International Journal of Fatigue 101 (2017) 408–420

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Recent results on fatigue strength improvement of high-strength steel welded joints

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ARTICLE INFO

Article history:
Received 9 August 2016
Received in revised form 21 October 2016
Accepted 25 October 2016
Available online 26 October 2016

Keywords:
Fatigue strength improvement
HFMI
TIG dressing
High strength steel
Lightweight design

ABSTRACT

Economic considerations push technology towards new lightweight structural solutions. This results in great interest in using high-strength steels (HSS) for structural applications like in railway vehicles, bridges, offshore structure and high-speed ships. In all these applications, welding is the main joining method and fatigue of welds is the major design criterion despite the existence of locally deteriorated microstructure, increased stress concentration and unfavourable tensile residual stresses after welding. Good weld design is a must to ensure the structural durability and performance, however this does not guarantee lightweight design alone. Special applications, such as post-weld treatment methods, can be performed following the welding. Therefore, this study concerns about the recent developments on such improvement techniques by considering two most-commonly used fatigue strength improvement methods; high frequency mechanical impact (HFMI) treatment and tungsten inert gas (TIG) dressing. Evaluations based on more than 1500 fatigue data points extracted from the literature. Investigations include presentation of the individual data analyses and fatigue strength assessment of all the data points by the effective notch stress approach with the reference radius $r_{ref} = 1.00$ mm. The influence of material strength, residual stress state, weld toe profile and loading conditions on the fatigue strength improvement are all discussed.

1. Introduction

Structural components containing geometrical and microstructural discontinuities like design notches, weld notches, imperfections show lower fatigue strength compared with samples without any discontinuities because the fatigue crack initiation period is shortened due to high stress concentrations existing at such details, see Fig. 1. Typically, this kind of notches may occur after welding, and apparently most of the structural components are composed of complex welded details [1]. For example, 70–80% of a truck's weight consists of steel plates and steel castings including tens of different welds. During its service life, truck is typically subjected to severe cycling loading which can result in fatigue damage at welded joints since welded details are prone to fatigue failure due to irregular geometries, notches, metallurgical effects and unfavourable tensile residual stresses which are induced by the process itself. Consequently, fatigue strength of welded structures is lower than that of their base materials. Therefore, while designing components with welded details, end-users are strongly recommended to follow up the best practice guidelines suggested by various societies and organizations [2–6].

In the past decades, there has been an enormous work given to improve the fatigue strength of welded structures as the greater benefit of high strength steels (HSS, $f_y > 355$ MPa) can only be gained once welded details are treated. Fatigue strength improvement methods can be applied during the welding process, e.g., by weld profile control [7] or using special electrodes [8,9] which help to produce beneficial compressive residual stresses. Alternatively, some improvement techniques can also be performed as separate work operations after the welding process, i.e., post-weld treatment. In the technical literature, these post-weld treatment methods are generally divided into two groups: weld profile modification methods, and residual stress modification methods. For the weld profile modification methods, the primary aim is to remove or reduce the size of the weld toe flaws which may result in an extended crack initiation phase of the fatigue life. The second aim is to reduce the local stress concentration due to the weld profile by achieving a smooth transition between the plate and the weld face. The most well-known weld profile modification methods are machining or grinding of weld seam and toe, and remelting the weld toe by TIG, plasma or laser dressing [10–13].

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http://dx.doi.org/10.1016/j.ijfatigue.2016.10.026
0142-1123/

Nomenclature

f_y	yield strength [MPa]
FAT	IIW fatigue class, i.e., the stress range in [MPa] corresponding to 95% survival probability at $2 \cdot 10^6$ cycles to failure (a discrete variable with 10–15% increase in stress between steps)
K	stress concentration factor
l	length of the specimen [mm]
L	weld toe distance [mm]
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	number of test specimens
N_f	number of cycles to failure
P_s	probability of survival
R	stress ratio ($\sigma_{min}/\sigma_{max}$)
S	nominal stress [MPa]
ΔS	nominal stress range [MPa]
t	plate thickness of the specimen [mm]
w	width of the specimen [mm]
ρ	radius [mm]
$\Theta°$	weld flank angle
σ_N	standard deviation in Log(N_f)

Subscripts

a	amplitude
K	characteristic value corresponding to 95% survival probability at $2 \cdot 10^6$ cycles to failure (a continuous variable)
m	mean value corresponding to 50% survival probability at $2 \cdot 10^6$ cycles to failure
n	notch stress

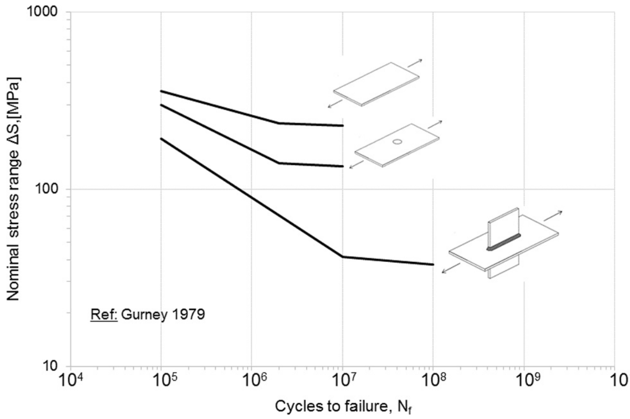

Fig. 1. Fatigue strength dependency on geometry and manufacturing according to Gurney [3].

For the residual stress modification methods, on the other hand, the aim is to eliminate the "harmful" tensile residual stress state, which is introduced after welding process, by imposing "beneficial" compressive residual stress state at the weld toe region. These methods also result in a reduced stress concentration at the weld toe as in the case of weld profile modification methods. Shot peening, hammer and/or needle peening as well as more recently developed high-frequency mechanical impact (HFMI) treatment are some of the well-known residual stress modification techniques. These improvement methods can be performed either at the initial fabrication stage or under the service loading of components. Detailed information and recommendations for end-users on these post-weld improvement techniques can be found, for example, in the International Institute of Welding (IIW) best practice guidelines which concern post-weld treatment methods for steel and aluminium structures [14]. After recent developments in the field of post-weld treatment techniques, it is necessary to conduct a comparative study on commonly used weld profile modification and residual stress modification methods. Therefore, analyses of more than 1500 fatigue data points have been carried out and results are discussed in order to investigate possible ways of improving the fatigue performance of welded structures by post-weld treatment techniques. For this purpose, TIG dressing was selected for weld profile modification method and HFMI method was selected as a residual stress modification method.

2. Available fatigue data for as-welded and improved welds

The as-welded data considered in this study was obtained from two main sources in which literature reviews have been conducted for re-analyses of longitudinal stiffeners, transverse non-load carrying attachments, and butt joints [15,16]. The extracted data were analysed individually to calculate the characteristic fatigue strength and the best-fit slope, see Table A.1. When the exact geometries are known, the effective notch stress analyses were also performed according to IIW recommendations [14], using the reference radius $\rho_{ref} = 1.00$ mm and the Principal (Normal) Stress Hypothesis. The calculated characteristic value of 215 MPa is shown in Fig. 2 with a fixed slope of $m_1 = 3$ and it was a bit lower than the IIW recommended FAT 225. An S-N slope of $m_2 = 22$ is assumed below the knee point at 10^7 cycles as recommend by Sonsino [17] and adopted by the IIW Recommendations [14].

As a weld profile modification technique, TIG-dressing method re-melts the weld toe region to a shallow depth which results in substantially increase in fatigue strength. This is achieved by improved weld toe profile with reduced stress concentration factor, and removal of slag inclusions and weld toe undercuts. Standard equipment for TIG welding is used without the addition of

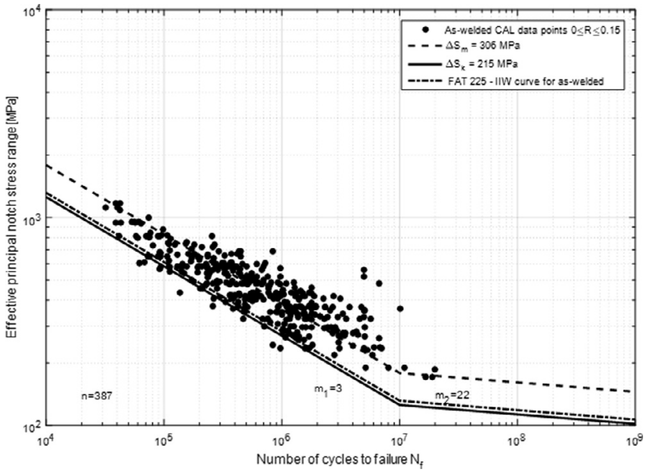

Fig. 2. Fatigue data of as-welded joints in the effective principal notch stress method (ρ_{ref} = 1 mm).