

Assessment of Recently Developed Low-force Extrusion Methods for Manufacturing Aluminium Vehicular Hydrogen Tank Liners

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Abstract. With increasing climate concerns and the urgent need to reduce carbon emissions, hydrogen as a clean and renewable energy source for vehicles has attracted rising interest. A major challenge is the on-board storage of flammable hydrogen gas, which restricts the commercialisation of fuel cell electric vehicles (FCEVs). This paper investigates the advantages and limitations of the existing backward extrusion techniques in producing the aluminium liners of the Type III tanks. Backward extrusion is a simple and efficient method that can manufacture near net-shape cylindrical liners in one step without the requirement of welding. However, this process requires high extrusion force, which makes the production of large tanks difficult and leads to high manufacturing cost. In the recent decades, several advanced tool designs have been proposed to reduce the extrusion force, and the merits and limitations of these designs are reviewed and analysed in this paper. Furthermore, the feasibility of these designs in processing aluminium alloys is assessed using the finite element analysis (FEA). The simulation results show that these designs are effective in reducing the extrusion load as compared to the conventional method, but the product size is restricted. Further improvements are required to make these designs suitable for producing large and long tanks for practical applications.

Keywords: Hydrogen Storage Tanks, Aluminium Alloys, Backward Extrusion

1 Introduction

To reduce the adverse effects of global warming and maintain a sustainable development, the Paris Agreement has set a goal to achieve net-zero emission by 2050 [1]. Thus, clean and renewable energy sources as the alternatives of fossil fuels have attracted great interest.

Hydrogen is one of the promising energy sources. It is abundant in nature and produces no carbon emissions when used as a vehicle fuel [2]. Also, it has an energy density of 120 MJ/kg, which is about three times that of the diesel or the petrol [3]. Despite these advantages, the uptake of hydrogen fuel cell vehicles (FCEVs) is rather slow since its first prototype is proposed in the 1990s [4]. One of the main challenges

is the difficulty in on-board storage of the flammable hydrogen [5]. There are generally three hydrogen storage methods that can be applied to vehicles: liquid form storage, compressed gas storage, and material-based storage [6]. The current FCEVs are dominated by a compressed hydrogen gas system due to its simpler technique, lower cost and shorter refilling time as compared to other methods. The compressed hydrogen gas is stored in high pressure hydrogen tanks, and such tanks can be classified into 5 major types as summarised in Fig. 1 according to the structure of the materials used.

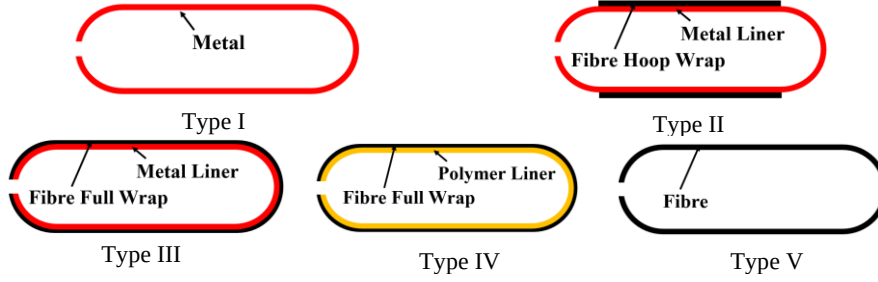


Fig. 1. Schematic illustration of different hydrogen tanks.

Type I is all-metal tank, and it is made of steel or aluminium alloys [7]. Such tank is the easiest and cheapest to manufacture but it is heavy and can only resist to a pressure up to about 200 bar [8]. To accommodate higher internal pressure of about 300 bar, carbon fibre or glass fibre are used to wrap around the straight body part of the tank to provide extra strength (Type II) [8]. However, to carry enough hydrogen fuel for long mileage and to ensure fuel efficiency, commercial FCEVs require lighter tanks which can withstand an internal pressure of 350 bar or 700 bar [9]. Thus, Type III and Type IV tanks with full carbon fibre wrappings are applied due to the merits of lower density of higher strength of carbon fibre as compared to metals [10]. The only difference between these two types is the liner material, where Type III uses metallic liner and Type IV uses polymeric liner [7]. Type V full carbon fibre tank which is even lighter is also under development, but it is seldomly used commercially due to the high cost of carbon fibre [11].

This study mainly focuses on the review of the existing backward extrusion techniques in producing the Type III aluminium liner, and the emphasis is put on the recent development of extrusion designs in reducing extrusion force. The merits and limitations of each method are analysed and potential suggestions for future development are proposed.

2 Backward Extrusion of Hydrogen Tank Liners

Hydrogen gas is highly flammable, and the tank liners must have very good integrity to prevent the leakage of small hydrogen molecules into the environment to ensure safety. Thus, manufacturing methods such as roll forming are unfavoured as welding

is required which could result in poor tank integrity. Instead, the backward extrusion has attracted increasing interest in recent decades [12]. This is a process that can produce near net-shape tanks in one step without welding. The conventional backward extrusion (CBE) is shown in Fig. 2a, where a metal billet is put in the container and a punch strikes the billet and forces the material to flow in the opposite direction of the punch movement [13]. The inner diameter of the formed tank is the same as the punch diameter and the thickness is determined by the gap between the punch and the container wall. Besides, this method uses metal billet instead of metal plates, and the preform preparation cost is thus greatly reduced. However, due to the high yield strength of the metals, very high extrusion force is required. For example, for Type III tanks, the liners are commonly made of AA6061, which has a yield strength of about 241 MPa [14]. To extrude its billet with a diameter larger than 250 mm, over 5000 tonnes of power are required [15]. Such high force requires the use of very large machines and will also cause high energy cost. Thus, recent development focuses on the reduction of extrusion force.

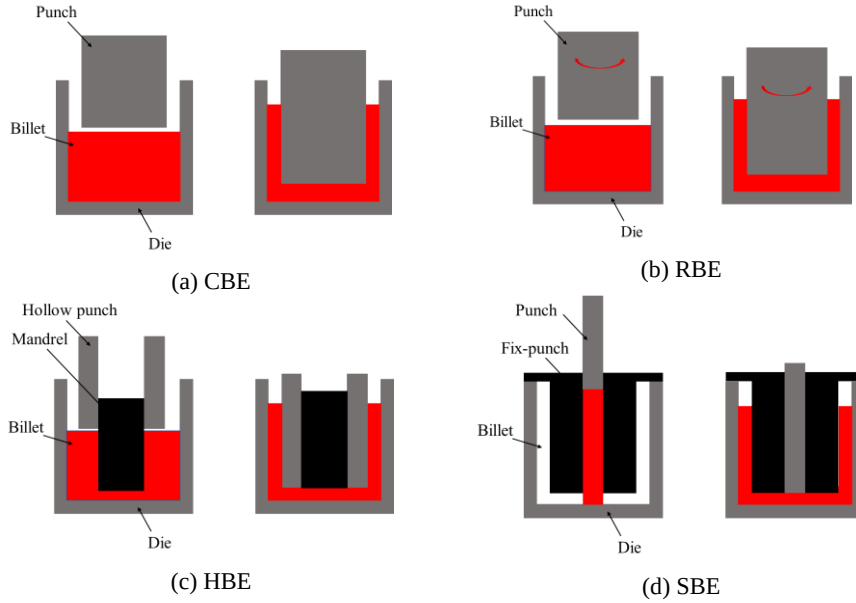


Fig. 2. Schematic illustration of different backward extrusion designs: conventional backward extrusion (CBE), rotating backward extrusion (RBE), hollow-cylinder backward extrusion (HBE) and small-diameter backward extrusion (SBE).

Figs. 2b-d show some of the low-force backward extrusion designs proposed by different research groups in the past decade.

The rotating backward extrusion (RBE) (Fig. 2b) was proposed by Che et al. [16]. This design uses a rotating open punch and a moveable die which moves up to extrude the alloy. The rotational movement of the punch changes the stress state experienced by the billet and reduces the primary yield stress of the material. Thus, lower

extrusion force is required. However, the machine design is much more complicated as compared to the CBE. Also, the friction between the rotating punch and the billet could cause high punch wear and frequent punch replacement is required which increases the manufacturing cost further.

The hollow-cylinder backward extrusion (HBE) (Fig. 2c) was proposed by Wang et al. [17]. This method uses a hollow punch to extrude the hollow metal billet with a solid mandrel in the middle. As a result, the extruded area of the billet is greatly reduced, and a lower extrusion force is required accordingly. By varying the mandrel diameter and punch diameter combinations, tank liners with different sizes and thicknesses can be produced. However, one more processing step is needed to prepare the hollow billet preform as compared to the CBE, which leads to increasing processing time and cost.

Shatermashhadi et al. [18] proposed the small-diameter backward extrusion (SBE) (Fig. 2d) design. Like the HBE method, this method reduces the extrusion force by reducing the extruded billet area, but solid billet is still applied instead hollow ones with the help of the hollow fix-punch. By decreasing the billet diameter to about 1/3 of the conventional billet, this group managed to reduce the extrusion force of lead at room temperature to about a quarter of the conventional backward extrusion method [18]. Although the additional fix-punch makes the tool design more complicated as compared to the CBE method, it is much simpler than the RBE and the HBE designs discussed above. Thus, this SBE design is promising in industrial applications. However, the product size is restricted as the hollow fix-punch will experience a high hoop stress during the process due to the high extrusion force, and thus a minimum thickness must be met to provide enough strength against the hoop stress. Besides, as the diameter of the billet is reduced, its length must be increased to keep the same amount of material for manufacturing of tanks with unchanged dimensions. Thus, longer and thinner punch is needed, which is prone to buckling. For steel, the slenderness ratio (effective length/radius of gyration) needs to be lower than 40 to prevent buckling [19]. Thus, the maximum length of the punch is only about 10 times of its diameter. Due to the combined effect of limited punch length and large fix-punch diameter, the material volume that can be used for extrusion is greatly restricted and it is difficult to manufacture long tanks. As such, potential future improvements should lie on the method to increase the extrudable material volume.

3 Finite Element Analysis (FEA) of Extrusion Forces

The actual efficiency of these advanced designs in reducing the extrusion force of AA6061 hydrogen tank liner at high temperatures has not been verified experimentally. Thus, FEA using Qform has been performed to investigate its feasibility. All methods are designed to produce tanks of the same size: 120 mm inner diameter, 9 mm thickness and 110 mm length. The dimensions of the tool components and the billets are listed in Table 1. Simulations are done at a temperature of 480 °C and a punch speed of 3 mm/s without lubricant.

Table 1. Dimensions of the tool components and billets for different backward extrusion methods in producing tanks of 120 mm inner diameter, 9 mm thickness and 110 mm length.

Method	Punch diameter (mm)	Container inner diameter (mm)	Billet diameter (mm)	Billet length (mm)
CBE	120	138	138	33.6
RBE	120	138	138	33.6
HBE	Mandrel: 60 Hollow punch: 120 Punch: 40	138	Inner: 60 Outer: 138	39.3
SBE	Fix-punch outer diameter: 120	138	40	400

Fig. 3 below shows the extrusion force evolution of each method, and the comparison of the maximum extrusion forces required in the four methods. Fig. 3a shows the extrusion force of the CBE method. According to the theory of friction hill, the extrusion force increases exponentially with decreasing billet length. Thus, as the extrusion process goes on, the billet length to be extruded decreases and the extrusion force increases continuously to a maximum of about 2.60 MN.

The extrusion force of the RBE process is shown in Fig. 3b. It has the same evolution trend as the CBE method after the first second as the tool dimensions and billet size are the same. The initial sharp (but not immediate) increase in extrusion force is probably due to the punch rotation which changes the stress state of the billet. The maximum extrusion force reached with this method is about 1.55 MN, which is about 40% reduction as compared to the CBE.

Fig. 3c shows the extrusion force of the HBE method. It also has the similar evolution trend as the CBE, but the starting and final extrusion forces are smaller due to decreased extruding billet area. The maximum extrusion load is about 1.70 MN, which has a 35% reduction as compared to the CBE. However, there is great potential to decrease this force further by varying the diameters of the mandrel and the hollow punch.

With SBE, the maximum extrusion force is decreased to only about 0.75 MN, which gives a 71% force reduction as compared to the CBE. However, the evolution curve (Fig. 3d) shows many sharp strikes which are due to the defects formed during the extrusion process, and such defects could affect the mechanical properties of the tank adversely. At time of about 30 s, there is a sharp increase in extrusion force, which is the point where the billet material starts to turn and flow into the vertical gap. The material at the bottom gap will then experience restrictions from both the billet in the fix-punch channel and the material in the vertical gap. Thus, if there are any unfilled positions in the bottom gap, folds will form due to force pushing the material from both ends to the cavity as demonstrated in Fig. 4. These folds will be the points with high stress intensity and affect the mechanical property of the tank significantly. Thus, this design needs to be further improved to ensure good and uniform material flow.

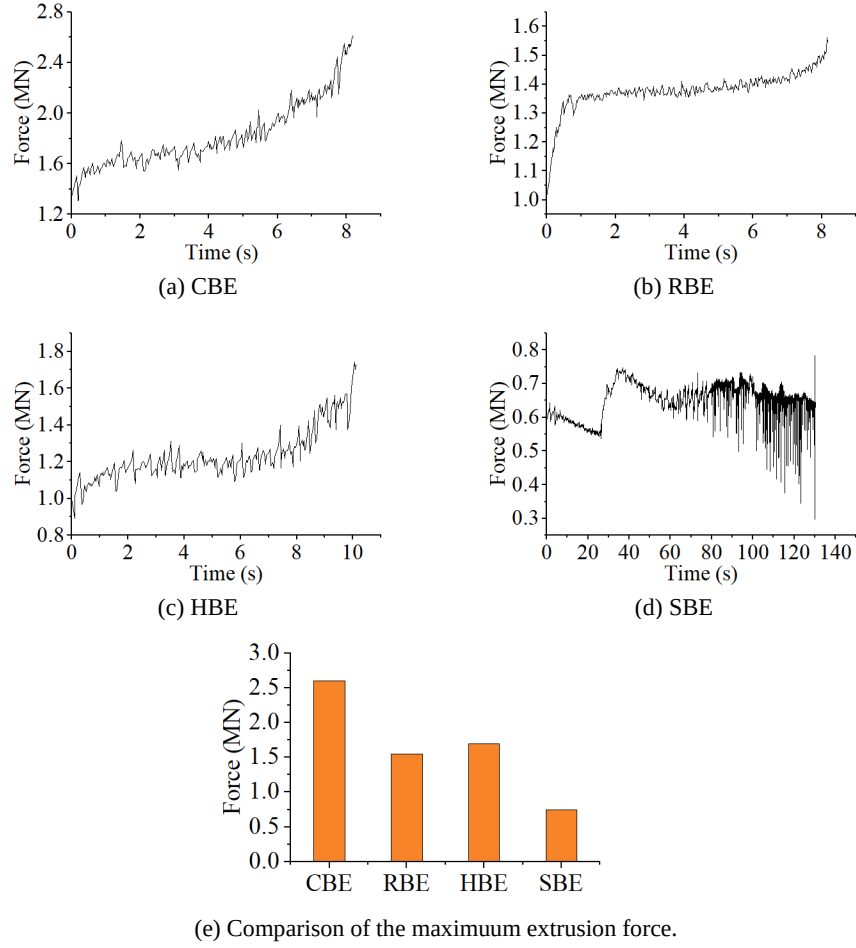


Fig. 3. Extrusion force evolution of different backward extrusion designs and the comparison of their maximum extrusion force.

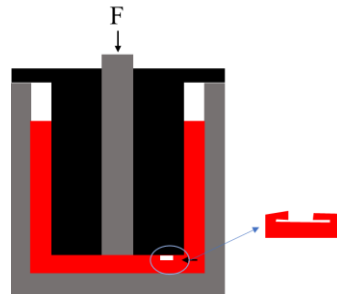


Fig. 4. Schematic illustration of the formation process of folds.

4 Conclusions

In this paper, different hydrogen storage tanks and the low-force extrusion methods for manufacturing aluminium alloy hydrogen tank liners are discussed. Some key conclusions are summarised:

- All advanced designs (rotating backward extrusion (RBE), hollow-cylinder backward extrusion (HBE) and small-diameter backward extrusion (SBE)) are effective in reducing the extrusion load as compared to the conventional backward extrusion (CBE) method, with SBE giving the maximum force reduction of about 71%.
- The SBE method is relatively the easiest design in force reduction, but further improvements are required to increase the extrudable material volume and to ensure good material flow.

References

1. BEIS (2021) Net zero strategy: build back greener – October 2021, pp. 367.
2. Cadwallader L C, Herring J S (1999) Safety issues with hydrogen as a vehicle fuel. Department of Energy, United States.
3. P. Molloy (2019) Run on Less with Hydrogen Fuel Cells. ACT news. <https://www.act-news.com/news/fcevs-run-on-less/>, last accessed 2022/07/27.
4. FUEL CELL Store Homepage, <https://www.fuelcellstore.com/blog-section/fuel-cell-vehicles-automobiles>, last accessed 2022/02/07.
5. Wilkinson S (2022) Hydrogen fuel cells: do hydrogen cars have a future? Auto Express. <https://www.autoexpress.co.uk/electric-cars/93180/hydrogen-fuel-cells-do-hydrogen-cars-have-future>, last accessed 2022/07/13.
6. Züttel A (2004) Hydrogen storage methods. *Naturwissenschaften* 91:157-172.
7. Barthélémy H (2012) Hydrogen storage – industrial perspectives. *International Journal of Hydrogen Energy* 37(22):17364-17372.
8. DIDION'S MECHANICAL Homepage, Hydrogen Storage Tanks: The Types, The Pitfalls, & the Solutions. <https://didionvessel.com/hydrogen-storage-tanks/>, last accessed 2022/02/13.
9. Hua T, Ahluwalia R, Peng J K, Kromer M, Lasher S, McKenney K, Law K, Sinha J (2010) Technical assessment of compressed hydrogen storage tank systems for automotive applications. *International Journal of Hydrogen Energy* 36(4):3037-3049.
10. Ma X, Zhang Y (2015) Life prediction on a T700 carbon fiber reinforced cylinder with limited accelerated life testing data. *Mathematical Problems in Engineering* 2015(902157):1-9.
11. Yang T H (2021) Hanwha solutions developing Type 5 hydrogen tank. THE ELEC, Korea Electronics Industry Media. <https://www.thelec.net/news/articleView.html?idxno=3450>, last accessed 2023/01/27.
12. Labanova N, Liewald M, Felde A (2015) Production of extremely deep sleeves by backward cold extrusion. In: *Proceedings of the 4th International Conference on New Forming Technology*, pp. 1-7. EDP Sciences, France.

13. Lefteri (2013) Backward impact extrusion. Making it: Manufacturing Techniques for Product Design. 2nd edn. Laurence King Publishing, United Kingdom.
14. Ferguson Perforating Homepage, <https://www.fergusonperf.com/the-perforating-process/material-information/specialized-aluminum/6061-aluminium-alloy/>, last accessed 2022/07/27.
15. King J R (2001) The aluminium industry. Woodhead Publishing Limited, Cambridge, England.
16. Che X, Wang Q, Dong B, Meng M, Zhang Z (2020) Numerical and experimental analysis of rotating backward extrusion as a new SPD process. *Metals and Materials International* 26(12):1786–1796.
17. Wang Q, Zhang Z, Li X, Zhang H (2018) Development of a novel high straining backward extrusion process. In: *Proceedings of the 5th International Conference on New Forming Technology*, pp. 1-5. EDP Sciences, France.
18. Shatermashhadi V, Manafi B, Abrinia K, Faraji G, Sanei M (2014) Development of a novel method for the backward extrusion. *Materials & Design* 62:361–366.
19. efunda Homepage, https://www.efunda.com/formulae/solid_mechanics/columns/intro.cfm, last accessed 2022/07/27.