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Experimental study on the magnetic pulse welding process of large aluminum tubes on steel rods

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Abstract. Solid state welding technologies enable dissimilar metal welding without critical intermetallic phase formation. Magnetic Pulse Welding (MPW) is a promising joining method for hybrid sheet connections in car body production or for manufacturing of dissimilar tube connections. Given a suitable MPW process design, the shear testing of MPW joints usually leads to failure in the weaker base material. This finding emphasizes the high strength level of the joining zone itself. Consequently, the transmission of higher forces or torques, respectively, requires stronger materials or adapted geometries. In the present experimental study, the diameter of an exemplary driveshaft was doubled to 80 mm at constant tube wall thickness to increase the load bearing capability. The characteristic impact flash was recorded at different positions around the tube's circumference and it was used to adjust the most relevant process parameters, i.e. working length and acceleration gap, at the lower process boundary. In metallographic analysis, the final shapes of both joining partners were compared with the original driveshaft dummies on macroscopic and microscopic scale. The typical wavy interface between aluminum and steel was analyzed in detail. Doubling the tube diameter lead to four times higher torque levels of failure during quasistatic and cyclic torsion tests.

1. Introduction

Lightweight designs are of great importance in the transportation sector in order to reduce the energy consumption of vehicles. At the same time, reducing the mass leads to less energy that has to be absorbed in case of a crash. Multi material concepts are essential to reach this goal and require suitable methods for joining dissimilar metals. In most cases, conventional fusion welding processes are not applicable due to the differences in the thermophysical material properties and the formation of brittle intermetallic phases in the weld seam. Purely mechanical connections based on form or force fits do not show these disadvantages but often require additional elements like fasteners or elaborate preparation steps to achieve close fits. There is a wide variety of joining by forming processes that reduce or overcome these drawbacks [1]. For example, high speed forming processes can be utilized to



connect dissimilar metals by form fit, force fit or even by welding. Magnetic pulse welding (MPW) is a representative of the last mentioned methods and is applicable for the production of hybrid drive shafts [2–6]. The torsional load bearing capabilities of these connections have already been proved in former studies [7, 8]. It was found that sound welds can be produced even with non-contoured inner parts by fine-tuning the energetic and geometric parameters and, thus, reducing the preparation effort compared to [4, 6]. Failure occurred in the outer tube's base material next to the weld seam. Consequently, this tube has to be toughened in order to increase the overall torsional load bearing capability. Since the material is often a preset boundary condition due to cost or process related factors, the outer tube's geometry has to be adapted. Table 1 highlights the advantage of an increased tube diameter (setup 3) compared to an increased tube wall thickness (setup 2). On the one hand, the cross-sectional areas of the tubes and their weights, respectively, are comparable. On the other hand, the polar section modulus calculated according to equation 1 is more than doubled for the larger tube diameter and increased by a factor of four compared to the reference setup 1. Aiming for higher load bearing capabilities, setup 3 is favorable with respect to weight saving aspects. Furthermore, the high speed forming process of the thicker tube in setup 2 would require a comparatively high magnetic pressure which would have negative influence on the lifetime of the tool coils.

Table 1. Characteristic values for different outer tube geometries.

	Outer tube diameter D_e (mm)	Tube wall thickness (mm)	Inner tube diameter D_i (mm)	Polar section modulus Z_p^a (mm ³)	Cross-sectional area (mm ²)
Setup 1 [8]	40	2	36	4,322	239
Setup 2	40	4	32	7,419	452
Setup 3	80	2	76	18,648	490

$$^a Z_p = \frac{\pi(D_e^4 - D_i^4)}{16D_e} \quad (1)$$

In this paper, the process adjustment for MPW of aluminum tubes with an outer diameter of 80 mm on steel parent parts is described. Previously developed methods [9] are applied to adjust the diameter of the non-contoured parent parts and axial position of the flyer tube in the working coil in order to ensure suitable collision conditions within the welding window. Finally, the welding interface is analyzed in detail.

2. Experimental setups and materials

2.1. Joining setup

The principal joining setup and the geometrical definitions are depicted in figure 1. The chemical compositions of the materials are given in table 2, while table 3 lists the specific geometries and characteristics of the deployed pulse generators for both setups. The quasistatic yield strength of the aluminum alloy was determined in tube tensile tests with approximately 222 MPa. During the joining experiments the joining partners were positioned coaxially inside a single turn tool coil made of CuCr1Zr. When the capacitor of the pulse generator is discharged via the tool coil in a damped, sinusoidal current (see exemplary course in figure 2), the magnetic pressure accelerates the flyer radially. After the joining standoff g the flyer collides with the polished parent surface ($R_a < 1 \mu\text{m}$). A weld seam is generated, if the impact velocity and the collision angle are in a proper range, called “welding window”. The joining standoff g , the charging energy and the working length l_w are key parameters to ensure these favorable collision conditions and have to be adjusted carefully. [9]

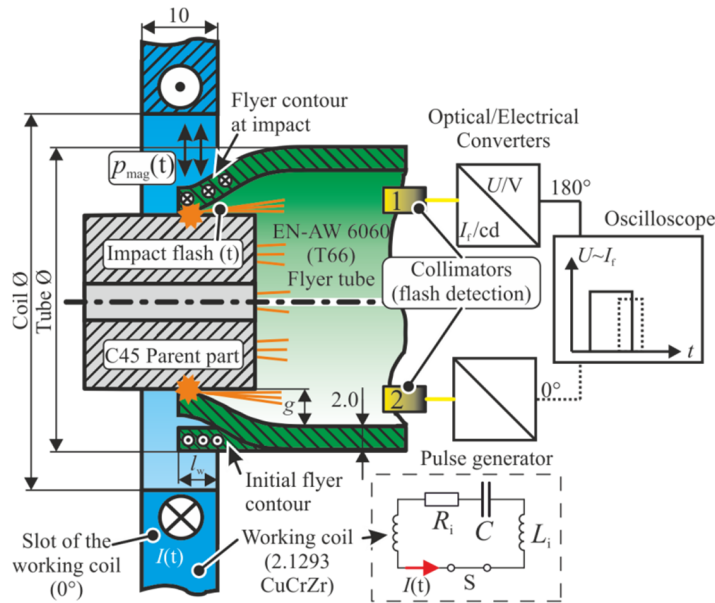


Figure 1. Geometrical definitions of the joining setup and measurement system for flash detection (not true to scale, all values in mm).

Table 2. Aluminum EN AW-6060 alloy composition [10] and steel C45 (1.0503) alloy composition [11].

Flyer part EN AW-6060, T66		Parent part C45 (1.0503), normalized	
Element	Weight %	Element	Weight %
Mg	0.35-0.6	C	0.42-0.5
Mn	≤0.1	Mn	0.5-0.8
Fe	0.1-0.3	P	<0.045
Si	0.3-0.6	S	<0.045
Cu	≤0.1	Si	<0.4
Zn	≤0.15	Ni	<0.4
Cr	≤0.05	Cr	<0.4
Ti	≤0.1	Mo	<0.1

Table 3. Characteristics of the deployed pulse generators for the complete RLC-circuit with working coil and workpieces.

	Setup 1 [8]	Setup 3
Machine	Bmax MPW50/25	EmGen5
Coil diameter (mm)	41	81
Outer tube diameter (mm)	40	80
Tube wall thickness (mm)	2	2
Max. discharge energy $E_{\max}$ (kJ)	32	160
Max. discharge voltage $U_{\max}$ (kV)	20	24
Capacitance C_i (μF)	160	560
Inductance L (nH)	372	111
Discharge frequency f (kHz)	approx. 21	approx. 25
Damping coefficient γ (s ⁻¹)	16,500	8,500

2.2. Measurement devices

High speed collisions between metals are accompanied by so called impact flashes, as reported in [12, 13]. The evaluation of the time depended light intensity can be utilized to study and adjust collision welding processes like MPW [9, 14–16]. Therefore, collimators are positioned at different azimuthal locations as depicted in figure 1. The light intensities at these positions are recorded with the device described in [15] and can be plotted over time together with the tool coil current, exemplary shown in figure 2. The maximum intensity and the flash appearance time $t_{f,start}$ are key values for process analysis and optimization. Since a circumferential weld is required, special attention was paid to the position of the coil's slot (0° in figure 1), where the magnetic field intensity is reduced. The coil current $I(t)$ was measured by Rogowski current probes CWR 3000 B from Power Electronic Measurements Ltd.

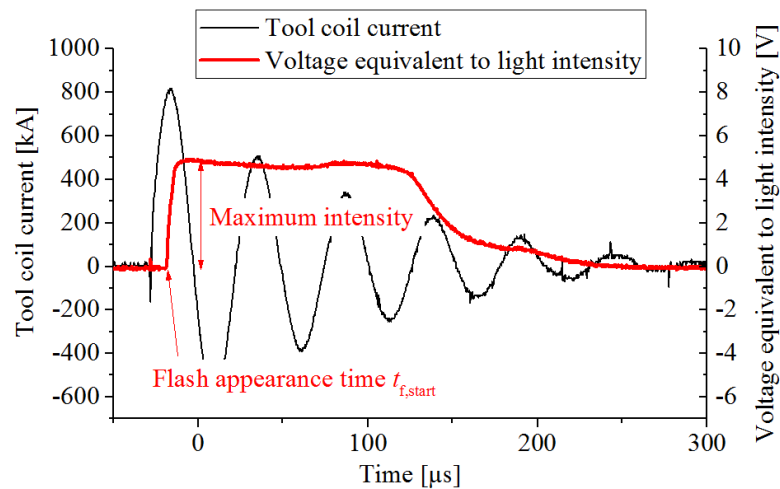


Figure 2. Tool coil current and light intensity over time for MPW experiment with 18 kJ charging energy.

2.3. Process adjustment and peel testing

The joining standoff g , the charging energy and the working length l_w in the MPW setup were adjusted using the method presented in [9] while the intensity of the impact flash served as a welding criterion. During this process adjustment, the circumferential weld quality was checked by a manual peel test, as described in [14].

2.4. Metallographic and metallurgical analysis

Weld seams formed during high-speed collisions are of special interest from the metallurgical point of view since the prevalent pressures, temperatures and process durations differ significantly from conventional fusion welding processes. In order to correlate the influence of certain collision conditions with the morphology of the interface, metallographic investigations were performed on cross-sections polishes. The weld seam length and the shape of the interfacial waves are schematically depicted in figure 3 and were compared for both welding setups. Furthermore, the deformations of both joining partners were determined. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) were applied to identify the element distribution perpendicular to the weld interface.

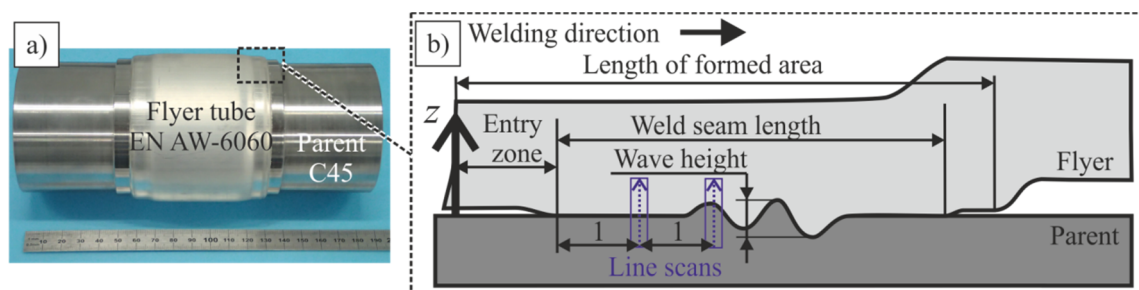


Figure 3. a) Joined sample with location of the cross section, b) schematic cross section with characteristic values of the weld seam.

2.5. Torsion testing

Samples for torsion testing were manufactured with the identified welding parameters, see figure 3a). The two weld seams between the aluminum tube and the steel rods were manufactured successively. Compared to real driveshafts, the length of the outer tube was reduced to 70 mm in order to avoid buckling and to assure the ability to test the weld seam itself. A servo-hydraulic axial-torsional testing machine from Inova was used for the torsion tests. The axial force in the samples was controlled to zero during all tests. For quasistatic testing, a constant angular velocity of 10° / minute was applied while the torque was measured. The cyclic testing was performed according to DIN 50100:2016-12 by using an alternating torque (stress ratio $R = -1$), a constant load amplitude, 20 Hz test frequency and a maximum number of two million load cycles as truncation criterion [17]. The so called staircase test method was applied to evaluate the torque amplitude with 50 % failure probability. The tests were aborted and the samples were classified as failed, if the angle amplitude overstepped the initial value by more than 10 %. Additionally, the aluminum's outer surface in the joining zone of each sample was analyzed in detail with optical microscopy and dye penetrant testing in order to identify any cracks.

3. Results and discussion

3.1. MPW experiments

The MPW experiments were divided into two parts. First, simplified parts were joined in order to identify suitable combinations of the joining standoff g , the charging energy and the working length l_w in the MPW setup depicted in figure 1. The maximum light intensities detected by the optical sensors at the positions 0° (slot of the working coil) and 180° served as necessary criterions for the tuning of the charging energy and the joining standoff g . Then, the collision angle needed for a proper weld formation was adjusted by the working length l_w . The details of the procedure for process parameter identification are described [9] and the results are compared to the initial setup 1 in table 4.

Table 4. Experimental data for both joining setups.

	Setup 1	Setup 3
Machine	Bmax MPW50/25	EmGen5
Outer tube diameter (mm)	40	80
Tube wall thickness (mm)	2	2
Joining standoff g (mm)	1.5	1
Working length l_w (mm)	6	6
Charging energy (kJ)	8	18
Maximum tool coil current (kA)	499±5 (12 tests)	507±1 (4 tests)
Flash appearance time (μ s)	10.49±0.57 (12 tests)	8.88±0.20 (12 tests)
Calculated impact velocity ^a (m/s)	300	239

^a Based on a steady acceleration and 0.5 μ s delay between collision and mean flash appearance time [18].

In the second step, generic hybrid driveshafts were produced as demo parts and were partly cut for metallographic analysis, see figure 4. Samples for torsion testing were joined with the same MPW parameters, but consisted of 70 mm long aluminum tubes to avoid buckling during the static tests.

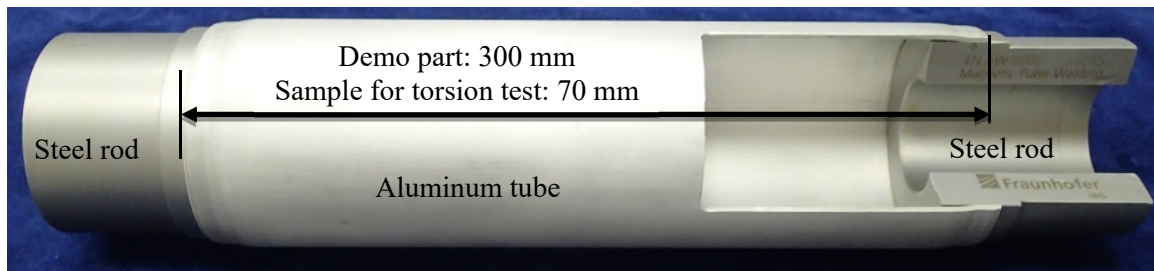
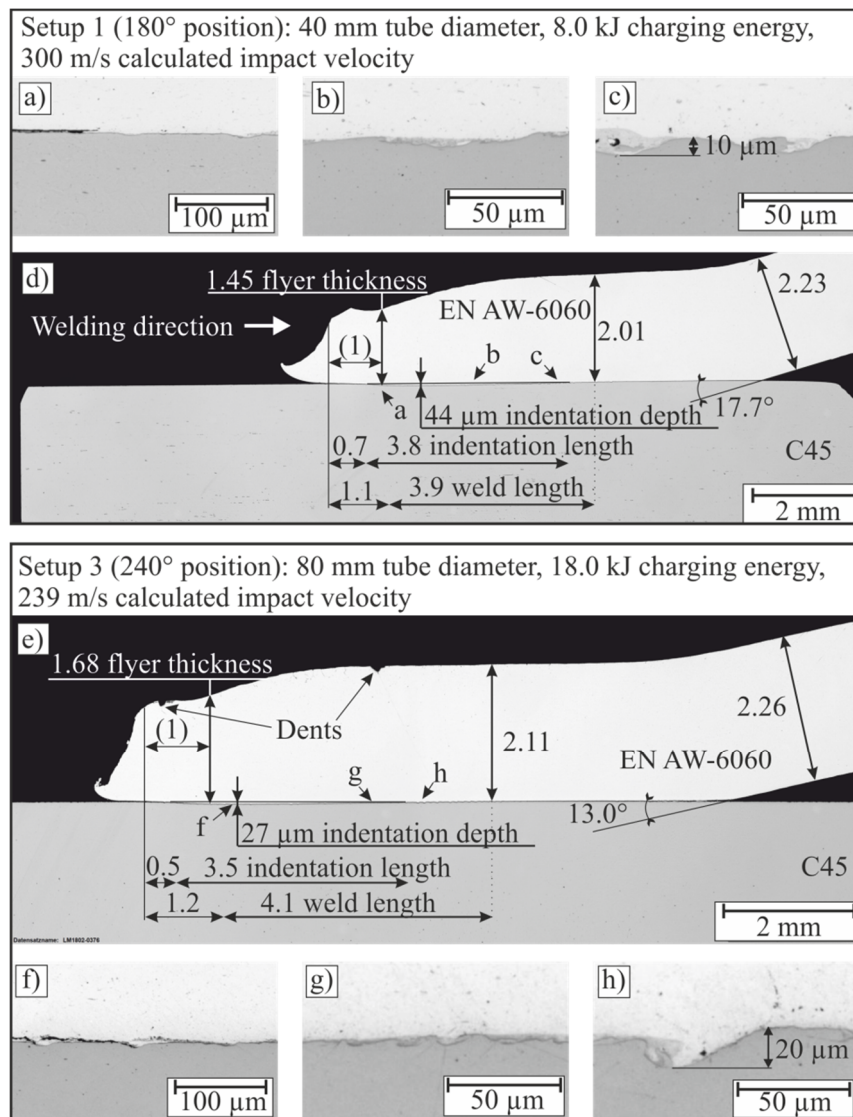


Figure 4. Driveshaft dummy, partly cut to reveal the joining zone.

3.2. Metallographic analysis

Cross-section polishes of the welding interface were prepared at different locations and optical microscopy was performed to study the morphology of the weld seam. Figure 5 compares the global and local deformation of both joining partners for the reference setup 1 with the actual setup 3.



The charging energy was significantly increased in setup 3 since the tube diameter and the accelerated material volume, respectively, were doubled. Assuming uniform flyer acceleration, the flash appearance times and corresponding joining standoffs g allows for the calculation of the impact velocities to be 300 m/s for setup 1 and 239 m/s for setup 3. The reduction of the kinetic flyer energy at the time of impact did not affect the weld seam length. It corresponds to the decreased indentation depth of the flyer into the parent material and a higher flyer wall thickness very well, especially at the indicated position 1 mm behind the free flyer edge. The final angle between parent and flyer surface was measured and it decreased significantly from 17.7° (figure 5 d) to 13.0° (figure 5 e). It is assumed that the reduced joining standoff g leads to a smaller collision angle and a higher collision front velocity in welding direction, respectively. From explosive welding experiments it is known that this leads to higher temperatures in the joining gap [19] and wave heights [20], especially at the end of the joining zone. Dents are visible at the outer flyer surface at setup 3. A structure, which is typical for melted and solidified material is indicated in figure 6. A possible explanation for the extensive heating during the high speed forming process might be the energy input to the outer flyer surface subjected to joule heating. It is increased for the MPW setup 3, since its damping factor is smaller compared to setup 1, see table 3.

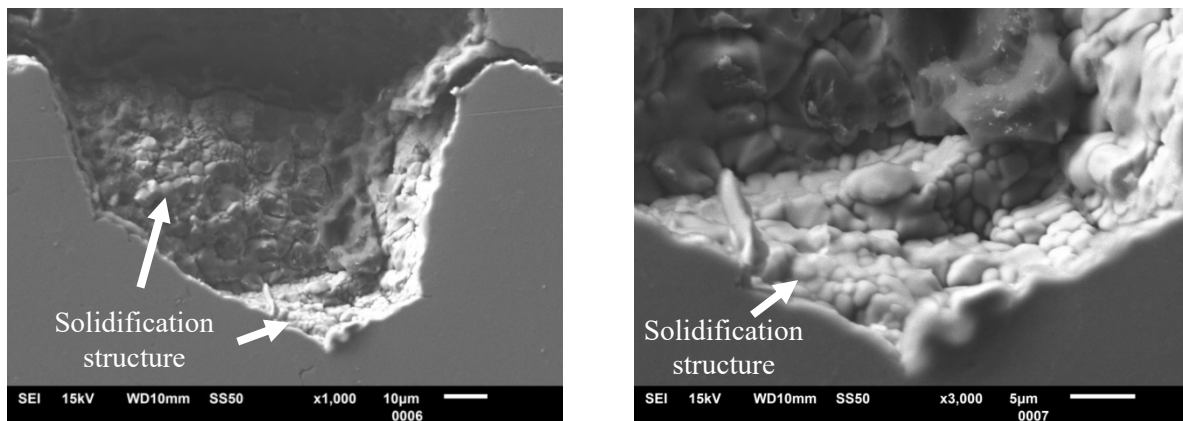


Figure 6. Secondary electron images of the solidified material in the dent at the outer flyer surface in figure 5 e) at two different magnifications.

The morphology of the wavy interface changes in welding direction as shown in figure 5. The height of the waves increases and, simultaneously, the mixed zones at the transition from steel to aluminum are extended. Figure 7 indicates the locations of ten parallel line scans for EDS-analysis one millimeter behind the weld seam beginning. The obtained average is plotted in figure 8 and exhibits a zone with a roughly linear transition between the two elements for $0 \mu\text{m} < z < 1 \mu\text{m}$. The linear transition might be attributed to the activation volume during EDS measurements and needs not inevitably reflect the real element distribution within this narrow zone. The element distribution for $z > 1 \mu\text{m}$ is assumed to be a real effect, since it also occurs distinctly at other locations along the weld front propagation. Figure 9 was taken two millimeters behind the weld seam beginning and includes ten line scans, averaged in figure 10. Here, the major part of the roughly $5 \mu\text{m}$ thick transition zone shows an almost homogenous distribution and consists of approx. 90 atomic percent aluminum and 10 atomic percent iron. A similar ratio was found in a previous study for MPW of aluminum and steel, where the effect of reactive interlayers was investigated [21]. At faraway positions from the initial impact point, the jetting effect acts on the surfaces over a longer time before they get in contact. Thus, it can be assumed that the introduced energy and the resulting surfaces temperatures are higher. Consequently, more material is involved in exothermic reactions that occur at the interface and the transition zone is enlarged compared to figure 7.

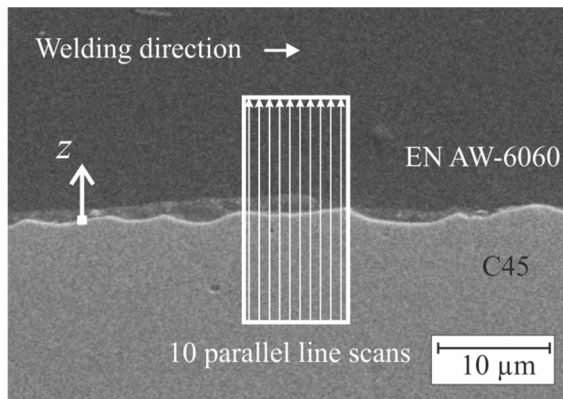


Figure 7. Secondary electron image of the interface 1 mm behind weld seam beginning.

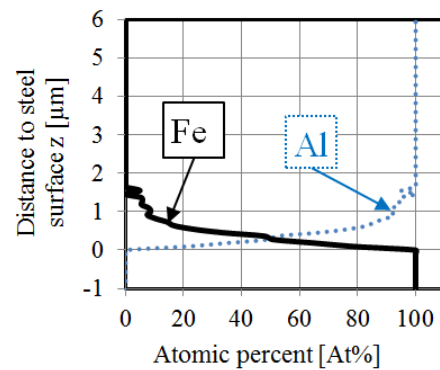


Figure 8. Average element distribution from 10 line scans in figure 7 perpendicular to the steel surface.

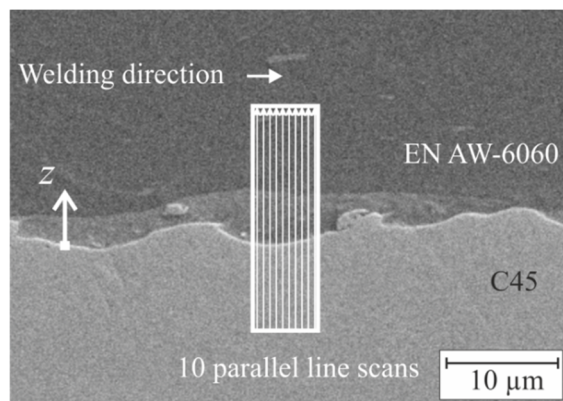


Figure 9. Secondary electron image of the interface 2 mm behind weld seam beginning.

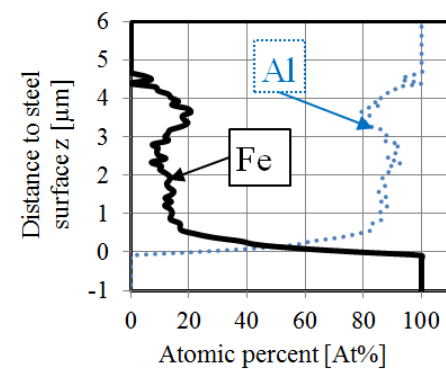


Figure 10. Average element distribution from 10 line scans in figure 9 perpendicular to the steel surface.

3.3. Torsion testing

Table 5 lists the results of the static and cyclic torsion tests with the parameters described in chapter 2.5. Although statistical evidence in support of the results is not provided by the small sample number, clear tendencies can be derived. For both loading conditions, the maximum torque or torque amplitude until failure, respectively, was four times higher for the setup with 80 millimeter tube diameter. This result was expected since the same tube material was used in both setups, but the polar section modulus Z_p of setup 3 was four times higher, see table 1. During the quasistatic tests, no buckling occurred and all samples failed by a circumferential rupture in the tube's base material next to the weld. Cyclic loading lead to crack initiation in the aluminum tube at the tapered area next to the weld seam and crack growing was detected in both axial orientations. Once the crack reached the welded zone, the propagation direction became radial, leading to a circumferential rupture next to the weld seam.

Finally, the maximum static torque is divided by the cross-sectional area of the tube, which is proportional to its weight, see table 5. This specific value is doubled for setup 3 compared to setup 1, which is a clear improvement in the design from a lightweight point of view.

Table 5. Comparison of the static and cyclic torsional load bearing capabilities of magnetic pulse welded drive shaft dummies in two different joining setups.

	Setup 1	Setup 3
Outer tube diameter D_e (mm)	40	80
Tube wall thickness (mm)	2	2
Polar section modulus Z_p (mm ³)	4322	18,648
Cross-sectional area (mm ²)	239	490
Static tests: average maximum static torque (Nm) (3 samples)	755±2	3,181±12
Cyclic tests: torque amplitude for 50 % failure probability (Nm) (6 samples)	124±8	510±14
Maximum static torque per cross-sectional area (Nm/mm ²)	3.16	6.49

4. Conclusion

The aim of the study was to increase the torsional load bearing capabilities of hybrid drive shafts consisting of aluminum tubes and steel rods, which are joined by MPW. To reach this goal, the tube diameter was doubled, while the material and tube wall thickness were kept equal. Adjusting the joining standoff, charging energy and working length was realized by using the impact flash intensity as a necessary welding criterion according to [9]. Aluminum tubes (EN AW-6060 T66) with an outer diameter of 80 mm were successfully welded with non-contoured steel parent parts (C45) at the lower process boundary. An impact velocity of approx. 239 m/s was sufficient to establish a four millimeter long circumferential weld seam. The impact velocity of the flyer was decreased compared to previous joining setups, which is reflected in the reduced global plastic deformation of both joining partners. Interestingly, the height of the characteristic interfacial waves increased. It is assumed that the reduction of the joining standoff and the collision angle, respectively, lead to an increased collision front velocity and thus, higher temperature in the joining gap [19], which allows for increased local deformations. EDS line scans perpendicular to the weld interface revealed a transition zone with an almost homogenous element distribution of 90 atomic percent aluminum and 10 atomic percent iron. Depending on the distance to the start of the weld seam, they differ with respect to their width. The mechanical performance of the generic drive shafts was proved in quasistatic and cyclic torsion tests and found to be on a four times higher level compared to the reference setup.

Acknowledgments

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