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Prediction of prior austenite grain growth in the heat-affected zone of a martensitic steel during welding

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ABSTRACT

Engineering components operating at high temperature often fail due to the initiation and growth of cracks in the heat-affected zone (HAZ) adjacent to a weld. The size and morphology of the prior austenite grains (PAGs) in the HAZ of a tempered martensite steel weld can have a strong influence on the final martensitic microstructure. However, there are few available models to predict PAG size in the HAZ of martensitic steel welds. In this work two approaches are examined to predict PAG growth in the HAZ of a martensitic steel (P91) weld. Phase field (PF) methods, which explicitly represent the changing morphology of a representative volume of martensite grains, and approximate analytical solutions for grain growth at high temperature are examined. The predicted grain growth kinetics and final grain diameter using a two term analytical solution is shown to agree well with experimental data and with the validated PF simulation. The two term analytical model provides a versatile tool to analyse PAG growth at low computational costs. In addition, a simplified equation for predicting the final PAG diameter in the HAZ of P91 welds is proposed for engineering applications. The methods have been used to estimate the final grain diameter in the HAZ of a single bead-on-plate weld.

1. Introduction

Engineering steels, such as modified 9Cr-1Mo-V-Nb (P91) steel, widely used in high temperature piping and steam headers in power plant, have optimised microstructures to enhance their operating performance [1–3]. However, thermo-mechanical process (e.g. welding and associated post weld heat treatment) may significantly change the original microstructure of the base material, leading to microstructural degradation and premature failure of components [4,5]. It is reported that crack initiation has been observed mainly in the heat-affected zone (HAZ) of P91 welds [6–8].

The welding thermal cycle induces many changes in the final microstructure of the HAZ in a welded joint [9–12]. In particular, for martensitic steels, prior austenite grain (PAG) size and morphology determine the martensite start temperature and the final martensite microstructure and have a significant influence on welding-induced residual stresses [13,14]. The HAZ of a P91 weld is divided into a number of sub-zones depending on the peak temperature, T_p, reached during welding in these regions [15,16]: coarse-grain (CGHAZ, $T_t \le T_p < T_s$), fine-grain (FGHAZ, $A_{c3} \le T_p < T_t$) and intercritical (ICHAZ, $A_{c1} \le T_p < A_{c3}$), where T_s is the solidus temperature (= 1773 K for P91), A_{c1} is the temperature at which transformation from martensite to austenite starts during heating (= 1063 K for P91), A_{c3} is the temperature at which transformation from martensite to austenite is completed during heating (= 1193 K for P91) and T_t is an intermediate temperature to be discussed in Section 2.2 (= 1373 K for P91).

There are numerous models for predicting the thermal field during welding [17,18] and numerous models for predicting the influence of microstructure on thermo-mechanical properties [19,20]. However, to make full use of such models, it is necessary to develop relevant microstructure evolution models to link process-microstructure-property models as shown in Fig. 1. Such a multi-scale, multi-physics modelling scheme would make it possible to integrate welding process models, microstructure evolution models and structural deformation models for process parameter optimization and ultimately component lifetime prediction. The application of such multi-scale, multi-physical simulations to develop process-microstructure-property models to aid in process optimisation and microstructure design has been reported in [21,22]. In Ref. [21], a combined phase-field and finite-element model has been used to analyse the process-microstructure-property relations in a Ni-base superalloy. In Ref. [22] an overview of multi-scale, multi-physics modelling of process-microstructure-property-performance relationships in additive manufacturing has been provided.

Several methods have been developed to simulate temperature-driven grain growth in the HAZ of a welded joint, such as the Monte-Carlo (MC) method [25–27], the cellular automata (CA) method

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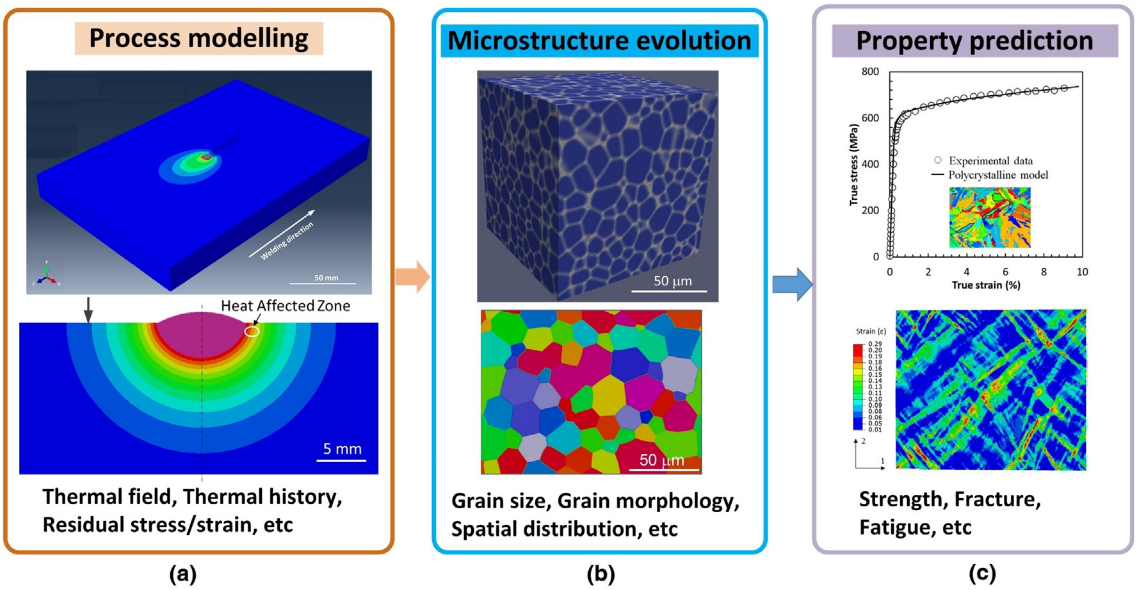

Fig. 1. Multi-scale modelling framework to facilitate process‾-microstructure‾-property predictions for materials design and process optimization [21]. (a) process model [23], (b) microstructure evolution model [24], (c) property prediction model [20].

[28,29] and the phase field (PF) method [9,30]. The MC and CA methods provide very flexible frameworks to study microstructural changes in materials. However, both methods are implemented by considering a time-dependent probability of grain growth due to the thermal history. For these models the real time of the physical system is not considered, due to the probabilistic nature of the techniques [31,32]. Thus, it is difficult to scale the numerical time step of these methods to the physical time, particularly in non-isothermal grain growth studies where time dependence is important and the time increment may vary throughout the analysis [30,32,33]. For example, in the MC method for grain growth the experimental data based (EDB) model can be used to relate the dimensionless model simulation time and real physical time. Alternatively, an atomistic model or a grain boundary migration model can be used [26]. Thus, the validity of these models depends on the reliability of the models used to establish the relationship of the simulation time with the physical time. The PF method is more suitable for simulation of non-isothermal grain growth and grain morphology in the HAZ since the thermal history can be directly included in the analysis without establishing a relationship between the simulation time and the physical time. The overall intention of the work (Fig. 1) is to couple microstructure evolution models with constitutive (stress-strain) behaviour using crystal plasticity finite-element approaches. Such approaches have been successfully implemented using a fully coupled PF and FEA [21,22]. Thus, the PF method seems more suitable for simulation of grain growth and prediction of the grain morphology in the HAZ for multi-scale modelling. However, we would expect that an appropriately calibrated MC/CA model would provide a similar level of accuracy to the PF model used in our work and there has been some success in combining CA models and crystal plasticity FEA models [31]. Analytical solutions for predicting grain growth in HAZ have also been reported [34–36]. In our previous work, application of the existing analytical solutions show poor prediction of grain growth in the HAZ of a precipitation strengthened martensitic steel, such as P91 [24]. This is because the existing analytical solutions do not consider the dissolution of precipitates at high temperature (above 1373 K), which is the determinant factor for final austenite grain size during welding of P91 steel. A modification of these solutions is therefore necessary to allow its application in precipitate strengthened martensitic steels such as P91.

To date, there are limited studies investigating the influence of thermal cycles on PAG growth in the HAZ of P91 welds [24]. Pandey et al. [37,38] have studied the influence of post-weld heat treatment (PWHT) on microstructure evolution in various zones of gas tungsten arc welded P91 pipe weldments. Austenite grain growth during austenitization in T91 steel has been studied experimentally using a Gleeble thermo-mechanical simulator, which indicates that austenite grain growth was relatively insensitive to heating rate [39]. In Ref. [40] a physically-based macroscale thermomechanical model was developed to predict PAG and lath size in P91 welds, based on a grain growth model used in the annealing process [41]. However, grain morphology and grain growth kinetics cannot be captured explicitly using this type of macroscale model. Recently, Shi et al. [24] have employed the finite element method in conjunction with the PF method to predict grain growth in the HAZ of a single bead-on-plate weld geometry. However, the effects of welding thermal cycle parameters (i.e., heating and cooling rate, peak temperature) on grain growth kinetics have not been quantitatively studied. Furthermore, as it is computationally expensive and time consuming to use the PF method to analyse grain growth kinetics, alternative methods are required to meet the demands of industry and academia to develop a full understanding of grain growth in the HAZ of precipitate strengthened martensitic steels. In the current work, three methodologies have been proposed for predicting prior austenite grain growth in the HAZ of a martensitic steel to aid in process optimisation. The influence of the heating rate, peak temperature and cooling rate on grain growth in the HAZ of a P91 steel is quantified using PF simulation in conjunction with a macroscale analytical solution. A modification of an existing macroscale grain growth model is proposed to account for precipitate dissolution in P91 steel during welding. In addition, a simplified equation is proposed to predict the dependence of PAG size in the HAZ on thermal history. The PF method, the modified two term analytical solution and the simplified equation are calibrated and validated from independent experimental data.

2. Methods for predicting grain growth

2.1. Welding thermal cycle

Fig. 2 shows a typical welding thermal cycle at a material point calculated by finite element analysis for a single bead-on-plate geometry [24,42]. During welding, the heating rate and cooling rate vary with time, making it difficult to identify which factors (i.e., heating and cooling rate, peak temperature) determine the final grain size and

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