15th International Conference on Fracture (ICF15)
June 11-16, 2023 Atlanta, GA USA

FATIGUE PERFORMANCE ASSESSMENT OF A QUENCHED ALUMINUM COMPONENT WITH PROCESS INDUCED RESIDUAL AT DIFFERENT DIPPING ANGLES

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Abstract

Quenching is a heat treatment process for the rapid cooling of a metallic workpiece in water, oil or air to obtain certain desired material properties. The accurate determination of resulting residual stress and distortion of a large aerospace aluminum part is challenging due to the nature of fast transient thermal process that includes the coupling of thermal, metallurgical, and mechanical interactions. The use of heat transfer coefficients (HTCs) in empirical tools requires an extensive testing matrix to calibrate these HCTs based on measured temperature data at selected locations of the workpiece. The use of a thermal multi-phase FSI tool is essential for the rational design of the flow rate quenchant with agitation to reduce the quenching residual stress by decreasing the thermal gradient from the center of the work piece to the surface. Given the temperature and phase profiles predicted from the Fluid Structure Interaction (FSI) based heat transfer module, a residual stress and distortion prediction module is developed by including fields mapping, temperature and phase dependent property evolution, and a user-defined material model for Abaqus. The fatigue performance of a quenched T-stiffener is evaluated in the presence of quenching induced residual stress under different dipping orientations.

1. Introduction

Forging aluminum alloy structural components are widely used in critical aircraft structural components such as aircraft bulkhead, helicopter airframe components, and automotive parts because of the increased demand in reducing the number of parts and weight and improving fuel efficiency. One major concern that arises during the processing of large aluminum components is related to the quenching step since this is the first step to introduce the residual stress into the large structure. While rapid cooling during quenching of the aluminum alloy can inhibit the formation of precipitate, the resulting residual stresses can induce excessive distortion of the workpieces and has a direct impact on the mechanical performance such as fatigue life. Current empirical tools without using an explicit fluid-structure interaction (FSI) model cannot capture the cooling process in an evaporable liquid quenchant in the presence of boundary layers that are dependent on the used medium, its agitation and temperature, the shape mass and dimensions of the workpiece, and the surface geometric configuration. The presence of the high thermal gradients causes non-homogeneous plastic straining resulting in residual stresses after quenching. Given the coupling of the thermo-metallurgical-mechanical effects, advanced constitutive models have to be applied to include the effects of the temperature, strain rates, and microstructure evolution on the material response. In this study, a multi-physics-based modeling approach was developed to capture the thermal-metallurgical-mechanical interactions and the resulting residual stress and distortion after quenching. A fatigue performance evaluation was performed next to evaluate the effects of the residual stress on the crack propagation and the resulting total life in a quenched aluminum component.

2. Results

A fully coupled and first-principle-based thermal multi-scale FSI framework was constructed to directly model the quenching processes for a given set of part temperature, tank temperature, agitation rate, and dipping orientation. The fluid motion in the quenching tank is governed by the two-phase (gas and liquid) Navier-Stokes equations, which accounts for the compressibility due to evaporation and condensation. The volume of fluid (VoF) method, enhanced with the evaporation and condensation models, is utilized to handle the evolution of the vapor-liquid interface. A thermodynamics equation, considering convection, conduction, and phase transition, is employed to model the temperature field. The output from the thermal multiphase FSI simulations, including the time-dependent pressure and temperature profiles, is imported into the user-defined subroutines in Abaqus to determine the temperature dependent material properties for the prediction of the residual stress and distortion. The residual stress field was mapped into our extended finite element toolkit for Abaqus (XFA3D) for the crack growth and fatigue life prediction.

An aluminum T-stiffener was selected to investigate the effects of dipping orientation on the residual stress and fatigue performance after quenching. Three different dipping angles are studied: along length, along width, and along thickness. An FSI model for the prediction of temperature, phase transformation, and pressure prediction is shown in Figure 1 along with the comparison of residual stress and distortion. The FSI model captures the cooling rate and the spatial and temporal distribution of temperature for the residual stress and distortion prediction. After mapping the residual stress field into the XFA3D model, a fatigue performance was evaluated using an initial defect embedded at the intersection of the web and skin area as shown in Figure 2 along with the display of fatigue crack growth for the horizontal dipping.

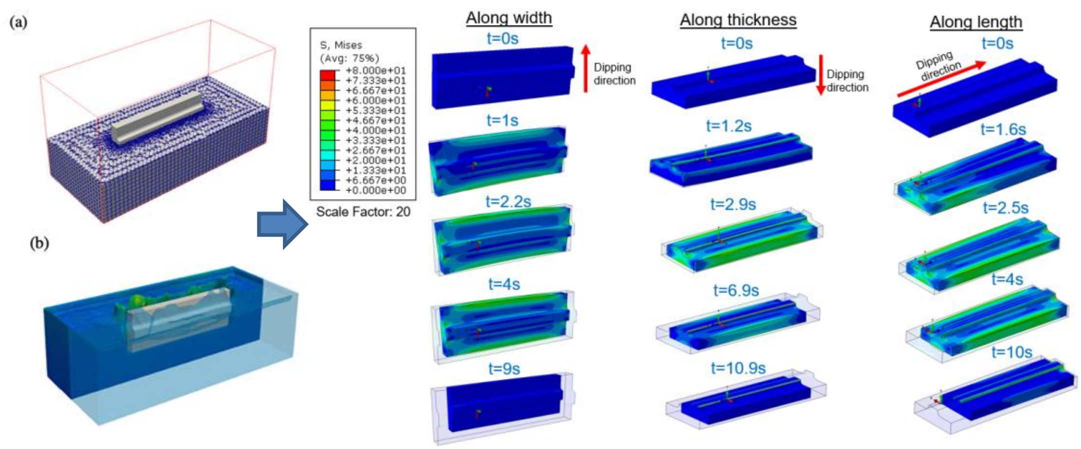

Fig.1 – FSI based quenching process simulation and its coupling with the customized Abaqus model for the residual stress and distortion prediction for the T-stiffener at different dipping orientations

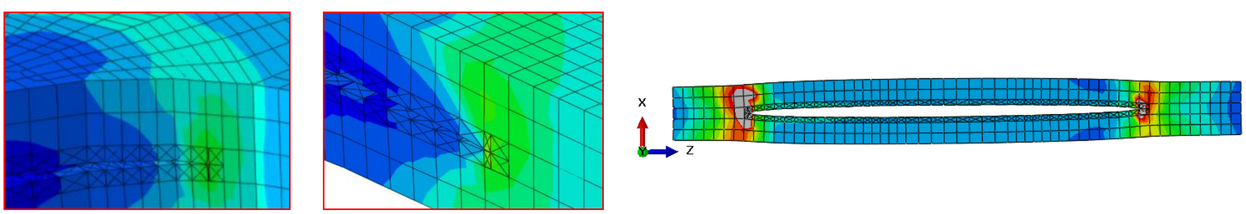

Fig.2 – Fatigue assessment of the T-stiffener using the along-the-width dipping configuration

3. Conclusions

A high-fidelity multi-physics framework has been established to directly simulate the quenching process, the resulting residual stress and distortion, and the effects of the residual stress on the fatigue performance. The FSI has captured the compressible turbulent multi-phase flows in the quenching tank and capture the local boundary layer effects to predict the multi-stage thermal process. A temperature and strain rate dependent constitutive model has been implemented as a user-defined material model in Abaqus. A T-stiffener has been used to demonstrate the use of FSI/Abaqus coupling for the assessment of fatigue performance in the presence of quenching induced residual stress field.

Acknowledgements
The work is funded by Naval Air Warfare Center, Aircraft Division under the Contract of N68335-22-C-0293.