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Critical investigation on the influence of welding heat input and welding residual stress on stress intensity factor and fatigue crack propagation

Ramy Gadallah[a,b,*], Naoki Osawa[a], Satoyuki Tanaka[c], Seiichiro Tsutsumi[b]

[a] Graduate School of Engineering, Osaka University, Suita, Osaka, Japan
[b] Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka, Japan
[c] Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima, Japan

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ABSTRACT

This paper investigates the influence of the change in welding heat input (HI) and welding residual stress (RS) on the behavior of stress intensity factor (SIF) and fatigue crack propagation (FCP) by means of finite element method. Three welding HI cases were examined using a bead-on-plate FE model. One of the applied welding HI cases represents welding conditions used in experiments. Furthermore, for the sake of comparison, a stress-relieved case that does not consider the influence of welding RS was employed. Experimental data used in the analyses and verification were taken from a Ph.D. dissertation conducted by Kusuba (http://hdl.handle.net/10069/16925). A thermal-elastic-plastic analysis was firstly conducted to simulate welding process and to predict welding RS. A powerful fracture analysis technique named WARP3D interaction integral method that provides crack face traction integral was employed. WARP3D is an open research code for nonlinear FEA of large-scale, 3-D solids and structures subjected to static and dynamic loads. The employed technique was used to precisely calculate SIF with considering the influence of welding RS under different constant stress amplitude loadings. The results revealed that the ranges of welding RS induced by the simulated welding HI cases have a negligible influence on the behavior of SIF and FCP, whilst when increasing the magnitude of those welding RS a larger influence can be observed. The influence of welding RS induced by the simulated welding HI cases on FCP was manifested by comparing FCP obtained by the cases that consider the effect of welding RS with that given by the stress-relieved case. A large reduction of fatigue lives was obtained when welding RS is considered compared with that obtained by the stress-relieved case. A reduction percentage of 35.9–40.7% in fatigue lives was obtained when welding RS is considered compared with that calculated by the stress-relieved case for the applied stress loading conditions. The calculated fatigue lives were verified with experimental data taken from the literature. Facture behaviors of the studied cases were discussed, as well. Furthermore, a basic study was conducted to examine the influence of the change in the magnitude of RS on FCP behavior.

1. Introduction

Welding, nowadays, is used in manufacturing most of the steel structures in engineering practice. Welding offers various

* Corresponding author at: Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka, Japan.
E-mail address: gadallahramy@gmail.com (R. Gadallah).

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Nomenclature

a	crack depth (mm)
BOP	bead-on-plate
c	crack half-length (mm)
CFT	crack face traction
FCP	fatigue crack propagation
HI	heat input
IIM	interaction integral method
LEFM	linear elastic fracture mechanics
K_{Imin}, K_{Imax}	minimum and maximum stress intensity factors for mode-I, respectively (MPa$\sqrt{\text{mm}}$)
Q	shape parameter for elliptical and semi-elliptical cracks
R	stress ratio
R_{eff}	effective stress ratio
R^+	stress ratio including clamping stress
RS	residual stress
SIF	stress intensity factor
TEP	thermal-elastic-plastic
U	stress range ratio
$U_{R_{eff}=0}$	stress range ratio without considering the effect of welding RS
$U_{R_{eff}>0}$	stress range ratio with considering the effect of welding RS
U_x, U_y, U_z	displacement in x, y, and z-directions, respectively
ΔK	stress intensity factor range (MPa$\sqrt{\text{mm}}$)
ΔK_{eff}	effective stress intensity factor range (MPa$\sqrt{\text{mm}}$)
$\Delta\sigma$	stress range (MPa)
$\Delta\sigma_{eff}$	effective stress range (MPa)
σ_{cl}	clamping stress (MPa)
σ_Y	yield stress (MPa)
φ	parameter angle for the ellipse (deg.)

advantages such as simple set up, low manufacturing cost and high joint efficiency. However, due to the non-uniform temperature distributions produced by welding, unavoidable residual stress (RS) is obtained [1,2]. Since many of welded structures subject to external cyclic loadings, therefore the presence of welding RS in these structures can considerably influence the fatigue life [3,4]. As a result of the superposition of external tensile cyclic loading with welding RS, a reduction in the maximum endurable load of a structure occurs especially when a tensile welding RS is produced [5]. This reveals that tensile welding RS is generally detrimental to fatigue life where it increases the rate of fatigue crack propagation (FCP).

Due to the complexity of welding process, that includes localized heat, non-uniform temperature distributions, moving heat source and temperature-dependence material properties; accurate and effective methods are needed to predict welding RS. Therefore, the finite element method (FEM) has considered a robust tool for the prediction of welding RS [6]. A large number of thermo-mechanical finite element (FE) simulations, until now, have been conducted to predict welding RS for different welded joints [6–11].

According to the linear elastic fracture mechanics (LEFM) approach, the superposition principle is frequently utilized to evaluate the stress intensity factor (SIF). For a reliable prediction of FCP rate, accurate estimation of SIF is needed. The key task is to calculate SIF with considering the influence of welding RS. There are several methods are available to calculate SIF resulting from welding RS using either FEM or the weight function method [12]. Different methods are employed to calculate SIF using FEM such as the domain integral method [13] and interaction integral method (IIM).

The IIM is considered a powerful method and the most readily and accurate approach to estimate mixed-mode SIFs [14]. An interaction energy integral method [15,16] was derived by means of the domain integral method by combining the actual field and known auxiliary field in order to extract mixed-mode SIFs. The IIM was thereafter utilized to determine mixed-mode SIFs along straight, 3-D interface cracks [17]. Gosz and his coworkers [13,18], then, developed an IIM to extract the mixed-mode SIFs along planar interface cracks and non-planar crack tips in 3-Ds. To calculate SIFs for a surface crack in a stress field, Walters et al. [14] have developed interaction integral procedures for 3-D curved cracks that consider crack face tractions.

Recently, some researchers have studied the behavior of SIF and FCP of welded joints with considering the influence of welding RS. Bao et al. have evaluated SIF considering welding RS as initial condition state by the weight function and FEM [19]. Božić et al. have studied the influence of welding RS on effective SIF solutions and FCP in welded stiffened panels by using power law models [20,21]. They have considered the influence of welding RS on FCP by introducing the effective SIF ratio in the employed power laws. Deschênes et al. [22] have studied the influence of welding RS on FCP rate in mode-I. They measured welding RS by the contour method and the weight function method was then employed to calculate SIF resulting from welding RS. Taheri and Fatemi [23] have simulated FCP in power plant residual heat removal system by means of XFEM in the presence of welding RS. In their work, welding RS was decomposed into a local effect in tension near the weld and a structure effect in compression farther away. Further, Zhang et al. [24] have investigated fatigue life of a dissimilar joint between duplex stainless steel and 304 austenitic stainless steel including the influence of welding RS. They have reported that welding RS mainly affect the mean stress rather than the stress amplitude. Shen et al. [25] have studied fatigue damage evolution of butt welded joints under cyclic loading through a continuum damage mechanics approach. They have predicted fatigue lifetimes of the applied joints with considering the influence of welding RS as well as porosity. Tra et al. [26] have discussed the behavior of FCP in friction stir welded joint including the roles of RS and microstructure. Lee et al. [6] have investigated the behavior of high cycle fatigue of T-welded joint including welding RS by means of continuum damage mechanics. They have reported that welding RS could not be neglected in an estimation of fatigue life of welded joints. The influence of initial crack orientation and distance of notch tip on FCP in a welding RS field has been studied by Vaidya et al. [27]. In addition, Mikkola et al. [28] have assessed the fatigue life of high-frequency mechanical impact treated welded joints subjected to high mean stresses and spectrum loadings. Furthermore, Tchoffo et al. [8] and Rettenmeier et al. [7] have addressed the influence of welding RS on FCP of different welded joints. They have found that the influence of welding RS could be neglected for large load amplitudes. On the other hand, Hemmesi et al. [9] have estimated the torsional fatigue of tubular joint considering the influence of welding RS using the critical plane approach.