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Stability of high frequency mechanical impact (HFMI) post-treatment induced residual stress states under cyclic loading of welded steel joints

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ABSTRACT

This paper investigates the effect of cyclic loading on the stability of compressive residual stress fields induced by high frequency mechanical impact (HFMI) post-weld treatment. First, the effectiveness of the post-treatment technique is shown by fatigue tests incorporating mild steel S355 and high-strength steel S960 longitudinal stiffener specimens. Extensive X-ray residual stress measurements support the beneficial impact on the compressive residual stress state for mild and high-strength steel structures. They also illustrate that cyclic loading leads to a significant local relaxation of this condition. Second, a numerical simulation chain incorporating a structural weld simulation, numerical analysis of the HFMI-treatment, and a final cyclic loading step for the investigated mild steel specimen is set-up. The results show that the residual stresses at the surface of the weld toe are in agreement to the X-ray measurements for both the as-welded and HFMI-treated condition, which basically proofs the applicability of the manufacturing simulation. The numerical computation including the first five load-cycles demonstrates that the simulated residual stress relaxation again exhibits consistent results with the measurements. An additional utilization of an analytical relaxation model from literature reveals that the estimation of the residual stress state in the high-cycle fatigue region is well employable. Therefore, the scientific results in this paper proof the applicability of the presented consecutive numerical-analytical procedure to assess the local compressive residual stress stability of HFMI-treated welded steel joints in both the low- and high-cycle fatigue region.

1. Introduction

The beneficial effect of high frequency mechanical impact (HFMI)-treatment in order to enhance fatigue strength is primarily based on an improvement of the weld toe topography, a local hardening of the material and compressive residual stresses. Prior fatigue tests involving different kind of weld details and base material yield strengths in [1] reveal the positive effect of the HFMI-treatment. In [2], the influence of grinding and hammer peening on crack propagation is investigated showing again that the post-treated conditions exhibit significantly advantageous fatigue properties. Due to the forming process in the course of the peening procedure, HFMI-treatment leads to a local change in microstructure. However, an analysis by [3] concludes that this effect is not mainly relevant for the increase in fatigue resistance. A recently published guideline [4] provides recommendations to the practical application of the HFMI-treatment and includes benefit factors for nominal and local fatigue strength assessment. Especially in case of ultra-high strength steel joints, this technique seems to facilitate an essential increase in fatigue life [5], removing surface-near imperfections like undercuts at the weld toe, which are particularly harmful for high-strength materials [6]. Besides this geometrical impact, the local residual stress condition is of great importance for the fatigue strength of HFMI-treated joints. In [7], HFMI-treatment is applied as rehabilitation method, whereat it is found that the depth of the HFMI-induced compressive residual stress field is fundamental for the lifetime extension. HFMI-process parameters and the corresponding final post-treated condition such as properly-, under- or over-treated affect this residual stress state and hence the fatigue behaviour [8]. Measurements by [9] indicate that the compressive residual stress is decreased just after the first load-cycle, whereby only a comparably small relaxation due to the further loading up to the high-cycle fatigue region takes place.

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These findings are of special interest in case of variable amplitude loading, which commonly occurs in real load applications. Fatigue tests in [10] using S700 high-strength steel longitudinal stiffeners in as-welded and HFMI-treated condition under constant and variable amplitude loading exhibit that the increase factor by the post-treatment is reduced in case of the latter load-scenario. This effect may be drawn to a local relaxation of the beneficial compressive residual stress state at higher load-levels, leading to a reduced fatigue life for variable amplitude load-spectra. An extensive literature survey focussing on the stability and significance of residual stresses during fatigue by [11] summarizes that many of the pronounced cyclic relaxation effects identified in the literature appear to be static effects, e.g. appearing at the first loading cycle or in the course of overloads. This statement is basically confirmed in [12] showing that the compressive residual stresses at the surface in the HFMI-treated weld toe region are relaxing from about −400 MPa to −250 MPa due to a single tensile load of 90% of the yield strength or alternatively, by a single compressive load of 60% of the yield strength. Additionally, experimental analysis in [13] with shot-peened round steel specimens concludes that just one single cyclic overload could decrease the fatigue life time by 25% to 60% compared to the situation with no overload. Similar results are presented in [14] for single overloads involving different temperature and notch conditions, and in [15] focusing on cyclic loading in the low cycle fatigue region. However, investigations by [16] reveal the occurrence of a certain residual stress relaxation in the high-cycle fatigue region, hence this effect should also not be neglected.

Therefore, one efficient method to study the effect of residual stress stability during fatigue loading is based on numerical analysis. In [17], a coupled thermo-mechanical numerical simulation with a subsequent elastic-plastic analysis incorporating cyclic plasticity based on a nonlinear kinematic hardening rule is conducted. Furthermore, a finite element study in [18], which numerically investigates the residual stress stability and fatigue damage in HFMI-treated welded joints, concluded that the benefit from compressive residual stresses decreased with an increasing stress range, stress ratio and peak load magnitude due to increasing level of residual stress relaxation. However, this work is based on a simplified procedure considering the residual stress state by mapping an analytical field in the numerical model. An elaborated approach to incorporate the significant manufacturing process, such as welding and HFMI-treatment, within a numerical simulation is exemplified in [19]. In the course of own preliminary numerical studies this principal procedure, by setting-up a numerical simulation chain involving a structural weld simulation and a subsequent numerical analysis of the HFMI-process, is also scientifically researched with focus on a mild steel butt joint specimen, see [20]. On the basis of this work, the residual stress stability of a thin-walled mild steel S355 longitudinal stiffener specimen is analyzed in this paper, which contributes to the following scientific topics in detail:

- Experimental investigation of the cyclic stability of HFMI-induced compressive residual stress states based on X-ray residual stress measurements for mild steel 355 and high-strength steel S960 joints.
- Presentation of numerical simulation chain including structural weld simulation and numerical HFMI-treatment analysis for the investigated mild steel S355 longitudinal stiffener.
- Numerical assessment of cyclic residual stress relaxation for the first five load-cycles and further estimation up to run-out level of fifty million load-cycles by an engineering feasible analytical model.

2. Review of analytical models for cyclic residual stress relaxation

Besides the applicability of numerical approaches, several analytical procedures to estimate the residual stress relaxation under cyclic loading exist, which are reviewed in [21]. Herein, the models proposed for both residual stress relaxations due to thermal and mechanical loadings are reviewed. It is summarized that residual stresses do relax during the service life of a component, but it may not affect the fatigue life significantly. It is also concluded that the proposed residual stress relaxation models require further detailed study to examine their validity. One of the early models for residual stress relaxation is presented by Morrow and Sinclair [22]. They conducted strain-controlled fatigue tests to quantify the cyclic residual stress relaxation and recommend a basic relationship considering the yield strength, the amplitude and the mean stresses as well as the number of load-cycles, see Eq. (1).

$$\frac{\sigma_{mN}}{\sigma_{m1}} = \frac{\sigma_y - \sigma_a}{\sigma_{m1}} - \left(\frac{\sigma_a}{\sigma_y}\right)^b \cdot \log(N) \quad (1)$$

where σ_{mN} is the mean stress at the N-th cycle, σ_{m1} is the mean stress at the first cycle, σ_a is the alternating stress amplitude, σ_y is the material yield strength, and b is a constant dependent on material softening and the applied strain range $\Delta\varepsilon$. This model is only applicable for a load ratio of R = −1, because the surface residual stress is only analogous to the mean stress when the material is subjected to completely reversed loading. The model is experimentally verified for $N > 10^6$ and $\sigma_{mN} < 20$ MPa.

Jhansale and Topper [23] suggest a power law relationship between the mean stress and the load-cycles to quantify cyclic residual stress relaxation. The relationship is given by Eq. (2), where σ_{mN} is the mean residual stress state after N-cycles, σ_{ml} is the mean load stress state, and B is the relaxation exponent dependent on the material softening and applied strain range $\Delta\varepsilon$.

$$\sigma_{mN} = \sigma_{ml} \cdot N^B \quad (2)$$

$$\sigma_N^{res} = A + m \cdot \log(N) \quad (3)$$

Kodama [24] proposes a linear logarithmic relationship for residual stress relaxation, see Eq. (3). Thereby, σ_N^{res} is the surface residual stress after N-cycles, A and m are material constants, which are depending on the stress amplitude σ_a. It is noted that the experimental data, which supports the linear logarithm, decreases the relationship between residual stress and the number of load-cycles only after the first cycle.

Zhuang and Halford [25] recommend an analytical model for the relaxation of residual stresses. Their model incorporates the initial cold work and is based on finite element results. The model could predict the relaxation at R = 0 and R = −1 quite close to that obtained by numerical analysis. Their proposed relation is given in Eqs. (4) and (5) depicting the estimation without and with consideration of the effect by the load ratio R.

$$\frac{\sigma_N^{res}}{\sigma_0^{res}} = A \cdot \left(\frac{\sigma_{\max} \cdot \sigma_a}{(C_w \cdot C_y)^2}\right)^m \cdot (N-1)^B - 1 \quad (4)$$

$$\frac{\sigma_N^{res}}{|\sigma_0^{res}|} = A \cdot \left(\frac{2 \cdot \sigma_a^2}{(1-R) \cdot (C_w \cdot C_y)^2}\right)^m \cdot (N-1)^B - 1 \quad (5)$$

where C_w defines a parameter, which accounts for the degree of cold working. Material constants m and A are dependent on the cyclic stress and strain response, and need to be considered for each mean stress condition. Constant B controls the relaxation rate versus loading cycles and the initial residual stress is considered by