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Experimental determination of accurate fatigue crack growth data in Tailored Welded Blanks

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A B S T R A C T

Joining of Tailored Welded Blanks (TWB) with Friction Stir Welding (FSW) is very attractive for future aircraft applications. This article provides the main findings of extensive studies of fatigue crack propagation in FSW-TWB made of AlMgSc alloy. The measurement of actual mechanical test conditions in combination with finite element simulations allows overcoming inherent drawbacks of conventional single edge notch tension (SENT) specimens. Residual stresses as result of the FSW process are measured via the cut-compliance-method. It is shown, that in case of FSW-TWB only the consideration of actual test conditions and residual stresses yields accurate fatigue crack propagation data.

1. Introduction

Loading of aircrafts in service induces non-uniform stress levels and distributions in the fuselage [1]. In order to achieve advanced lightweight designs, local skin thicknesses are generally load-optimized and thus, vary throughout the aircraft fuselage. Nowadays, mainly two different approaches are applied for the production of such fuselage structures. The first approach is based on joining sheets of different thicknesses by riveting, which currently represents the state of the art technology in airframe structures. Its main disadvantages are the inherent overlapping of sheets, additional weight from the rivets themselves, introduction of stress concentration points, and an overall costly assembling process including e.g. sealing treatment. The second approach consists simply of milling off redundant material either mechanically or chemically [2]. Again, this is a comparably expensive manufacturing process resulting in a poor material utilization rate, in aerospace industry commonly referred to as a low fly-to-buy-ratio.

A promising candidate as substitution for the approaches described above is the Tailored Welded Blank (TWB) with different sheet thicknesses. As sheets can be welded as butt joints, TWB provide weight savings if compared to overlapping sheets. In addition, the application of Friction Stir Welding (FSW, see e.g. [3]) instead of riveting might reduce manufacturing costs even for small joint lengths [4].

TWB have been used in the automotive sector for decades. Typically, steel sheets of different thickness and/or strength are welded together prior to forming [5]. Recently, TWB made of aluminium alloys are coming into focus for aircraft applications. For instance, [6–8] investigated the use of TWB with emphasis on the forming process. Unlike in automotive industry, damage tolerance is a very important aspect for the actual implementation of new structural designs or joining technology in primary aircraft structures. Damage tolerance generally considers cracks in load carrying structures and e.g.

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Nomenclature

a	crack length [mm]
E, E'	elastic modulus [N/mm^2]
F	load applied during mechanical testing [kN]
K	stress intensity factor [(N/mm^2) m$^{1/2}$]
M	correction factor (Huang's model) [1]
N	number of load cycles [1]
R	load ratio [1]
u	displacement [mm]
Y	geometry factor [1]
$Z(a)$	influence function [m$^{-1/2}$]

Greek characters

β, β_1	parameters (Huang's model) [1]
ε	strain [1]
ν	Poisson's ratio [1]

Subscripts

K_{eff}	effective stress intensity factor [(N/mm^2) m$^{1/2}$]
K_{max}	maximum stress intensity factor [(N/mm^2) m$^{1/2}$]
K_{op}	(nominal) stress intensity factor at crack opening [(N/mm^2) m$^{1/2}$]
K_{res}	stress intensity factor due to residual stress [(N/mm^2) m$^{1/2}$]
K_V	comparative stress intensity factor [(N/mm^2) m$^{1/2}$]
K_{2D}	2D stress intensity factor [(N/mm^2) m$^{1/2}$]
K_{3D}	stress intensity factor at mid-plane [(N/mm^2) m$^{1/2}$]
R_{tr}	*true* load ratio (affected by residual stress) [1]
ε_{Mres}	strain measured at specific point during cut-compliance procedure [1]

Further abbreviations

BM	base material [–]
CMOD	crack mouth opening displacement [mm]
CTOD	crack tip opening displacement [mm]
DIC	digital image correlation [–]
FCG	fatigue crack growth [–]
FSW	friction stir welding [–]
SENT	single edge notched tension (specimen) [–]
SIF	stress intensity factor [–]
TWB	tailored welded blank [–]
UD	uniform displacement [–]
US	uniform stress [–]

assesses inspection intervals to check the structures for emerging flaws. Consequently, the present paper focuses on crack propagation in TWB structures using linear elastic fracture mechanics (LEFM) and its concept of stress intensity factor (SIF) K.

FSW is used for joining two sheets with different thicknesses to form a TWB. As FSW is a solid state joining process, various high-strength aluminium alloys used in aircraft industry can be joined with only a slight loss in mechanical properties [9]. Nevertheless, temperature evolution, local plastic deformation and boundary conditions (e.g. clamping, backing) during the FSW-process bring about long-range residual stresses in the welded joint. Consequently, the effect of residual stress on the crack driving force K is measured by the Cut-Compliance-Method [10–12]. A finite-element-simulation is used to account for the geometry of the TWB and to consider the actual boundary conditions during fatigue crack growth (FCG) experiments. It is shown that the application of single edge notch tension (SENT) specimens, as applied in these studies, requires grate carefulness regarding actual boundary conditions prevailing during mechanical testing.

The paper is organized as follows: Firstly, materials, specimen preparation including the FSW process and the experimental setup are briefly described. Secondly, the details of the FE-model and the numerical simulations, respectively, are introduced. Finally, the experimental and numerical results are presented and discussed. It will be comprehensively shown, that