Coupling Heat Transfer, Microstructure Evolution and Thermal Stress Analysis in Weld Mechanics

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Abstract

The mechanical behavior of welds is sensitive to the close coupling between heat transfer, microstructure evolution and thermal stress analysis. Since the temperature field computed from a heat transfer analysis can be considered to drive the mechanics of the welding process, the first step is to solve the energy equation usually with FEM. The research issue is decoupling the physics of the arc and weld pool from the energy equation. This is done by modeling the heating effect of the arc. Although the effects of microstructure and stress-strain evolution on heat transfer are not large, the effect of temperature on the microstructure and thermal stress is dominant. In addition, the coupling between microstructure and thermal stress can be strong and subtle. The microstructure evolution is modeled with algebraic equations for thermodynamics and ordinary differential equations for kinetics. The thermal stress analysis involves large strains and large rotations. The most popular constitutive equation has been elasto-plastic. Phase transformations such as the austenite to martensite transformation, can dominate the stress analysis. Since realistic welding problems tend to be truly three dimensional with complex geometry, transient and nonlinear, numerical methods have advantages. However, the computational demands have limited the size of welds that can be analyzed. In the past five years considerable progress has been made in developing numerical methods to solve this coupled problem with increasing speed and accuracy. Major gains have been made with better mesh grading and more efficient solvers. In addition, software engineering has played a major role in managing the complexity of software.
Introduction

From industry's viewpoint, the most critical mechanical effects of welding are cracking, distortion, and buckling. The influence of welds on crack propagation, either in stress corrosion cracking, fatigue or fracture is also a concern. To predict and control these effects, it is an advantage to understand and be capable of predicting the macroscopic transient fields of temperature, displacement, strain and stress. In principle, this can be done by solving the equations of continuum mechanics.

In practice however there are many aspects of welding that have made the rigorous analysis of welds challenging. At the macroscopic level a weld can be considered to be a thermo-mechanical problem of computing transient temperature, displacement, stress and strain. At the microscopic level, it can be considered to be a metal physics problem of computing the phase transformations including grain growth, dissolution and precipitation. The equations of continuum mechanics are macroscopic. In the case of welding they typically resolve length scales that range from 1 mm to 10 m. At the next finer length scale, 0.01 μm to 1 mm, microscopic phenomena deal with grains, precipitates, subgrains. This is the realm of the metallurgist. The deformation of a material is sensitive to the structure at this level. At a length scale of 0.1 nm to 0.01 μm, the phenomena are usually described in terms of atoms and their interactions. This is the realm of the metal physicist. Each level of abstraction or spatial resolution has its own set of equations and utilizes parameters from the level below it.

Fig. 1 Length scales in welds range from atomic through microstructure to continuum mechanics.