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

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A B S T R A C T
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 irreproachable 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], CEBG 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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Nomenclature

\[ a_1 \] saturated value of \( Q \)  
\[ a_2 \] saturated value of \( L \)  
\[ a_{h1} \] front length of the heat source  
\[ a_{h2} \] rear length of the heat source  
\[ b \] rate of the evolution rule of \( R_{NL} \)  
\[ b_1 \] rate of the evolution rule of \( R \)  
\[ b_0 \] half width of the heat source  
\[ c_1 \] rate of the evolution rule of \( Q \)  
\[ c_2 \] rate of the evolution rule of \( L \)  
\[ c_0 \] height of the heat source  
\[ c_t^L \] rate of the evolution rule of \( r_t^L \)  
\[ c_t^N \] rate of the evolution rule of \( r_t^N \)  
\[ C \] material parameter related to \( q \)  
\[ E \] Young's modulus  
\[ f_{h1} \] fraction of heat deposited in the front part  
\[ f_{h2} \] 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  
\[ I \] fourth unit tensor  
\[ K \] drag stress constant  
\[ K_0 \] bulk modulus  
\[ K_s \] acoustoelastic coefficient  
\[ K_n \] normalized acoustoelastic coefficient  
\[ l \] third order elastic constant  
\[ L \] saturated value of \( R \)  
\[ m \] third order elastic constant  
\[ n \] third order elastic constant  
\[ n_t \] time exponent  
\[ n_v \] viscous exponent  
\[ n^l \] unit normal to the yield surface  
\[ n^p \] unit normal to the memory surface  
\[ p \] accumulated plastic strain  
\[ p_i \] the \( i \)th accumulated plastic strain rate  
\[ q \] radius of the memory surface in plastic strain space  
\[ q_{h0} \] heat flux vector  
\[ Q \] saturated value of \( R_{NL} \)  
\[ Q_i \] saturated value of \( R \)  
\[ Q_{eff} \] effective activation energy  
\[ Q_d \] activation energy for diffusion  
\[ Q_{gen} \] 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 \( r_i \)  
\[ r_i^{NLl} \] non-linear part of the evolution function for \( r_i \)  
\[ \Delta r_i^{(r)} \] amount of increment of the evolution rule of \( r_i^{NL} \)  
\[ R \] isotropic hardening parameter  
\[ R_g \] universal gas constant  
\[ R_e \] linear part of \( R \)  
\[ R_{NL} \] non-linear part of \( R \)  
\[ R_y \] stress ratio  
\[ s \] softening term of the isotropic hardening rule  
\[ s \] deviatoric stress tensor  
\[ t \] ultrasonic travel-time in the welded joint  
\[ t_0 \] ultrasonic travel-time in an unstressed reference sample  
\[ t_1 \] welding time  
\[ t_r \] time for total dissolution at \( T_r \)  
\[ t_{r(N)} \] time for total precipitation dissolution at temperature \( T \)  
\[ T \] reference temperature  
\[ v \] ultrasonic wave velocity in the welded joint  
\[ v_{00} \] ultrasonic wave velocity in an unstressed reference sample  
\[ v_{sh} \] 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  
\[ \alpha \] deviatoric back stress tensor  
\[ \beta \] the \( i \)th deviatoric back stress tensor  
\[ \beta_{NL} \] stress ratio  
\[ \beta_{NL} \] strength mismatching ratio  
\[ \Delta \] center of the memory surface in plastic strain space  
\[ \Delta t^{(r)} \] amount of relaxation of longitudinal residual strain  
\[ \Delta t_{NL} \] amount of relaxation of transverse residual strain  
\[ \Delta t_{NL} \] amount of relaxation of longitudinal stress after \( N \) cycles  
\[ \Delta t_{NL} \] amount of relaxation of longitudinal residual stress  
\[ \Delta t_{NL} \] amount of relaxation of shear residual stress  
\[ \Delta t_{NL} \] amount of relaxation of shear residual stress  
\[ \Delta t_{NL} \] amount of relaxation of shear residual stress  
\[ \Delta t_{NL} \] total tensor  
\[ \Delta t_{NL} \] elastic strain tensor  
\[ \Delta t_{NL} \] plastic strain tensor  
\[ \Delta t_{NL} \] kinematic hardening material parameter  
\[ \Delta t_{NL} \] material parameter related to \( q \)  
\[ \Delta t_{NL} \] Lamé constant  
\[ \Delta t_{NL} \] initial value of \( \mu_i \)  
\[ \Delta t_{NL} \] rate of the evolution rule of \( \mu_i \)  
\[ \Delta t_{NL} \] the \( i \)th ratcheting parameter  
\[ \Delta t_{NL} \] saturated value of \( \mu_i \)  
\[ \Delta t_{NL} \] equivalent von-Mises stress  
\[ \Delta t_{NL} \] maximum stress in a loading cycle  
\[ \Delta t_{NL} \] maximum stress in a loading cycle  
\[ \Delta t_{NL} \] minimum stress in a loading cycle  
\[ \Delta t_{NL} \] yield stress in fully softened state  
\[ \Delta t_{NL} \] initial as-welded residual stress  
\[ \Delta t_{NL} \] residual stress after \( N \) cycles  
\[ \Delta t_{NL} \] yield stress of current cycle  
\[ \Delta t_{NL} \] initial yield stress  
\[ \Delta t_{NL} \] yield stress of the monotonic loading  
\[ \Delta t_{NL} \] viscous stress  
\[ \Delta t_{NL} \] second-order identify tensor  
\[ \Delta t_{NL} \] MacCauley bracket

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 mater-rial. 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 nonde-structive ultrasonic method. Secondly, the redistribution of WRSs...
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