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Theoretical and numerical modeling of the thermomechanical and metallurgical behavior of steel

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ABSTRACT

Welding or heat treatment of steel structures generate important heat gradients. These heat gradients are generally very localized and involve local dilations that lead to the appearance of residual strain and stress fields. These fields play a very important role in fatigue life prediction of structures. In addition, thermal cycles induced by welding or heat treatment operations can generate phase transformations within the material. The work presented in this paper describes an anisothermal model for steel where thermomechanical and metallurgical aspects are taken into account. In the proposed model, the thermomechanical behavior of each phase is treated independently and the macroscopic behavior is obtained using a Reuss model. In order to quantify the importance of the TRansformation Induced Plasticity (TRIP: plastic deformation due to the variation of the proportion of phases under applied stress) as well as viscosity, two descriptions are presented: first, the phases are assumed to be elastoplastic; second, the low-temperature phases are considered as elastoplastic whereas the high-temperature phase is assumed to be viscoplastic. For each description the influence of TRIP is considered by comparing results obtained with or without TRIP. These models have been implemented into the numerical code COMSOL Multiphysics by developing new modules capable of simulating phase transformation and inelastic deformation. Numerical simulations show good agreement with experimental data. Moreover, it is shown that taking into account TRIP and assigning for each phase an appropriate behavior improve the predictions of residual displacements and stresses.

1. Introduction

This paper proposes a model to describe the behavior of low-alloy ferritic steel such as 16MND5 (or SA533 in ASTM norms) which is used for manufacturing pressurized water nuclear reactor vessels. Like all low-carbon steel, this type of steel presents an austenitic structure at high-temperature and a ferritic structure at ambient temperature. Depending on the cooling rate, several types of ferritic metallurgical structures, with different thermomechanical characteristics, can be obtained. Transition from one metallurgical structure to another is often accompanied by volume change. As a consequence, this leads to interactions between thermal, metallurgical and mechanical phenomena.

In order to determine residual strains and stresses in a welded structure, it is necessary to model the thermal, metallurgical and mechanical phenomena as well as their interactions. Difficulties mainly arise when modeling phase transformations and when modeling the mechanical behavior of the multiphasic material.

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