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Fracture analysis of laser beam welded superalloys Inconel 718 and 625 using the FITNET procedure

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Abstract

This paper presents results of the analysis for residual strength prediction of two laser beam welded superalloys (Inconel 625 and 718) using the fitness-for-service (FFS) procedure FITNET. The analysis is based on Option 3 of the Fracture Module of the procedure arising from the European Community funded project FITNET (www.eurofitnet.org). Analysis option 3 requires full stress–strain curves of the materials as input data. Since the strength mismatch ratio (*M*) between the weld and the base metals for both alloys was less than 10%, a homogeneous solution route has been used for welded tension loaded specimens containing through thickness central cracks. The FITNET predictions of the attained maximum load levels of the specimens were verified with the generated experimental results. The analysis methodology, as well as comparison between predictions and experimental results are provided. Accurate yet conservative estimation of the maximum load carrying capacities have been achieved depending on the input data; as the input data becomes more detailed, the degree of conservatism decreases.

Keywords: FITNET FFS; Failure assessment; Laser beam welding; Residual strength; Superalloy

1. Introduction

Use of laser beam welding as a joining method is being rapidly developed in various industries, from automotive to aerospace, due to advantages over conventional welding methods such as high speed, low distortion, low heat input, and narrow width of the fusion zone (FZ) and the heat affected zone (HAZ) [1–5]. Consequently, there is an increasing demand for ‘‘fitness-for-service’’ (FFS) assessment of advanced welded structures by considering the specific features of these weld joints (such as narrow weld width, high-strength mismatch, etc.).

Ni-base superalloys exhibit a combination of superior properties at higher temperatures (between 150 and 1500 °C) in terms of higher strength, resistance to corrosion, stress-rupture strength, toughness and resistance to thermal fatigue. They are mostly used in components of aerospace structures, gas turbines, submarines and nuclear reactors. Inconel 718 is an age-hardenable, high-strength alloy, which has a high fatigue strength, as well as good oxidation resistance up to 980 °C [2]. It is also reported to be resistant to strain-age cracking as a result of the sluggish precipitation kinetics of its principal strengthening precipitate γ'' (Ni_3Nb) [3]. This alloy may have some weldability problems that include solidification cracking and microfissuring in the HAZ [4]. The second material, Inconel 625, is a solid-solution matrix-stiffened face-centered-cubic alloy. It may contain carbides, in the form of MC and M_6C (rich in Ni, Nb, Mo and C), which are inherent in this type of alloy. The hardening effect that takes place in the material on exposure in the range centered around 650 °C, is due to sluggish precipitation of a Ni–Nb rich γ' phase [5]. Ni–chromium alloy 625 is used for its good high temperature strength, excellent fabricability including joining and corrosion resistance. High weldability properties of Inconel 625 make it of interest to the aerospace field.

Laser beam welding, due to its inherently narrow HAZ, offers potential promise for producing crack free joints in

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Nomenclature

a	half-crack length (mm)
B	specimen thickness (mm)
E	modulus of elasticity (GPa)
$f(L_r)$	failure assessment line, Eq. (5)
F	externally applied load (kN)
F_Y	yield load of the cracked component (kN)
F_{YM}	mismatch yield load (kN)
H	half-weld width (mm)
J	J-integral
J_e	elastic part of J integral, Eq. (4)
K	elastic stress intensity factor (MPa $\sqrt{m}$), Eq. (8) for $M(T)$ type specimen
K_r	measure of proximity to fracture in linear elastic conditions, Eq. (1)
L_0	initial gauge length (mm)
$L_{0\ eff}$	effective gauge length (mm)
L_r	measure of proximity to plastic yielding
m	constraint parameter
W	half-specimen width (mm)
Δa_{phy}	difference in physical crack length (mm)
ε	strain
ε_{ref}	reference strain
δ	crack tip opening displacement, CTOD (mm), Eq. (2)
δ_e	elastic part of δ (mm), Eqs. (3) and (4)
δ_5	crack tip opening displacement measured over a gauge length of 5 mm (mm)
v	Poisson's ratio
σ_{ref}	reference stress (MPa)
σ_Y	yield strength (MPa)
σ_{UTS}	ultimate tensile strength (MPa)
$C(T)$	compact tension specimen
$M(T)$	middle crack tension specimen
BM	base metal
CTOD	crack tip opening displacement
FZ	fusion zone
HAZ	heat affected zone
M	mismatch ratio
WM	weld metal

Inconel 718. Welding studies of Inconel 718 on joints made with a 15 kW CO_2 laser indicated that it could be an effective joining method for up to 12 mm thickness [6], although some microcracks and porosity were reported in the literature [7]. Çam et al. [8] have investigated in the framework of EU project ASPOW [9], the 2 kW Nd:YAG laser welding of both Inconel 718 and 625 in 3 mm thick materials, which resulted in crack free welds.

The residual strength of a structure is defined as the remaining load capacity of a structure in the presence of one or multiple cracks [10,11]. The residual strength of a homogeneous structure is basically a function of material properties (strength, toughness, etc.), flaw and component geometries and stress condition [12]. Assessment of defects in welded structures also requires detailed information on the local weld joint (fusion and heat affected zone) properties and weld geometry. Several fracture mechanics-based Engineering Critical Assessment (ECA) methods are being increasingly used for failure investigations and fitness-for-service (FFS) assessment of engineering structures worldwide. These methods provide an estimate of load or crack size below which failure will not occur [13]. The fitness-for-service assessment procedure FITNET FFS [14] has been developed within the framework of a European Community funded thematic network. It covers structural integrity analysis modules to avoid failures due to fracture, fatigue, creep and corrosion. The FITNET FFS procedure has adapted the SINTAP [15] approach for assessing flaws in welded structures. The use of an FFS procedure is important specifically to assess the structural significance of welding induced imperfections (pores, flaws, defects or cracks), particularly crack-like flaws that need to be assessed to prevent failure of the welded component during service [14]. The FITNET FFS procedure [13] contains analytical expressions that are being developed to assess the structural significance of the flaws or damage in metallic structures with and without welds [16–20]. It includes a Fracture Module, which provides a special analysis option (identical to the SINTAP procedure) to deal with welded structures by considering the special features of the welded joints [14]. During the development of these options, as well as the SINTAP procedure, a number of validation studies were carried out on various configurations. However, particular emphasis needs to be given to welded structures joined by advanced welding techniques (laser, hybrid or friction stir) to address the need to use the FITNET FFS procedure at the design stage, since these technologies are increasingly used in new structural components, including thin-walled structures. Specifically, there has been a lack of information on the fracture toughness properties and failure assessment procedures of CO_2 laser beam welded Inconel 718 and 625 alloys in thin plate forms. The first part of this study, which has been published earlier, deals with the fracture toughness analysis of laser beam welded superalloys Inconel 718 and 625 [21], while the second part presented here, focuses on the assessment of the structural integrity of flaws using the Fracture Module of the FITNET FFS.

2. The FITNET FFS procedure

The FITNET FFS procedure contains techniques to demonstrate the fitness-for-service of engineering metallic components (with and without welds) transmitting loads. They are of value at the design stage to provide assurance for new constructions, particularly where these may be