Strength of Tubular Joints Made by Electromagnetic Compression at Quasi-static and Cyclic Loading *

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Abstract

Electromagnetic compression of tubular profiles with high electrical conductivity is an innovative joining process for lightweight structures. The components are joined using pulsed magnetic fields which apply radial pressures of up to 200 MPa to tubular work-pieces, causing a symmetric reduction of the diameter with typical strain rates of up to 10^4 sec^{-1}. This process avoids any surface damage of the workpiece because there is no contact between component and forming tool.

The strength of electromagnetically formed joints made of aluminum tubes under cyclic loads is essential to establish electromagnetic forming in automotive structures. In the present paper, the quasi-static performance of tubular joints made by electromagnetic compression produced of different mandrel materials will be analyzed as to the influence of process parameters. Therefore, experimental investigations on aluminum tubes (AA6060) joined on mandrels made of different aluminum, copper, and steel alloys were carried out. Furthermore, the behavior of joints with both mandrel and tube made of AA6060 at swelling cyclic loads ($R = \sigma_{\min}/\sigma_{\max}$ = 0) has been evaluated.

Keywords:

Assembly, Electromagnetic compression, Cyclic load

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1 Introduction

The dead weights of car bodies can be significantly reduced by introducing lightweight materials (e.g. aluminum) in the manufacturing of car body components. Therefore, the demand on joining technologies is to produce joints of high strength for the manufacturing of lightweight frame structures. In general, joints could be established by e.g. welding, bonding, and mechanically by dominating form-fit or dominating force-fit. Joining processes like laser-welding, screwing, clinching, riveting, and bonding are established in the manufacturing of lightweight frame structures, but they contain process-related constraints. Exemplary aspects are a complex preparation of the joining area, an accurately guiding during the joining process as well as a long process duration. The mentioned constraints do not have be considered if joining has been done by compressing cylindrical tubes on mandrels by electromagnetic forming. Besides this, composite materials or two non-weldable alloys can be joined without extensive preparations of the joining area.

Experimental investigations have been done to evaluate both feasibility and capability of joining by forming processes. The influence of process parameters on the performance of the joints is actually in the focus of investigation. On the one hand, it is the joint strength under quasi-static loads, but on the other it is necessary to know the performance and behavior of joints made by electromagnetic compression at cycling loads to establish electromagnetic forming in industrial production [1,2 3,4,5].

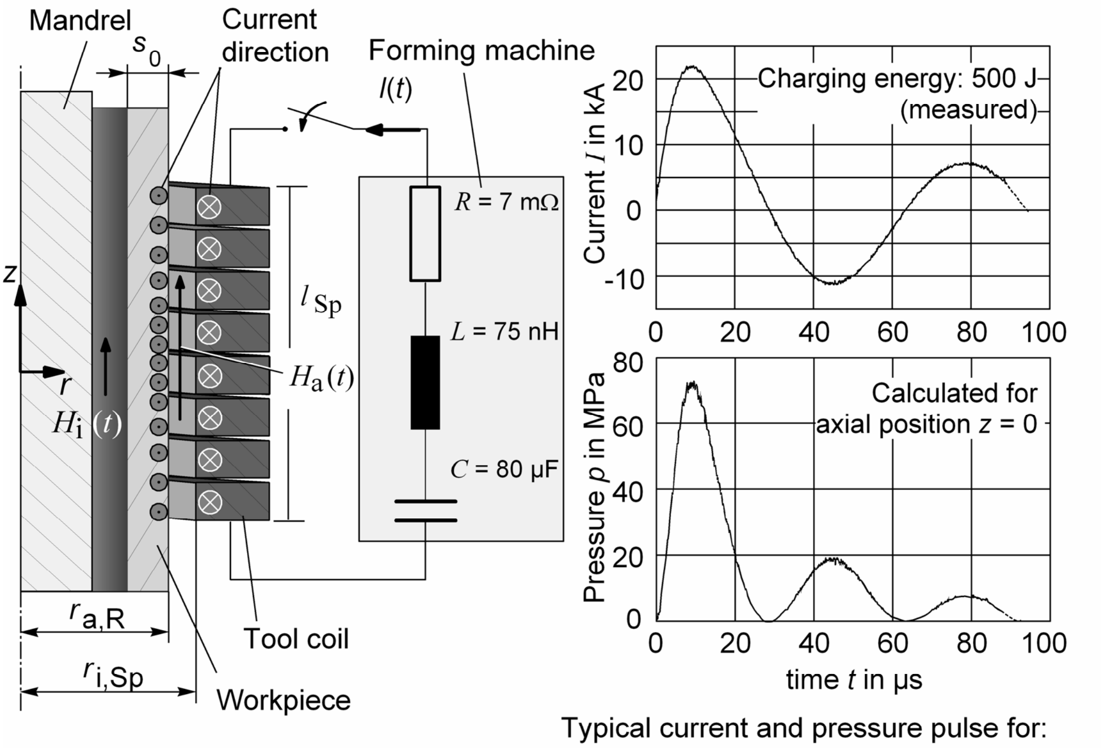
2 Process principle and characteristic of force-fit joints

Electromagnetic forming is a high speed process using a pulsed magnetic field to form metals with high electrical conductivity such as aluminum. The energy density of a pulsed magnetic field is used for the contact-less forming of a workpiece. The resulting deformation is closely related to the electromagnetic properties. The process model (Figure 1) can be described as an oscillating circuit which includes the capacitor *C*, the resistance *R*, and the inductance *L* of the pulse generator as well as the consumer load consisting of tool coil and workpiece, here a solenoid and a tube. After the capacitor bank has been charged it is suddenly discharged by closing a high current switch. As a result, a damped oscillating current flows through the coil, generating a corresponding magnetic field. According to Lenz's law, a current in the workpiece will be induced flowing in the opposite direction to its cause. Due to the skin effect the current as well as the magnetic field penetrate the workpiece wall.

The resulting magnetic pressure *p(t,r,z)* is determined by the energy density of the magnetic field outside H_a and inside H_i of the workpiece and can be calculated on the basis of the measured coil current by [6]

$$p(t,r,z) = \frac{1}{2} \cdot \mu_0 \cdot \left(H_a^2(t,r,z) - H_i^2(t,r,z) \right)$$

The resulting pressure pulse acts vertically on both the field strength and the induced current [7], i.e. in radial direction on tube and tool coil, as Figure 1 shows. If the yield strength of the tube is exceeded, radial necking occurs. This deformation mode can be used for realizing a joint between a tube and a cylindrical mandrel. During this process the tube is deformed plastically and the mandrel ideally remains elastically. After a decrease of the forces a corresponding elastic recovery of mandrel and tube proceeds [8]. If a full relaxation of the mandrel is prevented by the tube, a permanent pressure in the joining area in radial direction is established. This pressure is a balanced condition of the mandrel's stress relief, on the one hand, and the resulting reinduced stress (by the elastic recovery of the mandrel) in the tube, on the other hand.



Workpiece			Tool coil		
Conductivity	κ	= 26.5 MS/m	No. of turns	n	= 14
Wall thickness	s_0	= 1.25 mm	Length of the coil	l_{Sp}	= 27 mm
Outer radius	$r_{a,R}$	= 8.95 mm	Inner radius	$r_{i,Sp}$	= 9.6 mm

***Figure 1**: Process principle*

In the case of massive shafts, their pure elastic deformation determines the maximum allowable joint pressure in the contact zone to realize an optimum interference pressure. The strength of interference-fits strongly depends on the area of the contact zone, the friction coefficient, and the remaining interference stress in the contact zone. While the first two aspects directly influence the strength of the joint, the last point depends on material parameters like yield point and Young's modulus as well as the geometrical stiffness of the parts to be joined [8, 9, 10, and 11]. In the following, the influence of the tube compressing velocity and the joint material of the inner join partner (mandrel) on the joint quality has been evaluated by quasi-static and exemplarily cyclic-load.

3 Materials and testing method

For the present experimental investigations aluminum tubes were electromagnetically compressed on mandrels made of different materials at the Institute of Forming

Technology and Leightweight Construction, Universität Dortmund (Germany). The material of the tube was AA6060 and its outer diameter was 20 mm along with a wall thickness of 1 mm. The joining process was made with charging energies of 1.1 kJ and 1.5 kJ. In Table 1, yield strength and Young's modulus of the mandrel materials are listed.

ID	Material	Alloy composition	Yield strength [MPa]	Young's modulus [MPa]
A	AA5754	AlMg3	100	70,000
B	AA6060	AlMgSi0,5	160	70,000
C	AA7075	AlZn5,5MgCu	460	70,000
D	C1100P	Cu-ETP	180	116,000
E	CW106C	CuCrZr	470	116,000
F	NSB4	CuNi3Si1	590	116,000
G	S235		235	210,000
H	1.0715	9SMn28k	440	210,000
I	1.0601	C60	580	210,000

Table 1: *Typical values of yield strength and Young's modulus of the different mandrel materials, taken from literature [12].*

Mandrels of nine different materials were joined in order to study the influence of the mandrel's stiffness and strength on the mechanical properties of the joint. Aluminum alloys, copper alloys and steels were chosen to compare the influence of strength and stiffness. Furthermore, three different alloys of each material with the same Young's modulus were joined to compare the influence of yield strength. The tensile tests were carried out in a 200 kN Zwick machine with a crosshead velocity of 2 mm/min to assure an approximate strain rate ($\dot{\varepsilon}$) of 3.10^{-3} 1/s. Cyclic tests at swelling loads ($R = \sigma_{\min} / \sigma_{\max}$ = 0) were carried out in a 63 kN Instron (Fast-Track 8800) servo-hydraulic machine. The test frequency was 2 Hz. The maximum and the middle loads were varied from 2 kN to 12 kN and 1 kN to 6 kN respectively. The quantities measured were the force, the relative displacement of the tubular component, and the complete displacement of the test tube. The relative displacement of the tubular component was measured with a capacitive sensor (small measuring range with high resolution) and the complete displacement of the test tube was measured with an inductive sensor (large measuring range with low resolution). The experiments were stopped either by test tube's failure or by 10^6 cycles.

4 Experimental results

4.1 Influence of the forming velocity and mandrel material on the mechanical properties

In contrast to quasi-static forming and joining procedures, the forming velocity plays a decisive role in the EMF process. The velocity of the tube being compressed as well as its mass determine the kinetic energy at the moment of impact, and therefore the force which takes effect on the mandrel. To investigate the influence of the necking velocity, the radial displacement has been measured during the forming process without a mandrel by the light–shadowing–method, as described in detail in [1, 13, and 14]. A line-shaping laser beam will be shadowed by the smallest cross section of the tube during the compression progress. The related velocity of the radial displacement at the smallest cross section can be calculated by derivation of the measured and smoothened displacement curve. The characteristic shape of the necking velocity during this high speed process shows a characteristic acceleration and deceleration progression.

A mandrel inside the tube limits the radial displacement. So, the gap a_0 between tube and mandrel is the distance which can be used for tube acceleration. In Figure 2, the influence of this acceleration gap a_0 on the strength of the joints is presented.

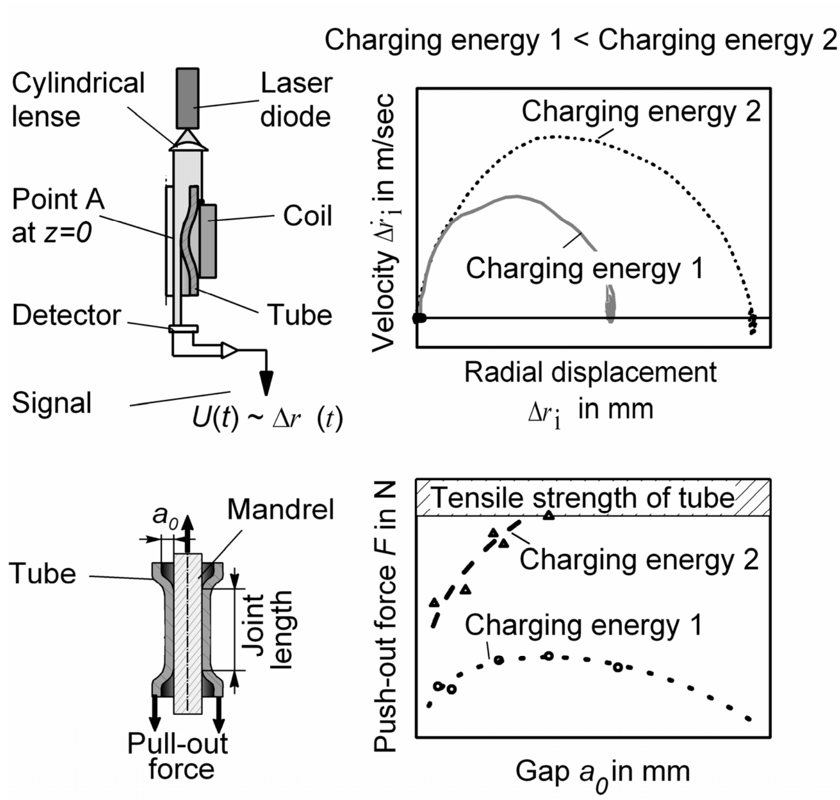


Figure 2: *Influence of the compression velocity on the push-out force*

On the one hand, it is possible to increase the velocity (and therefore the kinetic energy) of the tube at the moment of impact by increasing the charging energy. On the other hand, the charging energy which is required for a particular velocity at the moment of impact can be reduced by an increase of the gap a_0.

In former full scale experimental investigations joints were produced with tubes of the alloy AA6060 (with a diameter of 20 mm and a thickness of 1 mm) and with three different mandrel materials [1]. In that work AA6060 and AA2007 were chosen to compare the influence of strength for the same stiffness, and 9SMn28k to compare the influence of stiffness for a comparable strength at different charging energies as well as acceleration gaps. The strength has been evaluated by the required force to separate the inner and outer part by pressing the inner part (mandrel) out of the tube. Failure was defined by means of the force value that refers to the first relative movement between tube and mandrel. As expected, the push-out force increased with an increasing charging energy and the non-linear correlation between the strength of a joint and the gap width a_0 could be observed. This corresponds to the theory that the kinetic energy of the deformed part at the moment of impact with the inner part determines the remaining interference stress within the contact zone (*Figure 2*). This is an important aspect in consideration of an efficient design of the joining process because the smaller the gap the higher the required discharge energy.

The results of pull-out tests in Figure 3 indicate that a force-fit without any acceleration gap (a_0 = 0 mm) on massive mandrels could not be produced.

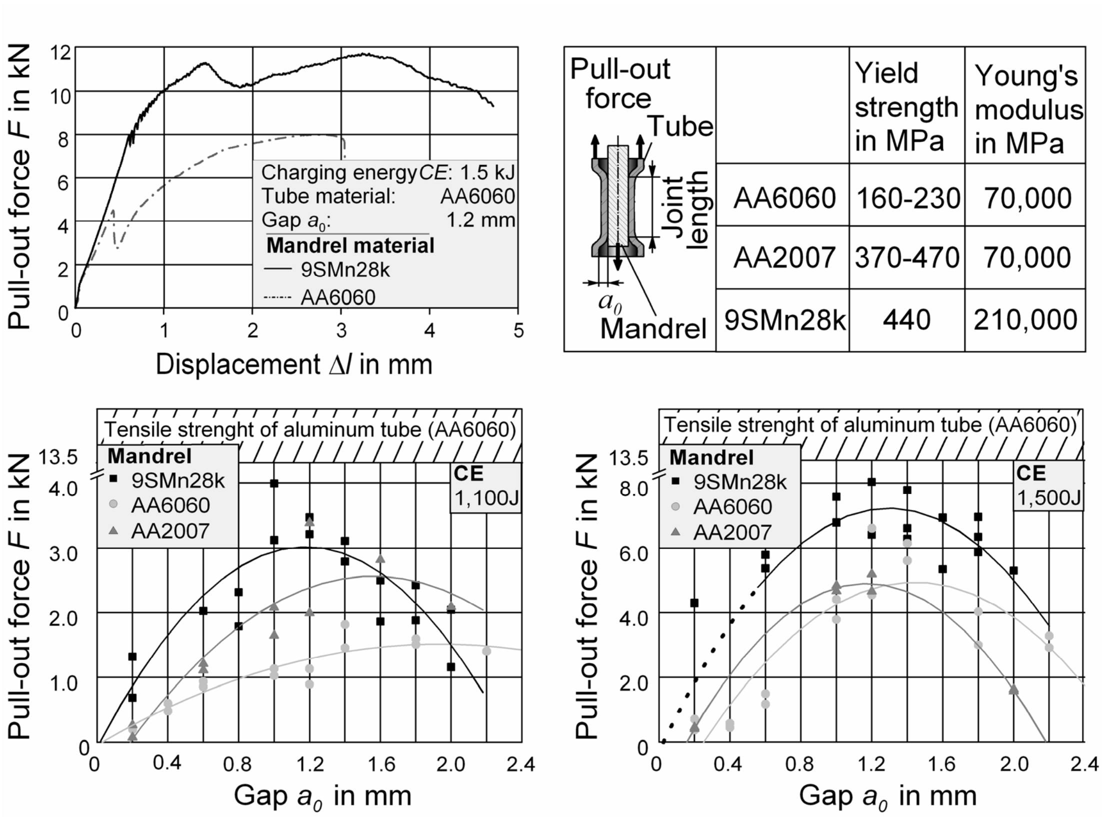


Figure 3: *Left: Results of pull-out-tests for a charging energy of 1,100J (AA6060, AA2007 and 9SMn28k). Right: Results of pull-out-tests for a charging energy of 1,500J (AA6060, AA2007, and 9SMn28k) [1]*

On the contrary, an increase of the gap width, and therefore an increase of the acceleration distance, causes a reduction of the necessary charging energy. An increase of the charging energy leads to higher levels of pull-out forces. In addition, it was found that by using a mandrel material of both higher strength and stiffness results in higher pull-out loads, too. The pullout loads of test tubes joined with different mandrel materials are presented in Figure 4. All columns show an increase of the pull-out load by increasing the yield strength of the mandrel. Furthermore, the pull-out loads increase if the Young's modulus of the mandrel increases. By comparing the results from a single curve, meaning at constant stiffness, a joint produced with the same charging energy (same impact velocity due to the joining process with the same parameters) seems to cause a higher radial reaction force of the mandrel if the mandrel's strength is higher, too, leading to higher pull-out loads. Furthermore, the different columns, meaning different stiffnesses, show higher pull-out forces in the case of stiffer materials, especially steels. From this point of view, it will be favourable to use a mandrel material of higher strength and stiffness than the tube material. Basically, joining by EMF provides the opportunity to produce joints which can resist axial forces as high as the yield strength of the tube.

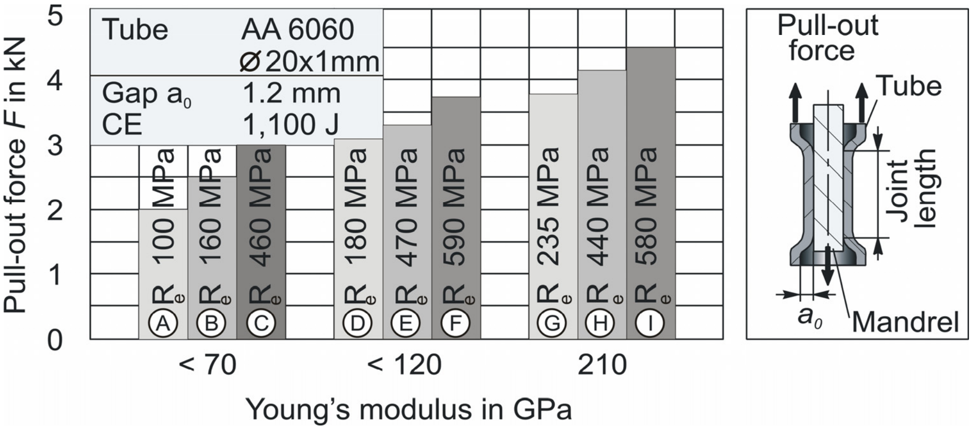


Figure 4: *Results of pull-out-tests for different mandrel materials*

4.2 Behavior under cyclic load

Though joints with a steel mandrel have higher levels of pull-out loads than joints with an aluminum mandrel [1], cyclic tests were first carried out for reasons of lightweight construction at the specimens mentioned above, Figure 5.

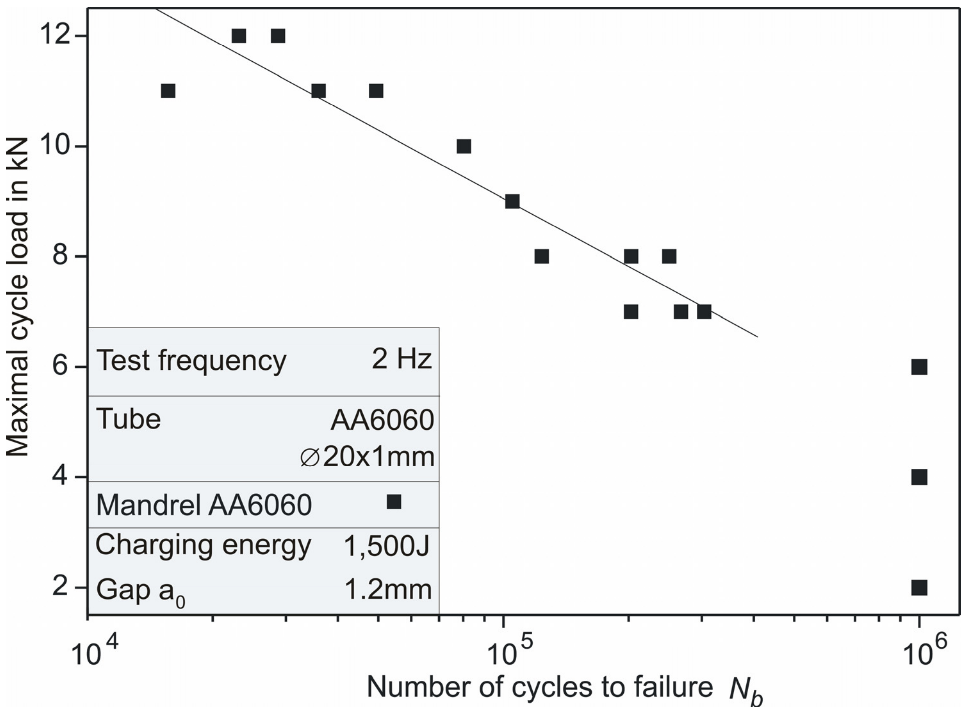
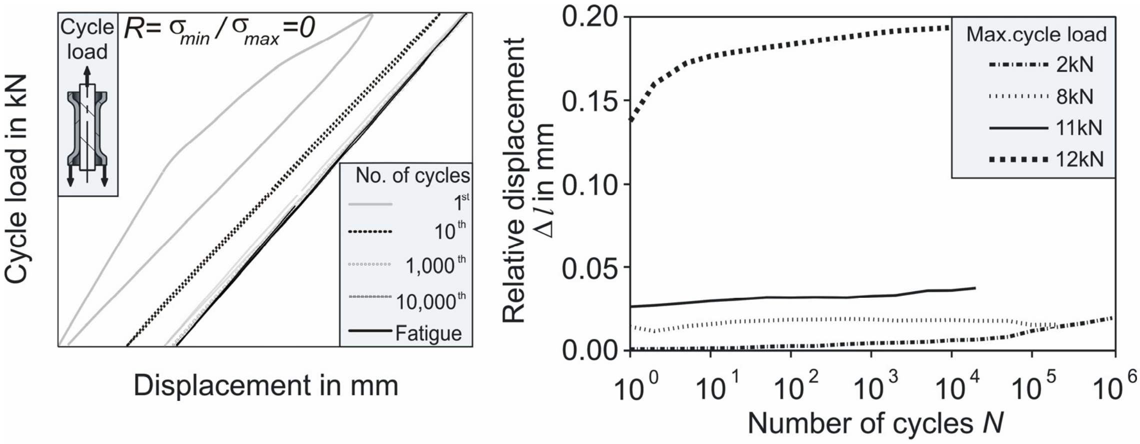


Figure 5: *Swelling curve for joints made with an aluminum mandrel*

The influence of the mandrel material at cyclic load will be investigated in further studies. Figure 5 shows a linear relationship between the uniform load amplitude and the number of cycles causes failure / separation of the test tube. The fatigue life is about 2.10^4 cycles for a load of 12 kN and it increases up to 5.10^5 cycles for a load of 7 kN. The fatigue limit for 1.10^6 cycles of these joints is about 6 kN. It can be noticed that all maximal loads are fairly higher than the pull-out and the maximal loads found by [1] in tensile tests. Such a behavior could not be expected since conventional joints can not transmit higher loads than the maximal load in a tensile test for more than one cycle. Figure 6 right shows the relative displacement Δl of the tubular component during a cycling test for different maximal loads, and Figure 6 left shows the hysteresis curves from a test with a maximal load of 8 kN of five different cycles. In Figure 6 left it can be seen that the first cycles lead to a shift of the tubular component on the mandrel. This initial displacement becomes bigger the higher the maximal load is, especially for the maximal load of 12 kN (Figure 6 right). After a few cycles the displacement decreases and remains nearly constant. Finally, there is no further glide until test tube's failure. The slipping of the tubular component out of the mandrel was continuous only in the test by a maximal load of 12 kN.



Tube	AA6060	Mandrel	AA6060	Charging energy	1,500J
	∅20x1mm	Gap a_0	1.2mm	Test frequency	2 Hz

Figure 6: *Left: hysteresis curves from a test with a maximal load of 8 kN for five different cycles. Right: Relative displacement of the tubular component during test for different maximal loads*

This high displacement of the tubular component at the beginning of the test, which is followed by a small glide until test tube's failure, is evidence for a "hardening process" which takes place in the beginning of the test.

The metallographic examination after test tube's failure points out that the specimen failure always occurs in the transition zone between deformed and undeformed zone of the tubular component, as Figure 7 A shows. Then the crack propagation along the transition area finally causes complete collapse of the tubular component. To investigate this in detail, samples of the mentioned region were cut out and then examined in a Scanning Electron Microscope (SEM). Figure 7 B shows a SEM picture with a magnification of factor 50 of the crack initiation zone. In the lower area of the picture it is possible to identify that a fragment of the tubular component is fused with the mandrel. The fusion between both components is clearly observable in Figure 7 C. Furthermore it can be noticed that the crack propagates in the mandrel, too.

With this observation it is possible to understand the high level of loads that the joint can transmit under swelling cyclic loads (Figure 5). Besides this, the relative displacement of the tubular component (Figure 6) can be explained as follows:

Due to testing there is a relatively high level of friction between both components of the joint. First, this friction clears the oxide layer of both components in the contact points between them. Afterwards, the friction produces a local increment of the temperature which induces diffusion welding. When this happens the further displacement of the tubular component is largely impeded

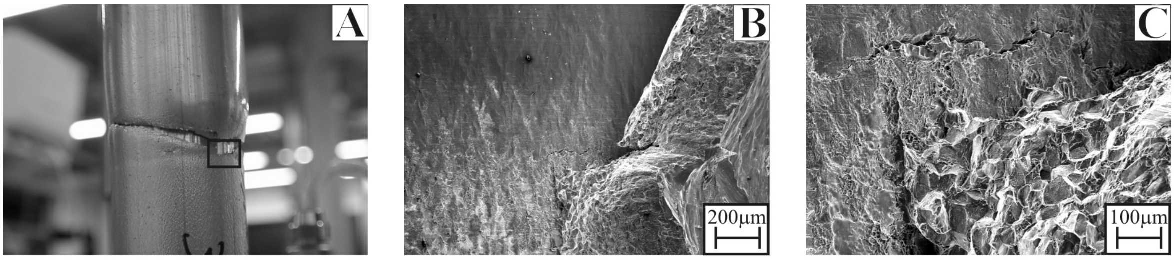


Figure 7: *A: Fracture mode by cyclic test B: SEM picture of the crack initiation zone C: Magnification of picture B*

5 Conclusions

In the present work, electromagnetically joined tubes of AA 6060 and mandrels of different materials were investigated at quasi-static and cycling loads. The results of tensile tests show that higher levels of pull-out load are achievable by increasing strength or stiffness of the mandrel material by the same impact velocity due to the joining process with the same parameters. This is because the radial reaction force of the mandrel is higher if the mandrel's strength or stiffness is higher as well which, therefore, leads to higher pull-out forces.

The results of cyclic swelling tests indicate that the fatigue life and the fatigue limit of the joints are a multiple factor higher than the pull-out loads found in quasi-static tensile tests. Furthermore, the displacement of the tubular component shows a big slide at the beginning of the test, which is followed by a small continuous glide until test tube's failure. The explanation is that friction during the first cycle may clear the oxide layer of both components in the contact points between them. Subsequently, the friction produces a local increment of the temperature, which induces diffusion welding impeding the further displacement of the tubular component.

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