Journal of Constructional Steel Research 150 (2018) 23–30

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Numerical analysis of optimum treatment parameters by high frequency mechanical impact

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ARTICLE INFO

Article history:
Received 27 April 2018
Received in revised form 23 July 2018
Accepted 6 August 2018
Available online xxxx

Keywords:
High frequency mechanical impact (HFMI)
Stress concentration
Fatigue strength improvement
Residual stress
Finite element analysis (FEA)

ABSTRACT

In the study, finite element analyses were carried out systematically to investigate the optimum treatment parameters of high frequency mechanical impact (HFMI) on the basis of notch effect reduction and residual stress, which are generally considered to be the dominating factors of fatigue strength improvement of welded joints by HFMI treatment. Taking strain rate into account, the combined isotropic-kinematic hardening model was used to describe the elastic-plastic behavior of the HFMI-treated welded joint of S355 steel. The notch stress concentration factors (SCFs) and residual stresses under different impact depths and diameters of indenter were determined, respectively. Moreover, their synthetic effects on stress distributions of HFMI-treated joints under static load were investigated. It is found that the stress distributions of HFMI-treated joints under static load are affected significantly by impacted groove depth, independent of indenter diameter. The HFMI treatment can achieve the optimal status when the original weld toe is just removed with a groove depth ranging from 0.1 to 0.2 mm. At final, the optimized diameters of 3 to 4 mm are recommended for the indenter in terms of stress concentration and avoidance of crack.

1. Introduction

Fatigue is one of the most important failure modes of welded joints. Weld toe region tends to be fatigue crack initiation site due to local stress concentration caused by weld reinforcement and residual tensile stress from welding process. To improve the fatigue resistance of welded joints, some post-weld improvement techniques have been proposed, including burr-grinding, TIG re-melting, hammer, shot peening, high frequency mechanical impact (HFMI) and so on [1, 2]. Of these, HFMI treatment is widely considered to be comfortable, effective and user-friendly. During the treatment, hardened cylindrical metal indenters with a spherical tip are used to impact the weld toe surface with high frequency of >90 Hz.

Extensive studies on HFMI treatment have been published during the past decade, focusing on the improvement mechanism and fatigue assessment of HFMI-treated joints. Generally, the effectiveness of HFMI on fatigue strength improvement of welded joints is principally considered to depend on the beneficial effects of notch effect reduction, compressive residual stress and localized strain hardening of the HFMI-treated surface [3, 4]. Leitner conducted experimental and numerical investigations on the influence of local mean stress condition and weld geometry on fatigue strength of welded and HFMI-treated S960 steel joints and found that the compressive residual stresses act as most significant factor by improving the fatigue strength due to the HFMI treatment [5]. Mikkola et al. [6] carried out a finite element study on the residual stress relaxation of HMI-treated joints under different stress ratios and peak loads. Even the full residual stress relaxation was observed, the fatigue strength of HFMI-treated joints was still higher than that of as-welded joints, which indicating that the improvement of fatigue strength after residual stress relaxation was due to geometric modification and strain hardening. Gao et al. [7] carried out fatigue tests of underwater weld joints under the treatment of burr grinding, HFMI and grinding + HFMI, and their result shows that burr grinding + HFMI is the most effective method to improve the fatigue life of underwater wet welded joint, indicating geometric modification and residual compressive stress are two vital factors responsible for the improvement of fatigue strength. Mikkola et al. [8] found that the increase of fatigue strength for strain-hardened material is only effective in high-cycle fatigue and will be eliminated in low-cycle fatigue region. Besides the fatigue improvement mechanism of HFMI treatment, fatigue assessment of HFMI-treated joints is another research focus. Taking the residual stresses and stress concentrations at the weld toe into account, Yuan and Sumi [9] proposed a fracture mechanics based method to predict the fatigue strengths of HFMI-treated joints. Based on the stress distribution of HFM-treated joint under load, Deng et al. [10, 11] proposed the fatigue design curve of HFMI-treated joints by modifying the fatigue

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https://doi.org/10.1016/j.jcsr.2018.08.004
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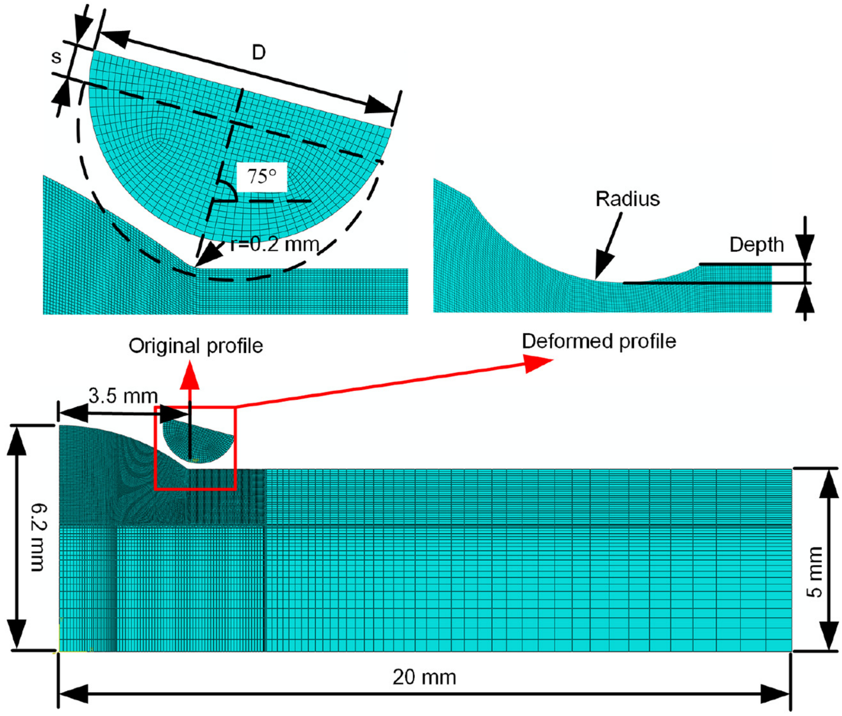

Fig. 1. 2D symmetric FE model for HFMI treatment of the butt joint.

design curve of as-welded joints using the effective stress concentration factors (SCFs). The effective SCFs consider the combined effects of residual stresses and stress concentrations. A three-dimensional simulation loop is proposed by Leitner et al. for assessing the fatigue property of HFMI-treated joint by stress/strain-based and fracture mechanical approaches [12]. The proposed procedure systematically considers the preceding welding simulation, HFMI simulation and local material properties.

Nevertheless, as a manufacturing process, the effect of process parameters on fatigue improvement by HFMI treatment was seldom studied. In the IIW recommendations, Marquis and Barsoum [13] chosen the profile of HFMI groove as an index to conduct quality control of the HFMI treatment, with the groove depth and radius being the two key parameters. For instance, Marquis and Barsoum [14] pointed out that the depth of HFMI groove is an excellent indicator of the extent of HFMI treatment. It is recommended in the IIW Documentation that the optimum HFMI groove will be 0.2–0.6 mm in depth based on the yield strength and the size of indenter [13]. A final groove depth of 0.25–0.5 mm is recommended but not required in the AASHTO Bridge Construction Specification [15]. Malaki and Ding [16] has proposed that the depth of HFMI groove is in the range of 0.3–1.0 mm. However, the groove depth is relatively shallow in reality as reported in the literature. Zhang et al. [17] measured the groove depth at the middle and edge of the HFMI-treated specimen, with the value of which 0.13 mm and 0.17 mm respectively. Yildirim and Marquis [18] measured the groove depth after four different HFMI treatments, and an average depth of 0.2 mm was obtained. A German research project presented that the optimal depth of HFMI groove is 0–0.25 mm [19]. Therefore, the recommended groove depth is diverse, which leads to confusion for the researchers and engineers to determine to which groove depth the welded joints should be achieved. On the other hand, the radius of HFMI groove, which is mainly determined by the diameter of indenter, is also an important aspect of the groove profile. In most cases, the indenter with the diameter of 3 mm is recommended for the treatment of steel welded joints. Whereas, there are also other size of indenters used in the literature. Shimanuki and Okawa [20] used the indenter with the tip diameter of 6 mm and Mikkola et al. [8] used the indenter with the diameter of 4 mm to carry out the HFMI treatment. The systemic study on the effect of groove radius (or the diameter of indenter) on HFMI treatment has not been reported yet.

The primary aim of the work is to determine the optimized HFMI treatment parameters for fatigue strength improvement of welded joints. In the study, numerical simulations of HFMI process were performed to study the effect of groove depth and radius on the notch effect reduction and the resultant stress distribution. Firstly, the notch stress concentration factors (SCFs) with different groove depths and radii were determined using the 2D model. Moreover, the 3D model was used to investigate the residual stress distributions under different HFMI treatment parameters. In order to obtain more practical stress field, a combined isotropic-kinematic hardening model of rate-dependence was used to describe the elastic-plastic behavior of the impacted specimen. Finally, the combined effects of notch SCFs and residual stresses on stress distribution of HFMI-treated joints under load were discussed. Accordingly, a groove depth and an indenter diameter are suggested.

2. Numerical analysis

Some attempts have recently been made to simulate the HFMI process, which can be mainly categorized into two approaches: displacement-controlled and velocity-controlled methods [9, 21]. In the

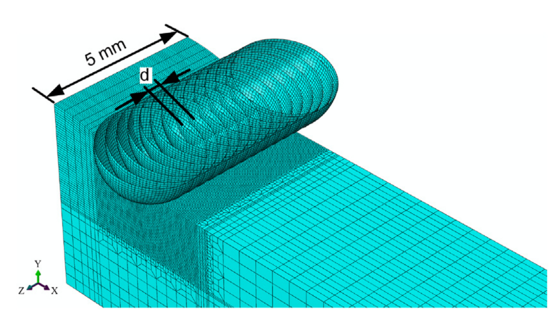

Fig. 2. 3D symmetric FE model for HFMI treatment of the butt joint.