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Modelling of heterogeneous precipitate distribution evolution during friction stir welding process

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Abstract

A numerical model based on the Kampmann and Wagner method is developed to predict the evolution of precipitate distribution during friction stir welding (FSW). The model has been applied to FSW of AA7449, an aerospace aluminium alloy. It considers both metastable and equilibrium precipitate phases and the transition between them. It also predicts the evolution of grain boundary precipitates and their effect on the precipitate free zone size. The model has been calibrated against results from isothermal and quench experiments. Subsequent predictions for welds show good qualitative agreement between the model and observation. The model has also been used to explore the effect of different FSW parameters on the predicted precipitate evolution.
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1. Introduction

Friction stir welding (FSW) is a solid-state joining method in which a rotating tool is used to mix material across the join line, subjecting it to both heat and deformation. This results in profound microstructural changes, particularly for materials that contain precipitate distributions that are unstable at elevated temperature, such as aerospace aluminium alloys. FSW usually results in the replacement of fine, homogeneously arranged precipitates (typical of the starting condition) with coarse, highly heterogeneous distributions. The size, distribution, and nature of the precipitates after welding depend sensitively on the local thermal cycle and extent of deformation; these are functions of the alloy, process conditions, and position relative to the tool.

To understand these interactions and optimise the welding process, it would be very useful to have a microstructural model for precipitate evolution during FSW. This also presents a major scientific challenge due to the complexities of the interactions between the process and microstructure. To date, the most successful models for microstructural evolution during FSW have been based on semi-empirical approaches. For example, a process model has been developed by Hyoe et al. [1] and applied to predict hardness profiles after FSW in age-hardenable aluminium alloys. This model assumes the change in hardness can be directly related to the dissolution of the strengthening precipitate. As such, it is only applicable for alloys where the precipitate fraction is at a maximum prior to welding (T6 or T7 conditions). The model is calibrated using isothermal heat treatments and hardness measurements and there is no explicit account taken of the microstructure itself. Furthermore, only thermal effects associated with FSW are considered. Despite this simplicity, the model is remarkably good at predicting the complex hardness profiles observed across welds. However, since the model does not predict the microstructure explicitly, it is not possible to use it to investigate how the particle distribution is modified, which is critical in determining

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more complex properties such as fracture toughness and corrosion resistance.

More sophisticated models have been developed for other welding processes, which do provide a prediction of the precipitate characteristics [2–6]. The most successful of these models are based on classic kinetic theory and the Kampmann and Wagner numerical (KWN) framework [7]. This method is capable of tracking the full precipitate size distribution during a non-isothermal heat treatment cycle, and of dealing with concomitant nucleation, growth, and coarsening. Such an approach has been used by Myhr et al. [2,3] to model precipitate evolution during welding of 6xxx alloys. This model treats a single population of precipitates, and does not differentiate between the various metastable and equilibrium phases. Grain boundary precipitation is not modelled.

Deshamps, Brechet, and co-workers have developed a number of models for precipitate evolution in 7xxx alloys under both isothermal [5,8,9] and non-isothermal conditions (including welding [5]) using the KWN framework. Additional complexity has been introduced by considering two types of nucleation site (homogeneous nucleation and heterogeneous nucleation on dislocations). The multicomponent nature of diffusion is considered by ensuring flux balance is maintained, assuming the precipitates to have a fixed, stoichiometric, composition. Again, only a single precipitate type is considered. The KWN approach has also been used by Robson et al. [10–12] to predict dispersoid precipitation in aluminium alloys. An important feature of this model is that it accounts for the non-uniform solute distribution, and is thus capable of predicting the heterogeneous distribution of dispersoids observed in practice. The ability to predict heterogeneous microstructures is of key importance for simulation of the effects of FSW.

The aim of the present work was to build on these models to develop a more complete description of the precipitate evolution during FSW. In particular, two key developments have been made. Firstly, the model considers explicitly metastable and equilibrium precipitate populations. This allows the balance between different precipitate types to be explored and enables competition for solute between particles to be studied. Secondly, the model considers grain boundary precipitation. By doing this, it is also possible to predict important microstructural characteristics, such as the precipitate free zone width. In common with existing simple models for precipitate and property evolution during FSW [5,13], the present model deals only with the thermal effects associated with FSW and does not yet consider the influence of the deformation imparted by the tool on precipitate evolution. Although this deformation undoubtedly will have an influence on precipitate evolution, evidence from both experimental and modelling studies [5,6] suggest this is of second order compared to thermal effects. To demonstrate the model, it is applied to predict the precipitate evolution during FSW of AA7449, a current-generation high-strength Al–Zn–Mg–Cu alloy.

2. Modelling

The model framework is based on the KWN model [7]. A full description of the KWN method is given elsewhere [12]. This model describes the nucleation, growth, and coarsening of particles in the system considered and calculates the particle size distribution evolution during discrete time steps. Classic nucleation and growth theory is used to calculate the formation, growth, coarsening, and dissolution of particles, assuming that changes in particle size are governed by the diffusion rate of solute to or from the particle/matrix interface. Matrix compositions are determined after each time step using a mean-field approach. The updated matrix composition is used for the calculations in the subsequent time step. Using this method, the transition from nucleation and growth to a coarsening-dominated regime is naturally predicted as the precipitate volume fraction increases.

To date, the KWN model has only been applied to predict precipitation of phases of a single type. However, the method is readily extended to predict precipitation of multiple phases, which may be competing with each other for the available solute. Further complexity arises in age-hardenable aluminium alloys, where there is the possibility of metastable phases acting as preferred nucleation sites for more stable precipitates.

In AA7449, the dominant precipitate phases are η and its metastable precursors. Welding is often performed on material containing a prior dispersion of metastable and equilibrium precipitates (e.g., in the T7 condition). On exposure to a weld thermal cycle, many of the metastable precipitates dissolve or transform to the equilibrium phase. Precipitation at high temperatures during post-weld cooling is also dominated by the equilibrium phase. The aim of this work was to be able to reproduce this transition in a simple way that represents the underlying physics. To reduce model complexity, a single metastable variant is considered (η') along with the equilibrium η phase. It is assumed that both these phases possess their stoichiometric composition ($MgZn_2$). A number of studies [14–16] have shown that, in practice, the composition of both phases may differ significantly from stoichiometry, with Mg/Zn ratio in η' having been reported to be closer to 1.2 [15,16]. However, ignoring variation in precipitate chemistry greatly reduces the model complexity, without greatly influencing the results.

The model does not consider the other phases, which may form in 7449, such as T and S phase. These phases are expected in much smaller amounts than η phase, and therefore it is reasonable to neglect them. The model also does not yet include formation of Guinier–Preston (GP) zones. This means that it does not predict post-weld natural ageing. However, the maximum GP zone fraction formed by natural ageing can be estimated from the residual solute left at the end of the weld cycle, which is predicted by the model. The models used for the nucleation and growth of precipitates are described below.

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