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Review

Lightweight Materials in Electric Vehicles

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Abstract: Lightweight materials are highly demanded in electric vehicles (EVs) to reduce environmental impacts and energy consumption. Aluminium alloys are promising materials in EVs due to their advantages such as high specific strength, corrosion resistance and recyclability. However, forming complex-shaped thin-wall aluminium products is challenging due to their poor formability and limited dimensional accuracy. Meanwhile, recycling some of the high-strength aluminium alloys from EVs is still challenging. This review highlights some of the future potential aluminium forming techniques for EV production, including incremental sheet forming (ISF), hot forming and quenching (HFQ®) technique, and transverse stretching and local bending (TSLB). Also, the issues associated with aluminium recycling are listed and discussed. This review provides scientific guidance to the industry and the scientific community for advancing the applications of aluminium alloys in EVs.

Keywords: aluminium alloys; electric vehicles; formability; dimensional defects

1. Introduction

Zero emission policy significantly drives the global demand for electric vehicles (EVs), aiming to ease the energy and climate crisis. There were over 16.5 million EVs on the road in 2021, expected to reach 145 million by 2030 by International Energy Agency [1,2]. Although being strongly supported by national policies, EVs still have obstacles to their fast development such as limited driven range per charge and limited resources for EV materials compared with internal combustion engine-powered vehicles.

Using lightweight materials is an effective strategy for EVs. The reduction of 100 kg in car weight was predicted to be able to improve energy efficiency by 3.5% or save energy by 15 kJ/km [3,4]. Among the lightweight materials such as light alloys and composites, aluminium alloys are especially favoured due to their high specific strength, high thermal conductivity, good corrosion strength and high recyclability [5,6]. The aluminium alloys are used to replace the steel components gradually. For example, the 2006 Chevrolet Corvette Z06 replaced the steel frame with aluminium, reducing the weight by 30% [7]. Owing to the high thermal conductivity of aluminium, an increasing number of car companies such as Tesla [8,9] are using aluminium alloys as their battery pack materials. It is predicted that nearly 10 million tons of aluminium will be demanded for EVs in 2030 [10].

The batteries are the cores of EVs, which require complex-shaped aluminium channels for the battery packages and closures [11]. However, forming complex-shaped thin-walled aluminium products with high geometric accuracy is still challenging, due to the relatively low formability and high springback. To overcome these issues, new forming techniques have been developed such as incremental sheet forming (ISF), hot forming and quenching (HFQ®) and transverse stretching and local bending (TSLB). Meanwhile, recycling aluminium parts on EVs is essential [12–14]. Currently, it is still challenging to produce recycled aluminium with equivalent mechanical properties to the original ones at a low cost. To address this, techniques such as solid-state recycling have been developed [15,16].

This review briefly covers three manufacturing topics concerning the aluminium parts used on EVs, including forming, post-processing and recycling. Some key stages in the aluminium alloy's full life cycle are described in Section 2, followed by the advanced forming, post-processing and recycling techniques in Sections 3 to 5. In the last section, the main problems associated with the sustainable development of aluminium alloys used on EVs are summarized.

2. Key Stages in the Full Life Cycle of Aluminium in EVs

Figure 1 illustrates the key stages of the aluminium alloy's full life cycle, including the forming, post-processing and recycling processes. The forming process ensures high mechanical properties and high-precision products. For some specific cases such as with the narrow dimensional tolerance and high mechanical process, post-processing such as reshaping and heat treatment is necessary. Recycling can take place during the manufacturing process (R2 and R3) or after applications (R1 and R4). Recycling can save energy and cost by avoiding purchasing raw materials or conducting extra manufacturing processes [17,18]. More details about the closed-loop recycling strategy or circular economy for automotive aluminium can be found in the references [19,20].

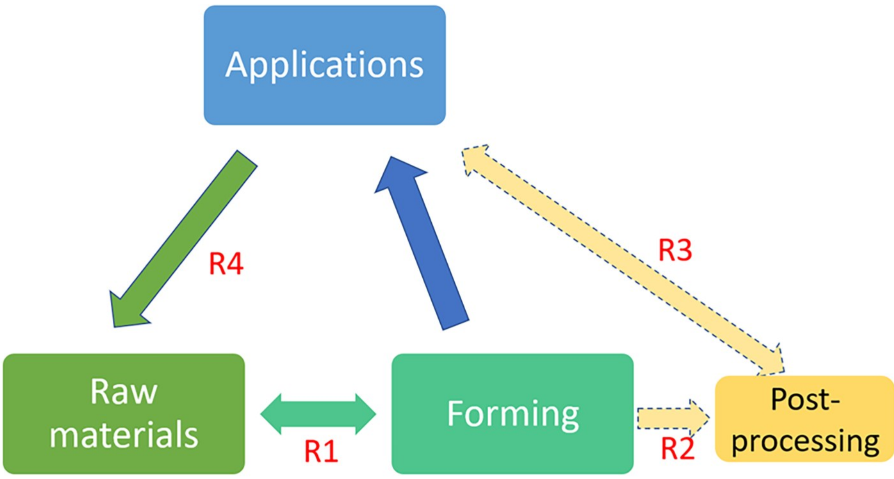

Figure 1. Key stages in the full life cycle of aluminium alloys in EVs (R1-R4: possible recycling processes).

3. Advanced Forming Process

The aluminium forming processes are diverse. Two techniques, ISF and HFQ®, for complex-shaped and thin-walled products have been developed and are described below.

ISF deforms the metal sheets locally and gradually using a hemispherical-head tool controlled by the CNC machine, capable of manufacturing complex and thin-walled products [21,22]. It has advantages such as low cost, high flexibility and improved mechanical properties, suitable for manufacturing prototypes or small panels [22–24]. There are different types of ISF, such as the single-point or two-point ISF, heat-assisted ISF, a hybrid of stretch forming and ISF [25]. The two-point ISF shows better formability than the single-point one due to the plane strain deformation mode [26]. In the heat-assisted (assisted by hot air blowers, laser beam, electric heat, friction-stir or ultrasonic vibration) processes, the hard-to-deform materials are heated locally for higher formability and more complex products [27–31]. The stretch bending was integrated with the ISF for high production efficiency [32, 33]. Although it offers many benefits for building prototype car parts without needing expensive tools (forming dies), the drawbacks of this technique, such as the low process efficiency, low geometric accuracy or poor finish surface, prohibits its applications in mass production.

HFQ®, proposed by Lin et al. [34–36], overcomes these disadvantages by integrating the quenching process with the hot stamping process using rigid dies. It enables the products with high mechanical properties and high geometric accuracy by tailoring the microstructure evolution along the entire process via

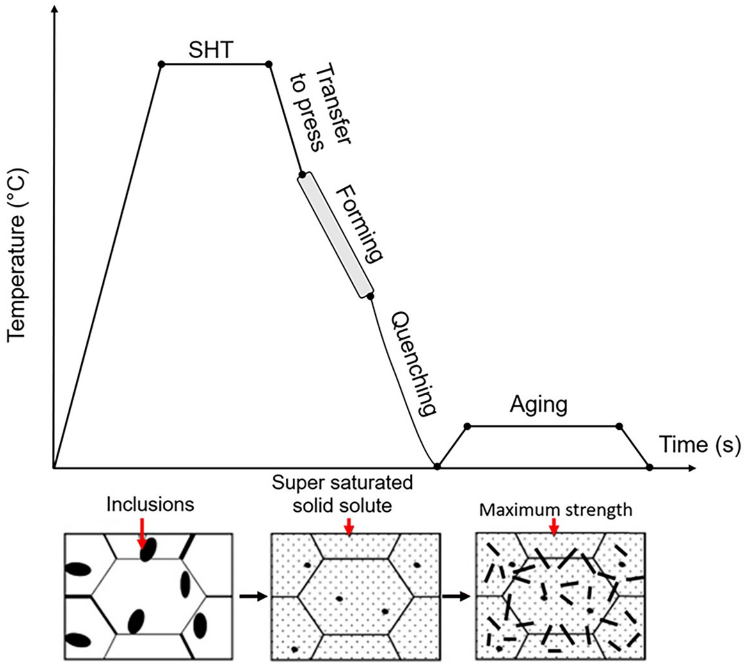

Figure 2. Temperature history and micro-mechanisms in hot form and quench (HFQ®) process. Reprinted/adapted with permission from [35,36].

carefully controlling the temperature and strain rate history. The temperature profile on the blank during the process, along with the mechanisms, is shown in Figure 2. The high forming temperature above its solid solution temperature dissolves the hardening precipitates and guarantees high material formability and capability for producing complex-shaped products [5,37]. Fast quenching with die constraints can effectively avoid the potential springback and ensure high dimensional accuracy [38]. This technique efficiently drives the applications of aluminium in automotive from small volume to mass volume [39 – 41]. Recently, this technique is integrated with equal channel angular pressing, achieving improved mechanical properties and formability [42,43].

4. Post-Processing

Post-processing includes heat treatment for improved mechanical properties and reshaping for improved geometric accuracy. Reshaping techniques have been studied and used in industries intensively for a long time, such as in straightening [44, 45] and ironing [46]. However, these techniques can only correct dimensional defects in products with simple geometries. Advanced reshaping techniques have been developed for dimensionally correcting the cross sections of complex U channels. For example, the transverse stretching and local bending technique corrects the large gap opening, sidewall and bottom convexity efficiently and at a low-cost [47]. This technique integrates the stretching and bending mechanisms, mitigating and offsetting the springback. The dimensional deviation is as low as 0.4% of the nominal value in the case of correcting a U channel with an uneven thickness [48]. Hence, this technique can be potentially applied to future high-precision aluminium sheet parts used on EVs.

5. Recycling of Aluminium

One critical issue with recycling high-strength, heat-treatable aluminium alloys used on EVs is the wide range of the portion of unwanted elements such as iron and copper in the recycled metal chips [18,49–51]. To solve this, different solutions have been proposed, including advancing the sorting techniques such as colour sorting and laser-induced breakdown spectroscopy, able to separate different kinds of aluminium alloys [52–54]; purifying the materials by fluxing [55] or segregation [56]; and solid-state recycling based on severe plastic deformation [15]. Solid-state recycling convents the aluminium chips directly into the bulky materials without melting, presenting high energy saving and high material utilization capabilities compared with the conventional remelting process [57]. Many techniques are available for the solid-state recycling process, such as hot extrusion [58], equal channel angular pressing [59, 60] and high-pressure torsion [61], which can achieve equal or higher mechanical properties compared to the original products. For further improved mechanical properties, the semisolid extrusion process was developed, whereby the pre-compacted chips are heated to a specified semisolid temperature before the final extrusion [62, 63]. It was studied that the mechanical properties can also be improved by suitable heat treatments [64]. However, solid-state recycling has not been widely used due to potential problems such as the dispersion of the second phase and the formation of the micro-voids [15]. Thus, more attention should be devoted to developing aluminium recycling techniques for high-performance aluminium alloys.

6. Conclusions and Outlook

Lightweight materials in EVs can efficiently enhance driving performance and reduce the environmental impact and energy consumption. The critical topics along the full life cycle of aluminium alloys are reviewed, including forming, post-processing, and recycling.

The aluminium alloys are reviewed particularly, due to its features of lightweight and high recyclability, contributing to zero-emission policy. Compared with the traditional vehicles, the battery materials are specific for EVs. More related information can be found in [65–67].

In EV mass manufacturing, the complex-shaped thin-walled aluminium alloys are highly demanded to produce EV batteries. Advanced techniques for forming complex thin-walled products are reviewed, including SIF and HFQ®. They encounter different difficulties, such as low efficiency and high cost. More flexible and intelligent manufacturing processes should be developed for complex products.

Post-processing such as reshaping can efficiently improve the material efficiency by correcting the dimension defects and improving the dimensional tolerance, such as the transverse stretch and local bending technique. However, the reshaping techniques for correcting the cross sections of long profiles with varying cross sections are still lacking.

Recycling high-strength, heat-treatable aluminium is urgently demanded by the large wave of end-of-life vehicles. Solid-state recycling can achieve recycled aluminium with high mechanical performance, but more research is required to improve the consistency of mechanical properties by better understanding the second phase formation and voids closure process.

Due to the page limitation, only a few representative techniques are reviewed briefly, expected to provide the audiences with general understandings of the key challenges in manufacturing the lightweight materials in EVs.

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