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Fatigue Behaviour of Aluminium Tube Crimp Connections Applying the Electromagnetic Pulse Technology

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Abstract

During a still running European Project the feasibility of vehicle light weighting technologies for the manufacturing of light urban electric vehicles with new standards of mechanical performance will be demonstrated. One of the innovative technologies of the project, the Electromagnetic Pulse Technology (EMPT), which is a high speed crimping method, will be applied for joining of particular structural parts of the body, especially to join different lightweight materials such as Al- or Mg-tubes and Al- and Mg-cast or forged nodes.
Current heat-intensive joining processes are faced with a number of drawbacks and “cold” classical adhesive techniques require cost-intensive preparation methods plus long curing times and show design uncertainties in terms of mechanical strength. Hence, joining of dissimilar materials is presently not widely used.
The Electromagnetic Pulse Technology (EMPT) is an innovative approach for joining particular structural parts, where different lightweight materials can be joined without any significant heat input by a fast process. Therefore, this technology is determined as a high efficiency joining process from the quality and the energetic point of view, with virtually no loss of energy in form of heat.
Presently, no design relevant characteristic values of such joints, neither endurable stress amplitudes (fatigue) nor stiffness behaviour of the connection during cyclic loading, are available. Hence, the reliability of such EMPT joints has to be validated with regard to fatigue and stiffness behaviour in order to guarantee a durable connection under typical service loading conditions.
This paper will present first fatigue testing results for aluminium tube joints of EN AW-6082-T6 with a diameter of 40mm. Within this investigation the endurable strength and stiffness behaviour of EMPT joints will be determined in order to validate the performance of the Electromagnetic Pulse Technology for reliable applications under cyclic loading for e. g. urban electric vehicles.

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Keywords: Aluminium; Fatigue; Crimp joint; stiffness; EMPT

1. Introduction

The project URBAN-EV aims to demonstrate the feasibility of light weighting technologies for the manufacturing of light urban electric vehicles with new standards of mechanical performance and occupant safety. The target is placed in a two seats car, with a targeted final weight of maximum 450 Kg (excluding rechargeable energy storage system).In order to achieve this goal, the URBAN-EV consortium will design, manufacture and demonstrate new lighter architectures with enhanced engineering reliability for the principal systems of the vehicle such as chassis and body in white. Most of the applied materials will be light

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alloys and low cost, high integrity polymeric composites, which will be combined using an advanced multi-material design approach.

Current heat-intensive joining processes (arc welding, uncontrolled resistance spot welding) are faced with a number of disadvantages, such as need for using gases and filter wire, the generation of a heat affected zone, usually rich in brittle intermetallics as far as metals are concerned, and a relatively low productivity. On the other hand, “cold” classical adhesive techniques require cost-intensive preparation methods plus long curing times, and show uncertainties in terms of mechanical strength. Mechanical fastening, in turn, is inherently faced with the stress concentration around the joint and will be increased by joining dissimilar materials (especially when metals are concerned). In consequence heat-intensive methods will be reduced to the minimum extent possible within the URBAN-EV project.

Hence, the Electromagnetic Pulse Technology (EMPT) will be applied for joining of the particular structural parts of the body. The reliability of the EMPT joints has to be validated with regard to stiffness and fatigue behavior in order to guarantee a durable connection under service conditions. Despite multiple and various applications applying the EMPT joining technique were approved by end users, no design relevant data are available due to confidentiality reasons.

Therefore, a coupon test program has been defined in order to generate fundamental data on manufacturability, stiffness, strength and fatigue of EMPT joints. The present paper presents first results under constant amplitude axial loading.

2. 2 Electro Magnetic Puls Technology

The electromagnetic pulse technology (EMPT) basically consists in deforming one of the components to be joined by means of the induction of high electrical currents in it, Figure 1 [1]. The deformed component then replicates the shape of the counter-part, creating a strong link just by a crimpling effect [2, 3]. In special chances, particularly in sheet metal joining, the technology can be tailored in order to have an additional ‘welding effect’. EMPT is suited to join tubular profiles of any cross sectional area (not necessarily circular) as well as sheets.

The technology is of purely cold nature (the assembly, once formed can seemingly gripped by hand), which totally eliminates the problems associated to heat affected areas (stress concentration, material inhomogeneity, distortion). EMPT doesn’t require any auxiliary material, such as gases or filler wires; it is clean (no fumes and residues are generated) and fast (the weld is produced in microseconds). On the other hand, the contactless character of the process allows to create a more uniform crimpling pressure with constant quality and no tool marks inherent to mechanical processes. The EMPT technology is especially suited for dissimilar materials joining (metal to metal or polymeric based material to metal), as it involves no chemical or metallurgical transformation.

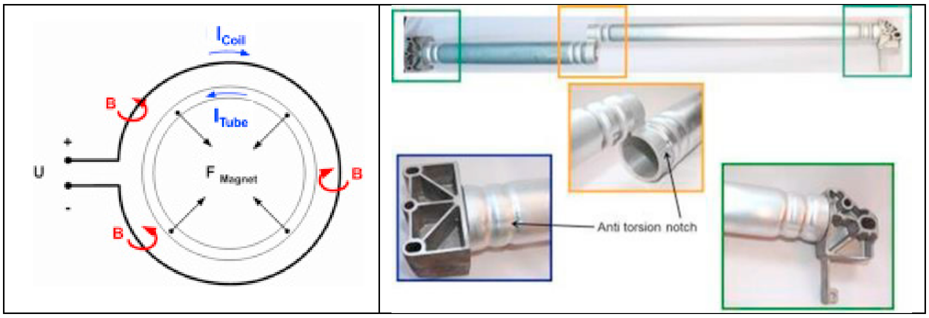

Figure 1: left: process fundamentals: by means of a high coil current pulse (Icoil), a high magnetic pulse (B) is generated, which induces electric current in the part (tube) causes a deformation by means of magnetic forces; right: examples applying EMPT technology

3. Design, materials and manufacturing of the coupons

The coupon test program has been defined applying geometry, quality and choice of materials similar to the vehicle design. The test samples need to be manufactured at the lab facility of PSTproducts in Alzenau/Germany. Respective materials have to be provided according to the design specification by LKR/AIT in Austria. Upfront the testing program the joint design and joint strength as well as the related crimping parameters were simulated in computer model and calculated by means of a Finite Element Analyzes (FEA) model. Then based on the simulation investigation of the FEA the test environment for the crimping procedure was defined.

3.1. Coupon design, materials and manufacturing of semi-finished coupons

EMPT crimp joint design has to consider the forces to be transmitted and the load cases, e. g. axial tension/compression, bending or torsional loading. A two-groove joint design has been chosen creating high strength crimp joints in order to transmit high axial forces, Fig. 2. With regard to expected torsion loading of the crimp joints during service a plane area was considered as a torsional locking. The joint design is based on joint geometries which were proven in the past by PSTproducts and with regard to the application for a vehicle structure the design was implemented for tube diameters 40 x 3.

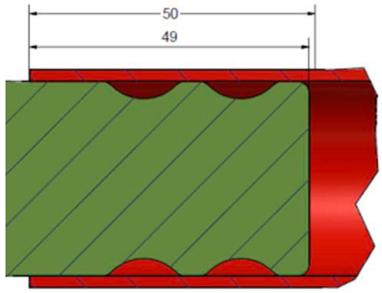

Fig. 2: Two grooved joint design.

Groove geometry is designed by smooth radii. This groove geometry is similar to the geometry the tube would be formed to when a pulse would be applied to the tube without an interior part. By this, a full face contact between tube and inner bolt will be facilitated. This is beneficial especially with respect to joint life under cyclic loading. The coupon design itself result in a specimen geometry of diameter 40 mm and a length of about 450 mm, Fig. 3, with two wall thicknesses in the crimped area, 3mm and 2 mm.

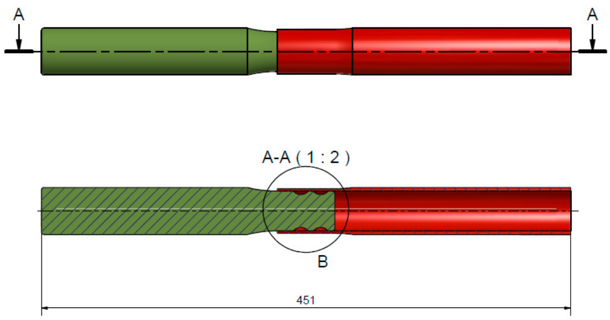

Figure 3: Coupon design

The material EN AW-6082-T6 was chosen for the coupon test program. The stubs have been manufactured from pultruded bars whereas the tubes were extruded. The tube material was analyzed by spark spectroscopy and compared with allowed alloy composition being within specification, Table 1.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
	in %								
specified	0.7-1.3	<0.5	<0.2	0.4-1	0.6-1.2	<0.2	<0.1	<0.25	bal.
measured	1.01	0.235	0.031	0.527	0.659	0.032	0.016	0.005	bal.

Table 1: Chemical composition of extruded tube material EN AW-6082-T6 in comparison to specifications defined in [4]

During selection of a suitable raw material also its dimension tolerances has to be taken into account since an influences of the fatigue testing results due to mounting of the crimped samples, e. g. axial offset, has to be avoided. In order to receive constant condition over the whole testing range raw material with a narrow manufacturing tolerance has to be chosen.

This could be achieved by applying a pultruded bar for the stubs. After delivery the obtained bars and tubes were measured to guarantee the defined tolerance in joining diameter of 0/-0.16 mm and selected for crimping. Finally, some of the tubes have been reduced in outer diameter in order to investigate the joints in different wall thicknesses, e. g. 3 mm and 2 mm.

3.2. Joining

The groove geometry was computed by FEA. For this a fully coupled electromagnetic- mechanic model was set up in simulation software LSDYNA, Fig. 4. The material behavior was modelled by a Johnson- Cook material for Aluminum EN AW-6061-T6, which is similar to the used material EN AW-6082-T6. The material model was proven by high speed material test and is described in literature [5]. Additionally, this material model is used quite often by PSTproducts for modeling similar application like this coupon test. FEA results match normally the test results in terms of forming depth quite good.

The joining process – here a pure crimping process – is based on a consistent tubular magnetic force in which the outer tube joining area (flyer) is accelerated and moved by means of this force up to 170m/s within approx. 19µs on the target (node geometry). Assumption for the process is a defined gap between the joined materials for the high-speed acceleration. The flying material adopts the given geometry of the target component and forms a high-strength and high-tensile form-fitting connection.

All coupons were produced applying a discharge current between 276 kA for the coupons with 2mm wall thickness and about 278 kA for the coupons with 3mm wall thickness, Fig. 5.

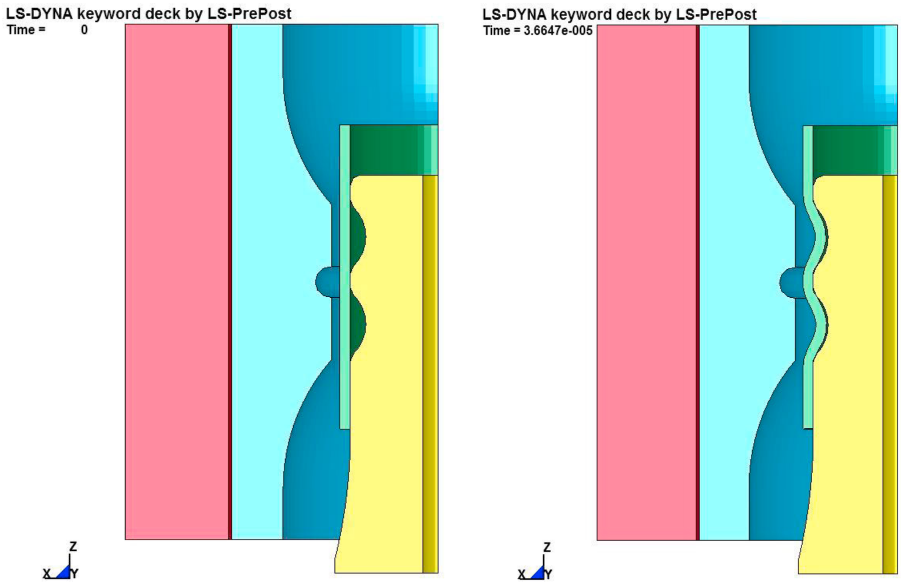

Figure 4: Schematic illustration of the EMPT process before (left) and after (right) the simulated process

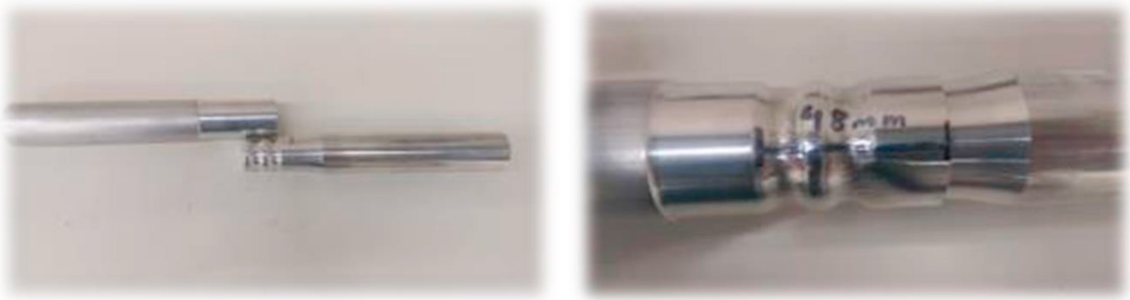

Fig. 5: Coupons before (left) and after (right) EMPT joining process.

4. Experimental investigation

All tests with the manufactured coupons have been performed under axial loading on a servohydraulic test rig, nominal load capacity of 40 kN, Fig. 6. In order to validate the EMPT joints tests have been performed under quasistatic and constant amplitude loading conditions with a frequency of about $f = 30\ s^{-1}$. In order to analyse the performance of the EMPT joints with regard to durability as well as stiffness loss during loading, load and deflection were recorded and the stiffness behaviour was calculated.

Fig. 6. Set-up for axial testing.

4.1. Quasi-static tests

The first investigation of the coupons was intended to determine the quasistatic behavior under axial conditions of the coupons and to compare this behaviour with the calculations of the pre-design. Based on a preliminary calculated tensile strength of about F = 22 kN for the present crimp design of the coupons with a wall thickness of 3mm the tests have been arranged on a test rig with a maximum nominal load capacity of 40 kN.

The result of the first tensile test with a coupon having a wall thickness of 2 mm is presented on Fig. 7 with the applied tensile load and additionally with the calculated nominal stress in the tube cross section. The achieved endurable axial load results in much higher endurable strength than estimated by the calculation and the load capacity of the testing machine. At about 40 kN only small plastic deformations could be recognized for the coupon with a wall thickness of 2 mm. A tensile load of nearly 40 kN results in a nominal stress in the tube of about σ_n = 175 MPa. Extrapolating this result to a coupon with 3 mm wall thickness not even plasticity will be achieved up to a load of 40 kN. Therefore, no further tensile test have been performed in the present test campaign.

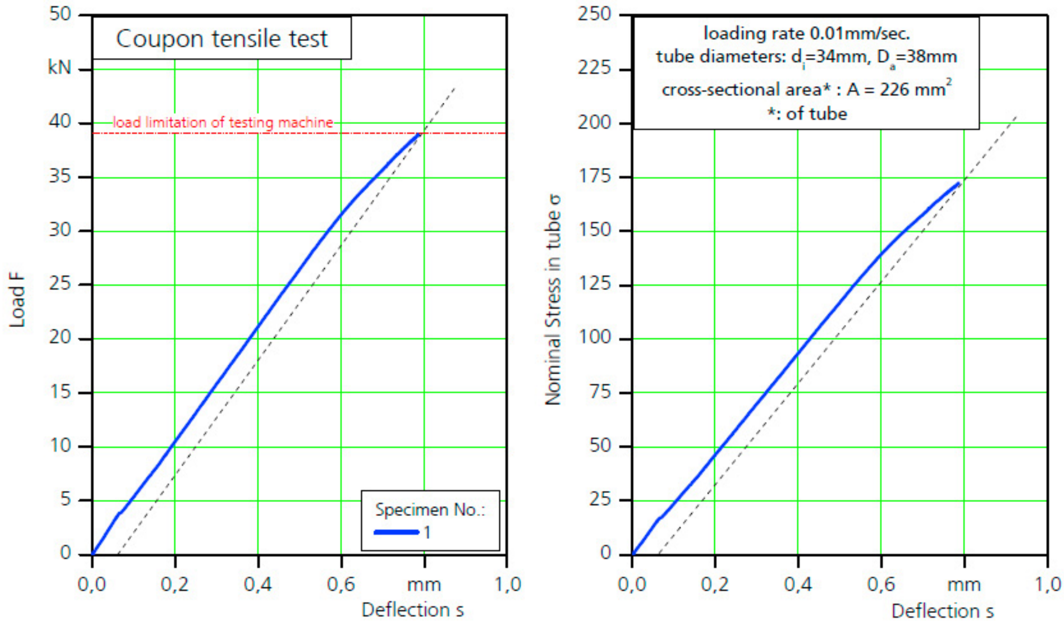

Fig. 7. Tensile test result with coupon having 2 mm wall thickness concerning tensile load (left) and nominal stress (right)

4.2. Fatigue tests

The fatigue testing was performed under constant amplitude axial loading with a frequency of $f = 30\ s^{-1}$ and a load ratio of $R_F = -1$. The tests were stopped achieving a reduction of stiffness by 20 % or maximum defined loading cycles without failure. Maximum number of loading cycles have been defined to $N_L = 2 \cdot 10^6$.

The results obtained under axial loading are presented in Fig. 8 for the endurable load amplitude of the coupons with 2 mm and 3 mm wall thickness. The Woehler-curves were evaluated according to the Maximum-Likelihood-Method [6] with a slope in the finite-fatigue region of k50% = 4.0 and a knee-point at $N = 2 \cdot 10^6$ loading cycles resulting in an endurable load amplitude of $F_a = 8.5$ kN (2 mm wall thickness) respectively $F_a = 15$ kN (3 mm wall thickness) for $N = 2 \cdot 10^6$ loading cycles. After the knee-point defined at $N = 2 \cdot 10^6$ loading cycles a further degrease of the endurable load amplitude can be estimated by 5% per decade [7] resulting in an endurable load amplitude of $F_a = 8.2$ kN respectively $F_a = 14.5$ kN. The scatter was calculated to $T_F = 1 : 1.17$ (2mm) respectively TF = 1 : 1.1 (3mm).

The endurable load amplitudes result in endurable nominal stress amplitudes for the tube of σa = 36.4 MPa for 2mm wall thickness respectively σa = 41.6 MPa for 3mm wall thickness, Fig. 9.

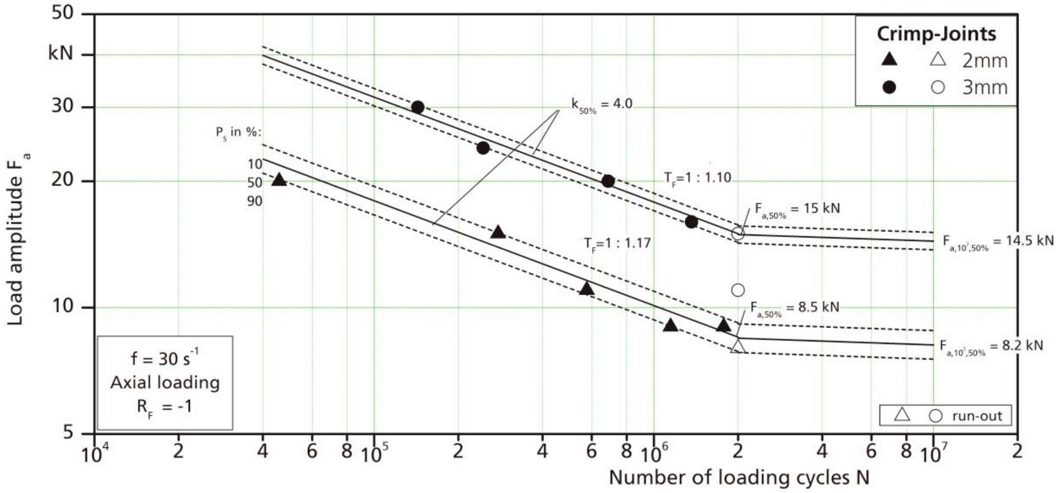

Fig. 8: Test results under constant amplitude axial loading concerning load amplitude

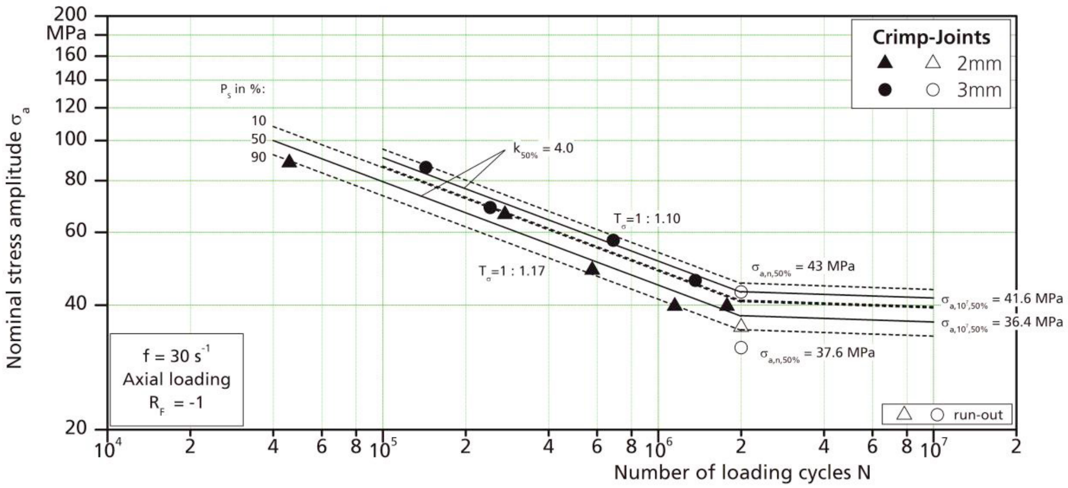

Fig. 9: Test results under constant amplitude axial loading concerning nominal stress amplitude

During the fatigue tests no stiffness loss could be identified for run-outs, means for coupons reaching $N = 2 \cdot 10^6$ loading cycles without crack or rupture. However, an upcoming failure of the coupons by a crack initiation can be clearly recognized by a stiffness loss, Fig. 10.

Failures of the coupons occurred in the first groove of the stub taking most of the axial loading, Fig. 11. Analysing the fracture surface, the crack is initiated at the outer surface of the tube, Fig. 12, expecting high tension residual stresses due to the crimping process there. More detailed analyses of the behaviour of the EMPT joints are still planned respectively in progress.

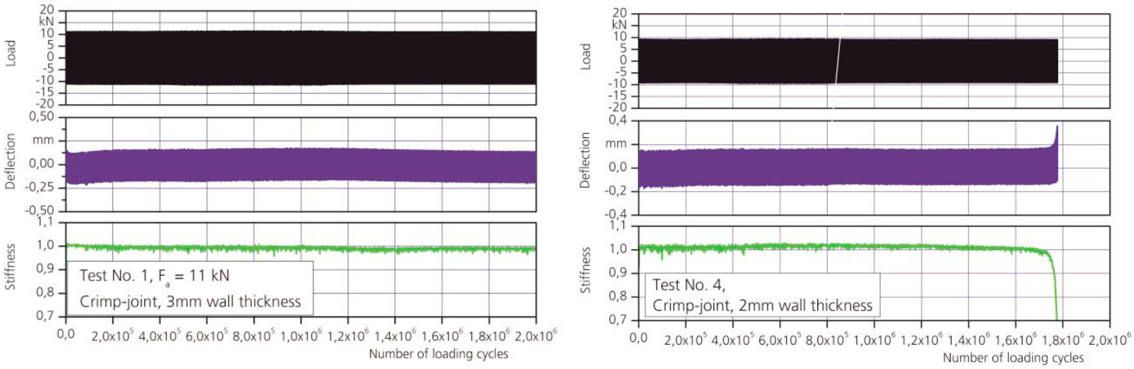

Fig. 10: Recorded data during axial fatigue testing left: run-out without any indications of stiffness loss (left) and appearance of stiffness loss after crack initiation (right)

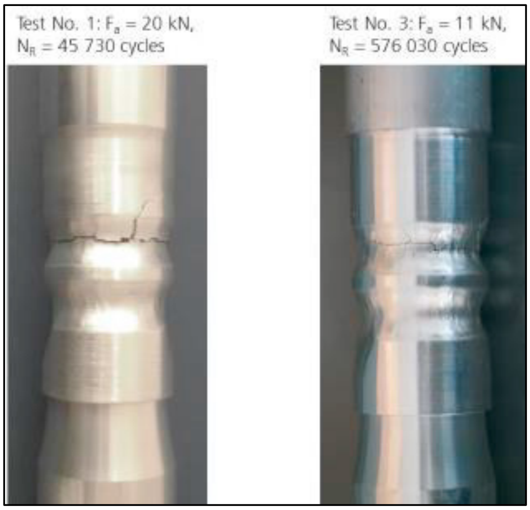

Fig. 11: Typical failures under axial loading

Fig. 12: Typical rupture (left) and fracture surface analysis (right)

5. Summary and assessment of the quasistatic and fatigue testing results

In order to validate the performance of the EMPT-joints under quasistatic and cyclic axial loading conditions a coupon test program was performed. Quasistatic tests were performed in order to analyze the behavior of the coupons with regard to maximum endurable load and for a first estimation of the cyclic behavior.

The quasistatic loading results in a relatively high load capacity with a tensile load of more than 40 kN for the coupon with a wall thickness of 2 mm. A first plastic deformation could be recognized above F = 30kN respectively above σ_n = 130 MPa. For the coupons with higher wall thickness of 3 mm a higher strength can be expected exceeding the load capacity of the testing machine. Therefore, the performance under quasistatic loading conditions has been assessed to be more than sufficient and no further tests were performed.

Under cyclic loading (fatigue) following endurable constant amplitude axial loading respectively nominal stress amplitudes have been achieved for $N = 2 \cdot 10^6$ loading cycles and a probability of survival of 50%:

Coupons	axial loading	
2 mm wall thickness	F_a = 8.5 kN	$\sigma_{a,n}$ = 36.6 MPa
3 mm wall thickness	F_a = 15.0 kN	$\sigma_{a,n}$ = 43.0 MPa

Failure criterion was crack initiation respectively rupture in the first groove. A stiffness loss couldn't be analyzed under axial loading neither for 3 mm wall thickness nor for 2 mm wall thickness.

Preliminary load calculations for the light urban electric vehicle "URBAN-EV" result in maximum axial loads at the locations of such crimp joints of about 5.1 kN during service load considering also misuse the present design of the EMPT joints should guarantee a reliable service taking into account only axial loads. Further tests are planned for bending and torsional loading in order to demonstrate the feasibility of a vehicle structure by the EMPT technology.

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