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Advances on manufacture methods for wide lightweight aluminium stiffened panels

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Abstract. Wide aluminium panels with stiffeners are extensively applied in aviation, bridge and marine structures due to their high stiffness and light-weighting. Many efforts and contributions have been made to overcome the manufacturing difficulties of wide aluminium stiffened panels over years. The aim of this study is to analyse and compare current methods for producing wide stiffened panels for different applications. The manufacturing techniques for stiffened panels such as riveting, welding, machining, additive manufacturing, extrusion, are discussed. Thereinto, extrusion is a very promising technology in the production of wide aluminium stiffened panels as it can efficiently obtain extruded products with high material utilisation, good mechanical properties and structure integrity. Therefore, the methods of widening the stiffened panels in extrusion technology such as spread extrusion and postproduction flattening after extrusion are analysed emphatically. The present study is an attempt to analyse these efforts in order to guide future work in the area of producing much wider aluminium stiffened panels.
Keywords: Extrusion; wide plates; stiffened panels; aluminium alloys; manufacture methods; lightweight structure

1. Introduction

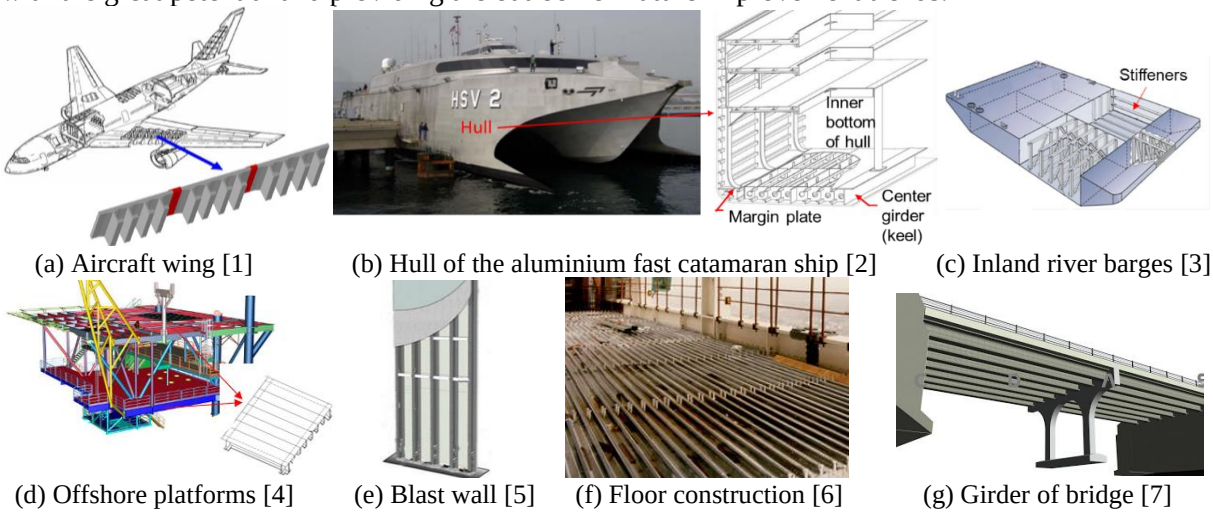
Due to the global focus on saving energy and reducing CO_2 emissions, wide stiffened panels which can greatly reduce the weight of structural components and obtain high stiffness without sacrificing strength and serviceability, have been widely applied in numerous industrial sectors, as shown in figure 1. In aerospace applications, the stiffened structures are used in the aircraft wings and fuselage assembly [1], and they are also employed in jet engine components such as pods, aircraft landing brake components, bulkheads and fairings, etc. In the field of navigation, most ship structures contain stiffened plates such as deck, bottom and side of hull [2, 3], and offshore platforms have the decks built up by stiffened plate structures [4]. In addition, stiffened panel components are applied in the construction of blast walls [5], buildings [6], slab-girder bridges [7], etc. Steel is mostly used for stiffened structures in the early years, but with the development of lightweight materials, aluminium alloys have gradually replaced steel. The density of aluminium alloys is only one-third that of steel, but the resulting strength difference in structures may not be obvious in some applications [8]. Therefore, it is apparent that using aluminium stiffened panels have become an effective way to achieve lightweight goals, and contributed to reducing fuel consumption and CO_2 emissions.

Considering the increasing demands for wide lightweight aluminium stiffened panels in a variety of industries, research into their fabrication methods has been a subject of interest over the past years. Industries, nowadays, are inclined to use much wider integral stiffened panels, as they are cost-effective and have good mechanical properties. Although there is the challenge of structural complexity and the difficulty to widen the panels, the rapid improvement in manufacturing techniques has contributed to forming wide plates with stiffeners, giving rise to the expanded applications. However, currently there

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is no systematic summary of manufacturing methods and analysis of recent advances for wide aluminium stiffened plates driven by industrial demands.

In this paper, the advances and trends in manufacturing methods of wide lightweight aluminium stiffened panels are reviewed and analysed. Different fabrication techniques of plates with stiffened ribs and their advantages and disadvantages are compared first. In addition, some new techniques to widen panels in extrusion are analysed, and difficulties of these methods are also discussed. Finally, conclusions on manufacturing methods of wide stiffened panels are drawn identifying the technology with the great potential and providing the outlook on future improvement trends.



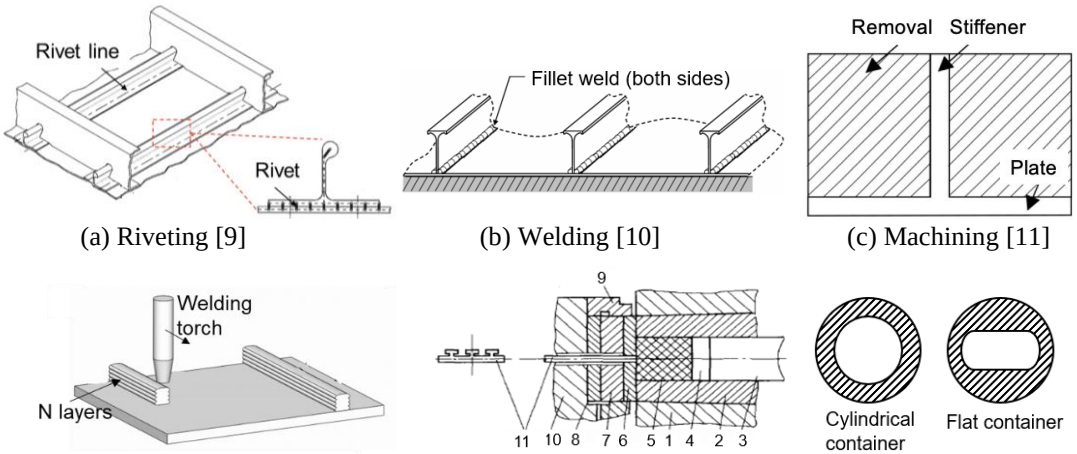
(a) Aircraft wing [1] (b) Hull of the aluminium fast catamaran ship [2] (c) Inland river barges [3]

(d) Offshore platforms [4] (e) Blast wall [5] (f) Floor construction [6] (g) Girder of bridge [7]

Figure 1. Typical applications of stiffened panels in different industrial sectors.

2. Manufacturing methods for stiffened aluminium panels

The existing fabrication methods for stiffened aluminium structures, such as riveting, welding and machining, are to a large degree based on experience from stiffened steel structures. These conventional manufacturing methods for the panels with stiffened ribs have been commonly used and developed for many years, however, some new manufacturing techniques based on additive manufacturing and extrusion also gradually play a significant role in the fabrication of stiffened aluminium panels. Figure 2 shows the current manufacturing methods for aluminium panels with stiffeners.



(a) Riveting [9] (b) Welding [10] (c) Machining [11]

(d) Additive manufacturing [11] (e) General extrusion and flat container extrusion [12]

Figure 2. Manufacturing techniques for stiffened panels. In (e): 1 – Extrusion container; 2 – Working bush; 3 – Ram; 4 – Dummy block; 5 – Billet; 6 – Extrusion die; 7 – Die cushion; 8 – Pad; 9 – Support; 10 – Pressure nozzle; 11 – Stiffened panels.

2.1. Riveting

Riveting (figure 2 (a)), as a traditional joining method, has been investigated by many researchers [9, 13, 14] and used for many years in different joining applications, including stiffened structures. In general, no heat is applied for riveting and the material microstructure is not affected in riveting operations. However, the stress concentration would occur in the riveted areas, which affects the structure integrity of the riveted parts [13]. Besides, static failure of riveted joints which is a kind of structural damage under ultimate static loads, including rivet shear, sheet tension, and hole bearing failure, has been the key concern in aircraft industries, and the riveting process parameters need to be optimised to minimise their effect on the stiffened structures [14].

2.2. Welding

Welding, as shown in figure 2(b), is a common method to join components of stiffened structures. Conventional welding such as arc welding, resistance welding and energy beam welding, puts large heat into the welding areas of the structures, which leads to severe thermal gradients with the uneven cooling subsequently in the heat-affected zone (HAZ), resulting in high residual stresses, low fatigue strength and distortion [15, 16]. Since invented by Wayne Thomas in 1991, the friction-stir welding (FSW) method has been mostly used to weld aluminium materials in the aerospace industries [17]. Ohashi et al. [18] used FSW method to obtain a 3 mm thick AA5083 aluminium alloy panel with 4.29 mm high ribs. By utilising this method, better mechanical properties in friction stir welds and fine grain size can be obtained. Compared with conventional welding, FSW is energy-efficient and environmentally friendly due to the absence of external heating, but it has low working efficiency and HAZ still affects the performance of the structures. Overall, welding is a simple and effective technique to realise the manufacture of aluminium stiffened panels, however, it could modify the microstructures and mechanical properties in the HAZ which influences the structural integrity. In addition, there may be severe residual stress and many defects such as the slag inclusion, internal air pocket, etc.

2.3. Machining

To date, machining (figure 2(c)), as an alternative to riveting or welding, can produce integral structures which have low cost associated with the assembly tools and labour. Machining ensures the mechanical properties of the stiffened profiles and enables to produce extremely wide plates with complex-shaped stiffeners [19]. But the main issues of this technique are the poor material utilisation rate leading to a great deal of material waste and low efficiency. Besides, high stiffeners may be subjected to distortion during the machining process due to the build-up of compressive stress in thin-wall design [20].

2.4. Additive manufacturing

Additive manufacturing, which can improve the design flexibility and has high material utilisation and energy efficiency, is gradually applied in the manufacture of stiffened panels. More recently, the wire arc additive manufacturing with milling process (HWMP) for stiffened plates has been proposed [11], as shown in figure 2(d). A welding torch deposits N stiffened layers onto the plate and then the stiffeners are milled to the required size and surface quality. Compared with the traditional machining method, this technique improves the material utilisation from 34% to 91% [11]. However, the welding process may induce residual stress and thus the distortion would appear due to the large heat input, and additive manufacturing method has low efficiency.

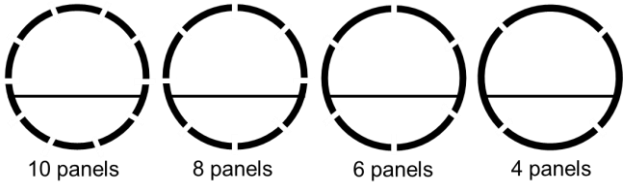
2.5. Extrusion

Extrusion technology (figure 2(e)), as one of the plastic-forming methods, has high working efficiency and good mechanical properties for aluminium profiles. The easiest way to produce profiles with stiffeners is extrusion using a solid cylindrical container/billet, but the extrusion ratio will be extremely high for the wide panels and the extrusion force will thus be large. Hence, extrusion using a flat container/billet has been developed for the applications with reduced extrusion ratio and forces. But it has the problem of stress concentration for the container, which resulted in high wear and low life [21]. In general, extrusion forces greatly increase as the panel width increases, resulting in an increase in the energy consumption. Additionally, the width of panels is limited by using extrusion technique. For

example, it has been reported that on the 8000 tonnes extrusion press, the hard aluminium alloys (2024, 7075) can be used to produce thin-walled profiles with a width not greater than 460 mm, while the soft aluminium alloys (6061, 6005, 6063) can be extruded to panels with a width not greater than 650 mm [12].

Generally, wider stiffened panels can be obtained by assembly methods, for instance, welding or riveting individual extruded profiles [22, 23]. Aalberg et al. [22] produced a 1.26 m wide panel by welding several extruded L-shaped AA6082 profiles with a width of 252.5 mm. The disadvantages of welding are that tensile residual stress could be generated in the HAZ and the material has a decreased yield strength in the vicinity of the welding lines. Using riveting can also cause residual stress around joints. Therefore, much wider integral structures should be extruded, in order to reduce the joints between components throughout the assembly, which can improve the structure integrity and thus improve performance of the assembly for the applications.

In addition, manufacturing wider integral stiffened panels will significantly cut the cost. It is reported that by reducing the longitudinal joints of the each part of fuselage larrel in aircraft, the manufacturing cost decreased dramatically, up to 50% [24], as illustrated in Figure 3. These values are nominal and will change according to the type of aircraft and airline operator. The drop in cost of part fabrication and assembly is noticeable when the number of panels reduces from 10 to 4, while other costs such as engineering cost and material cost also have slight decline. Weight of the fuselage larrel assembly also decreases slightly, which is also beneficial to save energy and protect environment. In a word, wider integral extruded aluminium stiffened panels in the assembly for the applications can improve the performance of the structures, reduce cost and energy consumption, thereby becoming the concern in various industries.



Number of Panels	10 (Basis)	8	6	4
Engineering Cost	1	0.90	0.80	0.70
Material Cost	1	0.95	0.90	0.85
Part Manufacture Cost	1	0.80	0.65	0.50
Assembly Cost	1	0.85	0.70	0.50
Weight	1	0.98	0.96	0.94

Figure 3. The effect of reducing the number of longitudinal joints on fuselage larrel assembly costs.

2.6. Discussions of different manufacturing methods for stiffened panels

The comparison of different methods for manufacturing stiffened panels is shown in table 1. Manufacturing wide integral stiffened panels is increasingly becoming a trend in industry due to cost-effectiveness and good mechanical properties. Among these five manufacturing techniques (riveting, welding, machining, additive manufacturing, and extrusion) for stiffened panels, riveting, welding and additive manufacturing have the concerns of structure integrity, especially for thin-plate structures. Residual stress is easily generated around the joints during production process in these three methods. Machining and extrusion enable to produce the integral profiles with good structure integrity and light-weighting features. However, machining may waste a mass of materials when producing thin-plates with high stiffeners and it is time-consuming [11], while extrusion has high material utilisation and working efficiency. On the other hand, in terms of mass production, extrusion is more efficient than other methods for the applications. Therefore, extrusion technique is considered as a promising manufacturing method to produce the stiffened aluminium panels. However, main limitations of extrusion, such as the lack of ability to extrude much wider plates and high extrusion forces, hinder the expansion of its applications.

Table 1. Comparison of manufacturing techniques for stiffened panels.

Techniques	Advantages	Disadvantages
Riveting	1. The machine tools of riveting and operation are simple 2. Easy to assemble	1. Stress concentration easily occurs at the riveted areas 2. The holes would weaken the working cross-section of the plate 3. Added weight due to strap-plate and rivets 4. High force may be required in riveting 5. Structure integrity concerned
Welding	1. Simple operation 2. Easy to realise mechanisation and automation 3. Flexible	1. Thermal stress and shape distortion easily occur 2. Microstructure and mechanical properties are modified in HAZ 3. Structure integrity concerned
Machining	1. Good for complex-shaped profiles 2. High repeatability 3. Good mechanical properties & structure integrity 4. Flexible & lightweight panels	1. Large material waste 2. Low working efficiency 3. Equipment cost may be high for producing long, large panels with stiffeners
Additive manufacturing	1. High material utilisation 2. Flexible	1. Low working efficiency 2. Thermal/residual stresses 3. Structure integrity concerned
Extrusion	1. High material utilisation 2. Good mechanical properties & structure integrity 3. High efficiency 4. Lightweight panels 5. Mass production	1. Limited width of extruded panels due to large extrusion forces 2. Only for longitudinal ribs

3. Recent progress of extrusion for wider aluminium panels

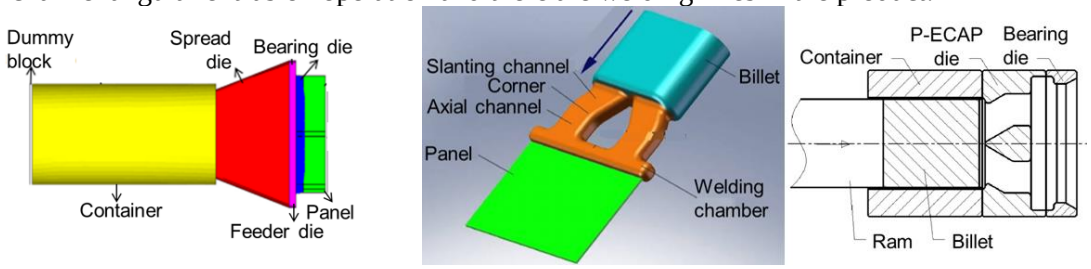
As discussed above, extrusion is a promising technology to produce aluminium stiffened plates and the challenge to be solved is to manufacture much wider integral panels, which can improve the quality of the components and reduce the cost. Many researchers have made progresses in the field of extrusion for wider aluminium panels [25-29], essentially there are two different extrusion methods which have been reviewed in this section.

3.1. Spread extrusion

Spread extrusion can expand the width of products to a value larger than the diameter of the cylinder, as shown in figure 4(a). Liu et al. [25] used the spread extrusion method to produce large-scale AA6061 aluminium plates with ribs which can be used in high-speed trains. Using this extrusion method, panels, whose width is 10% ~ 30% larger than the diameter of cylinder, can be obtained. However, the extrusion force of spread extrusion is higher than that of ordinary extrusion of the same profile [26], so it is difficult to produce thin-walled profiles with large extrusion ratio. It is also difficult to control the material flow by means of spread die and feeder die where the uniform velocity has to be achieved.

Another technique as the improvement in spread extrusion, is the porthole equal channel angular pressing (P-ECAP) which enables to extend the width of the extruded panels [27]. This method is the combination of the flat container extrusion, spread extrusion, porthole extrusion and equal channel angular pressing technology. The process of the porthole equal channel angular extrusion is presented in figure 4(b). The billet is extruded into the equal channel angular pressing structure and divided into two parts, which are welded in the welding chamber to achieve the horizontal size enlargement. In

addition, the microstructure of the billet would be refined by the shearing effect of the equal channel angular extrusion, which is beneficial for the welding process. The advantages of this technology are that (1) the quality of product is high because the grains are refined; (2) the ability to spread the width of panels is greater than that of general spread extrusion. However, the extrusion force is large due to equal channel angular extrusion operation and there are welding lines in the product.



(a) General spread extrusion [25] (b) Porthole equal channel angular extrusion [27]

Figure 4. Spread extrusion for extending the width of extruded panels.

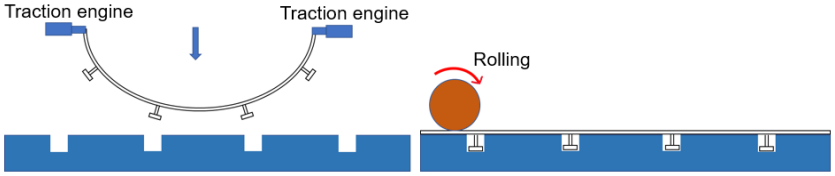
3.2. Postproduction flattening after extrusion

To widen the width of the extruded panel, NASA 'Integral Airframe Structures' program [24] proposed that an additional development work, postproduction flattening, was required for the extruded stiffened profiles. V-, U-, C-, O-shaped extruded panels for this program were produced with the intention of the subsequent flattening and rolling operations. Figure 5 shows the process of postproduction flattening and rolling after extrusion [24] and the general relationship between the width coefficient, *w*, and different panel shapes. *w* is defined as [12]:

$$w = \frac{B_{shapes}}{B_{lines}} \tag{1}$$

where B_{shapes} is the width of the profile after flattening, B_{lines} is the maximum width of the line-shaped panel using the same extruder. The width coefficient increases with the order of V-, U-, C-, O-shaped panels. Herein, the O-shaped extrudates after the process of flattening and rolling can form plates with the maximum width.

All-Russia Institute of Light Alloys (VILS) [29] extruded a 4 m long pipe with eight L-shaped stiffeners using a central mandrel to sustain concentricity and wall thickness. These stiffened pipes were slowly air cooled, cut, unfolded mechanically, and then flattened on a plate containing grooves for rib support. After that, stiffened plates were solution heat treated, water quenched, stretched, and flattened by cold rolling. The final profile had dimensions of 825 mm in width. The main drawback of this process is that flattening pipe with ribs is very complex and the time consumption is large. Besides, the wall thickness deviation is quite large when extruding thin-walled profiles. In general, this geometry processing which combines extrusion and flattening can conceivably be achieved to yield flat, wide extrusions and, therefore, to produce cost-effective structure. But a possible high-risk aspect would be the high demand of equipment improvement to produce the integral stiffened panels after they leave the extrusion die, because the equipment would be required to grab the extruded profiles and somehow stretch, flatten, and roll them, and keep the stringers in the correct alignment. Additionally, some defects like cracks would appear around the flattened areas and the microstructures and mechanical properties in these areas would also be different.



Panel shape	—	V	U	C	O
Width coefficient	1	1.6	2	2.2	2.35

Figure 5. Postproduction flattening after extrusion for widening panels and the width coefficient for different shaped extruded panels.

3.3. Discussions of extrusion methods for wider aluminium stiffened panels

At present, there is less research on the extrusion methods to enlarge the width of aluminium panels with stiffeners. Existing research mainly focuses on two technical routes. One is changing extrusion tools to realise the fabrication of stiffened panels with wider width [12]. Traditional extrusion method commonly uses larger extrusion container to produce wider panels, resulting in high extrusion forces and energy waste. Furthermore, novel extrusion die, such as spread die and equal channel angular pressing die in spread extrusion, can be designed to achieve widening goals. However, as the degree of widening increases, extrusion forces increase sharply, which limits the applications of spread extrusion. Another method is to seek a breakthrough in the process after extrusion. A typical example is flattening and rolling the V-, U-, C-, O-shaped extrudates to obtain the wider size panels with stiffeners [24]. Although the extrusion process is not changed, which is favourable for the popularisation of this method, the subsequent operations are complicated and the quality of the products may be changed during the flattening and rolling process. Table 2 compares the extrusion methods for wide panel production, with their advantages and disadvantages. Each method has its own limitation for manufacturing wider stiffened panels. Therefore, new extrusion techniques to produce wider aluminium stiffened panels should be researched in the future and efforts on the reduction of extrusion forces should also be made.

Table 2. Comparison of extrusion methods for prducing wider panels with stiffeners.

Techniques	Advantages	Disadvantages
Traditional extrusion method	1. Simple operations 2. Tooling could be cheaper	1. Unable to extrude wide panels with reasonable force 2. Material flow may be difficult
Spread extrusion	1. Extruded plates with a larger width 2. Simple operations	1. A limited ability to enlarge the width 2. Extra material waste
Postproduction flattening after extrusion	1. Products after flattening and rolling have a larger width 2. Extrusion tools are unchanged	1. Complex subsequent operations 2. Defects like cracks are easily formed when flattening the profiles 3. Low precision and efficiency

4. Conclusions and future research trends

In this paper, the advances and trends in manufacturing methods for wide aluminium panels have been reviewed. The advantages and disadvantages of different manufacturing techniques have been discussed and analysed. The following conclusions can be drawn:

(1) Riveting, welding and additive manufacturing have low working efficiency and the concerns of structure integrity, especially for thin-plate structures. Additive manufacturing can improve material utilisation but induces large residual stresses. Machining enables to produce integral profiles but has a high material waste and time consumption.

(2) Extrusion is a promising forming method for the production of wide stiffened plates with good structure integrity and ligh-weighting features. It can also improve mechanical properties of aluminium profiles and has high working efficiency and material utilisation. But the main issue is that the extrusion force is too large for wide plate and further efforts should be devoted to reducing the extrusion force.

(3) Due to significant reduction of manufacturing cost achieved using wider integral stiffened panels for assembling components, efforts have been made to produce wider panels. The manufacturing methods, such as spread extrusion and postproduction flattening after extrusion, have been used for expanding the width of extruded stiffened plates. However, spread extrusion can increase extrusion force and postproduction flattening after extrusion has extremely complicated subsequent operations.

According to the conclusions, the future research in the extrusion of wide aluminium stiffened panels should pay attention to two major issues: (1) develop novel extrusion techniques to produce wide

integral aluminium stiffened panels for the industrial applications; (2) reduce the extrusion forces to meet the increasing requirements of energy saving and environmental protection.

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