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Fatigue and Fatigue Crack Propagation of Laser Beam-Welded AA2198 Joints and Integral Structures

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Abstract. To meet the future demands of the aerospace industry with respect to safety, productivity, weight, and cost, new materials and joining concepts have been developed. Recent developments in the metallurgical field now make it possible to use laser-weldable Al-alloys of the 2xxx series such as AA2198 with a high structural efficiency index due to their high strength and low density. AA2198 holds the promise of providing a breakthrough response to the challenges of lightweight design in aircraft applications. Laser beam welding as an efficient joining technology for fuselage structures is already established in the aircraft industry for lower fuselage panels because the welded panels provide a higher buckling strength and lower weight compared with the classical riveted designs. The key factor for the application of laser-welded AA2198 structures is the availability of reliable data for the assessment of their damage tolerance behavior. In the research presented, the mechanical properties with regard to fatigue and fatigue crack propagation of laser beam-welded AA2198 joints and four-stringer panels were investigated. It was found that the fatigue endurance limit of laser beam-welded AA2198T3 is approximately 25 % below the endurance limit of the base material. With regard to the fatigue crack propagation behavior, the laser beam welded four-stringer panels with T-joints show a fatigue life increased by a factor of 1.7 compared with the base material. This work shows that high-quality laser beam welds of AA2198 can be produced on a large scale using the laser beam welding facilities of the Helmholtz-Zentrum Geesthacht.

Introduction

Laser beam welding (LBW) as an efficient joining technology is already established for the lower fuselage panels of 6xxx Al-alloys (Al-Mg-Si-Cu). Laser beam-welded structures provide higher buckling strength and lower weight compared with the conventional riveted design [1-3]. Newly developed Al-Li alloys of the 2xxx series, such as AA2196 and AA2198, with a higher structural efficiency index due to their high strength and lower density can significantly contribute to the further weight reduction of airplanes. Therefore, LBW processes are being developed and optimized for the realization of Al-Li integral structures [1, 4-5].

Some developments were also accomplished to optimize the AA2198 alloy to achieve a higher static strength and better damage tolerance properties [6]. In this study, the base material (BM) properties were investigated. Studies investigating the damage tolerance of welded integral structures of Al-Li alloys are scarce, however. Whereas some data are available on friction stir-welded butt joints [7-11] and laser beam-welded T-joints [1, 4, 12-13], data on laser beam-welded stiffened panels are lacking [15]. The present study of LBW process development was undertaken on the 3rd generation airframe-quality Al-Li alloy AA2198. In addition to investigating the mechanical performance of the joints, the damage tolerance behavior of the laser beam-welded four-stringer panels was also investigated.

Laser beam welding

LBW was performed using a 3.3-kW Nd:YAG laser with fiber optics (a 400- μm core diameter) and a 200-mm focal length in the case of butt joints (3.2 mm thick AA2198T3 rolled plates) (Fig. 1a). For the LBW of T joints and four-stringer panels (5.0 mm thick AA2198T3 rolled plates as skin and 1.9 mm thick AA2198T8 rolled plates as stringer), the large-scale LBW facility of the Helmholtz-Zentrum Geesthacht equipped with two 3.5-kW CO₂-lasers was used (Figs. 1b and 1c). To avoid hot cracks in the weld seam, a filler wire made of AA4047 with a diameter of 0.8 mm was used for laser beam welding of butt joints and T joints. Details on the process parameters and their influence on the microstructure and mechanical properties of the laser beam-welded aluminum alloy can be found in [12-14].

A phase separation was observed in all examined microsections (Figs. 1a and 1b). The phase separation appears as a different etching behavior, which indicates a different chemical composition and different grain orientation (Figs. 2c, 2d). The different chemical composition is attended by an atypical grain growth [13]. All examined microsections showed porosity that cannot be removed completely but can be reduced significantly by proper surface preparation of the weld zone and variation of the weld parameter sets.

Figure 1. a) Metallographic cross section of a butt-joint, b) metallographic cross-section of a T joint, and c) welded demonstrator panel from aluminum alloy AA2198 (AA2198T3 as skin and AA2198T8 as stringer).

The appearance of $\langle 110 \rangle$ /ND (ND is perpendicular to the figure plane) crystal directions is pronounced within the BM near the sheet surface (Fig. 2a). In the inner region of the BM, the $\langle 110 \rangle$ /ND crystal directions are not significantly visible (Fig. 2b). From this observation, it follows that the texture inhomogeneities are presented through the thickness of the sheet. At the heat-affected zone (HAZ) / fusion zone (FZ) boundary, a significant crystal misorientation can be identified (Fig. 2c). The $\langle 111 \rangle$ /ND preferential direction is dissolved in the FZ. The center of the weld shows larger grains compared with the FZ near the HAZ (Figs. 2c und 2d).

The fusion zone (FZ) of the laser beam-welded AA2198 exhibited a microhardness decrease compared with the HAZ and the BM. The HAZ of at least 4-mm in length consists of the over-aged zone and the annealed zone. The precipitation-hardened condition in this region was affected by the heat transport during LBW. Therefore, the HAZ shows a slightly lower microhardness compared with the microhardness of the BM. The EBSD orientation maps and corresponding microhardness profiles provide evidence to conclude that the grain size and the grain orientation do not have a significant effect on microhardness (Figs. 2c, 2d and Fig. 3).

Mechanical properties

The tensile test results for butt joints and hoop-stress test results for T joints show that there is a reduction of the ultimate tensile strength of approximately 25 % due to LBW (Figs. 4a and 4b). The use of a T joint of AA2198T3 as skin and AA2198T8 as stringer exhibited the maximum resistance to failure in the pull-out testing, especially in comparison to other alloy combinations that are common in the aircraft industry (Fig. 4c). The weakest area of butt joints and T joints where fracture starts is the HAZ/FZ boundary region.

Figure 2. EBSD orientation maps of different areas of a butt joint (the orientation calculation was conducted based on the GSHE method, whereas orthorhombic sample symmetry was assumed): a) the BM near the surface, b) the BM inner region, c) the HAZ/FZ near the surface, and d) the FZ inner region.

Figure 3. Microhardness profiles of a laser beam-welded butt joint.

Figure 4. Results of the static tests: a) tensile test results (butt joint), b) hoop-stress test (T joint) [12], and c) pull-out test (T-joint) [12].

Fatigue

A servohydraulic 25 kN machine with Instron electronic was used for load-controlled fatigue tests at ambient temperature in air with a frequency of 40 Hz and an R-ratio of 0.1.

The AA2198 BM shows noticeable anisotropy of the fatigue properties (Fig. 5). In this work, the performed EBSD analysis has shown that the AA2198 BM is characterized by the presence of a deformation texture, which is causal for the anisotropy. The S-N curve obtained in the L-direction (BM-L) has higher values than the curve obtained in the T-direction. A reduction of 25 % for the fatigue limit of the as-welded material (150 MPa) relative to the BM tested in the T-direction (200 MPa) can be seen. The fracture of laser beam-welded specimens always occurs in the HAZ near the HAZ/FZ solidification line. This is most likely due to the crystallographic misorientation between FZ and HAZ, as shown in Fig. 2c, which was obtained from the EBSD analysis.

Figure 5. S-N curves of BM and the laser beam-welded AA2198T3 (butt joint).

Fatigue crack propagation

Constant amplitude fatigue crack propagation (FCP) tests were carried out at three different R ratios—0.1, 0.3, and 0.7—using a servo-hydraulic machine at a frequency $f \leq 5$ Hz in close compliance with the ASTM E 647 standard [16]. The tests were performed to investigate the damage tolerance behavior of the laser beam-welded four-stringer panels compared with the AA2198T3 BM.

Four-stringer panels were notched using an electro-discharging technique at a predetermined location. A notch of $2a_0 = 65$ mm was placed in the center of the panel between the welded stringers. The crack direction was perpendicular to the stringers. The crack length was measured optically using a travelling microscope and indirectly using an extensometer for crack opening displacement (COD). A polynomial regression based on optically measured values was subsequently used for automatically acquiring the crack length. The stress intensity factor range ΔK value was calculated according to the ASTM E647 standard [16]. The details of the tests are described in [15].

Figure 6a shows the FCP rate vs. crack length ($2a$) curve of a laser beam-welded four-stringer panel tested at $R = 0.1$. Stringer positions are also indicated. There are noticeable fluctuations in the FCP rate, which are caused by the formation of several macroscopic crack fronts and crack deviations. At the beginning, the crack propagates horizontally. Relatively steady state crack growth occurred, and the stringers remained intact. At a length of approx. 90 mm, as the stringers were approached, the crack front deviated (turned) by approx. 30° . Such a crack deviation may be an effect of FCP perpendicular to the weld when the crack propagates into the residual stress field generated by the weld [17]. An additional effect that has to be taken into account is the structural misorientation between the different microstructure regions (Figs. 2a and 2b). At a crack length of

approx. 120 mm, the fracture surfaces contacted on the left side because of another crack deviation, and subsequently, one-sided crack propagation occurred on the right side. After passing below the left stringer with a crack length of approx. 165 mm, the FCP rate increased significantly until the right stringer at approximately 185 mm has been reached. Thereafter, the FCP rate decreased due to the influence of the stringer and fracture surface contact. After the fracture of both stringers at a crack length of approx. 250 mm, the crack front turned again in the horizontal direction, and the FCP rate increased up to a crack length of approx. 335 mm. During further propagation, fluctuations occurred such that the FCP rate decreased when the crack turned, deviated, or deflected and approached the next stringer or when fracture surface contact occurred.

A comparison of the FCP curves for the BM AA2198T3 and the welded four-stringer panels tested at $R = 0.1$, $R = 0.3$, and $R = 0.7$ are presented in Fig. 6b. Except for the retardation at the stringer (at approximately $12 \text{ MPa}\sqrt{\text{m}}$ and $30 \text{ MPa}\sqrt{\text{m}}$), the mean FCP curves for the BM and the welded panels are comparable. The crack length $2a$ of 350 mm for panels tested at $R = 0.1$ was achieved at 102,000 cycles in the case of the BM and at 176,000 cycles in the case of the welded four-stringer panel. Therefore, in the case of the welded panel, the fatigue life was increased by a factor of 1.7 compared with the BM.

Figure 6. a) FCP rate vs. crack length of the laser beam-welded panels tested at $R = 0.1$ and b) FCP rate vs. ΔK curves for laser beam-welded AA2198 four-stringer panels and BMs tested at different R ratios.

Summary

(1) The LBW process was developed for the realization of integral structures from the difficult-to-weld high-strength 3rd generation Al-Li-alloy AA2198. Using the LBW technique, sound fillet butt joints and T joints can be achieved.

(2) In comparison with other Al-alloys, the laser beam-welded AA2198 T joints exhibited the best performance in the pull-out test. However, the LBW of AA2198 causes a 25 % loss of tensile strength and a 25 % decrease in the endurance limit.

(3) The industrial maturity of the process was demonstrated on four-stringer panels, whereby the damage tolerance behavior of laser beam-welded AA2198 panels was also investigated. With

regard to the FCP behavior, the laser beam-welded four-stringer panels with T-joints show a fatigue life increased by a factor of 1.7 compared with the AA2198 BM. This work shows that high-quality laser beam welds of AA2198 can be produced on a large scale using the LBW facilities of the Helmholtz-Zentrum Geesthacht.

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