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Weidenmann, Kay A., Eberhard Kerscher, and Thilo Hammers. 2010. “Mechanical properties of compound extruded aircraft stringer profiles under cyclic loading.” *Advanced Engineering Materials* 12 (7): 584–86. https://doi.org/10.1002/adem.200900327.

Mechanical Properties of Compound Extruded Aircraft Stringer Profiles Under Cyclic Loading**

By *Kay A. Weidenmann*, *Eberhard Kerscher* and *Thilo Hammers**

The worldwide competition in the field of aircraft structures leads to an increasing need for functionality and safety as well as for cost and weight reduction. For instance stringers could be directly welded on the aircraft's skin sheet. The requirements to be met are increased safety against crack initiation and crack growth as well as improved residual strength against failure after harmful impact of foreign objects. The application of continuously reinforced aluminium profiles which are manufactured by compound extrusion leads to increased strength and stiffness of the profiles by combining the aluminium matrix with high strength wires. Thus aircraft stringers of such profiles represent an innovative concept with improved properties. The characterisation of compound extrusions based on medium and high strength aircraft aluminium alloys EN AW-6056 and EN AW-2099 shows that a good embedding of the reinforcing high strength wires (Co-based and Fe-based) can be achieved. Furthermore the mechanical properties under cyclic loading of the profiles were measured and the S/N-curves for the different compound combinations were determined. Subsequently the crack initiation and propagation was analysed by using metallographic and SEM investigations. The fatigue resistance of reinforced specimens is increased compared to unreinforced ones. The fatigue cracks originate at the surface of unreinforced specimen while the cracks in reinforced specimens are initiated at the wire–matrix interface.

Extrusion in general facilitates the flexible production of lightweight frame structures. Their stiffness and strength result from the material that is used, usually aluminium or magnesium alloys, as well as from the geometry of the profile. The efficiency of frame structures made from extrusion profiles can be increased directly during the extrusion process without changing the geometry of the profile by embedding reinforcements featuring high strength and high stiffness.[1] The fundamentals of this process and the emerging material properties have been analysed and are described by Schomäcker, Schikorra and Weidenmann for the embedding of spring steel wires in an EN AW-6060 aluminium matrix.[2–4] It was shown that the reinforcements can significantly increase the profile's strength and stiffness, if the volume fraction of the wires in the profile allows for it.

However, typical aluminium profiles used in aircraft fuselages—so-called stringers—are made of medium and high strength alloys of the 2xxx or 7xxx series. Up to now, research results on the extrusion of the medium and high strength aluminium alloys EN AW-6065 and EN AW-2099 showed that a stable process and a good embedding of the reinforcing elements can be achieved and that the mechanical properties under quasi-static loading conditions are increased significantly by the reinforcements as well.[5,6] However, the question if it is possible to increase the resistance against crack growth and crack propagation using these material combinations remained unanswered. Furthermore the influence of the process chain (solution annealing, quenching, stretch forming and artificial aging) on the interface between the aluminium and the wire has to be investigated.

Experimental

Materials

For the compound extrusion process two different aluminium alloys, EN AW-6056 and EN AW-2099, as well as two

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[**] *Acknowledgements, This paper is based on investigations within the scope of the Transregional Collaborative Research Center/TR10 which is kindly supported by the German Research Foundation (DFG).*

different wires, a Fe-based wire (X2 CrNiMo 12 9 4) and a Co-based wire (Co45Ni21Cr18Fe5W4Mo4Ti1) with a diameter of 1 mm each, were used. The underlined parts of these names are used below to identify the different combinations. After the extrusion process the profiles were solution annealed and quenched in water afterwards. Prior to the artificial aging of the profiles a stretch forming process of 0.6% for EN AW-6056 and 2.5% for EN AW-2099 was executed, which is compulsory for aircraft profiles.

From these compound extruded profiles reinforced and unreinforced specimens were turned with a gauge length of 10 mm at a diameter of 3 mm resulting in a volume fraction of 11% for the reinforcements with respect to a wire diameter of 1 mm.

Experimental Setup

The fatigue tests were conducted load-controlled on a servo-hydraulic testing machine with a maximum capacity of 10 kN. The specimens were clamped hydraulically and the testing frequency was set to 50 Hz at a stress ratio of $R = -1$. The strain measurement was carried out with a capacitive strain gauge which was mechanically clamped to the specimen in the gauge length.

Metallographic Investigations of the Matrix–Wire-Interface

Figure 1 shows metallographic sections along the wire direction of the different compounds after the process chain. Images (a) and (b) show specimens of reinforced EN AW-6056, images (c) and (d) of reinforced EN AW-2099. At the top of each image the wire material is visible and at the bottom the aluminium matrix, respectively.

In all cases the embedding of the wires by the compound extrusion process is very satisfactory however diffusion layers evolved between the aluminium and the wire. The thickness of these layers varies on the one hand depending on the different material combinations and on the other hand due to the different heat treatments for the aluminium alloys. The heat treatment applied to EN AW-2099 based extrusions results in a much thicker diffusion layer primarily at the Co-wire whereas the thinnest layer was found between EN AW-6056 and the Co-wire. The layers evolving in the EN AW-2099 compounds seem to be very brittle, which can be concluded from the numerous cracks occurring in these layers.

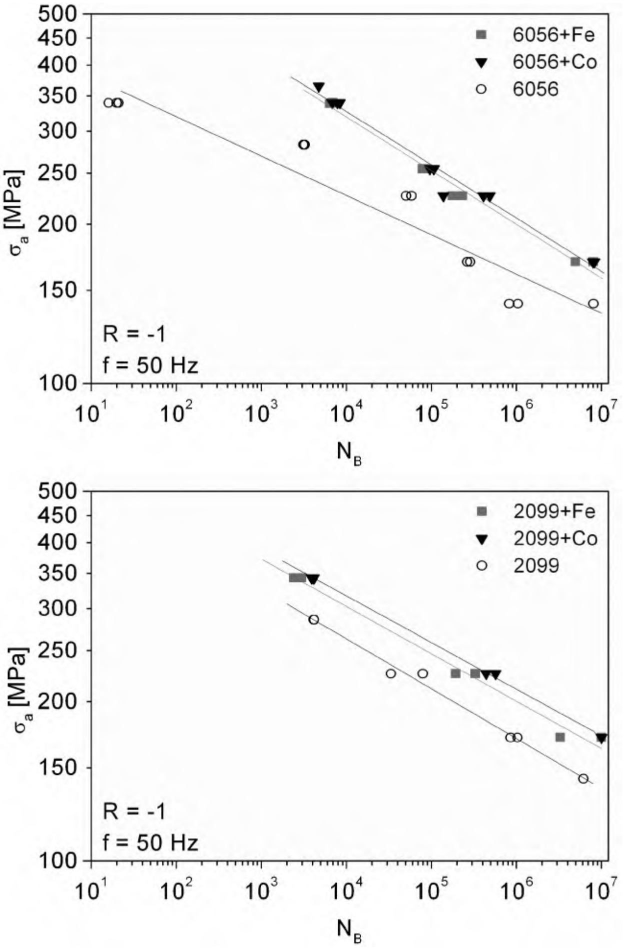

Fig. 2. S/N-curves after the process chain: EN AW-6056 (top), EN AW-2099 (bottom).

S/N-Curves

The S/N-curves of the pure and reinforced aluminium alloys are shown in Figure 2. Hollow circles represent the unreinforced specimens while grey squares (Fe-wire) and black triangles (Co-wire) represent reinforced specimens. It can clearly be seen that due to the reinforcing wires the fatigue life and the fatigue resistance of the specimens is increased. This effect is more pronounced for the reinforced EN AW-6056 specimens. The Co-wire improves the fatigue resistance rather than the Fe-wire for both aluminium alloys.

Investigations of the Crack Initiation

The characterisation of the crack initiation was done in two different ways. Firstly, the specimens were polished in the gauge length and subsequently examined with a light microscope in fatigue tests which were interrupted for this purpose. This procedure has proven to be successful when investigating unreinforced specimens where the crack initiation took place at the specimen's surface in contrast to the reinforced specimen obviously featuring interior crack initiation. In order to prove this hypothesis, the fracture surfaces of the reinforced specimens were investigated in scanning electron microscope (SEM). Exemplarily, the fracture surface of a 2099 + Fe specimen is shown in Figure 3.

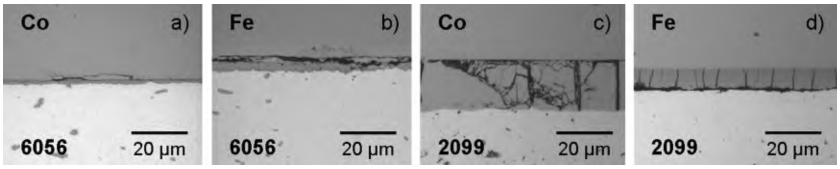

Fig. 1. Metallographic sections along the wire direction after the process chain; (a) 6056 + Co; (b) 6056 + Fe; (c) 2099 + Co and (d) 2099 + Fe.

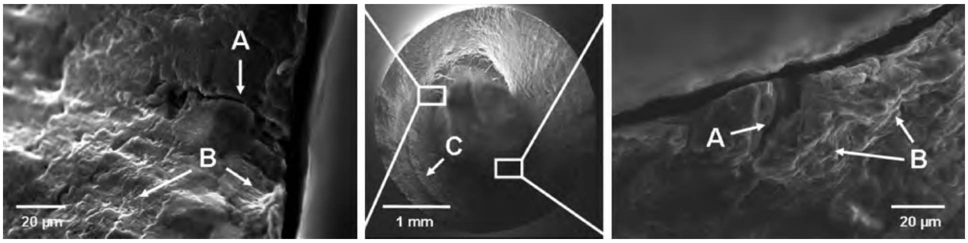

Fig. 3. SEM investigations of the fracture surface of a 2099 + Fe specimen ($\sigma_a = 226$ MPa, $N_f = 377{,}681$).

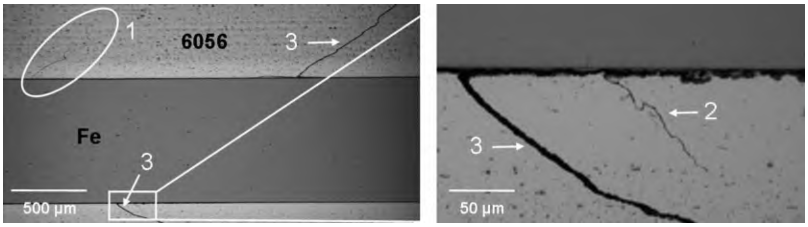

Fig. 4. Metallographic sections along the wire direction of a 6056 + Fe specimen, load direction is horizontally.

On the fracture surface, several cracks are visible which start at the interface between wire and matrix (A) and there are hints of fatigue like striations in the matrix material close to the wire (B). Furthermore lines of rest (C) caused by the interruption of the fatigue tests were found which show crack propagation from the wire–matrix-interface to the surface of the specimen. All reinforced specimens showed comparable indications on their fracture surfaces.

A further evidence of the crack initiation at the matrix–wire-interface is that cracks were found in microsections which clearly originate at the interface as shown in Figure 4.

The initiation of the cracks (1 + 2) at the interface has to be performed prior to the main crack (3) due to the fact that the interface is damaged in this region and thus the tension load in the matrix material is reduced which leads to an unloading of the cracks (especially crack 2).

Summary and Conclusions

It could be found that the fatigue limit can be increased significantly by reinforcing EN AW-6056 with high strength wires during the compound extrusion process. Furthermore the increase of the fatigue limit is less pronounced by reinforcing EN AW-2099 due to the bad condition of the wire–matrix-interface which was found in metallographic sections. Co-wire reinforced specimens appear more fatigue resistant compared to Fe-wire reinforced ones.

The investigations regarding the crack initiation showed that the cracks originate at the surface of the unreinforced specimen whereas crack initiation in reinforced specimens starts at the interface between wire and matrix material. This is on the one hand caused by the bad condition of the wire–matrix-interface. A diffusion layer could be found which is brittle and due to this pervaded by cracks. On the other hand cracks which started from the interface were found in the microsections. The fractographic investigations showed hints of fatigue and secondary cracks near the wire in the matrix material. Due to this it can be concluded that the cracks initiate at the interface between wire and matrix material.

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