ARTICLE IN PRESS

International Journal of Fatigue xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Influence of effective stress ratio on the fatigue strength of welded and HFMI-treated high-strength steel joints

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ARTICLE INFO

Article history:
Received 15 January 2017
Received in revised form 20 February 2017
Accepted 5 March 2017
Available online xxxx

Keywords:
Fatigue strength
Welded joints
High frequency mechanical impact (HFMI) treatment
High-strength steel
Effective stress ratio

ABSTRACT

This paper contributes to quantify the influence of the local mean stress condition and the local weld geometry on the high-cycle fatigue strength of welded and high frequency mechanical impact (HFMI) treated S960 high-strength steel joints. A calculation procedure is presented, which bases on the effective stress ratio at the weld toe considering the local residual stress condition as well as the specimen clamping-induced and load-dependent notch mean stress state to assess a final influence fatigue factor. Fatigue tests incorporating butt joint, T-joint, and longitudinal stiffener specimens present the effect of different welding parameters and the HFMI technique as post-treatment method. The results show that firstly, by an application of optimized welding parameters, such as filler material and shielding gas, an increase in fatigue strength of 7% for the butt joint and of 30% for the T-joint specimens is experimentally observed. Secondly, it is shown that all investigated specimen types reveal a significant increase in fatigue strength due to the HFMI-treatment up to an enhancement of factor 2.46 in case of the longitudinal stiffener specimens. A study on the effect of stress-relief annealing as post-weld heat treatment (PWHT) process highlights a decrease of about 25% in the high-cycle fatigue strength in case of HFMI-treated T-joint specimens. Applying the introduced calculation method, an effective stress ratio of $R_{eff} = 0.05$ for the butt joint and T-joint specimens, and $R_{eff} = -0.81$ for the longitudinal stiffener specimens in the as-welded condition is calculated. Comparing the computed fatigue factors with the statistically evaluated nominal fatigue strengths it is observed that the effect by the effective stress ratio is dominant, but not fully covers the fatigue enhancement. Furthermore, it reveals that the influence by the effective stress ratio may be related to the fundamental change in the local residual stress state. Especially the HFMI-treatment leads to a reduction of the local residual stress condition up to a difference of 650 MPa for the S960 high-strength steel, which significantly contributes to this influence.

1. Introduction

Welding, as thermo-metallurgical-mechanical manufacturing process, strongly influences the local material due to rapidly heating and subsequently cooling as well as the effect of additional filler material, resulting in inhomogeneous material properties. To assess the fatigue strength of welded high-strength steel joints not only the base material, also the welding process parameters and further post-treatment techniques are essential. According to the conservative IIW-recommendation [1], the fatigue strength of welded structures is mostly independent of the base material yield strength and thereby, the application of high-strength steels basically does not enhance fatigue life in the as-welded condition. To utilize the increased base material strength, post-treatment methods like the High Frequency Mechanical Impact (HFMI) [2] treatment are recommended and common in industrial applications.

In the course of this paper, the influence of the effective stress ratio including the local residual, clamping and load-induced mean stress states on the weld toe fatigue strength of S960 high-strength steel joints in as-welded and HFMI-treated condition is investigated. Firstly, this work bases on preliminary studies involving the effect of weld process parameters, such as filler material and shielding gas, on the fatigue strength of high-strength transverse stiffeners as T-joint [3], representing structural detail no. 511 in [1], and butt joint specimens [4] with focus on the as-welded condition. Secondly, the influence of HFMI-treatment on high-strength steel T-joints is analyzed utilizing the results in [5]. Herein, the effect by the local compressive residual stress state on the lifetime is specifically researched facilitating fatigue tests with HFMI-treated specimens before and after stress-relief annealing as post-weld heat treatment (PWHT) process. Utilizing these data sets, an enhanced calculation procedure is presented and validated in this paper, which is capable to distinguish between the influence of

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http://dx.doi.org/10.1016/j.ijfatigue.2017.03.008
0142-1123/

Nomenclature

α	angular deformation of specimen (°)	k	slope of S/N-curve (–)
θ	flank angle of weld seam (°)	N_k	transition knee point of S/N-curve (–)
ρ	weld toe radius (mm)	R	stress ratio (–)
$\Delta\sigma$	stress range (σ_n for nominal and σ_k for notch stress) (MPa)	R_{eff}	effective stress ratio (–)
$\sigma_{k,mean}$	load-dependent notch mean stress (MPa)	SCF	stress concentration factor (–)
$\sigma_{k,clamp}$	clamping-induced notch mean stress (MPa)	T_S	scatter band between 10% and 90% survival probability (–)
σ_{res}	residual stress (MPa)		

the effective stress ratio and the effect by the local weld toe topography, as geometrical notch parameter, on the fatigue strength in the high-cycle fatigue region. Finally, this approach is applied to assess the beneficial effect by the post-treatment technique for butt joint, T-joint, and longitudinal stiffener specimen test results [6] comparing the as-welded and HFMI-treated condition without any further post modification. In general, welding residual stresses states affect the fatigue design of welded joints and components [7]. In [8] it is shown that in case of high residual stresses, the fatigue strength is at a comparably minor level and additionally, roughly independent of load-induced mean stresses. This behavior is validated on the basis of numerous fatigue tests including welding residual stress states under alternating ($R = -1$) and tumescent ($R = 0$) stress ratios. The resulting local fatigue strength at two million load-cycles indicates almost no difference between these two testing conditions, mainly caused by the residual stress effect. Additionally, experiments in as-welded and stress-relieved condition reveal that under both constant and variable amplitude loading an influence of the welding residual stresses is observed. In [9] the effect of the local residual stress state for complex weld structures is analyzed, whereby it is concluded that for a reliable fatigue analysis of such cases, the consideration of residual stresses seems to be inevitable. Fracture mechanical calculations for a butt joint [10] and a T-joint [11] show that the residual stress condition can be incorporated by the effective stress ratio at the crack tip.

This work enhances the evaluation of the effective stress ratio by additionally incorporating the local clamping-induced mean stress state as well as the influence due to the stress concentration, majorly basing on the weld toe topography and loading condition. Recent investigations focusing on the relative effects of residual stresses and weld toe geometry on the fatigue resistance of cruciform joints in [12] conclude that the residual stress state has a relatively larger influence than the weld toe geometry. However, as this paper investigates both, mean stress and weld toe topography effects, additional aim is laid on the measurement of local weld toe geometry parameters, especially weld toe radius and flank angle. A study in [13] presents the fatigue analysis of as-welded joints with the aid of real three-dimensional weld toe geometry. Based on comprehensive three-dimensional scanning, statistical evaluation, and numerical stress concentration analysis it is concluded that final fracture is not necessarily starting from the weld with the highest stress concentration. In case of HFMI-treated joints, an analysis in [14] reveals the effect of HFMI process parameters on the weld toe topography and final fatigue strength. The results show an increase of 26% compared to the as-welded fatigue strength by applying optimized HFMI process parameters for welded high-strength steel joints.

2. Evaluation of effective stress ratio

2.1. Local stress condition

An overview of common concepts to assess the fatigue strength of welded joints is provided in [15]. Among these, the effective notch stress approach is one widespread method due to the comparably high accuracy at an acceptable amount of effort. The application of this approach is based on a fictitious reference notch radius of $\rho_{ref} = 1$ mm, which is derived from the micro-support hypothesis [16] assuming the worst case of a notch with a real radius of $\rho = 0$ mm [17]. Based on this approach, the fatigue-effective notch stress is facilitated for the fatigue assessment, whereby allowable fatigue resistance values are presented in [18] for the as-welded, and in [19] for the HFMI-treated condition. However, in this paper focus is laid on the calculation of the real local stress condition influencing the effective stress ratio at the weld toe. Therefore, not the fictitious reference notch radius, but the real weld toe radius is utilized. For the investigated specimens in this work, the notch stress range $\Delta\sigma_k$ at the weld toe is calculated by multiplying the nominal stress range $\Delta\sigma_n$ with a stress concentration factor SCF, see Eq. (1).

$$\Delta\sigma_k = \Delta\sigma_n \cdot SCF \tag{1}$$

In this work, the SCFs of the investigated specimen types under tensile loading are calculated analytically or by linear-elastic finite-element analysis. Analytical methods to determine the SCF of various weld geometries are given in [20]. Referencing to the work by [21], Eq. (2) shows an analytical computation procedure incorporating the weld flank angle θ, the plate thickness t, and the weld toe radius ρ. The factor A depends on the type of joint with a value of $A = 0.27$ for butt welds and $A = 0.35$ for cruciform joints.

$$SCF = 1 + A \cdot \tan(\theta)^{1/4} \cdot (t/\rho)^{1/2} \tag{2}$$

Based on the evaluated notch stress range $\Delta\sigma_k$, a computation of the notch mean stress $\sigma_{k,mean}$ considering the external load-dependent stress ratio R is enabled, see Eq. (3).

$$\sigma_{k,mean} = \frac{\Delta\sigma_k}{2} \cdot \frac{(1+R)}{(1-R)} \tag{3}$$

2.2. Effective stress ratio

As introduced, this paper investigates the influence of the effective stress ratio R_{eff} at the highly-stressed surface point of the weld toe incorporating the local residual stress σ_{res}, load-dependent notch mean stress $\sigma_{k,mean}$, and additionally, the local specimen clamping-induced notch mean stress $\sigma_{k,clamp}$, which arises in the course of the clamping procedure of specimens geometrically distorted by the welding process. The calculation of R_{eff} is presented in Eq. (4) considering the local stress condition due to the external loading and the aforementioned effects.

$$R_{eff} = \frac{(\sigma_{res} + \sigma_{k,mean} + \sigma_{k,clamp}) - \frac{\Delta\sigma_k}{2}}{(\sigma_{res} + \sigma_{k,mean} + \sigma_{k,clamp}) + \frac{\Delta\sigma_k}{2}} \tag{4}$$

Based on [1], the impact of R_{eff} on the fatigue strength is finally considered by defining a fatigue factor $f(R_{eff})$ based on Eq. (5).

Please cite this article in press as: Leitner M. Influence of effective stress ratio on the fatigue strength of welded and HFMI-treated high-strength steel joints. Int J Fatigue (2017), http://dx.doi.org/10.1016/j.ijfatigue.2017.03.008