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Investigating mechanical degradation due to fire exposure of aluminum alloy 5083 using crystal plasticity finite element method

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ABSTRACT

Fire exposure causes significant mechanical property degradation of metallic materials. This paper investigates the influence of fire exposure on mechanical response of AA5083 through in situ neutron diffraction tensile tests and crystal plasticity finite element simulations. The Mechanical Threshold Stress (MTS) model is utilized, with a focus on the lattice strain response under tensile loading before and after exposure. A rigorous material parameter calibration procedure is proposed for this MTS model directly based on yield stress, plastic flow, hardening and rate dependency as a function of temperature, requiring only the macroscopic stress–strain curve. Material parameters of virgin material and fire-exposed material with full recrystallization are calibrated separately using this procedure. To initiate the investigation of mechanical degradation caused by fire exposure, a fire-exposed specimen with partial recrystallization is simulated by assigning material parameters and texture of recrystallized grains to selected grains in the virgin material according to the recrystallization fraction. Experimentally measured stress–strain curves and lattice strain evolution are employed to validate the simulations. For the first time, the local mechanical response of AA5083 is compared between in situ testing and finite element simulations, and the discrepancies of lattice strain evolution between virgin and fire-exposed material are discussed. Finally, the influence of fire-exposure on stress and lattice strain distribution is investigated to provide insight into mechanical property degradation.

1. Introduction

AA5083 is commonly used for marine structures due to its resistance to seawater corrosion as well as high strength. Fire exposure, an extreme event that may occur during its service life, causes significant reduction in mechanical properties (Chen et al., 2015; Kandare et al., 2010; Lee et al., 2004, 2005; Summers et al., 2015a). Thus, understanding the microstructural evolution of aluminum resulting from fire exposure as well as the associated property degradation is important for the safe design of marine structures.

However, most existing studies investigating the influence of fire exposure on aluminum have only examined properties during fire exposure rather than determining the residual mechanical strength after exposure. For example, Kandare et al. (2010) investigated the creep failure of aluminum (5083-H116) subjected to fire exposure based on the modified Larson–Miller model. Therein, the Larson–Miller Parameter (LMP) from steady state was extended to predict the creep rate in unsteady-state heating conditions. In contrast to the virgin material, AA5083 after annealing at 300 °C exhibits a combination of refined equiaxial grains (200 nm) and elongated grains (Lee et al., 2004). Recrystallization that occurs during annealing causes yield strength and ultimate strength to decrease while ductility increases significantly. Chen et al. (2015) and Summers et al. (2015a) further investigated the creep behavior and deformation mechanisms of AA5083 during fire exposure. In related work, a dynamic recovery and recrystallization-based model was developed recently to predict the residual mechanical properties after fire exposure (Summers, 2014; Summers et al., 2015b). However, this model focuses on the macro scale such that local mechanical response at the grain level may not be well predicted. Also, this model is not applicable for complex loading conditions, and the difference of lattice strain evolution of aluminum between virgin and fire-exposed state remains unknown.

To quantify the mechanical property degradation as well as predict the serviceability of AA5083 aluminum structure resulting from fire exposure, either in situ observation or crystal plasticity (CP) based modeling is most appropriate. However, in situ observation of microstructure evolution during fire proves difficult. Also, phase-field modeling should be combined with the CP framework to simulate the evolution of grain size and shape during coupled

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thermal-mechanical loading (McDowell, 2010), and this coupling is not yet fully understood. To initiate the investigation of mechanical degradation caused by fire exposure, rather than in situ measurement or modeling of the microstructure evolution, we aim to develop a structural response model, whereby the material parameters for virgin material in as-received state and fire-exposed material with full recrystallization are calibrated separately. Then the fire-exposed material with partial recrystallization is simulated using representative volume elements (RVE) containing two kinds of grains: one with material parameters of virgin material and rolling texture, and the other with material parameters of fire-exposed material and uniform texture. The ratio of these two kinds of grains is determined by the recrystallization fraction. For validation, the lattice strain evolution inside of bulk specimens was measured through in situ neutron diffraction, which is presented in Puplampu et al. (2017). The combined CP modeling and in situ neutron diffraction can provide insight into the primary mechanisms affecting the mechanical property degradation due to fire exposure.

Several mesoscale modeling methods have been applied to predict lattice strain evolution. The viscoplastic self-consistent (VPSC) method is a widely used polycrystalline simulation method to link the variation of microstructure and macroscopic mechanical properties (Lebensohn and Tomé, 1993). The related elastic-viscoplastic self-consistent (EVPSC) method was employed to investigate the lattice strain evolution of copper and stainless steel (Neil et al., 2010) as well as a magnesium alloy (Wang et al., 2012) under finite deformation. Daymond et al. (2000) assessed the relative influence of texture, grain shape and residual strain on the accuracy of lattice strain calculation in the context of VPSC. However, the EVPSC method has limited capabilities to accurately represent the influence of adjacent grains within a homogenized medium, especially for non-linear problems (Roters et al., 2010). One example is the relatively poor accuracy of simulated transverse lattice strains compared with experimental measurement (Clausen et al., 1999). The Fast Fourier Transformation-based formulation (FFT) is an alternative numerical method for solving the partial differential equations of continuum mechanics and crystal plasticity (Kalidindi et al., 2006; Lebensohn, 2001). Recently, FFT was employed to predict the lattice strain distribution between grains in comparison with comparing with neutron diffraction results (Kanjarla et al., 2012). One limitation of FFT is that only cubic elements can be modeled; therefore the actual grain shape may not be represented accurately and only periodic boundary conditions can be applied. The crystal plasticity finite element (CPFE) method avoids the constraints of VPSC and FFT by allowing full field mesoscale simulation with arbitrary shaped grains. For example, transverse lattice strains in stainless steel under uniaxial tension are investigated in detail using CPFE method (Li et al., 2013, 2014a). To measure elastic moduli, lattice strains of four grains from CPFE method and high-energy X-ray diffraction are tracked through the deformation process (McNelis et al., 2013). Moreover, CPFE method typically exhibits greater accuracy for predicting the transverse strain evolution compared to VPSC (Abdolvand et al., 2011). Although computationally expensive, CPFE method is a more qualified approach in the current research regarding fire-exposure effects.

In our current research, the Mechanical Threshold Stress (MTS) constitutive model is utilized within a CPFE method to simulate the mechanical response of virgin material and fire-exposed material. The isotropic MTS model by Mecking and Kocks (1981) is a physically motivated model to predict the thermomechanical constitutive behavior of single crystal and FCC polycrystalline material. This model was first applied to the compressive deformation of pure copper (Follansbee and Kocks, 1988), and the physical meaning of each variable is clearly defined. This model was further extended to the polycrystal MTS crystal plasticity model (Kok et al., 2002), which is more suitable for finite element (FE) implementation and has also been applied to model AA5182. In this paper, we investigate the influence of fire exposure on the mechanical response of AA5083 under uniaxial tension through in situ neutron diffraction measurements and crystal plasticity FE simulations. A general procedure for calibrating material parameters of the polycrystal MTS model is proposed, whereby the constitutive relationship between resolved shear stress and shear strain of a slip system is estimated from macroscopic stress–strain curves based on the Taylor assumption. The validity of this simple approach compared with expensive techniques like the genetic algorithm is justified through the comparison of microstructural FE volume averaged stresses with measured macro scale stress–strain curves. For the first time, the lattice strain evolutions of AA5083 in virgin state and fire-exposed state are compared, and the underlying mechanism for the discrepancy of global and local mechanical response is further investigated by crystal plasticity FE simulations. In order to simulate the mechanical response of fire-exposed material with partial recrystallization, randomly selected grains in the virgin material are assigned material parameters from the fire-exposed material along with recrystallization based orientations. Finally, the difference of lattice strain evolution between virgin material and fire-exposed material is investigated, and the effect of fire-exposure on stress and lattice strain distribution is discussed in detail.

The paper is organized as follows: in Section 2, we present an overview of the in situ neutron diffraction experiments. Section 3 describes the MTS model based CPFE method and post-processing techniques. In Section 4, comparison of mechanical response between virgin and fire-exposed material is presented. Moreover, the lattice strain evolution and distribution of CPFE simulations are compared with in situ neutron diffraction measurements. Finally, mechanical response differences between virgin and fire-exposed material are discussed in detail in Section 5.

2. Experiment

The alloy used in the current research is commercial AA5083 aluminum alloy, which is widely used in marine structures due to its excellent seawater corrosion resistance as well as high strength. The virgin material was in cold-rolled state, with a thickness reduction of about 50%. An isothermal heat treatment process was designed to simulate the thermal cycle that aluminum structures experience during fire exposure. The virgin material was conditioned using diffusion flame at 400 °C for 30 min and then water-quenched, as described in Chen et al. (2015). This temperature is higher than the critical temperature for AA5083 recrystallization (~0.4–0.5 melting temperature).

In situ lattice strain measurements were carried out at the Neutron Residual Stress Mapping Facility (NRSF2) located at the HB-2B thermal port of the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). A schematic of the specimens and the beam configurations is shown in Fig. 1. Samples were deformed at a slow rate of 8–9 μm/min, corresponding to a strain rate of about 3.2×10^{-6} s^{-1}. For these measurements, the external load is added continuously, so that the stress values varied slightly during individual diffraction measurements. The d-spacing for ⟨3 1 1⟩ and ⟨2 2 2⟩ oriented grains were measured simultaneously while ⟨4 0 0⟩ was measured separately. Samples were deformed to a target deformation ranging between 3 and 5 mm. Axial load was then returned to the seating stress and d-spacings were measured at a few points. Details on the experimental setup are given in (Puplampu et al., 2017).

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