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Fatigue design of axially-loaded high frequency mechanical impact treated welds by the effective notch stress method

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ABSTRACT

The effective notch stress method (ENS) as defined by the International Institute of Welding is widely used by design engineers to assess the fatigue strength of welded components. This paper provides a comprehensive evaluation of published data for welded joints improved by high frequency mechanical impact (HFMI) treatment. The goal is to verify already-known fatigue classes for the ENS with the available axially-loaded fatigue data. In total, 280 experimental test results obtained from longitudinal, cruciform and butt welds subject to stress ratio of $R = 0.1$ axial loading are evaluated. Notch stress concentration factors (K_n) for each joint geometry are analysed based on the finite element method. Calculated K_n and reported nominal stress values are used to determine local stresses. Fatigue strength assessment of the all available data is performed by the previously-proposed and verified correction procedure for yield strength (f_y). A formerly-defined minimum K_n values as a function of f_y is used for butt welds. The already-known fatigue classes are found to be conservative with respect to available fatigue test data.

1. Introduction

In the literature, there have been an increasing number of publications dealing with high frequency mechanical impact (HFMI) treatment technologies [1–4]. In HFMI, the innovation of improving the fatigue strength of welded components comes from locally modifying the residual stress state by using ultrasonic technology. Compressive residual stress state is induced by eliminating tensile residual stress in the interest of region. Currently, there are numerous HFMI peening tool manufacturers and service providers, and the number is increasing steadily as the technique has proven to be reliable and effective. Although details of the tools may differ, the working principal is the same: cylindrical indenters are accelerated against a component or structure with high frequency (>90 Hz). Devices are known by the following names: ultrasonic impact treatment (UIT), ultrasonic peening (UP), ultrasonic peening treatment (UPT), high frequency impact treatment (HiFIT), pneumatic impact treatment (PIT) and ultrasonic needle peening (UNP) [1,2]. In the technical literature, HFMI is a common name firstly used in publications [2,3] to describe the all tools developed by mentioned manufacturers.

Contrary to other traditional residual stress modification techniques, such as hammer or needle peening [5], HFMI is less noisy and has smaller equipment. It results with a finer smooth finishing surface. Besides, the residual stress affected area in the thickness direction is deeper (e.g. 0.2 mm). The indenters are high strength steel (HSS) cylinders and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations. Fig. 1 shows cross sections of typical weld profiles in as-welded condition and following HFMI treatment [6,7] whereas, Fig. 2 shows an example of an HFMI device and several examples of indenter sizes and configurations [8].

The fatigue strength of HFMI-improved welds has been investigated recently, and the design procedures for this improvement method have been proposed after the evaluation of experimental data based on an extensive literature review. The presented fatigue resistant curves are recommended based on the nominal stress (NS), the structural hot-spot stress (SHSS) or the (ENS) approaches [1]. These stress analysis procedures are defined by the Commission XIII – Fatigue of Welded Components and Structures of the International Institute Welding (IIW). In the IIW system, fatigue strength is expressed in terms of S–N lines defined by a fatigue class, i.e., FAT class or simply FAT. FAT represents the stress range in MPa corresponding to 95% survival probability at 2×10^6 cycles to failure. Investigations for HFMI in terms of the NS method

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Nomenclature

f_y	yield strength (MPa)
$f_{y,o}$	reference yield strength (MPa)
FAT	IIW fatigue class, i.e., the stress range in MPa corresponding to 95% survival probability at 2×10^6 cycles to failure (a discrete variable with 10–15% increase in stress between steps)
K	stress concentration factor
k_o	strength magnification factor for high frequency mechanical impact treatment for steel $f_y = f_{y,o}$
k_y	strength magnification adjustment considering yield strength
m_1	slope of the S–N line for stress cycles above the knee point
m_2	slope of the S–N line for stress cycles below the knee point
N_f	cycles to failure
R	stress ratio ($\sigma_{min}/\sigma_{max}$)
S	nominal stress (MPa)
ΔS	nominal stress range (MPa)
t	plate thickness of the specimen (mm)
ρ	radius (mm)
σ_N	standard deviation in Log(N_f)

Subscripts

A	in the as-welded condition
K	characteristic value corresponding to 95% survival probability at 2×10^6 cycles to failure (a continuous variable)
H	following high frequency mechanical impact treatment
f	effective
s	hot spot stress
i	value for specimen i
m	mean value corresponding to 50% survival probability at 2×10^6 cycles to failure
n	notch stress
w	the notch factor or limit of a weld defined as the ratio of the effective notch stress to the structural hot spot stress

includes a single set of improvement procedure with various FAT values which depend on the specimen geometry, and assumes an S–N slope of $m_1 = 5$ [2,3]. These values for the NS system have been developed based on the three commonly-used test specimens, namely longitudinal, cruciform and butt welds. Further evaluations considering only longitudinal and cruciform welds have been performed for HFMI-treated fillet welds by using the local assessment approaches (the SHSS and the ENS) [9]. In the SHSS approach, two sets of characteristic values are suggested separately for load-carrying and non-load-carrying fillet welds. Meanwhile, in the ENS method, only one set of FAT values is recommended for all types of fillet welds. All of these suggestions have been compiled and are presented by Marquis et al. [1].

In addition, Marquis et al. [1] suggest the minimum SHSS concentration values ($K_{s,min}$) for the HFMI-treated welds with low stress concentration (K). These $K_{s,min}$ values are given based on different steel grades. This has been promising for the use of the SHSS approach. However, when HFMI-treated mild notches, e.g. butt welds, are analysed in the ENS system with respect to SHSS ($K_w = 1.6$) from Fricke [10] and $K_{s,min}$ values from Marquis et al. [1], still relatively weaker data points are obtained even though closer characteristic values are observed with respect to HFMI fillet welds in the NS system [3]. Thus, the characteristic values are certainly far below FAT classes suggested by Marquis et al. [1]. Nevertheless, FAT classes should also be valid for HFMI-treated welds with mild notches. Therefore, additional special considerations

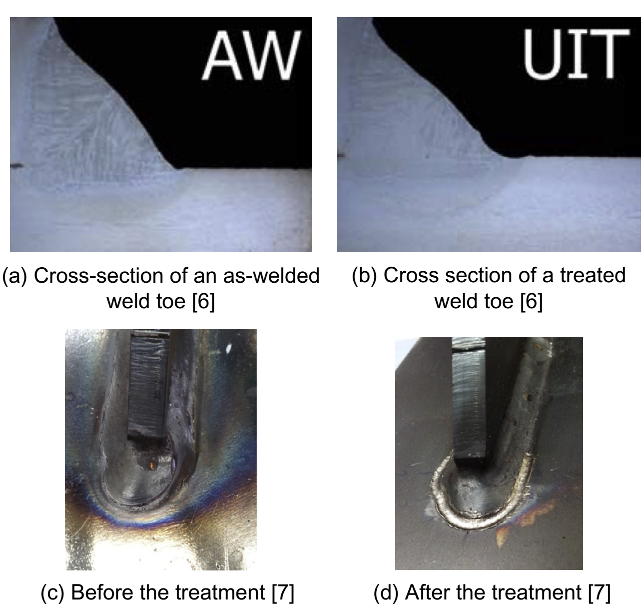

Fig. 1. Typical weld toe profiles in the as-welded condition and following HFMI treatment.

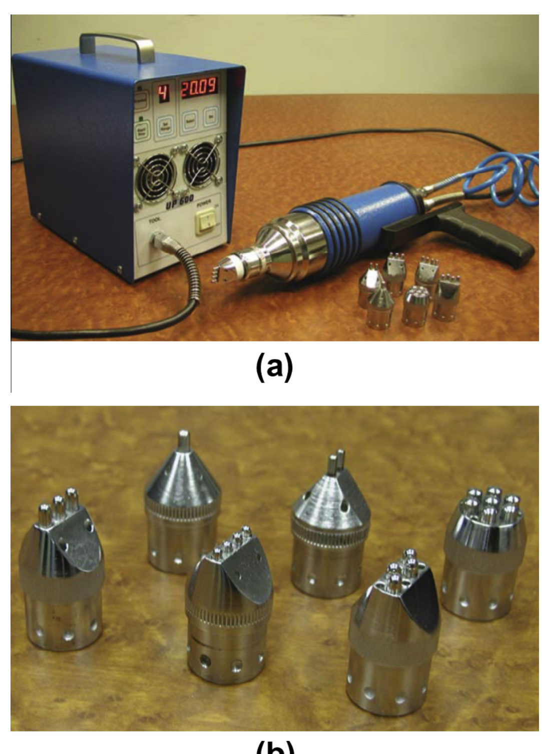

Fig. 2. Example of (a) and HFMI equipment and (b) indenter sizes and configurations [8].