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Retardation of fatigue crack growth in aircraft aluminium alloys via laser heating – Numerical prediction of fatigue crack growth

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ABSTRACT

The presented study discusses a quantitative numerical approach for predicting the fatigue crack growth in AA2198-T8 C(T)100 specimens containing one line of laser heating. By heating with a defocused laser residual stresses are introduced and the fatigue crack growth is retarded. The developed methodology, which investigates coupling of the structural process simulation, the extraction of the total stress intensity K_{tot} and the prediction of the resulting fatigue crack growth rates by an empirical crack growth law is stepwise validated on the basis of experimental results. The prediction is found to be highly accurate. Special attention needs to be given to the quality of the process simulation results because the prediction of fatigue crack growth is highly sensitive to the results obtained in this simulation step.

1. Introduction

As was demonstrated in an experimental study on the laser heating of AA2198-T8 specimens [1], residual stresses induced in metallic structures can have a significant impact on fatigue crack growth. Considering the growing interest in advanced manufacturing technologies for the production of metallic integral airframe structures, such as laser beam welding or friction stir welding [2,3], this issue gained special attention [4–6] because residual stresses are an unavoidable side effect of these technologies [7,8]. Hence, because precise predictions of fatigue crack growth are required for damage tolerant design, several recent studies have addressed the prediction of fatigue crack growth in integral aircraft aluminium structures including residual stress effects [4–6]. The approach that has found common acceptance consists of the following steps [4,6,9–19]:

- Measurement of the component of the residual stresses that acts perpendicular to the crack growth direction.
- Extraction of the residual stress intensity factor K_{res} attributable to internal stresses using, for example, the finite element method (FEM) or the weight function method.
- Calculation of the total stress intensity $K_{tot} = K_{res} + K_{appl}$ as the sum of K_{res} and the applied stress intensity K_{appl} using the law of superposition.
- Calculation of the fatigue crack growth rate da/dN by using K_{tot} in an empirical crack growth law, such as the Walker Equation.

This general approach shows good results but has two major limitations that need to be addressed. For cracks growing through compressive residual stress fields, nonlinear contact corrections are needed to prevent a physically unsound overlapping of the crack faces during the calculations [9]. Hence, the application of the superposition law is no longer valid. The underlying effects and their impact on the predicted fatigue crack growth rates have been discussed in an earlier study [20]. In addition to issues regarding the numerical approach, residual stress measurements are costly and difficult to perform for complexly shaped or large specimens, and they normally deliver only specific components of the stress tensor for the specific case that is being examined.

The study presented by Jang et al. [21] provided major input for the development of an extended prediction methodology, since it described a strategy to predict the observed fatigue crack growth retardation due to heating induced residual stresses for steel specimens on basis of numerical process simulation results. However, the crack closure based fracture mechanics analysis used does not describe the complex opening behaviour of the crack faces in the residual stress field physically sound. Therefore, the achieved prediction results only showed a qualitative agreement with the measurement results.

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Nomenclature

x, y, z	position coordinates
T	temperature
t	time
δ_{ij}	Kronecker delta
ϵ	strain tensor
ϵ^p_{eq}	cumulative plastic strain
u	displacement vector
σ	stress tensor
σ_{eq}	von Mises stress
Q	heat flux density
Q_0	heat source amplitude
v_y	heat source travelling speed
α	thermal expansion coefficient
E	Young's modulus
C, m, n	material constant of the Walker Equation
c	specific heat
ν	Poisson's ratio
ρ	density
σ_{ys}	yield stress
λ	thermal conductivity
a	crack length
da/dN	fatigue crack growth rate
F_{appl}	applied load
G_{tot}	total energy release rate
K_{tot}	total stress intensity factor
ΔK_{tot}	total stress intensity factor range
R_{tot}	total stress intensity ratio
N	number of load cycles
BM	name prefix for base material results or area with base material properties
EXP	name suffix for experimental results
FEM	finite element method, also name suffix for numerical prediction results
HZ	heating zone
HAZ	heat affected zone
LH	name prefix for laser heating results
MVCCT	Modified Virtual Crack Closure Technique

Another study pointing into a similar direction was published very recently [22]. Here also structural process simulation was coupled with subsequent mechanical simulations for the calculation of K_{res} in a steel butt-weld. However, the resulting crack growth rates were only predicted for one crack length under different applied loads, the crack tip was situated in an area of tensile residual stresses and the predicted crack growth rates were not validated experimentally.

Motivated by these studies the extended methodology shown in Fig. 1 was developed, consisting of the following steps:

1. Use of a FE based process simulation to predict the transient heating temperature field as well as the heating induced residual stresses and distortions.
2. Extraction of the total stress intensity factor K_{tot} in a fracture mechanics analysis using the MVCCT approach. In this analysis step the loaded model with predicted heating residual stresses and distortions is incrementally cut open and a contact condition is added continuously for the newly generated crack faces.
3. Calculation of the fatigue crack growth rate da/dN by using the extracted K_{tot} in an empirical crack growth law.

The implementation of this approach was realised using the programming language Python for embedding the two commercial FE codes Sysweld and Abaqus.

2. Prediction methodology

Fig. 2 shows the specimen geometry and coordinate system, which are identical to those used in [1], where the results of the experimental investigation on laser heating of AA2198-T8 C(T)100 specimens were presented in detail.

2.1. Step 1: Process simulation

To predict heating-induced residual stresses, a coupled thermal and mechanical FE analysis was conducted. Thus, the influence of the temperature on the mechanical response of the structure is accounted for by including the thermal strains attributable to thermal expansions in the mechanical analysis. However, coupling in the other direction, from the mechanical analysis to the thermal analysis, has not been included [23]. This approach is commonly used for structural simulations of welding processes [24–26]. A thorough overview of the topic is presented, for example, by Radaj in [24]. For further orientation [25,27] also provide some general discussion of the impact of specific simplifications and modelling strategies on the achievable quality of the results.

Although much research has been conducted in the past decades on the simulation of steel welding, few studies have been published on its application to aluminium aerospace alloys. However, in [28–30], for example, friction stir welding of aerospace aluminium alloys was investigated. In [26,31–36], the resulting distortions and residual stresses after laser beam welding of aluminium T-joints were predicted. In [37,38], the fusion welding of AA2024 butt joints was studied, and the impact of the testing conditions used to gain the needed temperature-dependent material properties on the prediction results was discussed.

2.1.1. FE mesh

Fig. 3 shows the FE mesh used for the process simulation and the extraction of K_{tot}. The mesh consists of approximately 40,000 linear solid elements and 50,000 nodes, and it has the outer dimensions of the C(T)100 specimens used for the experimental studies (see Fig. 2). As shown in Fig. 3, the specimen was modelled as a single piece of material, and for simplicity, no fixture holes were modelled.

2.1.2. Thermal FE analysis

For the thermal analysis, a pure heat conduction model including heat sinks and sources was used. The governing differential equation is given as follows [23]:

$$\rho(T)\ c(T)\ \frac{\partial T}{\partial t} - \mathbf{div}\ (\lambda(T)\ \mathbf{grad}\ T) - Q = 0 \tag{1}$$

where are T the temperature, c the temperature-dependent specific heat, ρ the temperature-dependent density, λ the temperature-dependent thermal conductivity and Q the temperature- and/or time-dependent heat flux density (heat sources, boundary conditions).

The heat flux density into the model Q_{in} has been modelled as a user-defined Goldak ellipsoid volume heat source and can be expressed as a function of the space coordinates x, y, z and time t: