International Journal of Fatigue 105 (2017) 43–59

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

On the mechanism of residual stresses relaxation in welded joints under cyclic loading

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ARTICLE INFO

Article history:
Received 21 May 2017
Received in revised form 12 August 2017
Accepted 16 August 2017
Available online 18 August 2017

Keywords:
Welding residual stress
Stress relaxation
Cyclic plasticity constitutive model
Aluminum alloy
Finite element analysis

ABSTRACT

This paper attempted to reveal the underlying mechanism of the relaxation of welding residual stresses (WRSs) under cyclic loading. Experimental and numerical investigations have been conducted on 7N01-T4 aluminum alloy welded joints. A novel experimental method to monitor the evolution of WRSs during loading was proposed. A series of numerical models have been developed to investigate the initial WRSs and their redistributions during mechanical loading. Results showed that the mechanical property heterogeneity in the aluminum alloy welded joint has a pronounced influence on numerical calculation of the WRSs relaxation. Continuous relaxation of WRSs occurred only under certain circumstances. The amount of relaxation depended not only on the number of applied cycles but also on the interaction between the stress ratio, the magnitude of mechanical loading, the post-welding residual stresses and the mechanical property of the material. Revealed by the analysis of internal variable evolution, the production of new plastic strains at each reversal of a cyclic loading was the underlying mechanism for the continuous relaxation of WRSs, and the positions for the production of new plastic strains during forward loading and reverse loading could be different.

1. Introduction

Residual stresses play a vital issue in structural integrity assessment [1,2]. Both compressive and tensile residual stresses can be generated in the manufacturing process of engineering components, in which the former created by such as shot peening [3,4] and cold expansion [5] is beneficial for prolonging the remaining lifetime of structures whereas the latter induced by such as welding and casting can be detrimental [1,3].

Among the numerous processing technologies, welding stands out for its irreplaceable role in certain engineering applications. It is well established, however, that fatigue failure usually occurs in the weld region where high tensile residual stresses and weld defects exist. Although using the as-welded state residual stresses, the peak of which is nearly equal in magnitude to or even larger than the mean material yield strength (because of work hardening), is preferred in common structural integral procedures such as BS7910 [6], CEGB R6 [7] and API579 [8] for its conservative nature, it is still meaningful to elucidate the relaxation of welding residual stresses (WRSs) at service and its influence on the fatigue performance of structures. This is because in some materials, e.g. low temperature phase transformation (LTT) steel and ferrite high strength steel, compressive WRSs can be generated in the weld bead due to solid-state phase transformation (SSPT), neglecting the relaxation of WRSs will lead to a dangerous estimation of fatigue performance. In the meantime plenty of studies have shown that the WRSs are released to a great extent in the first and the initial few loading cycles [9], using the high WRSs assumption in some procedures will result in an unnecessary conservative prediction of fatigue life, even zero residual lives in certain circumstances. Drastically different Fitness for Service (FFS) assessment results were found by Bouchard [10] applying different treatment of WRSs. Consequently, a comprehensive understanding of the WRSs evolution during mechanical loading is of remarkable importance for FFS assessment [3].

A critical review of the existing methods for WRSs relaxation evaluation reveals that they can be mainly categorized into two types: the empirical models based on experimental results and the numerical ones calculated by FE simulation. The empirical models are usually viewed as straightforward for application though lacking of physical basis. The latter ones, which are commonly raised by FE analyses, are considered as continuum mechanics based models and seems to be a more promising way to understand the process of WRSs relaxation. A comprehensive

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http://dx.doi.org/10.1016/j.ijfatigue.2017.08.016
0142-1123/

Nomenclature

a_1	saturated value of Q
a_2	saturated value of L
$a_{\mathrm{h}1}$	front length of the heat source
$a_{\mathrm{h}2}$	rear length of the heat source
b	rate of the evolution rule of R^{NL}
b_1	rate of the evolution rule of R^S
b_{h}	half width of the heat source
c_1	rate of the evolution rule of Q
c_2	rate of the evolution rule of L
c_{h}	height of the heat source
c_i^L	rate of the evolution rule of r_i^L
c_i^{NL}	rate of the evolution rule of r_i^{NL}
C	material parameter related to q
E	Young's modulus
$f_{\mathrm{h}1}$	fraction of heat deposited in the front part
$f_{\mathrm{h}2}$	fraction of heat deposited in the rear part
f_i	critical state of dynamic recovery
F	control function of the plastic strain memory surface
F_y	yield function
H	Heaviside function
HV	Vickers hardness
HV_{max}	Vickers hardness in T4 condition
HV_{min}	Vickers hardness in fully softened state
$\boldsymbol{I}$	fourth unit tensor
K	drag stress constant
K_0	bulk modulus
K_{a}	acoustoelastic coefficient
K_{n}	normalized acoustoelastic coefficient
l	third order elastic constant
L	saturated value of R^L
m	third order elastic constant
n	third order elastic constant
n_t	time exponent
n_v	viscous exponent
$\boldsymbol{n}$	unit normal to the yield surface
$\boldsymbol{n}^*$	unit normal to the memory surface
p	accumulated plastic strain
$\dot{p}_i$	the ith accumulated plastic strain rate
q	radius of the memory surface in plastic strain space
q_{h}	heat flux vector
Q	saturated value of R^{NL}
Q_1	saturated value of R^S
Q_{eff}	effective activation energy
Q_d	activation energy for diffusion
Q_h	internal heat generation rate
Q_s	solvus boundary enthalpy
r_i	kinematic hardening material parameter
r_i^0	initial value of r_i
r_i^L	linear part of the evolution function for r_i
r_i^{NL}	non-linear part of the evolution function for r_i
r_i^{Δ}	amount of increment of the evolution rule of r_i^{NL}
R	isotropic hardening parameter
R_g	universal gas constant
R^L	linear part of R
R^{NL}	non-linear part of R
R_{r}	stress ratio
R^S	softening term of the isotropic hardening rule
$\boldsymbol{s}$	deviatoric stress tensor

t	ultrasonic travel-time in the welded joint
t_0	ultrasonic travel-time in an unstressed reference sample
t_{h}	welding time
t_r	time for total dissolution at T_r
$t^*_{(T)}$	time for total precipitation dissolution at temperature T
T_r	reference temperature
υ	ultrasonic wave velocity in the welded joint
υ_0	ultrasonic wave velocity in an unstressed reference sample
υ_{h}	welding speed
x	coordinate in welding direction
X	volume fraction of dissolved hardening precipitates
y	coordinate in transverse direction
z	coordinate in through-thickness direction
z_0	initial position of the heat source in through-thickness direction
α	deviatoric back stress tensor
α_i	the ith deviatoric back stress tensor
β	strength mismatching ratio
β	center of the memory surface in plastic strain space
$\Delta t^n_{(T)}$	time increment
$\Delta\varepsilon_x$	amount of relaxation of longitudinal residual strain
$\Delta\varepsilon_y$	amount of relaxation of transverse residual strain
$\Delta\varepsilon_{xy}$	amount of relaxation of shear residual strain
$\Delta\sigma_{i,\,N}$	amount of relaxation of residual stress after N cycles
$\Delta\sigma_x$	amount of relaxation of longitudinal residual stress
$\Delta\sigma_y$	amount of relaxation of transverse residual stress
$\Delta\tau_{xy}$	amount of relaxation of shear residual stress
ε	total strain tensor
ε^e	elastic strain tensor
ε^p	plastic strain tensor
ζ_i	kinematic hardening material parameter
η	material parameter related to q
λ	Lamé constant
μ	Lamé constant
μ_0	initial value of μ_i
μ_b	rate of the evolution rule of μ_i
μ_i	the ith ratcheting parameter
μ_Q	saturated value of μ_i
ν	Poisson's ratio
ρ_0	initial density
σ	stress in a specific direction
σ	stress tensor
σ_{eq}	equivalent von-Mises stress
σ_{max}	maximum stress in a loading cycle
σ^0_{max}	base material yield stress in T4 condition
σ_{min}	minimum stress in a loading cycle
σ^0_{min}	yield stress in fully softened state
$\sigma_{res,\,ini}$	initial as-welded residual stress
$\sigma_{res,\,N}$	residual stress after N cycles
σ_y	yield stress of current cycle
σ_y^0	initial yield stress
σ_y^{0m}	yield stress of the monotonic loading
σ_v	viscous stress
$\mathbf{1}$	second-order identify tensor
$< >$	MacCauley bracket

literature summary concerning the formulas and equations for WRSs relaxation prediction can be found in [11].

The focus of the present study was to scrutinize the mechanical mechanism for the relaxation of WRSs. To this end, 7N01-T4 aluminum alloy welded joints were chosen as the investigated material. This paper was laid out as follows. Firstly, FE simulation of the welding process was carried out. The accuracy of the numerical analyzed post-welding residual stresses was calibrated with the help of experimental measurements performed by a novel nondestructive ultrasonic method. Secondly, the redistribution of WRSs