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Fatigue analysis of friction stir welded aluminium profile using critical distance

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ABSTRACT

A friction stir (FS) welded extruded aluminium alloy 6005A, which is used for train wall sides, was fatigue tested. The friction stir weld was a lap-butt joint with a sharp notch (interface between the work pieces) next to the weld nugget. Fatigue cracks and failure appeared at notches in the profile. In most profiles, cracks also initiated at the sharp notch at the weld, but the propagation was slow and complete fracture never took place there. Finite element method (FEM) stress analysis combined with the theory of critical distance was used to estimate the fatigue limit. Results from the analysis for the fatigue limit were within 3–28% of the observations. The stress analysis correctly predicted that failure would not occur in the welds.

1. Introduction

Friction Stir Welding (FSW) is a solid state joining process with low heat input. It is mainly used for low melting point metals such as Al and Cu [1]. It has been shown that FSW in general improves fatigue life in comparison with fusion welding. The smooth surface appearance of FS welded joints compared to fusion welds also give a longer time to crack initiation. The absence of filler material in the weld, limited risk of porosity formation and fine-grained equiaxial microstructure provide strength comparable to the base metal. Nowadays, the FSW process is widely used in transportation applications. Large Al profiles in railway cars, shipbuilding and aerospace are joined by this technology. This makes fatigue assessment of FS welded joints essential [2–4].

There are different guidelines for fatigue assessment of structures and weldments. For aluminium alloys Euro code 9 [5] and IIW recommendations [6] are worth mentioning. Euro code 9 is based on nominal stress strategy under the assumption of linearised or constant stress in critical cross-sections. During recent years several investigations have been made on fatigue properties of FS welded joints [7–13]. The great majority of available data from the fatigue analysis of FS welded joints are concerned with nominal stress approaches under uniaxial loading condition for simple geometry and they do not address real engineering components.

Fatigue failure is a highly localized phenomenon in engineering components and determining the nominal stress is not always possible. Due to the complexity of local stress raisers such as sharp notches and cracks, many approaches based on local parameters have been proposed [14–22]. All these strategies try to introduce a reference stress which is appropriate for estimating fatigue strength. Nowadays FEM is widely used to determine the local quantities in components. Local approaches can take full advantage of FEM analysis.

During recent years the concept of critical distance (TCD) has been further developed for fatigue analysis of notched components [22,23]. The investigations have been made for a range of materials such as aluminium [24,25], steel, cast iron [22,24,25] and polymers [26]. Since the present profile is a welded structure with a sharp notch close to the weld nugget and the profile has several notches with different features in the parent metal, TCD was identified as a suitable method for fatigue analysis. The aim of the present work is to apply TCD to fatigue assessment of FS welded joints in aluminium profiles.

2. The theory of critical distance

It is well known that the fatigue life of notches with a high stress gradient is not directly related to the maximum stress at the notch root. The maximum stress underestimates the true fatigue life and is consequently inappropriate for fatigue prediction. Neuber proposed that the averaged stress along a line drawn from the notch root should be used for assessment of the number of cycles to failure [27]. Later Peterson [28] proposed that the appropriate stress can be found at a point at a certain distance from the notch root. In recent years Neuber's proposal of the existence of a microstructural support length was analysed by Taylor and named the critical distance [22].

For determining the appropriate stress for fatigue prediction three methods were proposed by Taylor [29], which should give similar results. They are all based on the critical distance L

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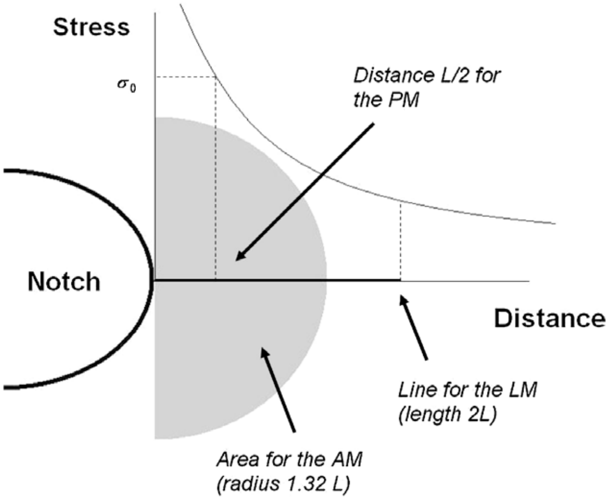

Fig. 1. Illustration of point method, line method, and area method and corresponding critical distance for each method. Fatigue failure will occur if the equivalent stress exceeds the fatigue limit of plain specimens σ_0.

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma_0}\right)^2 \tag{1}$$

where ΔK_{th} is the fatigue threshold stress intensity factor and $\Delta\sigma_0$ is the fatigue limit for uniaxial specimens. Since ΔK_{th} and $\Delta\sigma_0$ are both material constants, the critical distance L is also a material constant. The three methods are (see Fig. 1)

1. The point method (PM): the equivalent stress is determined at a distance of $L/2$ from the notch root.
2. The line method (LM): the equivalent stress is determined by averaging the stress along a line with the length of $2L$ drawn from the notch root.
3. The area method (AM): the equivalent stress is determined by averaging the stress over the semi-circular area centred on the notch root with the radius 1.32 L.

The drawn line direction for the point method and the line method depends on the stress field. For uniaxial loading, the line is perpendicular to the direction of the first principle stress at the point of maximum stress. The point method is also valid for multiaxial loading but using the Susmel–Lazzarin critical plane criterion increases the accuracy of prediction [30].

The resulting stress is called the equivalent (elastic) stress. This stress is compared with the fatigue limit of plain specimens. Fatigue failure will occur if the equivalent elastic stress exceeds the fatigue limit of plain specimens.

3. Experimental program

3.1. Material and welding

The profiles used in fatigue tests were made of extruded aluminium 6005A, in the T6 condition. Tables 1 and 2 show chemical composition and mechanical properties of the alloy. The tensile properties were measured on samples from the studied profile according to the standard EN 10002-1:2001.

Table 1
Composition (in wt.%).

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6005A actual	0.61	0.21	0.07	0.15	0.54	<0.01	<0.01	0.02	Bal
6005A nominal	0.5-0.9	<0.35	<0.30	<0.50	0.4–0.7	<0.30	<0.20	0.10	Bal

Table 2
Mechanical properties of the 6005A.

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Young's modulus (GPa)
6005A T6 actual	253	280	10	69.5
6005A typical (AluSelect)	260	285	13	69.5
6005A nominal	Min 225	Min 270	8	

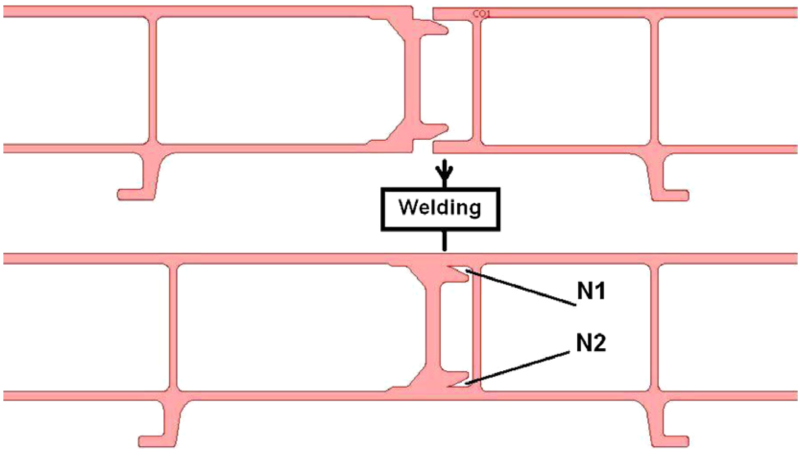

Fig. 2. Individual profiles were combined by welding to produce panels for train cars; after welding, notches N1 and N2 will form. The notches tips are at the stir zone (weld nugget).