A Taguchi–SVR Methodology for Friction Stir Welding of Dissimilar Aluminium Alloys for EV Battery Tray Applications

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Abstract: The need for Lightweight EV battery system parts is driving an increasing demand for welding technologies capable of joining distinct Aluminium alloys while ensuring adequate mechanical integrity. This work demonstrates a systematic experimental approach for friction stir welding (FSW) of AA6082-AA5083 and AA6061-AA7075 alloys couples. Emphasis was placed on the reduction of the experimental efforts with the investigation focused on the relationship between welding parameters and joint performance. The four welding parameters – tool rotational speed, traverse speed, axial force and tool pin profile were considered at 3 levels and planned using a Taguchi L27 orthogonal array design. Tensile and yield strength, hardness and impact properties of the welded samples were evaluated. Taguchi's Signal-to-Noise ratio was used to identify optimal levels and combinations of the welding process parameters and Analysis of Variance (ANOVA) used to determine the relative significance of the selected welding parameters. Support Vector Regression (SVR) with radial basis function kernel was used as a data driven modelling technique to predict tensile and yield strengths of welds as a function of welding parameters. This method was used with 5-fold cross validation and hyperparameter optimization in order to improve predictability of models against the limitations of available experimental data. This combined strategy involves design of experiments, experimentation, analysis and machine learning into a consistent framework for investigation of various Aluminium alloy FSW. This strategy could support evaluation of weld parameters and prediction of performance of welded Aluminium alloys in light weight EV battery trays.

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

Introduction

The increase in electric mobility requirements has underlined the need for light weight structural components that have sufficient mechanical resistance while contributing to the weight reduction of a vehicle. As Aluminium Alloys have good lightness; strength to weight ratio, corrosion resistance and are easy to weld. The Aluminium Alloys are an interesting option for designing Battery trays framework. However, Battery tray frameworks may require joining different Aluminium Alloys to provide the right balance of strength, plasticity, toughness, and energy absorption. Joining different Alloys is very challenging due to their different mechanical and Thermal properties which can affect their flow and heat distribution and joint stability. Therefore, Friction Stir Welding (FSW) can be considered an acceptable alternative to the conventional welding of inappropriate aluminium alloys. This is a solid-state process that relies on frictional heating, excessive plastic de formation and mechanical stirring process to create joint without complete liquefaction. It can overcome the problems associated with solidification and prolonged thermal exposure (1).

The FSW quality of a joint heavily depends on process parameters interaction of tool rotating speed; tool travelling speed, axial force, tool geometry and so on, if this latter combination is wrong the joint quality may not be guaranteed owing to improper plasticisation, too much generation of heat, inconsistent material flow (2).

Two suitable combinations of different alloys for heterogeneous jointing, i.e. AA6082 -AA5083 and AA6061-AA7075 alloys, have a good relation in terms of strength, hardness and behaviour under deformation; in fact, AA6082 is one of the higher strength and moderate formability Al-Mg-Si alloys while AA5083's excellent fatigue resistance and sea-water corrosion resistance have earned it a long-established property as, an All-Mg alloy with superior durability. AA6061 is a versatile aluminium alloy which' precipitation is Hardened; in parallel AA7075 alloy has greater strength but is less resistant to prolonged elevated temperature as welding implies. These differences imply more sensitive parameter choice to create FSW of light weight structural purpose joints (3).

One key problem faced during FSW investigation includes acquiring enough experimental data without excessive numbers of fabricating runs; for a full factorial study of four parameters with three levels each would involve 81 (3^4) test configurations which might have time, material & resources consumption costs. Keeping this problem in concern in our study a L27 orthogonal array from the Taguchi techniques is selected where the experimental work involves a total of 27 tests with proportional inclusion of all test conditions at the chosen levels of parameters.

The outcomes of experiment are subjected to Analysis of Variance (ANOVA) and signal-to-noise ratios to select the levels of the variables responsible for desirable welding parameters. Moreover, to obtain the best prediction of welding responses from known input variables, an analysis of machine learning is also investigated to formulate the nonlinear interdependency between input variables (welding parameters) and output responses (mechanical properties) by applying a Support Vector Regression (SVR) technique. Through this unified experimental & modelling (Taguchi, ANOVA and SVR) paradigm we attempt to provide a systematic, efficient, and informative research approach towards dissimilar Al alloy FSW; toward its application in lightweight structures like the EV Battery Tray.

Materials and Methods

Material Selection and Preparation

For this research, two combinations of alloys were decided from four commercially available Aluminium Alloys such as AA6082, AA5083, AA6061 and AA7075 to conduct two friction stir welding operations, AA6082-AA5083 & AA6061-AA7075 on the basis of the mechanical & metallurgical properties & its importance for usage in light structural applications. AA6082 is a Heat Treatable structural aluminium alloy having an excellent resistant capacity against oxidation. AA5083 is a good type of Al-Mg alloy having long durability and high corrosion resistant properties. AA6061 offer balanced combination of strength and weldability. AA7075 is high strength aluminium alloy which could have applications in the critical structural usage.

The metals for the experiments were available in plates of about 200 mm X 100 mm X 6 mm in dimensions. The plates were prepared to this dimension and joined surface were treated with SiC abrasive paper of 120-grit for removal of surface oxides and contaminations. After that cleaned surface was washed by acetone. All of these pre-treatments were carried out on order to attain a good state of contact at surface in the case of friction stir welding.

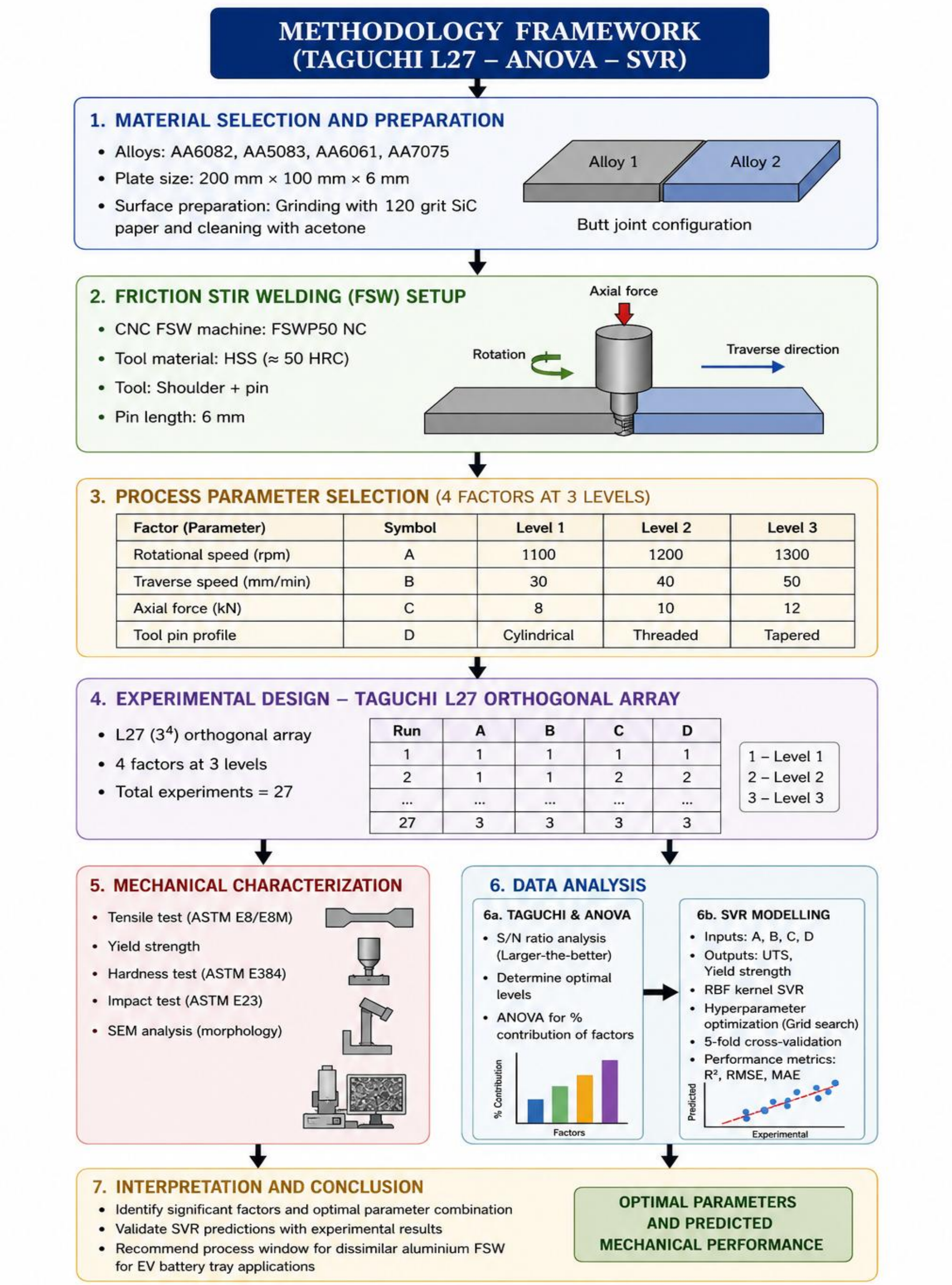

Fig. 1. Methodology and experimental workflow for Taguchi L27–ANOVA–SVR framework.

Friction Stir Welding Arrangement

The welding experiments were conducted utilizing a FSWP50 NC computer-numerical control friction stir welding machine, which provides control over rotational speed, welding speed and axial force. The two alloy plates were brought together with a butt joint and firmly secured to the table top to prevent movement during the welding operation. The surface of the joint between the two plates was properly aligned before applying any mechanical work.

A high-speed steel (HSS) tool of approximately 50 HRC was used. The tool consists of a shoulder and a cylindrical tool post of roughly 6mm in length. A tool capable of withstanding the temperature and mechanical strain due to friction stir welding was chosen. This experiment uses the second type of tool designed previously, though an experiment utilizing a tapered cylindrical tool shape was performed initially. This experimentation expanded the analysis to determine the behaviour of different pin profile configurations.

Design of Experiments

A Taguchi L27(3) orthogonal array was applied for efficiently design the experimental work, to systematically determine which of any number of potential combinations of factors to evaluate; namely the effect of four factors of FSW, rotational velocity (A), traverse rate (B), axial force (C) and pin geometric design (D). Each factor was determined three levels. Selected factors values used were such that: rotational rate varies between (1100 rpm to 1300rpm), traverse rate varies between (30 to 50 mm/min), the axial force has value varying between (8 and 12 kN). Three various pin-profile was applied. This approach reduced the number of test cases from 81 for 3 factorials to 27 test case runs. An equal representation is given by the orthogonal array that systematic evaluates individual effects. Each L27 level condition of a test was employed independently and treated as separate joining process before taking test pieces from weldments for evaluation (4).

Mechanical Characterization

The welded plates made from experiments, underwent a series of mechanical property tests. The welds were taken for impact tests as well as tensile tests to evaluate yield stress, ultimate tensile strength and overall joint characteristics. Hardness surveys were also conducted for tensile and impact test specimen for different locations around the weld region. The tests for tensile and impact strength were planned according to standard ASTM standards; ASTM E8/E8M and ASTM E384 respectively.

Mechanical and impact properties resulting from individual L27 experiments set the main database against which statistical analysis will be carried out and comparisons will be based. A number of responses were used as: tensile strength, impact strength, ultimate tensile strength and hardness (for surface, root and HAZ) etc, against different input factors. SEM analyses are also used to explore welded features and to supplement mechanical interpretation (5).

Taguchi and ANOVA Framework

The responses were considered with the aid of the Taguchi signal-to-noise (S/N) method. As higher values for yield strength, tensile strength, impact strength and hardness are desirable for such a structural member, the larger-the-better condition of the S/N has been used. It was used to find out optimum level of each parameter corresponding to better mechanical response.

The signal-to-noise response at each parameter was then determined for every level and the best level corresponding to better performance. Subsequently, the contribution analysis ANOVA was used to identify effects of traverse speed, rotational speed, tool pin and axial force on responses with some emphasis placed on their relative comparison. The study was conducted with a view to identifying preferred process variables on the basis of a numerical investigation based on results from the level-by-level, S/N (6).

SVR-Based Predictive Method

The FSW process parameters: rotational velocity, transverse velocity, axial force and tool pin geometry, were selected as independent parameters, whereas the main prediction outcomes were the ultimate tensile strength and yield strength of weld. Then, a predicted dependence between the FSW input process parameters and mechanical outputs was determined by using SVR, once, following experimental and statistics data analysis, the numerical parameters were normalized and the geometry of the tool pin were represented as digitized images before developing the model. An RBF kernel was adopted to deal with the potential nonlinearity between parameters and behaviours (7).

Because of the lack of sufficient measurements in the L27 experimental datasets, 5-fold cross-validation was performed in the model validation. Five-fold cross-validation was also included, to optimize some critical SVR parameters. The principal SVR parameters, namely **C, γ and ε**, were optimized through a grid-search procedure. Model performance was quantified using **R^2, RMSE and MAE**, and the resulting predictions were compared with the experimental observations through parity plots.

Results and Discussions

The experimental results from the L27 design show that the proposed reduced-experiment method can be used to study the effects of FSW process parameters on dissimilar aluminium alloy joints. A predictable difference in tensile strength, yield strength, hardness and impact energy was found by manipulating the four investigated parameters of rotational velocity, feed rate, axial force and tool pin profile. The analysis revealed that the two alloy couples did not have comparable reaction behaviour and the AA6082-AA5083 pair had a somewhat better balance between the measured tensile and impact energies while AA6061-AA7075 had higher hardness so it becomes imperative to consider different mechanical responses for different FSW joints.

The Taguchi L27 analysis provides a logical process to optimize four parameters at three levels a total of only 27 tests instead of the 81 required for a fully factorial design. S/N ratio was analysed by a larger-the-better criterion for all the measured mechanical responses to determine the optimal levels for the parameters for FSW. The level trends represent first approximations for parameter combinations expected to yield better performance. Finally, ANOVA was employed as to provide a relative significance of the process parameters as to help strengthen the Taguchi analysis since Taguchi analysis provides the optimum levels while ANOVA gives quantitative indications for importance.

The SVR analysis allowed to look beyond interpretation into prediction; a RBF based SVR was developed including five-fold cross validation where each mechanical response was mapped using rotational speed, traversing speed, axial force and pin profile as features. It can be seen that Ultimate Tensile Strength had an **R^2** value of 0.745, RMSE of 4.54 MPa and MAE of 3.67 MPa for the model. While for Yield strength it can be observed that the **R^2** value was 0.791 with RMSE=3.96MPa and MAE= 3.18 MPa suggesting that yield strength was predicted more consistently. The charts show the comparison between the experimental response and predicted response thereby illustrating the overall variation captured by the SVR model.

The SEM analysis complements the findings of the experiment qualitatively. AA6082-AA5083 showed a much more uniform and homogenous microstructure in comparison to the AA6061-AA7075 whose characterized by varied morphology. Both of these aspects can be interpreted to correspond to the differing mechanical characteristics shown by both alloy couples. It shows that the proposed Taguchi-ANOVA-SVR technique represents a coherent method for the combined experimental design reduction, statistical analysis and predictive modelling approach. This method with 27 tests provides a practical approach in identifying relevant FSW characteristics and generating preliminary mechanical response predictions for dissimilar aluminium alloys for use in light weight EV structural applications.

Conclusion

This work formulated a combined Taguchi-ANOVA-SVR method to investigate the effects of friction stir welding parameters on dissimilar aluminium alloy joints pertinent to light electric vehicle battery tray applications. Utilizing the L27 orthogonal array reduced the full-factorial design number of experiments from 27 experiments to 15 with a significant decrease in total experimental run-time when determining the effect of four three-level welding parameters-rotational speed, traverse speed, axial force, and tool pin profile. The Taguchi S/N and ANOVA analysis presented two mutually beneficial techniques to determine beneficial parameter levels and relative significance of variables among the study's process parameters.

The proposed extension to a RBF-based SVR model predicted performance levels, thereby moving beyond pure experimental and statistical analysis. With five-fold cross-validation, the optimally designed SVR model presented R^2 values of 0.745 and 0.791 for UTS and yield strength respectively and revealed helpful predictive ability for the experimental dataset generated. Analyses also proved that AA6082-AA5083 yields better balance of tensile-impact property than that the performance between AA6061 and AA7075 yields greater hardness. Overall, the developed framework of Taguchi-ANOVA-SVR is an effective tool in reducing experimental numbers, analysing process effects and developing initial predictions of mechanical performance in dissimilar aluminium FSW joints. The approach herein could serve as a basis of future validation and process optimization efforts toward electric vehicle battery tray production.

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