International Journal of Fatigue 31 (2009) 1327–1336

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Fatigue behaviour of AlMgSi tubular specimens subjected to bending–torsion loading

L.M.P. Abreu [a,*], J.D. Costa [b], J.A.M. Ferreira [b]

[a] ESTGA – University of Aveiro, Apartado 473, 3754-909 Águeda, Portugal
[b] CEMUC, Department of Mechanical Engineering, University of Coimbra – Polo II, Pinhal de Marrocos, 3030-788 Coimbra, Portugal

ARTICLE INFO

Article history:
Received 7 May 2008
Received in revised form 29 December 2008
Accepted 2 March 2009
Available online 12 March 2009

Keywords:
Aluminium alloys
In-phase biaxial fatigue
Tubular notched and welded specimens
Fatigue damage zone
Predictions

ABSTRACT

The work here presented is concerned with an experimental and numerical fatigue behaviour study of tubular specimens. Welded and notched tubular specimens of AlMgSi T6 alloy were submitted to in-phase bending–torsion tests. For both geometries, correlation of the fatigue lives was satisfactorily obtained by the distortion energy hypothesis based on the local stresses. A stress–strain field intensity approach and a novel energy-based approach were used to predict the fatigue lives. The applicability of fictitious radius concept at the welded toe was also tested. Comparison between referred theoretical predictions and experimental results reveal reasonable correlations, taking into account the scatter normally observed in fatigue results.

1. Introduction

Frequently, critical areas of structures and mechanical components are subjected to multiaxial states of cyclic stresses and strains, leading to fatigue damage. A multiaxial state can be consequence of local constrains at notches and welded roots, or may be caused by multiaxial external loadings. Because of the complex cyclic stress–strain responses of materials, the fatigue behaviour of structures under multiaxial loading cannot be easily described. According to the extensive reviews of multiaxial fatigue presented by several researchers [1–5] there is not yet a universally accepted model. For notched specimens submitted to in-phase bending–torsion fatigue tests, the von Mises and Guest criteria, suggested, respectively, by Gough [6] and Guest [7], provided reasonable correlations, but both neglected the influence of the notch geometry on cracking behaviour [8]. On the other hand, it was verified that any prediction concept based on von Mises criterion fails, when a combined out-of-phase bending–torsion loading was applied. In order to overcome these limitations, was proposed a local stress-based modification of von Mises, designated by effective equivalent stress hypothesis (*EESH*) [9]. Assuming that failure of ductile materials under multiaxial stresses states is initiated by shear stresses, this hypothesis establishes the determination of the effective equivalent stress by means of the effective shear stress and using a size effect factor [9]. The size effect factor reflects the influence of the maximum stressed material volume on the supportable local stress. The *EESH* has been successfully applied to several connections submitted either to out-of-phase bending–torsion loadings under constant and variable amplitude or to in-phase bending–torsion loadings [9,10].

The fatigue life predictions of components submitted to multiaxial states can only be consistent with experimental results if the effects of local stress–strain gradient and multiaxial characteristics at the notch are taken into account. According to several researchers [11–13], satisfactory predictions for components are achieved only if were considered all factors by the point of view of fatigue failure mechanisms at notches and weld roots, submitted to multiaxial states. One of the most recent methods applied to predict fatigue life is a macro-mechanical approach, designed by stress field intensity (*SFI*). *SFI* is based on the concept that the fatigue strength of a notched component depends not only on the peak stress range at notch root but also on the stress field intensity at the fatigue failure region or fatigue process zone [11,12]. This region can be defined as the material volume where micro or macro-plastic cyclic strain takes place, initiating the damage of the material microstructure. According to this approach fatigue failure of a component will occur from a feature that generates the highest local stress associated with high stress gradients. According to Shang et al. [13] the damage cumulative process within a small area at a dangerous position is not only related to local stress field intensity, but depends also on local strain field intensity in the small local area. Based on this theory the authors proposed the local stress and strain field intensity parameters to

* Corresponding author. Fax: +351 234 611540.
E-mail address: lmabreu@ua.pt (L.M.P. Abreu).

0142-1123/$ - see front matter
doi:10.1016/j.ijfatigue.2009.03.004

describe fatigue damage, so that the approach is designed by stress–strain field intensity (*SSFI*).

For the stress and strain field parameters calculation is necessary the knowledge of the stress and strain distributions in the vicinity of the notch roots, which can be obtained by finite element analyses if the geometric details were well known. Unfortunately the geometric details of the welded roots and other hidden details cannot be precisely established [9,14].

For the fatigue assessment of weld roots the concept of the micro-support theory of Neuber [15,16] and the concept of the fictitious radius [17] were recently developed. The micro-support concept considers that the fictitious notch radius ρ_f depends on the actual radius ρ, the multiaxiality coefficient s and the substitute micro-structural length ρ^*

$$\rho_f = \rho + s\rho^*. \tag{1}$$

The substitute micro-structural length ρ^* is a local material constant, which is dependent on the yield stress and is different for the base metal, the heat affected zone and the weld metal [16]. The notch stresses have to be averaged over the micro-structural length, which is normal to the surface. The coefficient s depends on multiaxiality of the notch stress (plane stress, plane strain or anti-plane shear loading) and on the applied strength hypothesis [15,16].

According micro-support concept, the fictitious notch radius must be determined separately for bending and torsion, for the assessment of the fatigue behaviour of welded joints submitted to bending–torsion loadings [18]. Otherwise the concept of the fictitious radius is more universal and does not need material constants. For steel welded joints from plates with thickness $t \geqslant 5$ mm, a fictitious radius of 1 mm is recommended [19,20]. This radius can be obtained from the micro-support concept assuming $\rho^* = 0.4$ mm, $s = 2.5$ for a plane strain condition at the root of sharp notches combined with von Mises strength criterion [15] and the worst case of a crack with a null actual radius [17]. A fictitious radius of 1 mm was also successfully applied to AlMg4.5Mn and AlMgSi1 T6 aluminium alloys welded joints from plates with thicknesses within 5 and 25 mm [21]. For plates with $t \leqslant 5$ mm of steel and aluminium alloys, the fictitious radius of 0.05 mm was successfully applied to studies based on the local stress concept [22].

In this study the fatigue behaviour of welded and notched tubular specimens, submitted to in-phase bending–torsion loading, was assessed by means of the pseudo-elastic equivalent local stresses evaluated by means of the von Mises criterion. For variable amplitude loadings composed of blocks, the equivalent stresses were estimated with Miner's rule. Two simplification hypotheses were considered for the weld toe of welded specimens: for one of them a fictitious radius equal to 1 mm was assumed and for the other was considered the average of the radius measurement at weld toes. Local stress–strain field intensity (*SSFI*) approach proposed by Shang et al. [13] was applied as damage parameter on fatigue lives predictions performed for both notched and welded tubular specimens. However, the authors introduced some modifications to *SSFI* in accordance with Qylafku et al. [12], being the approach presented in this paper a combination of both: (i) the effect of the fatigue damage zone is introduced by means of the effective distance [12]; (ii) von Mises equivalent stress and strain distributions are used to reflect the influence of the applied stress and strain on notch strength as is suggested by Shang et al. [13], in place of the σ_y stress as proposed in the Qylafku et al. [12] approach. Fatigue life predictions were based on Coffin–Manson approach with Morrow's modification to include mean stress influence. A proposed energy-based approach establishing a power law between field intensity of strain energy density and fatigue life was also used for life predictions. In this approach, the local strain energy density is estimated considering valid the equivalent strain energy hypothesis, avoiding non-linear elastic–plastic analyses, even when some plasticity occurs at the notch roots. Therefore, a new equation based on energy field intensity will be used to estimate fatigue lives. In both approaches the damage zone dimension was defined by the effective distance, x_{eff}. For this paper, the variation of x_{eff} with the notch radius and the material properties was numerically studied by means of finite element analyses. Finally, the predicted initiation fatigue lives of notched and welded tubular specimens of AlMgSi alloy with a T6 heat treatment alloy were compared with experimental data from in-phase biaxial fatigue tests.

2. Local stress–strain field intensity approach

The stress field intensity σ_{FI} is defined as [11,12]:

$$\sigma_{FI} = \frac{1}{V}\int_{\Omega} f(\sigma_{ij})\varphi(\vec{r})dv, \tag{2}$$

and the strain field intensity parameter ε_{FI} is defined by [13]:

$$\varepsilon_{FI} = \frac{1}{V}\int_{\Omega} f(\varepsilon_{ij})\varphi(\vec{r})dv. \tag{3}$$

In previous equations, Ω is the fatigue failure region, V the volume of Ω, $f(\sigma_{ij})$ the stress equivalent function, $f(\varepsilon_{ij})$ the strain equivalent function and $\varphi(\vec{r})$ a weight function.

The equivalent stress and strain functions reflect the influence of the applied stress and strain on notch strength. According to Shang et al. [13] von Mises equivalent stress and strain are used for ductile materials such as carbon steel and aluminium alloys, while maximum principal stress is used for brittle materials. Since the equivalent stress and strain contain the effects of the multiaxial characteristics at the notch, the stress–strain complex states generated by the notches are taken into account. In this work von Mises equivalent stress and strain are used to describe $f(\sigma_{ij})$ and $f(\varepsilon_{ij})$.

The weight function, $\varphi(\vec{r})$, introduces the contribution of the equivalent stress or strain at a point Q in the vicinity of the notch root to the peak stress at $|\vec{r}| = 0$ and is characterized by:

1. $0 \leqslant \varphi(\vec{r}) \leqslant 1$ and $\varphi(\vec{r})$ is a monotonically decreasing function about $|\vec{r}|$;
2. $\varphi(0) \equiv 1$, which means that contribution of the stress at the notch root is maximum;
3. $\varphi(\vec{r}) \equiv 1$, without stress gradient ($\chi = 0$).

The weight function, $\varphi(\vec{r})$, is defined by [13]:

$$\varphi(\vec{r}) = 1 - \chi|\vec{r}|, \tag{4}$$

where χ is the stress gradient and $|\vec{r}|$ is the distance from the point Q to the notch root. Considering that $\varphi(\vec{r})$ is related to the distance

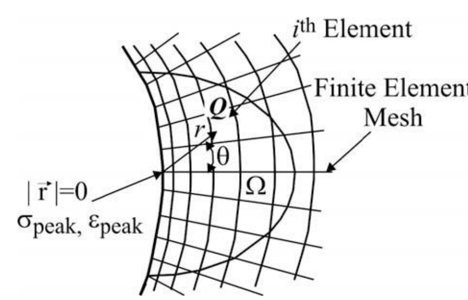

Fig. 1. Schematic diagram of a finite element mesh in notch vicinity with damage zone representation [13].