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Numerical Modelling Techniques Applicable for the Prediction of Residual Stresses and Distortion due to Mild Steel DH36 Friction Stir Welding

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Abstract: Friction stir welding involves a multi-physics phenomena, including visco-plasticity, material flow, metallurgical transformation, heat generation, thermal straining and structural interaction. Numerical modelling provides an efficient and cost effective tool capable to analysis and predict the different phenomena. This study integrates different numerical modelling strategies to ultimately develop a robust yet computationally efficient modelling technique capable of predicting residual stresses and distortion due to FSW. A computational efficient local-global numerical model capable of predicting the material visco-plastic flow, thermal transients, stir / heat affected zone, residual stresses and distortion developed due to friction stir welding of DH36 plates is described. Different thermo-elasto-plastic modelling strategies ranging from analytical to transient numerical models are explored and the most robust and computational efficient strategy is identified through cross-reference with the realistic experimental test results.

Keywords: Numerical models, Residual stresses, Out-of-plane distortion, FSW

Introduction

Numerical modelling provides an efficient and cost effective tool that is able to predict the temperature evolution, inherent residual stresses and distortion developed due to FSW

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[1]. A coupled multiphysics numerical model capable of simulating the interaction between heat generated, material flow, metallurgical evolution, visco-plastic and elasto-plastic structural response, is required to fully capture the different physical phenomena present in FSW [2], [3]. However some interactions are weak and can be significantly simplified. For example the thermal properties of the parent material are relatively independent from strain rate and material flow. Furthermore adopting a fully coupled approach requires significant computational power and time, defeating the purpose of having a numerical model capable of predicting residual stresses and distortion Acknowledgement

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[1]. This study explores and describes different modelling strategies that can be used to ultimately predict the residual stresses and distortion developed due to friction stir welding. A sequentially uncoupled local CFD - global thermo-elasto-plastic FEA model is adopted.

Local - global numerical models for the prediction of residual stresses and distortion due to FSW

The local – global modelling strategy adopted in this study and applied to FSW of DH36 steel is shown in figure 1. In the first instance the heat generated during FSW and the stir / heat affected zone shape, have to be identified. This could be done in various ways. For instance analytical solutions that define the heat generated developed during FSW, are available. Nonetheless the accuracy of such analytical solutions is highly dependent on the accurate definition of empirical variables such as shear stress or kinematic co-efficient of friction [4]. This can be achieved through comparison and reverse engineering, with experimental thermocouple results [5]. On the other hand the stir / heat affected zone shape can defined through macrographic images of welds [6]. However, it is not always possible to have such test results and a means to fully predict the heat generated and stir/ heat affected zone shape is required. This could be achieved through a local visco-plastic computational fluid dynamics model where the shear, material flow, heat generated and stir /heat affected zone shape for specific welding parameters are first predicted [7]. This model is described in more detail in another paper presented at this conference [8]. Through this modelling strategy influences due to heat sink parameters, tool shape and welding parameters can be investigated in terms of thermal transients developed during welding.

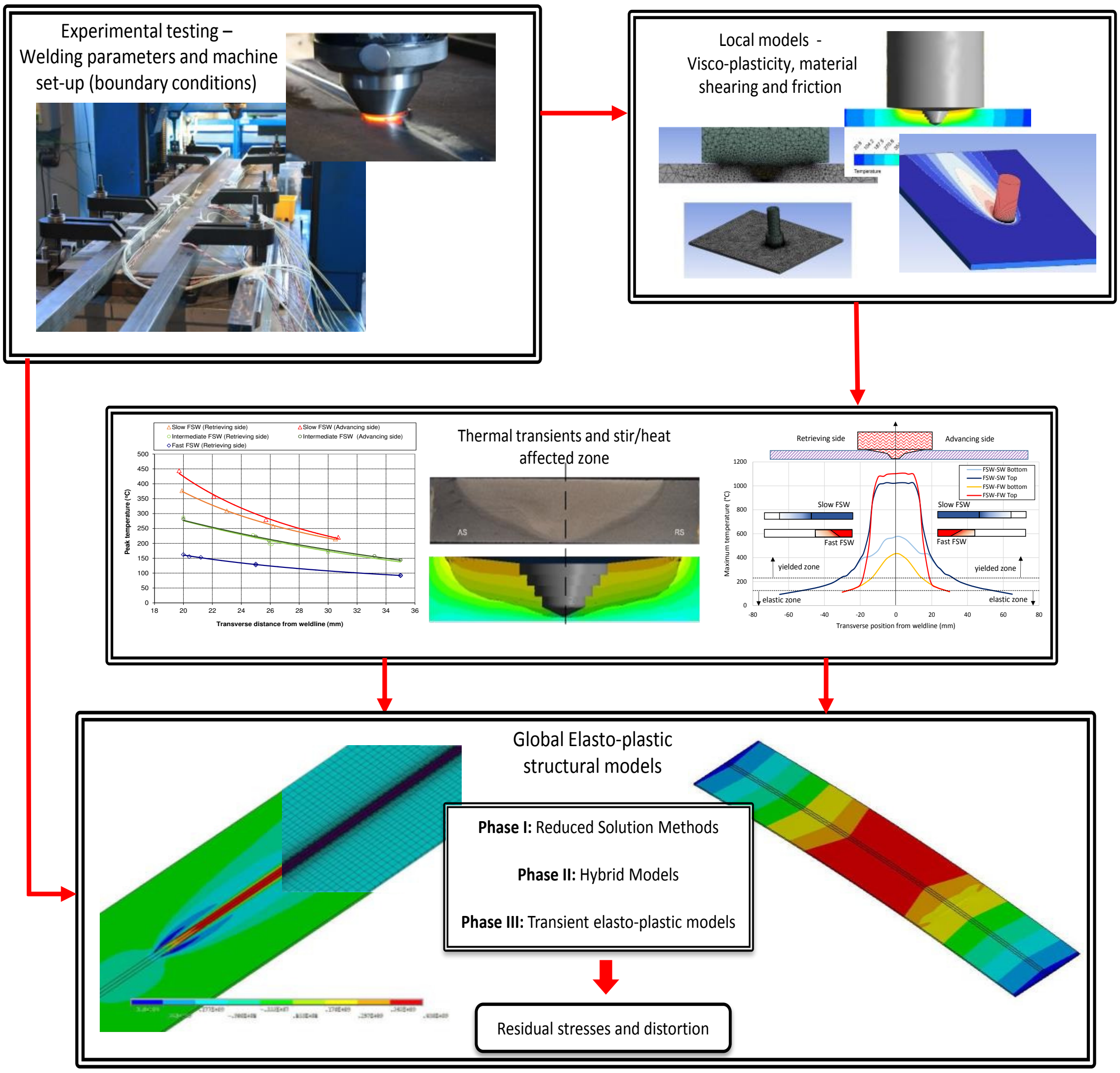

Figure 1: Numerical modelling strategy and integration between local and global models

The predicted thermal gradients are then fed into a global structural model for final prediction of residual stresses and distortion. Here the full plate stiffness properties including clamping boundary conditions are simulated. Three numerical modelling strategies ranging from computationally efficient analytical models to more complex transient elasto-plastic numerical models have been developed and investigated. These include:

- Phase I models: Reduced solution methods based on elasto-plastic analytical algorithms [9] that identify FSW contraction forces and applied to elastic static room temperature material properties structural models.
- Phase II models: Hybrid models [10] that take into account non-linear material properties but solved in a two-step heating and cooling cycle in a static manner
- Phase III models: Transient elasto-plastic models [5], [11] that applies the developed thermal strains in a transient manner with non-linear material properties included.

To maintain confidence in the numerical approach adopted, the numerical models are cross-referenced to realistic test results. In the first instance the thermal transients developed during welding are measurement by means of thermocouple arrays. These measurements gave an insight of the amount of heat being generated, together with highlighting the significant influence of heat lost to the machine bed acting as a massive heat sink and ultimately effecting the final residual stress and distortion outcomes. In fact temperatures in excess of 500˚C where recorded on the machine bed. Effects due to phase transformations and plastic strains are incorporated in the structural models by applying the appropriate material properties that are dependent on the cooling rates developed during welding. The predicted thermal strains, residual stresses and distortion are also validated through a series of strain gauge measurements, hole-drilling residual stress measurements and distortion surface topology measurements.

Reduced solutions provide a cost efficient method to identify the out-of-plane distortion through simple analytical solutions following elasto-plastic algorithms. These models are capable of identifying the welding contraction forces developed due to FSW and when applied to an elastic structural model, are able to predict the out-of-plane distortion. Due to the application of fictitious thermal loading and the use of room temperature material properties their accuracy is limited. Nonetheless these models are capable of giving an insight to which process parameter is capable of leading to less distortion. On the otherhand transient models are capable of fully modelling the evolution of strains and stresses where influences due to clamping, volume changes due to phase transformation and elasto-plastic temperature dependant material response are taken into consideration. The results attained through these models are in good agreement with the experimental test results but are highly computationally intensive. To this end hybrid models were developed that take into account all material non-linearities but are solved in a three step heating, cooling and unclamping phases. The results attained from the hybrid models are also in good agreement with the experimental test results and open up the possibilities to numerically analyse friction stir welded assemblies that are possibly in excess of 6m long. These models provide designers and industrial users to assess FSW in a fast and accurate manner.

The combination of experimental and numerical analysis provides a thorough understanding and advancement in knowledge on friction stir welding. For example both experimental and numerical models have shown that faster traverse speeds in friction stir welding, does not necessary lead to less out-of-plane distortion. Other influencing parameters such as heat sink and clamping boundary conditions, work-piece stiffness and support configurations effect the final residual stress and distortion outcomes that can be investigated using a local-global numerical approach.

Conclusions

The use of numerical models provides an insight on the parameters and boundary conditions influencing the development of residual stresses and distortion in FSW, that can be used to optimise the fabrication procedure. Various numerical modelling techniques are possible ranging from a fully coupled multiphysics, visco-plastic, material flow, thermo-elastoplastic numerical model to relatively simple local-global numerical approaches that uncouples the visco-plasticty and material flow from the thermo-elastoplastic response. The fully coupled modelling strategies require significant computational time that probably defeats the purpose for design engineers to use numerical models to explore different fabrication procedures. This study presents computationally efficient numerical modelling techniques applicable for the prediction of residual stresses and distortion in FSW of DH36 steel plates. A good agreement with the experimental test results was achieved proving that simplifications can be taken to model the FSW welding process. Various strategies have been adopted ranging from analytical solutions to transient thermo-elastoplastic numerical models. The numerical modelling strategies were employed to investigate the influential factors such as heat sinks and clamping boundary conditions on the inherent residual stresses and distortion.

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Main information of the work.