A Review of Friction Stir Welding and Machine Learning for Dissimilar Aluminium Alloy Joints in EV

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Abstract: The development in the electric vehicles (EVs) is tremendous in the modern-day transportation sector. The developments in this cutting-edge technology have resulted in modern vehicles in both transportation and logistics sector. The fast-growing electric vehicles have raised the demand of light-weight battery-tray structures made of high-performance aluminium alloys. Aluminium alloys play a vital role in automobile applications for its superior inherent properties. The combination of alloys such as AA5083/AA6082 and AA6061/AA7075 provide possibilities to achieve a balance between strength, corrosion resistance, formability and cost. Friction Stir Welding (FSW) has become a favored solid-state joining method for these alloys, as it decreases fusion-related defects and results in refined microstructures. At the same time, machine learning methods are increasingly applied to predict weld quality and optimize process parameters. This review focuses on recent progress in FSW of dissimilar aluminum alloys for EV battery trays, covering process parameters, mechanical properties, microstructural changes, and machine-learning-based modelling.

Keywords: Friction Stir Welding; Electric Vehicle Battery Trays; Dissimilar Aluminium Alloy Joints; Weld Quality Prediction; Machine Learning Optimization.

Introduction

The worldwide transition towards sustainable mobility has accelerated research, development, and commercialization of electric vehicles (EVs). Governments and car makers worldwide are investing heavily in EV technology to reduce greenhouse gas emissions, improve energy efficiency and reduce reliance on fossil fuels. The battery tray is one of the most important structural components of an electric vehicle because it is the primary structural framework for the battery modules. Battery trays must offer mechanical support, crash protection, thermal management and resistance to environmental degradation with minimal weight. This is the reason why the design and manufacturing of today's EV battery systems is heavily reliant on lightweight materials and advanced joining technologies.

Aluminium alloys are becoming preferred materials for EV battery-tray structures due to their good strength-to-weight ratio, corrosion resistance, recyclability and formability. Of the commercially available aluminium alloys, AA5083, AA6082, AA6061 and AA7075 have received much attention in transportation and automotive applications. AA5083 is known for its great corrosion resistance and weldability, while AA6082 is known for its higher strength and good machinability. Similarly, AA6061 offers a good balance of strength and weldability, while AA7075 is characterized by very high strength and fatigue resistance. By combining these alloys within a single structural assembly, engineers are able to optimize component performance for particular loading and service requirements. As a result, dissimilar aluminium alloy joints like AA5083-AA6082, AA6061-AA7075 are increasingly being studied for EV battery-tray applications [1].

In Friction Stir Welding (FSW) a non-consumable rotating tool (shoulder and pin) is inserted into the joint interface and traversed along the weld line. The frictional heat generated during the process softens the material, but does not reach melting point, hence promotes plastic deformation and mixing of the material. Fusion defects are removed, thereby eliminating many fusion-related defects and yielding better mechanical properties and improved microstructural integrity. Several studies have shown that FSW can be successfully applied to join dissimilar aluminium alloys and fine grain structures can be produced by dynamic recrystallization.

In recent years, artificial intelligence and data-based manufacturing have developed rapidly, which brings new opportunities for process optimization in welding engineering. Machine Learning (ML) techniques have shown a great potential in analyzing complex nonlinear relations between process parameters and weld quality characteristics. The tensile strength, hardness, surface roughness and defect occurrence in friction stir welded joints have been successfully predicted using artificial neural networks (ANN), Random Forest (RF), Support Vector Regression (SVR), Decision Trees (DT) and Gradient Boosting Machines (GBM). ML models can utilize experimental datasets for parameter optimization, which can decrease the number of physical experiments and enhance the prediction accuracy and manufacturing efficiency [2]. This review article gives a careful interpretation of the current advances in friction stir welding of dissimilar aluminium alloys, with particular emphasis on AA5083-AA6082 and AA6061-AA7075 combinations of interest for EV battery-tray applications.

Dissimilar Aluminium Alloys for EV Battery-Tray Applications

An electric vehicle's battery tray is structurally very important; it provides mechanical stability for the car, protects the passengers inside the car, and provides thermal control to ensure safe operating temperatures. In addition to the inert mass of the battery modules, the tray will be subjected to loads due to vehicle motion, vibrations during operation, forces caused by impacts, and contact with environmental conditions throughout the life of the vehicle. Due to the significant weight reduction versus traditional steel structures, modern electric vehicle battery trays and their supporting structures are made from aluminium alloys rather than steel alloys with comparable mechanical properties.

AA5083 is a non-heat treatable aluminium-magnesium alloy. It is largely known for its outstanding corrosion resistance, predominantly in nautical and severe environmental conditions. The alloy has good weldability and moderate to high strength, making it suitable for structural applications where robustness is a primary concern. The high magnesium content in AA5083 makes the alloy more resistant to stress corrosion cracking than many of the heat-treatable aluminium alloys. In EV battery tray structures, outer enclosure fittings are often considered to be mass-produced from AA5083 due to its resistance to environmental contact, humidity, road salinities and dynamic thermal cycling.

AA6082 is a heat-treatable aluminium-magnesium-silicon alloy. From an engineering perspective, AA5083 has enhanced strength relative to AA5082, decent corrosion resistance, and good machinability. The majority of its uses as a material are found in the fields of mechanical engineering and in the fabrication of automobile frames and other components used in transportation. Due to its superior yield strength and high cycle fatigue properties, AA5083 is a good candidate for use in sections of battery trays that will carry significant loads. However, while AA6082 has much better mechanical properties than AA5083, it has poorer corrosion resistance. Therefore, pairing AA5083 and AA6082 in a single part gives designers the ability to utilize AA5083's corrosion resistance along with AA6082's superior mechanical properties for the best combination of durability and structural integrity.

The AA6061 alloy is one of the most versatile and adaptable heat-treated aluminium alloys, commonly found in aerospace, automotive and construction industries. The key elements alloying an AA6061 are magnesium and silicon respectively. As a result of its well-balanced mechanical properties, AA6061 has traditionally been selected for its ability to provide lightweight structural components that are easily fabricated and consistently produce good results. AA6061 is therefore specifically suited for structural mounts, support structures and mounting components in applications such as battery trays where moderate to high strength properties and ease of manufacture are required [3].

AA7075 is an excellent strength to weight ratio aluminium-zinc alloy that has come into widespread use for aircraft structures due to its high strength when compared to AA6061, AA6082, and AA5083. The tensile properties of various grades of AA7075 are much higher than their respective grades of AA6061, AA6082 and AA5083. Friction Stir Welding has proven to be effective at aiding the joining of dissimilar alloys such as AA7075 to other aluminium alloys creating very reliable structural connections [4].

Table 1. Mechanical Property comparison of Different grades of Aluminium alloys

Property	**AA5083**	**AA6082**	**AA6061**	**AA7075**
Density (g/cm³)	2.66	2.70	2.70	2.81
Ultimate Tensile Strength (MPa)	290–340	310–340	290–320	510–600
Yield Strength (MPa)	145–215	250–280	240–280	430–500
Corrosion Resistance	Excellent	Good	Good	Moderate
Weldability	Excellent	Good	Excellent	Fair
Typical Application	Battery enclosure	Structural members	Frames & supports	High-load regions

Recent advances in computational modelling and machine learning have extended the scope of optimization opportunities for dissimilar aluminium alloy joints. Experimental datasets of AA5083-AA6082 and AA6061-AA7075 friction stir welding studies are being increasingly used for the progress of analytical models for tensile strength, hardness and defect formation. These trends suggest that the amalgamation of advanced joining technologies with data-driven optimization techniques will be an important aspect of future EV manufacturing systems.

Effect of Process Parameters on Mechanical and Microstructural Performance

Effect of Rotational Speed

Rotational speed is one of the most important parameters in the process of friction stir welding, as it controls the heat generation and material plasticization. Increasing the rotation speed increases the frictional heating between the tool and workpiece, thus promoting better softening and flow of the material. Sufficient heat generation is conducive to dynamic recrystallization and improves the metallurgical bonding between dissimilar materials.

Several researchers have found that mechanical properties are better at moderate rotational speeds than at excessively low or high rotational speeds. At low rotational speeds, low heat generation causes insufficient plastic deformation, poor material mixing, tunnel defects and weak bonding at the interface.

It has been observed that rotational speeds generally in the range of about 800 to 1200 rpm have often resulted in good tensile properties and fine microstructures for AA5083-AA6082 joints. Similar studies involving AA6061-AA7075 alloys also revealed optimal tensile strength at moderate rotational speed ranges with sufficient heat input to promote good mixing, but not so high as to cause significant thermal softening.

Effect of Traverse Speed

The traverse speed, also known as the welding speed, controls the speed at which the tool moves along the joint line and has a direct effect on the heat input per unit length of the weld. The thermal cycle of the material during welding depends on the ratio of the rotational speed and the traverse speed. Lower traverse speeds lead to an increase in heat input, as the rotating tool is in contact with a given region for a longer time. This additional heat improves softening of the workpiece and flow characteristics. However, extreme heat input can result in grain development and reduction in mechanical strength. Increased traverse speeds resulted in lower heat input and higher production competences.

Studies on AA5083-AA6082 joints illustrates that the finest mechanical properties are found at traverse speeds of 40–80 mm/min. Similarly, the studies on AA6061-AA7075 show that reasonable traverse speeds lead to best combinations of tensile strength and hardness. Consequently, the choice of traverse speed must be made vital in the productivity necessities and the metallurgical superiority. The interface between rotational speed and traverse speed plays an exclusively important role. Instead of optimizing these parameters independently, researchers are progressively looking into their collective effects with the use of statistical design approaches.

Effect of Axial Force

The axial force is a measure of the impact that the welding tool experiences due to the sliding motion of the tool against the workpiece during the welding process. This parameter is critical to ensuring that the tool shoulder remains in contact with the workpiece while ensuring proper material consolidation. A lack of sufficient axial force will result in poor association and the creation of voids in the weld nugget, leading to a reduction in the tensile strength and fatigue performance of the weld.

Research has shown that moderate axial forces usually provide the best welding conditions. Suitable axial pressure facilitates material flow and consolidation while sustaining dimensional stability. Researchers studying dissimilar aluminium alloys have reported that optimized axial force values progress tensile strength, hardness distribution, and defect resistance. Microstructural investigations reveal that suitable axial force increases dynamic recrystallization and encourages the formation of a homogeneous stir zone [5]. Recently statistical optimization procedures and machine-learning algorithms have been progressively used to find finest combination of parameters. These methods have revealed better predictions than traditional trial and error experimentation. Thus, machine learning is growing into a significant instrument for speeding up process development and refining the prediction of weld quality [6].

Table 2. Influence of Welding Parameters in FSW

Parameter	Primary Influence	Effect of Low Values	Effect of High Values
Rotational Speed	Heat generation, material flow	Poor mixing, tunnel defects	Grain coarsening, flash
Traverse Speed	Heat input per unit length	Excessive heat input	Insufficient plasticization
Axial Force	Consolidation	Voids, weak bonding	Excessive flash, thinning
Tool Profile	Material transport	Poor mixing	Improved flow
Material Positioning	Flow characteristics	Uneven structure	Improved bonding

Conclusion

Friction stir welding (FSW) has been confirmed to be an effective joining procedure for dissimilar aluminium alloys such as AA5083-AA6082, AA6061-AA7075 for electric vehicle battery-tray applications. The mechanical and microstructural properties of the joints are dynamically changed by the welding constraints, such as rotational speed, traverse speed, axial force and tool geometry. It has been newly reported that enhanced FSW conditions can produce fault free joints with increased strength and refined microstructure. Besides, the application of machine learning techniques has confirmed encouraging potential in forecasting weld quality and improving process parameters. FSW combined with machine learning provides a promising direction towards efficient, lightweight and intelligent manufacturing solutions for next-generation EV battery systems.

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