

Development of Friction Stir Weld Fatigue Evaluation Procedure Using Battelle Structural Stress Method

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ABSTRACT

Weld fatigue evaluation using the mesh-insensitive Battelle structural stress method has been applied to fusion welds, resistance spot welds and non-welded components. The effectiveness of the Battelle structural stress procedure has been demonstrated in a series of earlier publications for welded structures with different joint types, plate thicknesses, and loading modes. In this paper, a weld fatigue evaluation procedure using the Battelle structural stress method is proposed for friction stir welds currently being used in the automotive and aerospace industries.

The applicability of the Battelle structural stress procedure is demonstrated by comparing fatigue life predictions for friction stir welded specimens to well-documented test data from the literature. Different specimen types, plate thicknesses and loading ratios were analyzed for several aluminum alloys.

Based on this investigation, a FE based fatigue evaluation procedure for friction stir welds is established and a master S-N design curve for friction stir welds is constructed. As anticipated the master S-N design curve based on the equivalent structural stress range consolidates the test data with a small scatter band regardless of specimen type and thickness. However, this consolidation clearly shows a load ratio effect. Other fatigue important characteristics of friction stir welds of aluminum alloy are discussed.

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INTRODUCTION

The application of friction stir welding (FSW) technology in lightweight structures is rapidly expanded to the automotive, aerospace, rail car and shipbuilding industries. FSW is a solid-state joining processor with low heat input, which is suitable to low melting point metals such as aluminum (Al) alloys. FSW is being applied to joining various joint types such as lap joints [1, 2], T-joints [3, 4], tailor welded blanks [5], as well as butt joints [6, 7].

Many fatigue related studies have focused on seeking optimum FSW parameters to obtain superior fatigue strength. These parameters have included combinations of lateral travel speed/ rotation speed [6, 7, 8, 9], and the effect of tool geometry [2, 10]. Some of these studies indicate that the welding speed does not significantly affect the fatigue strength of butt welds [6, 7, 8] and that same is true of tool size and shape [2].

From these observations, it is inferred that the friction stir (FS) weld fatigue behavior is similar to fusion welds and therefore can be quantitatively evaluated under the condition of consideration of good quality weld.

The mesh-insensitive Battelle structural stress method and its master S-N curve approach have been developed and proven to be highly effective in correlating fatigue behavior of welded joints. This procedure has been adopted by design codes for weld fatigue, e.g., ASME Sec. VIII Div.2 and API 579/ASME FFS-1 in 2007 [11, 12] and by weld fatigue design guidance, e.g., Bureau Veritas NT 3199 in 2103 [13].

The Battelle structural stress method and its master S-N approach have been developed for fusion welds [14, 15]. Recently the Battelle procedure has been applied to simplified resistance spot welds [16] and weld-bonds [17].

In this paper, based on the observation of the FS weld fatigue behavior characteristics from the literature, an FE-based fatigue evaluation procedure for Al alloy FS welds is formulated using the Battelle structural stress method. When fatigue test data from the literature are plotted vs. cycles-to-failure (N_f) using equivalent structural stress range incorporating load ratio (R) effect good data consolidation is observed, regardless of specimen type and plate thickness. Finally the fatigue master S-N design curve applicable to heat-treated or strain hardened Al alloy FS welds.

The current available design rules for welded Al alloy joints such as IIW recommendations [18] and Eurocode 9 [19] are mainly focused on fusion welds. Through this study, the fatigue behavior of FS welds will be discussed and compared to these existing design rules.

STRUCTURAL STRESS METHOD

The Battelle structural stress method has been documented extensively [20, 21, 22, 23, 24]. It is based on an equilibrium-equivalent decomposition of an arbitrary through-thickness stress state at the location of interest such as geometric notch (weld toe in Fig. 1a) into the equilibrium-equivalent structural stress part (Fig. 1b) and a self-equilibrating notch stress part (Fig. 1c). The structural stress part is characterized as

$$\sigma_s = \sigma_m + \sigma_b \quad (1)$$

which represents a simple stress state in the form of membrane and bending components that satisfies the equilibrium conditions with external loading at the location of interest. To achieve mesh-insensitivity for welded joints within the context of displacement based FE methods, the equilibrium agreements can be most effectively implemented by using balanced nodal forces and moments in shell, plate, and 3D solid FE models for any arbitrary weld geometry. The detail formulation, calculation procedures, as well as calculation examples are given in previous publications [20, 21, 22, 23, 24].

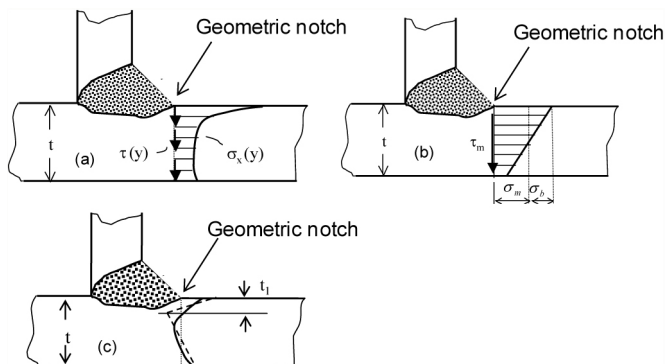


Figure 1. Through-thickness structural stress definition: (a) Local stresses from FE model; (b) Structural stress or far-field stress; (c) Self-equilibrating stress

The Battelle structural stress method prescribes the through-thickness stress state normal to a hypothetical crack plane in an equilibrium sense in the form of membrane and bending components indicated in Eq. (1). For the fatigue assessment of welds, the corresponding stress range is defined as

$$\Delta\sigma_s = \Delta\sigma_m + \Delta\sigma_b \quad (2)$$

Fig. 2 indicates the Battelle structural stress component definitions, including normal structural stress (σ_s), transverse shear structural stress (τ_z), and in-plane shear structural stress (τ_s) at the hypothetical crack surface for a sheet failure. The individual structural stress components can be defined as a combination of line forces and line moments using simple beam bending theory as shown in Eqs. (3, 4, 5). It is noted that the line forces and line moments are with respect to local coordinate system along the hypothetical crack surface. The x' , y' , and z' directions are normal to the hypothetical crack surface, parallel to weld traveling direction, and through thickness direction on hypothetical crack surface, respectively.

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_{y'}}{t} - \frac{6m_{x'}}{t^2} \quad (3)$$

$$\tau_s = \tau_m + \tau_b = \frac{f_{x'}}{t} + \frac{6m_{y'}}{t^2} \quad (4)$$

$$\tau_z = \frac{f_{z'}}{t} \quad (5)$$

where $f_{x'}$, $f_{y'}$, $f_{z'}$, and $m_{x'}$, $m_{y'}$ are line forces and line moments in the direction of local coordinates, respectively.

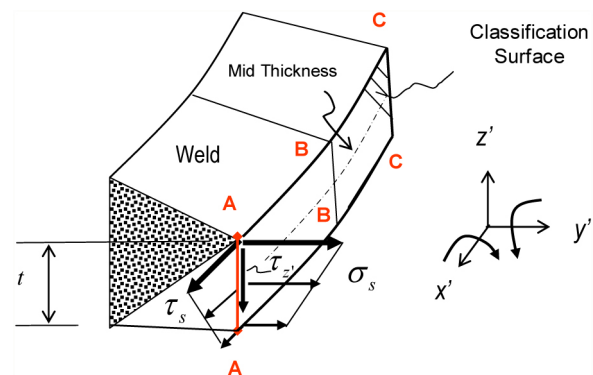


Figure 2. Definitions of structural stress components for weld toe failure of fusion weld

The effective structural stress range ($\Delta\sigma_e$) is defined in Eq. (6) in terms of the calculated structural stress components.

$$\Delta\sigma_e = \sqrt{\Delta\sigma_s^2 + 3(\Delta\tau_s^2 + \Delta\tau_z^2)} \quad (6)$$

In cases where the shear structural stress range is smaller than 1/3 of normal structural stress range, the shear structural stress terms can be ignored, i.e., $\Delta\sigma_e = \Delta\sigma_s$ [11].

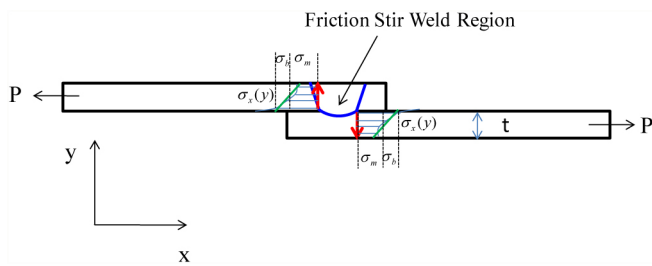


Figure 3. Structural stress definition for friction stir welded lap joint at welded region; red arrows indicate the hypothetical crack path fatigue (sheet failure mode) and the structural stress definitions are defined along the crack path.

The same concept of Battelle structural stress method for fusion welds is applied to FS welds. The common fatigue failure locations for a butt joint and a lap joint are the HAZ located at the weld flash [25] and the interface at the edge of a weld nugget [1], respectively. Fig. 3 illustrates the definition of structural stress for a lap joint under tensile loading. A through-thickness stress distribution at a fatigue critical location (red arrows) and the corresponding structural stress definition at the edge of a weld nugget are shown in Fig. 3.

For a butt joint under tension loading, an FE analysis is not required to calculate the structural stress. The size and shape of the geometrical notch at the FS welded are negligible. Thus, only the membrane component of the structural stress exists at a butt joint.

Based on a two stage crack growth model [26], an equivalent structural stress parameter derived using fracture mechanics principles has been shown to consolidate all plate joint fatigue data relevant to steel structures onto a narrow band, referred to as the master S-N design curve. The equivalent structural stress range (ΔS_s) is defined as

$$\Delta S_s = \frac{\Delta \sigma_s}{t^{* \frac{2-m}{2m}} \cdot I(r)^{\frac{1}{m}}} \quad (7)$$

where $t^* = t/t_{ref}$ with $t_{ref} = 1mm$, $m=3.6$, and $I(r)^{1/m}$ is a dimensionless polynomial function of the bending ratio r (under load-controlled conditions),

$$I(r)^{\frac{1}{m}} = 0.0011r^6 + 0.0767r^5 - 0.0988r^4 + 0.0946r^3 + 0.0221r^2 + 0.014r + 1.2233, \\ \text{where } r = \frac{|\Delta \sigma_b|}{|\Delta \sigma_m| + |\Delta \sigma_b|} \quad (8)$$

Previous Battelle studies of the crack growth rate curve (da/dN) vs. ΔK have shown that the slope (m) for Al alloys is similar with that of steel [26], i.e. $m=3.6$. The slope of the da/dN vs. ΔK curves for FS welded Al alloys was also observed to be 3.19 ~ 3.89 [27]. Therefore, use of $m=3.6$ is reasonable for Al alloy FSWs. It also consistent with the slopes for fusion welds [14, 15] and resistance spot welds [16].

As observed in the fatigue data in the literature [28], the load ratio (R) effect on Al alloy FS weld fatigue is clear. The load ratio effect can be evaluated by introducing the ΔK^* parameter [29], i.e.,

$$\Delta K^* = \sqrt{\Delta K^+ \cdot K_{max}} \quad (9)$$

This can be considered as two different situations depending upon whether the load ratio, R is positive or negative such as

$$K_{max} = \frac{\Delta K}{1-R} \quad \text{when } R \geq 0 \quad (10)$$

$$\Delta K^+ = K_{max} \quad \text{when } R < 0 \quad (11)$$

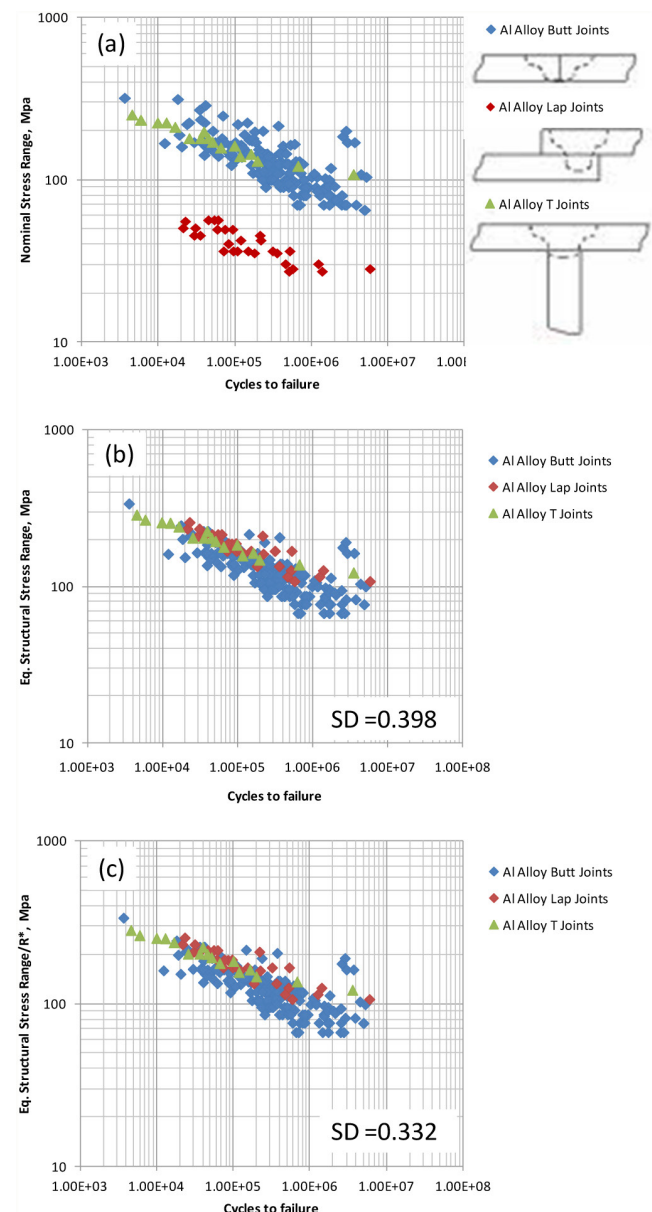


Figure 4. S-N data for friction stir welded aluminum alloy joints. (a) $\Delta \sigma_s$ vs. N_f ; (b) ΔS_s vs. N_f ; (c) ΔS_{SR^*} vs. N_f .