-state bonding are reflected in the load applied during the physical simulation. Load variations with punch displacement at different crosshead speeds are shown in

Fig. 5. At the first stage of the physical simulation experiment till a punch displacement of 6 mm, the billet was upset and the force rose quickly and reached a peak, when the clearances between the billet and the die were filled. Afterwards, the force descended slightly, when the material flowed into the vacant welding chamber. At the final stage when punch displacement reached 24 mm, the welding chamber was filled with the material and the two-half billet became solid-state bonded under increasing hydrostatic pressure along with a steep force increase. In other words, a steep increase in force is needed to reach large strains inside the welding chamber.

The force was affected by temperature and punch speed. Fig. 5 shows the punch displacement-force diagrams at 480 °C and 0.2, 0.4 and 0.8 mm/s. A higher punch speed resulted in a higher force. The effect of temperature on the force is shown in Fig. 6. The force decreased with increasing temperature, as the flow stress of the material decreased with rising temperature. At the lowest temperature of 400 °C and the lowest speed of 0.2 mm/s, punch displacement could not reach 24 mm for the billet material to fill the welding chamber completely. As a result of limited strains reached inside the welding chamber, bonding was weak, because the material was actually not subjected to high hydrostatic pressure inside the welding chamber.

It is thus clear that a large strain is fundamentally important for a sound weld seam (Fig. 2). Punch speed and temperature are important in ensuring sufficient plasticity of the billet to reach a critical strain.

3.5 Microstructure evolution affected by deformation condition

Fig. 7 shows the microstructures near the weld seams formed at different temperatures. At 400 °C, there were no obvious differences between the fibrous grain structure of the initial billet and the microstructure after the physical simulation experiment. The weld seam was easily recognizable and weak (Fig. 7a). With an increase in temperature to 440 °C, fine recrystallized grains appeared across

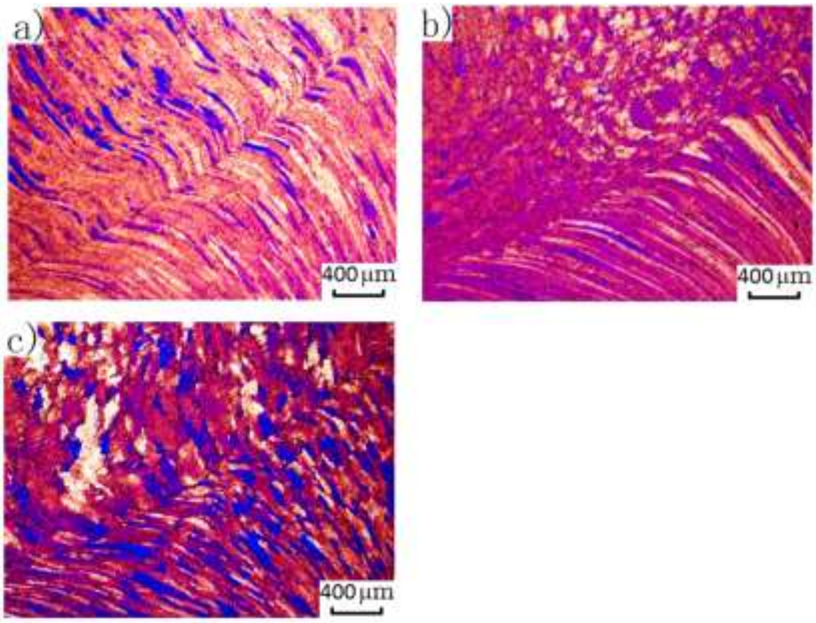

Fig. 8. Microstructures across the weld seams formed at a temperature of 480_C and punch speeds of (a) 0.2, (b) 0.4, and (c) 0.8 mm/s.

the vague weld seam (Fig. 7b). It indicates that recrystallization plays a critically important role in merging two metal streams and determining weld seam quality [2, 6, 7]. After the experiment at a temperature of 480 °C, recrystallized grains were present on both sides of the weld seam. It appeared that the upper half billet underwent recrystallization to a greater extent than the lower half billet (Fig. 7c).

The effect of punch speed on the microstructure across the weld seam is shown in Fig. 8. With an increase in punch speed, elongated grains in the billet showing the metal flow direction tended to vanish, while recrystallization occurred to an increasing extent. At a punch speed of 0.2 mm/s, the weld seam and flow lines (Fig. 8a) were still visible. Compared with the fibrous grain structure of the initial billet, the billet after the experiment showed no distinct changes. When the punch speed increased to 0.4 mm/s, however, flow lines in the upper half billet disappeared and recrystallization occurred

(Fig. 8b), while the lower half billet retained the fibrous grain structure. A higher punch speed of 0.8 mm/s promoted recrystallization across the weld seam so that the weld seam became hardly discernible and the two halves became well bonded (Fig. 8c).

4 Conclusions

A novel physical simulation method for the investigation of weld seam formation during extrusion into hollow profiles was developed. With this method, the weld seam quality of the 6063 aluminum alloy was evaluated. The pull tests of two-half billets welded at 400 – 480 °C and 0.2 - 0.8 mm/s confirmed sound weld seams that were achieved when a sufficient punch displacement was applied to allow the billet material to fill the welding chamber completely. Strain was found to be of fundamental importance for the weld seam quality. In combination with numerical simulation, a critical strain for each aluminum alloy could be determined. With decreasing temperature and increasing punch speed, the force needed for deformation and bonding increased. At a greater strain, temperature and speed, recrystallization occurred to a greater extent, being favorable for the formation of a stronger weld seam.

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Figure captions

Fig. 1 Split die and its dimensions (a), cross-section of the whole tooling set (b) (1. punch; 2. heating coil; 3. container; 4. die with a welding chamber; 5. billet; 6. thermocouple) and a two-half billet (c).

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Fig. 5 Extrusion load variations with punch displacement at a temperature of 480 °C and various punch speeds.

Fig. 6 Extrusion load variations with punch displacement at a punch speed of 0.8 mm/s and various temperatures.

Fig. 7 Microstructures across the weld seams formed at a punch speed of 0.8 mm/s and temperatures of (a) 400, (b) 440 and (c) 480 °C.

Fig. 8 Microstructures across the weld seams formed at a temperature of 480 °C and punch speeds of (a) 0.2, (b) 0.4 and (c) 0.8 mm/s.