

Feasibility study of a novel multi-container extrusion method for manufacturing wide aluminium profiles with low force

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ABSTRACT

Extrusion profiles are extensively used in industries and any improvement in the process could potentially have a large impact on energy and cost savings. In this study, a novel extrusion method, namely multi-container extrusion, was proposed for producing thin-walled wide aluminium components with low force. Its basic principle is to enable multiple billets to be welded and forced through die orifice simultaneously. To demonstrate its feasibility, a series of studies have been conducted including the experimental design and set-up of multi-container extrusion, microstructural and mechanical characterisations of the extruded components, and the comparison with the existing extrusion method. A three-container extrusion tooling was designed and manufactured to produce wide hollow profiles with plasticine and aluminium alloy AA6063. Optical microscopic observations and tensile tests were carried out for different positions of AA6063 extrudates. For the specimens near the extrudate front (8 mm and 23 mm away), tensile fractures occurred exactly along the distinct welds which were formed when individual billets met inside the die during extrusion. Further away from the extrudate front (83 mm, 98 mm and 113 mm), the welds were hardly observed, and the tensile fractures occurred outside the welds, indicating that good welding quality can be obtained in the multi-container extrusion process. Compared with the conventional porthole extrusion method, three-container extrusion could significantly reduce the required force to about 15 % for extruding the same profile. This study demonstrates that the proposed multi-container extrusion method can form wide profiles and greatly reduce the extrusion force requirement.

1. Introduction

Aluminium alloy profiles are widely required in automobile [1], aerospace [2], marine [3], and architecture [4] applications due to their high specific strength, good corrosion resistance, etc. The traditional assembly of separate parts is trending to be replaced by integral structures to minimise the jointing processes and improve the smoothness and reliability of products [5]. Wide, thin-walled aluminium components with complex and hollow cross-sections will play an increasingly important role for good product quality and energy saving due to the reduction of joints [6].

Wide aluminium profiles are formed usually using rolling or extrusion processes. Rolling is the most widely used forming method to produce large-sized aluminium flat plates and sheets, during which high rolling force must be applied. Reducing the thickness of an 1800 mm wide AA3003 ingot from 580 mm to 540 mm needs 8.11 MN of rolling force [7]; 20 % of thickness reduction from 6.27 mm for AA1100 requires 900 N/mm of rolling force per width [8]. In addition, multiple

rolling passes must be applied to fulfil the desired thickness reduction, e.g. at least 28 passes were conducted to form the thickness of an Al-Mg alloy ingot from 280 mm to 5 mm [9]. The ability of rolling is limited to simple cross-sections, such as plates and wires for solid profiles [10] and cylindrical parts for hollow profiles [11]. It is hard to apply the rolling method for producing hollow profiles with multiple complex-shaped cavities.

Extrusion is a popular method for producing wide aluminium profiles with complex cross-sections. Conventional extrusion technologies can be divided into two groups according to whether the extruded profiles are solid or hollow. The extrusion die classification for solid profiles includes flat-face die, pocket die and spread pocket die. The flat-face die is the most traditional design that contains openings matching the shape of extrudate exactly; while the pocket die contains a built-in cavity/pocket in the front of bearing land and the shape of the cavity/pocket can be straight or tapered [12,13]. Pocket die has been proven to be an effective way to balance metal flow, but it also increases extrusion force. A 40 mm wide AA6060 solid profile was extruded with 2.5 MN of extrusion load by using a flat-face die while around 3 MN by using a

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Nomenclature

D, D_p	container diameter and its specific values for porthole extrusion (mm)
F, F_3, F_p	extrusion force and its specific values for three-container extrusion and porthole extrusion, respectively (N)
h	height of upper die orifice, equal to the height of welding chamber (mm)
L_u, L_w, L_b	length of upper die and its specific value for welding chamber and bearing, respectively (mm)
L, L_p	container length and its specific values for porthole extrusion (mm)
P	extrusion pressure (MPa)
w	width of upper die orifice, equal to the width of welding chamber (mm)
Y_f	steady state flow stress (MPa)
λ, λ_p	extrusion ratio and its specific values for porthole extrusion
α	constant indicating the complexity extent of extrusion die, equal to 1.72 in this study
μ	friction coefficient, equal to 0.325 in this study

pocket die [14]. This high extrusion force requirement for the pocket die design is mainly due to the additional friction force in the pocket zone. Spread pocket die can reduce extrusion force and allows the material to be forced through a die opening that has a cross-section with a larger dimension than the diameter of an original billet [15]. Imamura et al. [16] fabricated the AA6063 sheet profiles with a cross-section of 80 mm $\times$ 2 mm and found that 1.9 MN of extrusion force was needed for flat-face die with a container diameter of 100 mm; while 26 % of load reduction can be achieved by using the spread pocket die with the container diameter of 60 mm. Flat-face die, pocket die and spread pocket die have been compared by Truong et al. [17] for extruding a complex and large-scale profile with a width of 240.35 mm and wall thickness from 2 mm to 5 mm. According to the research, the pocket die needed the highest extrusion force, and the spread pocket die needed the lowest, only about half of the extrusion force than the flat-face die.

For the extrusion of hollow profiles, traditional porthole die extrusion (referred to as porthole extrusion in the following text) is the most popular method in the industry [18]. Unlike the method of hybrid metal extrusion and bonding process (HYB) where material is first extruded and then welded [19,20], during porthole extrusion process a single billet is divided into multiple parts of materials and then welded and extruded simultaneously to form the extrudate with one or more cavities. Since a single container is used for porthole extrusion and the diameter of the container is larger than the dimensions of extrudate, extrusion ratios are usually very high for wide or thin-walled extrusions, resulting in extremely heavy extrusion load. For example, extruding an AA7003 billet with a diameter of 74 mm into a tube with an outer diameter of 16 mm and inner diameter of 12.6 mm at 400–460 °C needs an extrusion force of around 4.2–5.1 MN [21]. Similar to the difference between pocket die and spread pocket die, the spread porthole die can be designed for reducing the required force during the extrusion of hollow profiles. The trumpet flow area enables extruding wider profiles than the initial billet, leading to the lower force requirement than the porthole die due to its lower extrusion ratio [22]. For example, 65.25 MN of extrusion force was needed using a porthole die to extrude thin-walled wide hollow profiles of AA6005 with a width of 366.5 mm and height of 30.54 mm [23]; while by using a spread porthole die, with approximately the same extrusion force (61.69–66.35 MN), similar profiles with a larger width of 504.3 mm and height of 30.6 mm can be extruded [24].

Significant efforts have been made for the extrusion of wide aluminium profiles. Although the spread extrusion methods, i.e. spread pocket or spread porthole extrusion, can decrease extrusion force by 40 % than traditional flat die or porthole die to extrude the same profiles [25], the industrial production process still requires huge forming force and consumes much energy, resulting in environmental pollution and cost increase. For example, the fabrication of a 7N01 aluminium beam profile with a width of 203.9 mm used in high-speed trains requires a 44 MN extruding machine [26]; the fabrication of a 586.4 mm wide multi-cavity AA6005 aluminium profile for the floor of trains needs a huge 80 MN extruder [27]. It is generally agreed that reducing extrusion force for extruding wide aluminium profiles is an essential approach to reducing energy consumption and achieving carbon net-zero and lower cost [28,29]. The high energy consumption and the requirement of huge extrusion pressure owing to large extrusion force restrict the size of wide aluminium profiles that can be manufactured in the industry today. None of the extrusion methods can be used to produce thin-walled wide aluminium profiles with low force in efficient mass-production yet due to their intrinsic drawbacks.

Porthole extrusion is the most commonly used method to fabricate profiles with hollow sections, but the drawbacks of this extrusion process are a short lifespan of the porthole die and a susceptibility to cracking [30]. To overcome those drawbacks, multi-billet extrusion (MBE) was proposed by Murakami's team, where multiple billets are employed in place of the partitioning process of the billet during the porthole extrusion [31]. Various pipes of pure lead, pure copper, aluminium alloy AA7475 and AA1050/AA2014 composite, with diameters of about 20 mm, were fabricated with MBE where four billets were arranged in a circle and pressed together [30]. However, there is limited deep analysis of extrusion force for MBE, and the researchers focused more on the fabrication of multi-layer profiles by using MBE, where the multiple billets of different materials, such as aluminium and magnesium alloys, were together pressed to form the different layers. Madej et al. [32] fabricated the AA4343/AA1050 by-layered tubes with MBE method and investigated the geometrical defects and welding quality of the extrudate. Chen et al. [33] and Fan et al. [34] conducted MBE tests to fabricate the Al/Mg/Al and AA1060/AA6063 composite laminates respectively with the same cross-section of 18 mm $\times$ 5 mm to investigate the effect of die structures on the material welding quality. In addition, a variant of MBE called powder MBE was developed, where different kinds of particulate pastes were consolidated and then co-extruded into composite pipes with a diameter of about 15 mm [35–38] or into sheet profiles with a width of 10 mm and thickness of 1.8 mm [39]. These extruded profiles by powder MBE also consisted of multiple layers but the material for each layer was made of consolidated composite instead of a single material. The main application of MBE is the fabrication of small-scale multi-layer pipes/wires of which the cross-sectional diameter is less than 30 mm, and the configuration of the multiple billets is arranged in a circle. The secondary application of MBE is to fabricate the multi-layer laminates by extruding the multiple billets arranged along the direction of extrudate thickness. The research focuses are the effects of MBE die structure and extrusion conditions on microstructural and the mechanical properties of the extruded profile. For the powder MBE, researchers mostly consider the material extrudability varying with the powder compositions and its effects on the physical and mechanical properties of the final extrudate. To the authors' knowledge, no research has been reported to enable the extrusion of large-sized wide profiles by using MBE to greatly reduce the extrusion force.

The present research focuses on how to drastically reduce the extrusion force for manufacturing wide extrusions. A multi-container extrusion method is proposed to produce wide aluminium profiles with a hollow section, where the containers are arranged in a row along the extrudate width. The main aim of the research is to investigate the feasibility of the proposed method and examine the welding quality between materials coming out from the different extrusion containers through a series of experiments. A three-container extrusion die set was

designed and manufactured. Extrusion experiments were conducted using plasticine to study the material flow and AA6063 to study the welding quality of the extrudate and extrusion force. Microstructural observations and uniaxial tensile tests were conducted to characterise the welding quality and mechanical properties. The extrusion force of the porthole extrusion to extrude the same profile was estimated and compared with the proposed multi-container extrusion technology.

2. Multi-container extrusion method and test set-up

2.1. Multi-container extrusion method

Fig. 1 shows a schematic of the proposed multi-container extrusion system and method. The system is composed of three components: container block, upper die, and lower die. The key feature is that there are multiple containers arranged in parallel in the container block to insert billets, and each billet has a corresponding separate material flow path in the upper die. All billets are extruded simultaneously through the upper die, welded in the welding chamber of the lower die, and finally form the desired profile. This system and method are expected to reduce the extrusion ratio and required force as well as favour the balance of material flow during extrusion especially for thin-walled wide components.

2.2. Materials and profiles to be extruded

Two materials were used in this study, of which the first was plasticine. Extrusion was conducted by using different colours of plasticine for different containers so that the material flows from different billets can be distinguished easily. The aluminium material used for the subsequent extrusion was AA6063. Its chemical compositions are listed in Table 1. The as-received 6063 bar billets, with the dimension of $\Phi 38$ mm $\times$ 195 mm, were homogenised at 530 °C for 12 h and then cooled in a furnace before extrusion. The target extrudate is a 177 mm $\times$ 8 mm hollow profile with a flat upper plate and curved lower plate, as shown in Fig. 2. The distance between the upper and lower plates varies from 5.5 mm in the middle to 8 mm on the sides. Two reinforcing ribs are located across the upper and lower plates with a distance of 50 mm at

Table 1
Composition specification of AA6063.

Element	Al	Mg	Si	Fe	Zn	Cu	Mn	Cr	Ti
Content (wt%)	Bal.	0.8	0.5	0.35	0.2	0.1	0.1	0.1	0.1

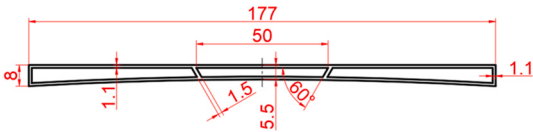


Fig. 2. Geometry of cross-sectional profile of the extrudate (in mm).

the upper plate and an inclination of 60°. The wall thickness of the profile frame and the ribs are 1.1 mm and 1.5 mm, respectively. The cross-sectional area of the extrudate is 423 mm².

2.3. Three-container extrusion die set

To demonstrate the feasibility of the multi-container extrusion method, a three-container extrusion die set was designed, as shown in Fig. 3, of which (a) shows the sectional views of the designed dies and the billets, (b) shows the manufactured extrusion die set, and (c) shows details of the upper die and the lower die. The container block has three

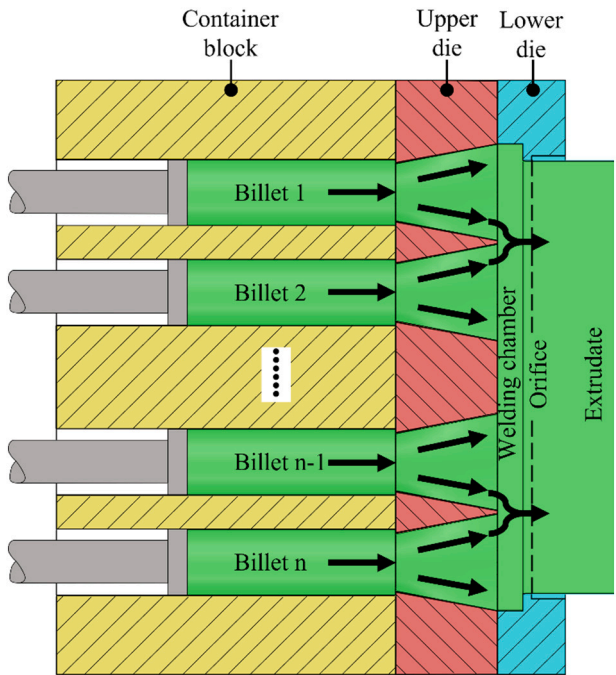


Fig. 1. Illustration of multi-container extrusion method.

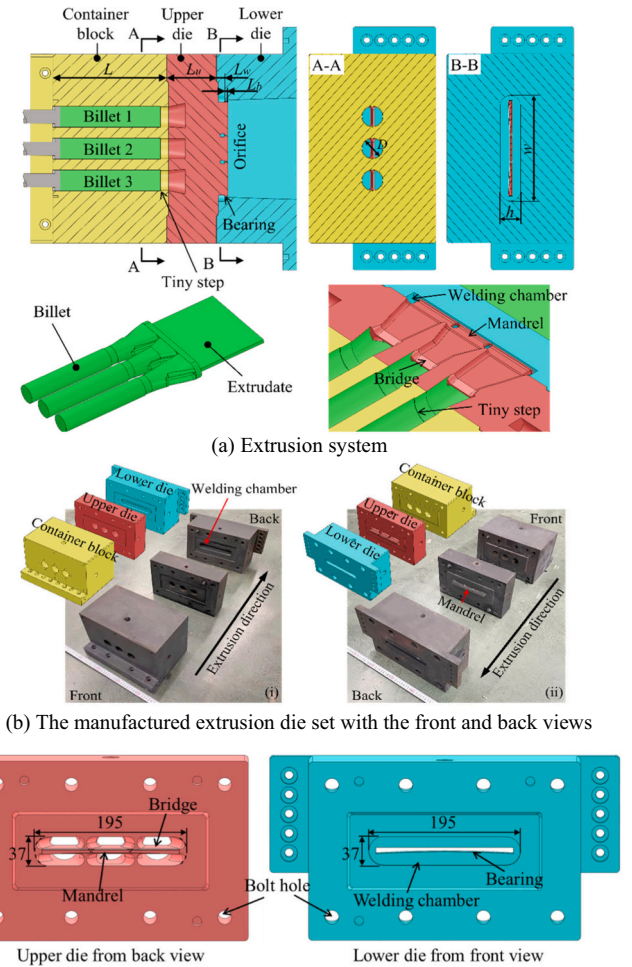


Fig. 3. The three-container extrusion system consisting of a container block with three extrusion containers, an upper die and a lower die.

$L=200$ mm long containers with a diameter of $D=39$ mm, so the extrusion ratio λ can be calculated as 8.5. The gap between each container is 20 mm. Tiny steps are positioned at the end of containers with a depth of 1 mm so that oxidised and contaminated surface layers can be stripped from the billets before the material enters the upper die. The upper die is designed to deform material wider and thinner gradually along the extrusion direction of $L_u = 90$ mm, according to the demand of extruding a thin-walled wide hollow profile. The orifice shape of the upper die is a rounded rectangle with the dimension of $w \times h = 195 \times 37$ mm. A mandrel is fixed on the inner wall of the upper die and extends into the welding chamber, i.e. the entrance part of the lower die, to form hollow cross-sections. In the $L_w = 12$ mm long welding chamber, materials from individual billets are welded together, and then go through the die bearing to form the final desired profile. The bearing length L_b is mostly 3 mm, while shorter (2 mm) near the reinforcing ribs to offset the higher friction resistance. The key geometries are listed in Table 2. The container block, upper die and lower die are all made with 50HRC H13 tool steel and assembled by high strength bolts (Grade 12.9).

2.4. Three-container extrusion assembly

In addition to the die set, supporting facilities including hydraulic press, stem, and heating system were also essential. As shown in Fig. 4, a horizontal hydraulic press with a load capacity of 3 MN, was used to push stems to move forward. Three stems were attached to the round plate of the hydraulic press by a stem supporter. With the adjustable bolts, this supporter can slightly reposition the stems to align with the containers. After installing stems and dies on the hydraulic press, heaters were assembled around the dies. The heaters included ceramic blocks, embedded heating wires, and thermal insulation mica plates, etc. Type-K thermocouples were embedded inside the dies for monitoring temperature in real time during extrusion.

3. Extrusion test and subsequent characterisation

3.1. Extrusion of plasticine

To determine the welds positions on the extruded profile, the first test was conducted using three plasticine bars with different colours, as shown in the upper image of Fig. 5. The test was conducted at room temperature with an extrusion speed of 0.5 mm/s with no lubricant. The cross-section of the die orifice in the lower image of Fig. 5 shows that the middle billet (yellow) formed the extrudate's middle part including two reinforcing ribs. The yellow material met the blue plasticine to form welds 1 and 3 on the left side of the ribs, and met the red one to form welds 2 and 4 on the right side.

3.2. Extrusion of AA6063

The extrusion experiments of AA6063 were undertaken without lubrication under five different sets of conditions which combine three temperatures and three extrusion speeds, i.e. 450 °C/0.5 mm/s, 480 °C/0.5 mm/s, 480 °C/1 mm/s, 480 °C/2 mm/s and 510 °C/0.5 mm/s. Before the extrusion test, the die set was heated to the desired extrusion temperature within about 4.5 h and then held at the temperature for 1 h. The billets were heated in a muffle furnace from room temperature to

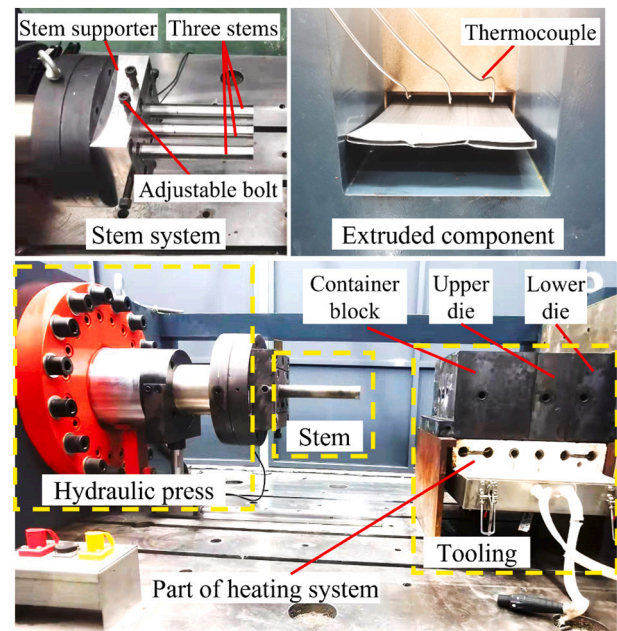


Fig. 4. Overall experimental set-up.

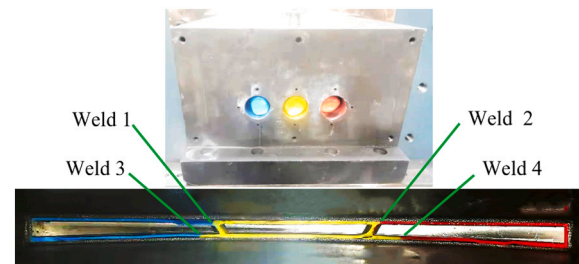


Fig. 5. Extrusion test using different colours of plasticine showing weld positions, where the upper image shows billets in the extrusion containers and the lower shows the cross-section of extruded profile. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

the extrusion temperature within 1 h and then held for 1 h. During each extrusion, three billets were simultaneously pushed forward by 185 mm to produce a 750 mm long extrudate profile, followed by air cooling and cutting.

3.3. Tensile test and microstructure observation

According to the design of the three-container extrusion die set, the schematic of metal flow and welds formation during extrusion is illustrated in Fig. 6. Three separate billets are pushed forward along the extrusion direction and deformed wider when passing through the upper die; the materials of the three billets then become contacted and welded in the welding chamber of the lower die, leading to the formation of welding planes; finally, the entire welded material is extruded with the

Table 2

Key dimensions of extrusion die sets.

Unit: mm	Container		Upper die		Lower die	
	Diameter D	Length L	Orifice cross-section $w \times h$	Length L_u	Welding length L_w	bearing length L_b
Three-container	39	200	195×37	90	12	2–3
Porthole	200	400	195×80	100	12	2–3

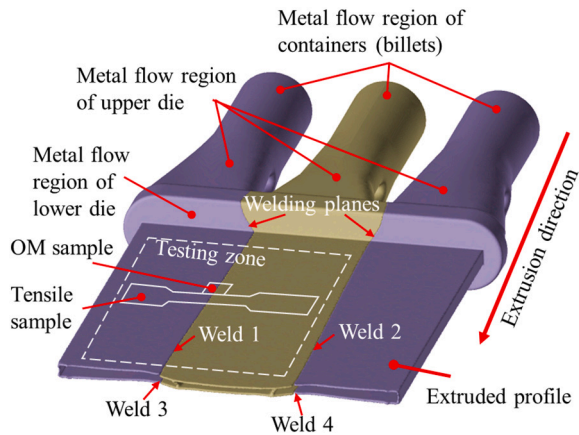


Fig. 6. Schematic of metal flow and weld formation during three-container extrusion process.

four welds. For evaluating the bonding quality of the extruded profile, tensile test and microstructural observation were conducted in the testing zone, where weld 1 is approximately located in the middle of samples.

Based on the analysis of Fig. 6, for each extrusion condition the upper plate of extruded profile as shown in Fig. 7(c) was cut and machined for further characterisation. Five tensile specimens with dog bone shape were cut at locations with different distances from the extrudate front, as shown in Fig. 7(a). Samples T1 and T2 were near the front end with 8 mm and 23 mm, respectively; while T3, T4 and T5 were further away from the extrudate front with 83 mm, 98 mm and 113 mm, respectively. The gaps between T1 and T2 and between T3 and T4 were both 5 mm. According to the measured weld positions of the plasticine extrudate, the centreline of the specimens was set as 59 mm away from the right-hand side of the extrudate. In this case, the weld 1 in Fig. 5 is positioned approximately at the centre of the tensile specimen, as indicated by the dash dot line in Fig. 7(a). Fig. 7(b) gives the detailed dimensions of the tensile specimen according to the ASTM-E8 standard [40]. The uniaxial tension tests were carried out at room temperature with a tensile speed of 1 mm/min, equivalent to a strain rate of around 0.00052 s^{-1} on an Instron testing machine. In addition, three repetitive tensile tests for the as-received billet were also conducted under the same testing conditions for comparison.

Microstructural examinations were carried out to confirm the position of welds and to investigate whether the welds still exist after steady extrusion. Four $32 \text{ mm} \times 9 \text{ mm}$ rectangular parts, namely M1 - M4, were cut between the tensile specimens for microstructural observation. The cross-sectional areas in the front side, indicated by the red solid lines, were grounded, polished and then etched in the solution of 1 ml HF, 1.5 ml HCl, 2.5 ml HNO_3 , and 95 ml H_2O , followed by microstructural observation using optical microscopy (OM). For ease of expression, both tensile and OM specimens will be identified by the distance between the red solid line and the front end in Fig. 7(a), i.e. 8 mm, 23 mm, 83 mm, 98 mm and 113 mm for T1/M1, T2/M2, T3/M3, T4/M4, and T5, respectively.

4. Experimental results and discussion

4.1. Profile extrudate

The front part (200 mm in length) of the extruded AA6063 profile under $450^\circ\text{C}/0.5 \text{ mm/s}$ is shown in Fig. 7(c). The frontmost part of the extrudate is slightly curved because of the unsteady stress state at the beginning, which is normal in an extrusion process. Beyond that, the entire profile is flat and straight, and the cross-section shows the same shape and dimensions as desired in Fig. 2. All other extruded profiles showed similar geometric features and no obvious difference in the extrudate dimensions and surface quality was detected among different extrusion conditions. This result suggests that the proposed multi-container extrusion method is feasible to produce wide components from multiple small billets.

4.2. Extrusion force

The evolutions of the applied forces (the total force of the three stems) with the stem stroke distance during extrusion tests are summarised in Fig. 8. It can be divided into five stages. In the beginning, the stems move forward from the entrance and the extrusion force increases to break through the bridge. Then, the material gradually flows forward in the cavity of upper and lower dies until being obstructed by the bottom of the welding chamber. The material subsequently fills the cavity of the welding chamber during which the extrusion force increases gradually. Once the material fills fully the welding chamber, it starts to break through the die bearing, resulting a significantly rapid force increase up to the maximum value. Finally, the material flows

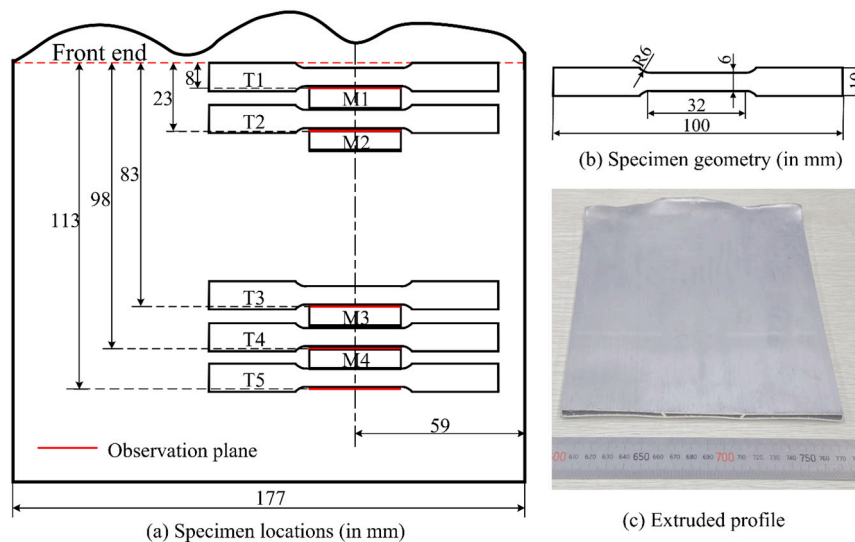


Fig. 7. Illustration of positions of the specimens taken from the top plate of the extruded component for tensile testing (T1 to T5) and microstructure examinations (M1 to M4).

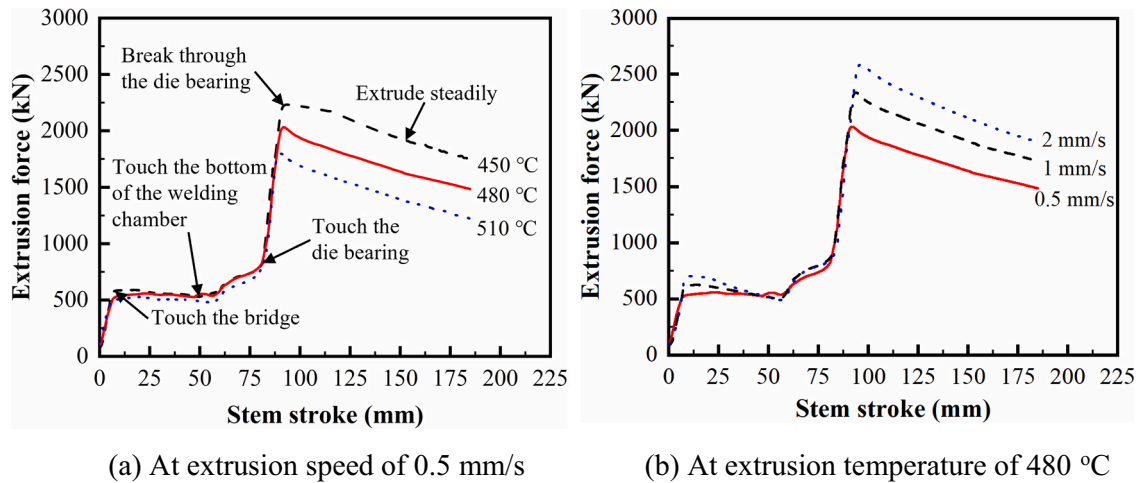


Fig. 8. Comparison of experimental extrusion force variations under different extrusion temperatures and speeds.

through the bearing and starts to be extruded into the desired profile, during which the extrusion force decreases gradually due to the decreasing friction between the billet and the inner walls of the container. The maximum forces recorded are 2224 kN, 2032 kN, 2336 kN, 2589 kN and 1800 kN for the extrusion condition of 450 °C/0.5 mm/s, 480 °C/0.5 mm/s, 480 °C/1 mm/s, 480 °C/2 mm/s and 510 °C/0.5 mm/s, respectively.

4.3. Microstructure

Fig. 9 shows the cross-sectional morphologies of the weld 1 at different distances from the extrudate front shown in Fig. 7(a) for the extrusion conditions of 450 °C/0.5 mm/s and 480 °C/1 mm/s respectively in the left and right columns. A continuous crack can be seen along the welds 8 mm away from the front end of the extrudate. The 23 mm welds appear less distinct than the previous one although a pore is

observed along the weld of the extrudate for 450 °C/0.5 mm/s condition. As the distance increases to 83 mm, parts of the welds are hardly seen anymore while other parts still show shallow marks. Finally, the whole welds disappear at the distance of 98 mm. The microstructural observations for the other three extrusion conditions show similar results. In addition, OM observations of the other three welds were also conducted and similar results have been obtained, i.e. along the extrusion direction, the welds become less distinct gradually and finally disappear within about 100 mm from the extrudate front. This evolution happened because the headmost material can flow easily in the empty die with little deformation, leading to insufficient compressed stress for good welding in the welding chamber. With the material continuously being extruded, the pressure in the welding chamber increases, which creates a better condition for welding, and hence causes the weld to fade away.

The experimental results of some researchers have shown that OM is an effective way for evaluating the bonding quality of the welds. For example, Yu et al. [41] compared three OM observations of the Al-Mg-Si porthole extruded profiles, and found that welds becoming less distinct means the improvement of bonding quality and the disappearance of welds indicates that good bonding quality is attained. By observing the optical microstructures of the AA6061 specimens produced by different cycles of accumulative roll-bonding, Lee et al. [42] concluded that good bonding can be attained for all the tested products since no clear bonding interfaces were observed. Chiba et al. [43] also used OM to judge the welding quality of the profiles extruded from recycled aluminium chips, and clearly showed that the product where no bonding interfaces were found under OM has good welding quality. In the present study, the evolution of welds from getting less distinct to finally disappeared as shown in Fig. 9 proves that although welding must happen between the adjacent billets in the extrusion process, materials can be welded very well except for the beginning part. In addition, these OM observations show the detailed locations of welds in the tensile specimens T1–T5 shown in Fig. 7(a).

4.4. Mechanical properties

To study the effect of weld on the mechanical property of the extrudate, uniaxial tensile tests were conducted. Fig. 10 shows the pictures of the fractured specimens from the profile extruded at 450 °C with the extrusion speed of 0.5 mm/s. The numbers on the left sides of the specimens in Fig. 10(a) represent the corresponding distances from the extrudate front shown in Fig. 7. The black dash lines indicate the welds positions which were determined by the microstructural observation of M1–M4. Since no welds can be found at M4, the hypothetical welds

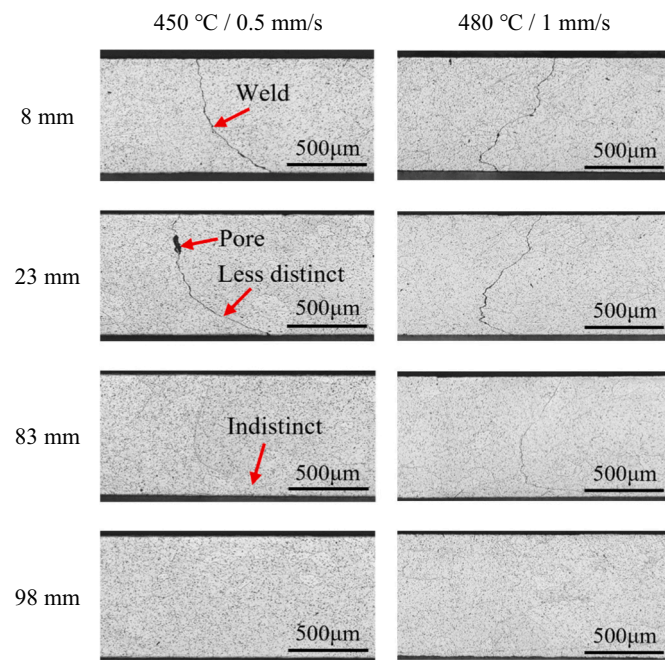


Fig. 9. Micrographs showing the extrusion weld-seam variation at different positions of the extrudates extruded under 450 °C/0.5 mm/s and 480 °C/1 mm/s, respectively. The samples are taken from 8 mm to 98 mm from the front end of the extrudates, showing the gradual disappearance of weld seams.

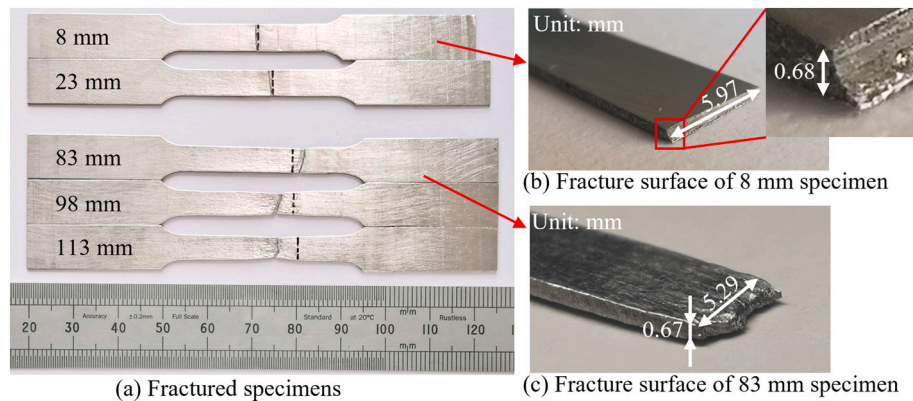


Fig. 10. Tensile tested specimens showing that the fracture occurred at the weld (8 mm & 23 mm) and away from the weld (83 mm, 98 mm & 113 mm). The black dash lines in (a) indicate the positions of welds.

positions for 98 mm and 113 mm were estimated the same as the 83 mm specimen. The 8 mm and 23 mm specimens were fractured exactly at the welds. As shown in Fig. 10(b), the fracture surface was in a very similar shape to the weld in Fig. 9, indicating that the welding quality at 8 mm and 23 mm is poor. However, other specimens (83 mm, 98 mm, and 113 mm) were fractured randomly away from welds with obvious necking phenomena, as shown in Fig. 10(c), indicating the welding quality is significantly improved.

The engineering stress and strain curves for tensile specimens from different extrusion conditions are shown and compared with the original billets in Figs. 11 and 12. For all extrusion conditions, fractures happened on the 8 mm specimens with very low stress and strain. The 23 mm specimens were stretched longer but still broke suddenly with relatively low strain. The 83 mm, 98 mm and 113 mm specimens all fractured in the matrix instead of the welds and performed similarly with high stress and strain, indicating that steady extrusion has formed from 83 mm. For the steady extrusion beyond 83 mm, the tensile properties vary with different extrusion temperatures and speeds and all the extrudates show higher strength and lower ductility compared with the original billet, due to different levels of recrystallisation and precipitation hardening [44–46]. Comparing to the original billet, the ultimate tensile strength of the profiles extruded at 450–510 °C (extrusion speed of 0.5 mm/s) and at the extrusion speed of 0.5–2 mm/s (480 °C) increases by 53 %–124 % and the elongation of the extrudates decreases by 18 %–39 %.

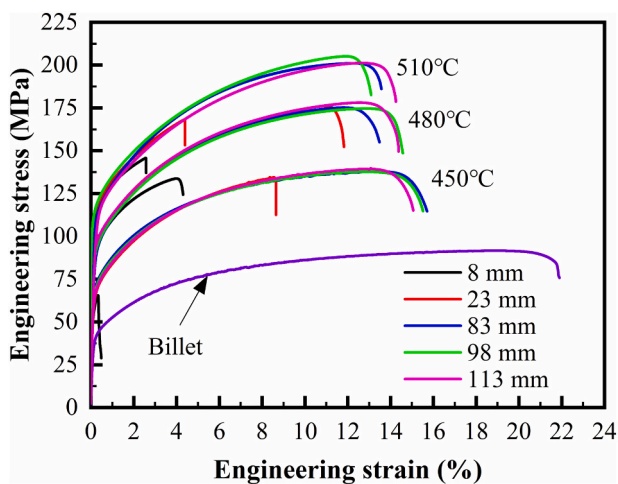


Fig. 11. Tensile stress-strain curves of the materials from the original billet and profiles extruded at indicated temperatures with the same extrusion speed of 0.5 mm/s. The samples are taken from different positions of the extrudates.

Tensile tests have been widely used to macroscopically evaluate the welding quality by researchers. For example, Loukus et al. [47] evaluated the mechanical properties of the weld region of AA6082 porthole extruded profiles by tensile tests with the weld located at 0°, 45° and 90° to the tensile axis. The fractures always located along the 90° weld while out of the 0° and 45° weld, indicating the importance of angle between weld and force direction to the mechanical property of the extruded profile. In the current study, all the welds beyond 83 mm nearly disappear as shown in Fig. 9, and the corresponding tensile fractures occurred outside the weld zones as shown in Fig. 10. This indicates that among the common range of extrusion temperatures, i.e. 450–510 °C, and the common range of extrusion speeds, i.e. 0.5–2 mm/s, the proposed multi-container extrusion method can steadily fabricate profiles with good welding quality beyond a short low-quality front end, i.e. 83 mm in this case study.

This paper aims to confirm the feasibility and practicability of the first-time reported extrusion method, and therefore only primary research on the welding quality including OM and tensile test is presented. However, deeper analysis on both welding zones and other different regions may be necessary for future work according to the special requirement for the extruded profile on specific applications.

5. Discussion and analysis

To evaluate the advantages of the proposed new method, a comparative study was carried out between the traditional porthole extrusion system and the three-container extrusion system in this section.

5.1. Design of porthole extrusion die set

Porthole extrusion die can only extrude the component of which the largest cross-sectional dimension is lower than the diameter of the container. Hence, to extrude the profile with the same cross-sections in Fig. 2, the porthole extrusion die with the key dimensions listed in Table 2 was designed according to industry experience. The diameter of container D is set as 200 mm, and the container length L is set empirically as 2 times the diameter (400 mm) referenced by open literature [48].

5.2. Extrusion force comparison

The applied pressure during extrusion is a key consideration to choose extrusion press and check the die strength. After many decades of development from 1931, different prediction methods of extrusion pressure have been proposed. The equation used in this study (Eq. (1)) has been validated and widely used of estimating the force demand of

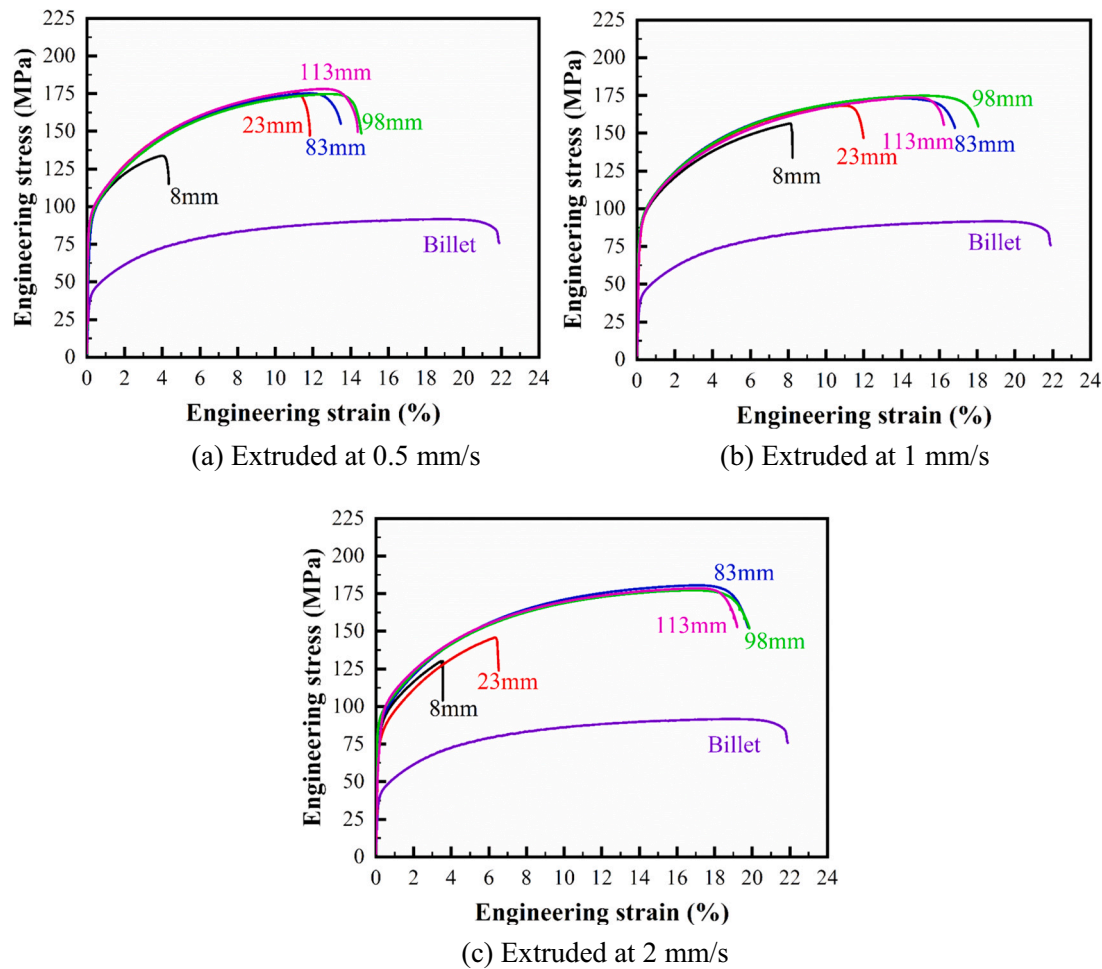


Fig. 12. Tensile properties of the materials from the original billet and profiles extruded at indicated extrusion speeds with the same extrusion temperature of 480 °C. The samples are taken from different positions of the extrudates.

porthole extrusion, which considers not only the force required by plastic deformation but also the friction effect between the billet and the container [49]:

$$P = \alpha Y_f \left(\ln \lambda + \frac{4\mu L}{D} \right) \quad (1)$$

where P represents the extrusion pressure, Y_f is the steady state flow stress of the deformed material at the extrusion temperature, and λ is the extrusion ratio. α is a constant representing the complexity extent of extrusion die, normally about 1.0–1.1 for solid profile and 1.1–2 for hollow profile. μ is the friction coefficient. L and D are the length and diameter of the container, respectively.

By multiplying the predicted extrusion pressure and cross-sectional area of the container, the maximum extrusion forces for the porthole extrusion method can be calculated as,

$$F_p = \alpha Y_f \left(\ln \lambda_p + \mu \frac{4L_p}{D_p} \right) \frac{\pi D_p^2}{4} \quad (2)$$

where the steady stage flow stress Y_f for AA6063 material is given in Table 3 for different porthole extrusion conditions according to the AA6063 material database of QForm simulation software [50]; α is calculated as 1.72 according to the cross-sectional perimeter and area of the extrudate [51]; and the friction coefficient μ is set as 0.325 [52]. The extrusion ratios λ_p is 74 for the porthole extrusion. Table 3 compares the maximum force demands at different conditions for three-container extrusion from the experiments and porthole extrusion calculated by Eq. (2). The ratios of the three-container extrusion force to the porthole extrusion force are 12.0 %, 12.6 %, 13.3 %, 13.6 % and 12.8 % for extrusion conditions of 450 °C/0.5 mm/s, 480 °C/0.5 mm/s, 480 °C/1 mm/s, 480 °C/2 mm/s and 510 °C/0.5 mm/s, respectively. This means the three-container extrusion only needs less than 15 % of force that the porthole extrusion needs for the common range of extrusion conditions. The extrusion ratio of the three-container extrusion (8.5) is significantly lower compared with the porthole extrusion (74), leading to the reduction of deformation-induced extrusion force. Also, the friction area between material and tooling inner walls of the three-container

Table 3

Comparison of maximum force demands for three-container and porthole extrusions.

	450 °C/0.5 mm/s	480 °C/0.5 mm/s	480 °C/1 mm/s	480 °C/2 mm/s	510 °C/0.5 mm/s
AA6063 steady-state flow stress (MPa) [50]	49.5	43.2	47.0	51.0	37.7
Maximum force for three-container extrusion from experiment F_3 (kN)	2224	2032	2336	2589	1800
Maximum force for porthole extrusion from Eq. (2) F_p (kN)	18,476	16,121	17,519	19,039	14,065
Extrusion force ratio F_3/F_p	12.0 %	12.6 %	13.3 %	13.6 %	12.8 %

extrusion is much smaller than the porthole extrusion, resulting in the decrease of friction-induced extrusion force than the porthole design. The reduction of both extrusion ratio and friction area has made the aim of reducing extrusion force achieved.

6. Conclusions

A novel multi-container extrusion method has been proposed to produce thin-walled wide profiles with low force. The featured extrusion process is to simultaneously push multiple billets positioned in a row, make them weld together inside the die, and finally extrude them into the desired profile. To study its feasibility, a three-container extrusion die set was designed and manufactured to extrude 177 mm × 8 mm hollow profiles. Plasticines were first extruded at room temperature with the extrusion speed of 0.5 mm/s to investigate the welding positions. AA6063 alloys were subsequently extruded under five combinations of three temperatures, i.e. 450, 480 and 510 °C with three extrusion speeds of 0.5, 1 and 2 mm/s. Optical microscopic observations and tensile tests were also conducted to characterise the welding quality and mechanical property of the extrudates. In addition, the required extrusion forces for the traditional porthole extrusion were estimated to extrude the same profiles as the proposed three-container extrusion. The following conclusions are drawn:

- (1) The concept of multi-container extrusion method and its feasibility have been proven in the study. The shape and geometry of the profile extruded using the novel multi-container extrusion method were as desired.
- (2) Good welding quality of welds can be achieved beyond 83 mm distance from the extrudate front end for the three-container extrusions at the common range of extrusion temperatures and speeds. Obvious welds were observed at 8 mm and 23 mm away from the extrudate front end, of which the corresponding tensile specimens were fractured along the welds. However, the welds became indistinct at 83 mm and completely disappeared at further distances, of which the corresponding tensile specimens were fractured outside the welds. Compared to the original billet, the ultimate tensile strength of the extrudates with good quality welds increases by 53 %–124 % and the elongation decreases by 18 %–39 %.
- (3) The three-container extrusion method can significantly reduce the requirement of extrusion press capacity. The porthole extrusion force demands at different temperatures and speed conditions were estimated and compared with the measured three-container extrusion forces. The three-container extrusion only needs less than 15 % of the force for the porthole extrusion to extrude the 177 mm wide profiles. This is mainly due to the significant reduction of the extrusion ratio from 74 for the porthole extrusion to 8.5. A secondary contribution is from the reduction of friction force due to the arrangement of three containers with a smaller total friction area during extrusion. The multi-container extrusion method can significantly reduce the extrusion force, which makes it possible to extrude large-sized wide profiles with a lower load capacity of the press.

CRedit authorship contribution statement

Jiaxin Lv: Methodology, Investigation, Visualization, Data curation, Writing - Original draft preparation. **Junquan Yu:** Methodology, Investigation, Validation, Supervision, Writing - Reviewing and Editing. **Zhusheng Shi:** Conceptualization, Project administration, Supervision, Writing - Reviewing and Editing. **Weishu Li:** Methodology, Investigation. **Jianguo Lin:** Conceptualization, Funding acquisition, Supervision, Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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