International Journal of Fatigue 52 (2013) 114–123

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

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

Strain-based approach to fatigue crack initiation and propagation in welded steel joints with arbitrary notch shape

Heikki Remes *

Aalto University, School of Engineering, Department of Applied Mechanics, P.O. Box 15300, FIN-00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 9 November 2012
Received in revised form 4 March 2013
Accepted 12 March 2013
Available online 21 March 2013

Keywords:
Fatigue strength
Fatigue initiation
Weld notch
Heat-affected zone
Grain size

ABSTRACT

In this paper, a novel strain-based approach for the fatigue strength modelling of welded steel joints is introduced. The actual weld notch geometry and the variation in the microstructure characteristics of the material are considered, and thus, the approach enables the fatigue crack growth simulation from the crack initiation to the critical crack length before the final fracture. The predicted fatigue strength is in line with the experimental results. By considering the crack tip plasticity and stress triaxiality, the approach is able to describe the different crack growth periods of the fatigue life: the short crack, long crack, and tearing-related long crack growth periods. For a welded joint with a smooth notch shape, the short crack growth period is observed to be dominant and to have a significant influence on fatigue life.

1. Introduction

The fatigue strength modelling of welded joints is commonly based on the nominal, structural stress, or notch stress approaches [1,2]. In these approaches, the fatigue strength of the joint is described by an *S–N* curve, where the total fatigue life is presented as a function of the specific reference stress range. The reference stress is obtained from the linear elastic analysis using the average weld geometry [1]. Consequently, the statistical variation in the weld notch shape and the material properties are not considered in the modelling and their effects on fatigue strength are included in the *S–N* curve. Thus, this modelling approach assumes that the statistics of the weld notch geometry are similar to those in the experimental database that are used in defining the reference *S–N* curve.

For a joint welded using advanced welding methods, such as laser welding, the weld notch geometry can differ significantly from that of a traditional welded joint. Traditionally, a welded joint is assumed to incorporate crack-like defects and, thus the crack propagation dominates the total fatigue life [1]. For smooth weld notch geometry, the macro crack initiation becomes more significant. A longer initiation time was observed to lead to a significant difference in the fatigue strength and slope value of the *S–N* curve in comparison to the existing *S–N* curves [3–5]. The modelling of this difference is not possible with the existing stress-based approaches since the assumption of the similarity of the notch geometry is no longer valid. In addition, the use of the initial notch geometry neglects the effect of fatigue crack propagation on the stress and stress gradient. This effect is evident in a smooth weld notch, where the initial smooth geometry differs significantly from that of a sharp crack.

The effect of crack propagation on the stress–strain state is considered in fracture mechanics-based approaches [1], but they require the initial crack. Therefore, these approaches neglect the crack initiation period. The crack initiation period is strongly related to material properties, and this period can be modelled using the strain-based approach originally developed for smooth notch geometries [6,7], but later also successfully applied to define the crack growth properties of parent material [8–14]. Recently, the strain-based approach has been developed further, to include the effect of the microstructure of the material on the stress–strain state and fatigue damage process [15]. The continuum and strain-based discrete crack growth approach that was developed was successfully applied to different weld metals. These results are promising, but the approach has not yet been applied to welded joints, with the combined effect of the weld notch geometry and material being included.

In this paper, the strain-based discrete crack growth approach is further developed for welded joints. There, special challenges are caused by the statistical variation in the weld notch geometry, the strength overmatching of the weld metal, and the arbitrary crack growth direction. The approach is validated with experiments. In addition, the influence of the weld notch geometry and microstructure of the material on the crack initiation and propagation are discussed.

* Tel.: +358 407 025268; fax: +358 9 470 24173.
E-mail address: heikki.remes@aalto.fi

0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.03.006

2. Strain-based discrete crack growth approach

2.1. Modelling of fatigue damage process

In the strain-based discrete crack growth approach [15], the fatigue damage process is modelled as a repeated crack initiation process within the volume related to the microstructure of the material, as illustrated in Fig. 1. The volume is the damage zone where the micro cracks nucleate and coalesce, causing macro crack growth. In the initial step $n = 0$, the initial joint geometry is applied without a crack, described by misalignments and weld and notch dimensions, as shown in Fig. 2. After the fracture of the initial damage zone, the crack is propagated until the critical crack size is reached. The size of the damage zone, i.e. the homogenisation unit for the continuum modelling, is defined on the basis of the strength of the material and microstructure. It is assumed that the damage process follows the weakest link scenario. According to the Hall–Petch relation [16,17], low strength is related to large grain size and thus the size of the damage zone, i.e. the so-called material characteristic length a_o, which is defined as a function of the averaged grain size d and the parameter c, which is dependent on the grain size distribution

$$a_o = c \cdot d. \tag{1}$$

In the present study, the material fatigue strength is assumed to correlate with the grain size $d_{99\%}$ at a probability level of 99%, according to [15]. Consequently, the parameter c is defined as the ratio between the grain size $d_{99\%}$ and the average grain size d

$$c = \frac{d_{99\%}}{d}. \tag{2}$$

This material characteristic length defines the length of the discrete crack growth step and the same length is applied to calculate the fatigue-effective stress and strain, the fatigue damage parameter P_{SWT} [18], and finally the number of load cycles N_{in} for a discrete growth step n. The number of load cycles N_{in} is obtained using the Coffin–Manson formula [6,7] and the hardness-based estimation [19] for fatigue strength coefficients. The total fatigue life for the final fracture N_f is the sum of the load cycle number covering all the discrete growth steps. The crack growth rate CGR_n at the step n can be defined on the basis of the discrete crack growth length a_o and the number of cycles at the growth step n

$$CGR_n = \frac{N_{in}}{a_o}. \tag{3}$$

The crack growth rate CGR is always related to a certain crack length, and thus it enables a comparison to be made between the present results and the previous results based on the fracture mechanical approach.

2.2. Modelling of arbitrary crack growth

A fatigue crack is typically observed to grow in the direction perpendicular to the maximum principal stress [20]. In the case of a welded joint, the direction of the maximum principal stress can vary according to the weld geometry and loading. In addition, the direction can change during the crack growth. Therefore, the crack growth direction is calculated for each growth step n. In order to model the arbitrary crack growth, the stresses and corresponding crack growth direction are calculated for several lines around the point of maximum stress or crack tip, as shown in Fig. 3. Thus, the stress values are obtained using the line method [21,22], where the fatigue-effective stress is calculated as an average value of the stress distribution within the characteristic length of the material a_o

$$\sigma_e = \frac{1}{a_o} \cdot \int_o^{a_o} \sigma ds. \tag{4}$$

In order to calculate the fatigue effective stress and strain based on the averaging line perpendicular to maximum principal stress, the direction of the maximum principal stress is defined as the mean value of all values within the highly stressed volume. This

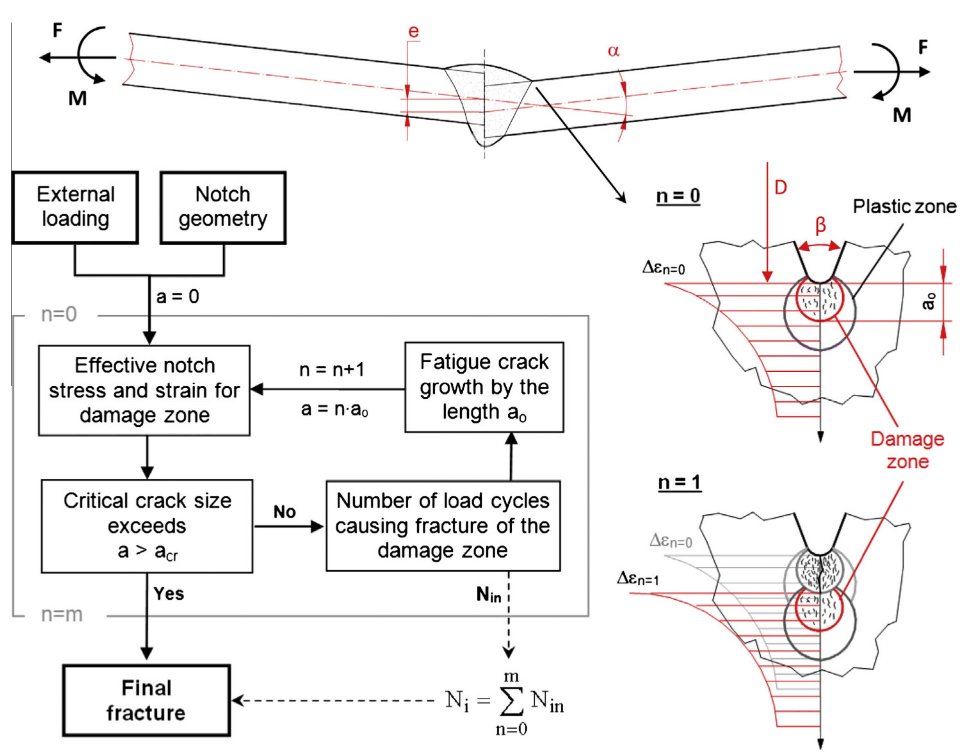

Fig. 1. Flow chart of the fatigue damage modelling of welded joints.