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Probabilistic fatigue-life assessment model for laser-welded Ti-6Al-4V butt joints in the high-cycle fatigue regime

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A B S T R A C T

The present paper focuses on the effect of inherent welding-induced defects on the high-cycle fatigue behaviour of laser-welded Ti-6Al-4V butt joints. The transition of the crack origin from the surface to the subsurface occurs upon removal of the surface stress concentrators. Under these circumstances, fatigue cracks nucleate at subsurface porosity and show a typical fish-eye pattern of fracture surface. A fatigue-life assessment model has been developed for internally flawed materials based on a fracture-mechanics approach, which takes effects of short-cracks into account. A novel approach for the simplified construction of the cyclic resistance curve of internal cracks is proposed herein. Using statistical methods, the experimentally determined porosity distribution has been incorporated into the model to predict the fatigue scatter range. The presented methodology can potentially be used to achieve a required reliability of the welded joints with respect to fatigue as a design criterion.

1. Introduction

Fatigue of welded joints has always been a matter of concern because their fatigue strength can be much lower than that of non-welded components [1,2]. Fatigue cracks in a welding seam frequently start from some type of weld defect in the early stage of the fatigue life [3]. Additionally, the fatigue properties of welded structures exhibit considerable scatter owing to the large variety of imperfections. Other relevant aspects are related to high tensile residual stresses [1] and undesired material property degradation in the fusion zone (FZ) of the weld [3–5]. In consequence, special attention has always been paid to the application of the welding technique for fatigue-critical components and parts. In this regard, the need for accurate fatigue-life assessment of welded structures is of great importance for ensuring a safe and reliable design.

A relatively straightforward practical approach for the prediction of the fatigue life of welded joints is based on the design codes, where the fatigue-life estimate depends on the joint classification [1,2]. However, these codes have been developed for various structural steels and do not include some recently emerged types of welding, such as laser beam welding (LBW). Due to its high productivity and flexibility, LBW of titanium alloys offers significant practical advantages over conventional joining techniques. LBW of Ti-6Al-4V alloy has numerous potential applications in aerospace [4], automotive [5], and ship-building [6] sectors, where the welded joints are often subjected to cyclic loading. It has been shown by the authors in the previous research [3] that in order to maximize the fatigue strength of the laser-welded joints, all geometry-specific stress-raisers such as weld toes and underfills must be removed. Under these circumstances, fatigue strength is still lowered by the presence of internal porosity, especially near the surface. As a result, fatigue cracks nucleate in the interior of the specimen and have the typical ‘fish-eye’ pattern of fracture surface.

The aim of this study is to investigate and quantify the effect of subsurface porosity on fatigue cracking in the high-cycle fatigue (HCF) regime. The methodology for the fatigue-life assessment of the laser-welded Ti-6Al-4V butt joints should take into account the peculiar features of the FZ microstructure and the LBW process. The latter, as is shown later, requires some modifications of conventional fatigue-life estimation concepts. Remarkably similar mechanisms of fatigue fracture have been reported for the parts produced by additive manufacturing [7], casting [8], and powder metallurgy [9,10] and also for the parts operating in very-high-cycle fatigue (VHCF) regime [11–13]. Thus, the methodology presented here can potentially be applied to not only welds but also various structural components where internal crack initiation and growth are observed.

Any HCF prediction model relies on the accurate prediction of the fatigue-crack initiation phase. It is generally agreed that the initiation period takes up the major part of the total fatigue life in the HCF regime. However, there are different viewpoints on the methodology for its assessment. The first investigations in this field were based on the so-called ‘engineering’ approach, in which the initiation period is considered as the number of cycles taken to form a crack of detectable size,

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Nomenclature

a	crack length (for internal crack—its radius)
a_i	initial crack length
a_f	final crack length
a_0	El Haddad parameter
a_1 and a_2	fit parameters in the extended El Haddad equation
d	pore diameter
f	Newman crack-closure function
h	pore depth
$p_D(d)$ and $p_H(h)$	probability density functions of the pore diameter and the pore depth respectively
$p_N(N_f)$	probability density function of the fatigue life
$p_{H\|D}(h\|d)$	conditional probability density function of H given D
q_{int}	notch sensitivity factor of the FZ related to internal porosity
r_{pl}	the size of the reversed plastic zone at the crack tip
$C,\ n,\ p$	fit parameters in the crack-growth equation
D	pore diameter as a random variable
$F_{min},\ F_{max}$	minimum and maximum applied loads respectively
H	pore depth as a random variable
$K_{f,int}$	fatigue notch factor corresponding to internal porosity
$K_{f,surf}$	fatigue notch factor of surface defects
K_t	elastic stress concentration factor
N_f	fatigue life
R_F	applied load ratio ($R_F = F_{min}/F_{max}$)
$U_{LC},\ U_{SC}(a)$	crack-closure ratio for long cracks and short cracks respectively
Y	boundary correction factor
σ_{max}	maximum stress of the fatigue-loading
σ_{min}	minimum stress of the fatigue-loading
σ_y	yield strength of the material
$\mu,\ s$	scale parameters of the log-normal distribution
$\Delta\sigma$	applied stress range
$\Delta\sigma_{e,BM},\ \Delta\sigma_{e,QBM}$	fatigue limits of the as-received base material and quenched base material respectively
$\Delta\sigma_{e,AW},\ \Delta\sigma_{e,int}$	fatigue limits of the as-welded and machined conditions respectively
ΔK	stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
$\Delta K_{th,LC}$	threshold stress intensity factor range for long cracks
ΔK_{eff}	effective stress intensity factor range
$\Delta K_{th,eff}$	intrinsic fatigue-crack propagation threshold
$\Delta K_{th,op}$	extrinsic part of the crack propagation threshold

usually ~1 mm. This methodology allows one to assess the initiation phase only by purely empirical models. Over the last several decades, an increasing number of studies have shown that fatigue-crack initiation in a narrower sense, i.e. formation of a microstructurally short crack, occurs at a very early stage of the fatigue life [14,15]. From this perspective, the period in which a detectable crack is formed can be estimated on the basis of semi-empirical models relying on the propagation of the so-called short cracks [16]. The main challenge arising while dealing with short cracks is that the extrapolation of linear elastic fracture mechanics (LEFM) in this region can yield over-conservative estimates because short cracks can grow considerably faster than long ones. The primary reason for this phenomenon is the violation of the similitude principle, which is the foundation of LEFM. To overcome these difficulties, several models of anomalous short-crack growth behaviour have been proposed [17–21]. A majority of the models rely on the crack-length dependence of the short-crack propagation threshold $\Delta K_{th}(a)$ or cyclic resistance curve (R-curve). Since the experimental procedure for the determination of cyclic R-curve is rather complicated [22], several analytical models for its construction are available [18,20,23]. In the present study, the features of the material and internal crack growth have hindered the application of the existing concepts for the R-curve construction. Therefore, several modified and adopted approaches have been proposed and implemented.

This work deals with a probabilistic fatigue-life prediction model based on the fracture-mechanics framework and accounting for the propagation of short cracks. Section 2 of this paper gives a brief overview of the experimental techniques used for the validation of the model. The results of the fatigue-testing of laser-welded Ti-6Al-4V butt joints with different surface states are given in Section 3. Fatigue testing is followed by careful fractographical analysis, which reveals very important features of the crack nucleation and growth at early stages. The porosity distribution, characterized by X-ray inspection of the FZ, has subsequently been used for the prediction model. In Section 4, the development of the deterministic fatigue-life prediction model is described. Special attention is paid to the environmental effect on the internal crack growth and short-crack behaviour. A simple and practical method for the simplified construction of the cyclic R-curve is presented. Finally, the developed model is applied for the prediction of the fatigue scatter range, which is of great importance for engineering applications. Most of the models existing in the literature are deterministic and predict only the mean S-N curve, without considering the fatigue scatter band. In practice, S-N curves for low probability of failure (5% or 10%) are usually required for design purposes. The experimental data on porosity distribution, which were incorporated into the model, have enabled the quantitative estimation of the fatigue scatter range of the laser-welded Ti-6Al-4V butt joints. A satisfactory agreement between the experimental data and the model prediction has been demonstrated.

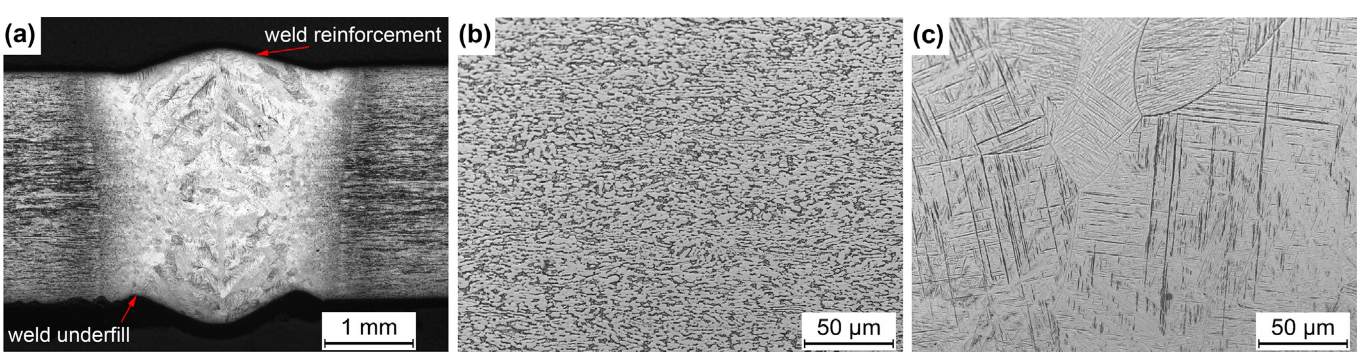

Fig. 1. Optical micrographs of the Ti-6Al-4V microstructure: (a) weld morphology and weld defects; (b) as-received globular microstructure of the BM; (c) acicular martensitic microstructure of the FZ.

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