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Retardation of fatigue crack growth in aircraft aluminium alloys via laser heating – Experimental proof of concept

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ABSTRACT

In this work, a defocused laser was used to modify the residual stress state in AA2198-T8 C(T)100 specimens with the goal of retarding fatigue crack growth. The manuscript provides a description of the process, the resulting changes of the material properties and the modified fatigue crack growth behaviour. The performed experiments, including thermocouple measurements, microscopical examinations, micro hardness measurements, residual stress measurements and fatigue crack growth measurements under constant amplitude loading show, that via laser heating a substantial retardation of fatigue crack growth can be achieved.

1. Introduction

The modification of the residual stress state in structures to improve their mechanical performance is a commonly used method. However, especially for safety-critical applications, such as airframe structures, a detailed review of the different aspects and problems is necessary, which can arise when utilising residual stresses based life enhancement techniques.

The work published by McClung [1] gives an informative and detailed overview of this specific topic. The key points are summarised as follows. The utilisation of residual stress modifications to extend the fatigue life of aerospace structures raises a dilemma for operators and regulators. Residual stresses can have notably beneficial effects on fatigue performance. However, after production, it is nearly impossible to measure the actual amount of induced residual stresses and there exists the possibility of changes of the initial residual stress state, e.g. due to applied service loads [1] or the changing service temperatures [2]. Besides, residual stress effects are normally not addressed by the methodologies commonly used for life prediction and damage tolerance evaluation [3]. For this reasons regulation authorities normally claim that damage tolerance requirements have to be reached without considering potential positive residual stress effects in the design.

Nevertheless, even without official credit the manufacturers and operators continue to use residual stress based life enhancement techniques, because experience has shown that they are effective and their use helps reducing the maintenance costs. For this reason these stress based methods are also believed to offer a cost-efficient way to significantly extend the service life of ageing aircraft [1]. Based on its substantial economic potential, this consideration is a strong motivation for manufacturers and operators to further improve established and investigate new stress based techniques for life enhancement.

The underlying principle of all processes that aim to improve fatigue performance by changing the residual stress state is the same. This principle is the induction of local, non-uniform plastic yielding to create compressive residual stresses at critical positions, which decrease the total stress intensity under application loads. Because a broad variety of work has been published during the last years examining such methods as shot peening, laser shock peening or cold expansion, these processes will not be discussed here. Instead, a brief review of the performed studies using local heating with and without additional mechanical loading for the well-directed introduction of residual stresses is be presented because this subject forms the basis of the presented work.

In an early work published by Gurney [4], local spot heating was used as a life extension and repair technique. Spot heating was applied to generate different stress states at the run-in and run-out positions of double-fillet welded mild-steel specimens. Significant improvement of the S–N behaviour was obtained. By comparing these results to those of specimens that were subjected to local

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Nomenclature

E	Young's modulus
F_{max}	maximum applied load
K	stress intensity factor
N	number of load cycles
R	stress intensity ratio or load ratio
T	temperature
BM	base material or zone with base material properties
HZ	heating zone
HAZ	heat affected zone
da/dN	fatigue crack growth rate
ν	Poisson's ratio
ϵ	elastic strain
σ_{xx}	transverse stress component
σ_{yy}	longitudinal stress component
$\Delta\sigma$	stress difference $\sigma_{yy} - \sigma_{xx}$
a	crack length
a_0	initial notch length
d_0	stress free lattice parameter
t	time
x, y, z, θ	coordinates

mechanical pressing with a punch that clearly produced compressive stresses at the critical positions, it was concluded that the observed effect in the heated specimens was mainly due to residual stresses. This work was later extended one step further by Harrison [5]. In this work, the spot heating technique was used to repair fatigue specimens on which premature cracking was observed in the run-in of some welds. It was shown that by applying spot heating the fatigue life of specimens could be extended significantly.

Verma and Ray [6–8] performed some mainly experimentally based work comparing the observed retardation effects of the fatigue crack growth rates in steel specimens after spot heating to the ones observed after single overloads. They examined the impact of process parameters like spot heating position or heating temperature and concluded that the effects of spot heating and of single mechanical overloads can be compared in general. However, the underlying physical effects were not further investigated.

Several authors combined the heating and mechanical loading of cracked specimens and components [9–14]. However, the aim of the proposed procedures was not a direct generation of thermally induced residual stresses. The heating was only applied to promote plastic yielding under an applied load at the crack tip by lowering the yield stress. This approach showed notably promising results. For one case [12], it was even possible to completely arrest a crack in a mild steel plate with an applied stress intensity $K_{appl} = 20\,\mathrm{MPa}\sqrt{\mathrm{m}}$. However, this method is only applicable to specimens or structures already containing cracks or sharp notches and where mechanical loading is easy to perform. If these two conditions are met, it can be a suitable method for fatigue life extension, as demonstrated for the case of aluminium gas cylinders in [13].

In the work presented by Tsay et al. [15–18] a laser was used to create heating lines on C(T) specimens composed of stainless steel. Afterwards, fatigue crack growth tests were performed. It was concluded that the observed retardation effects were caused by the heating-induced residual stresses because the effect ceased after a stress-relieving heat treatment.

In the presented work, a defocused laser was used to create heating lines on aluminium C(T) specimens with the goal of modifying the residual stress state in a manner that leads to the retardation of the measured fatigue crack growth. Experiments were performed on specimens containing one line of laser heating in comparison to base material specimens that were not subjected to laser heating. The results presented in this study are an experimental proof of this principle for aluminium specimens.

2. Material and experiments

2.1. Material and specimen preparation

The latest generation of Al–Li alloys was developed in the 1990s. Compared to previous alloys, these alloys show an improved ductility and fracture toughness, due to a reduction of the Li content (<2.0 wt.%Li). In these alloys, the main strengthening phase was T_1 (Al_2CuLi). Such alloys as 2195, 2x96, 2x97 and 2098 had commercial applications mostly in the USA. These alloys were able to match the balance between the strength and damage tolerance of standard aircraft alloys, such as 2024 or 7050 [19]. However, recent metallic airframes use more advanced high strength and high damage tolerant alloys. For this reason, the Al–Cu–Mg–Li alloy 2198 was developed by Alcan (since 2011 Constellium) as new aircraft skin material with the goal of reaching a higher static strength than AA7475 and to have better damage tolerance capabilities than AA2524 [19,20]. The alloy 2198 is a derivative of AA2098 with a lower copper content, several other minor chemistry adoptions and optimised thermo-mechanical processing [20]. Additionally, AA2198 is weldable via laser beam welding and friction stir welding [19–21]. Thermo-mechanical treatment during production leads to a microstructure consisting of flat, pancake-like grains lying in the L-T plane, which leads to a pronounced anisotropy of the mechanical properties [22].

2.2. Specimen preparation

A batch of C(T)100 specimens in the L-T orientation with a notch length $a_0 = 20$ mm and rectangular pieces with a size of 125 mm × 120 mm were produced from a sheet of AA2198 in T3 temper with a nominal thickness of 5 mm. Afterward, heat treatment to reach T8 temper was conducted. The dimensions of the C(T)100 specimens were in accordance with ASTM E647 [23], as shown in Fig. 1a. However, the thickness of only 5 mm is lower than the standard requirements but is common for thin sheet testing. During the fatigue crack growth experiments, the majority of the tested specimens unfortunately showed such severe deviations of the crack path that a clear evaluation of the results according to ASTM-E647 [23] could not be obtained. Therefore, a second batch of specimens with the same dimensions but in the T-L orientation was prepared from the same AA2198 sheet as used before, and the fatigue crack growth tests were repeated. Even though some crack deviation could be also observed for this second series of tests, it was much less pronounced than in the first series of tests. The results from the T-L orientation tests are presented in the following sections.

2.3. Laser heating

For the performed experiments, a Nd:YAG laser was used to produce a line of laser heating on the surface of the prepared C(T)100 specimens. For this, the laser was moved with a travelling speed of 3.33 mm/s in positive y-direction from one edge of the specimen to the other. Fig. 1 shows a sketch and a photograph of one of the specimens after the treatment. The heating line was positioned at $x_{heating} = 55$ mm for all specimens. Because the goal was to apply heat without localised melting of the material, a welding optic was used, but the working distance was increased to achieve a laser spot diameter of approximately 5 mm. A layer of silicon carbide powder with a thickness of 0.5 mm was placed on the irradiated surface to ensure the equal absorption of the laser light for all specimens.