Effects of Surface Coatings on the Joint Formation During Magnetic Pulse Welding in Tube-to-Cylinder Configuration

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Abstract

Magnetic Pulse Welding (MPW) is a joining technique favorable for the generation of strong atomic bonded areas between different metals, e.g. aluminum and steel. Brittle intermetallic phases can be avoided due to the high-speed collision and the absence of external heat. The demand for the use of this technique in industries like automotive and plant engineering rises. However, workpieces used in these fields are often coated, e.g. in order to improve the corrosion resistance. Since the weld quality depends on the material's behavior at the collision zone, surface layers in that region have to be taken into account as well.

This work investigates the influences of different coating types. Aluminum to steel welding is used as an example system. On the inner steel part (C45) coatings like zinc, nickel and chrome are applied, while the aluminum flyer tubes (EN AW-6060) are anodized, chromated and passivated. Welding tests are performed using two different welding systems with varying discharging frequencies and four geometrical part setups. For all combinations, the flyer velocity during the process is measured by Photon Doppler Velocimetry (PDV). By using the uncoated material combination as a reference, the removal of surface layers due to jetting is analyzed. Finally, the weld quality is characterized in peel tests, shear-push tests and by the help of metallographic analysis. It is found that certain coatings improve the joint formation, while others are obstructive for the performance of MPW. Some coatings have no influence on the joining process at all.

Keywords

Joining, Welding, Magnetic pulse welding

1 Introduction

The production of modern lightweight designs often requires the use of different materials to fulfil the criteria regarding strength, weight reduction and crash performance. Besides the development of new materials, it is also of great importance to employ suitable joining technologies. Magnetic Pulse Welding (MPW) has a great potential for large-scale industrial production, since it is an efficient, clean, and fast process. It generates strong atomic bonding between two different materials like steel and aluminum without the formation of critical intermetallic phases. **Figure 1** shows the MPW-process for cylindrical parts in three steps. At first, the aluminum flyer tube and the steel parent part are placed into the tool coil (a). Through the discharging of high voltage capacitors through the coil, the resulting current generates a strong magnetic pressure p_{mag} between the flyer tube and the inner side of the coil that consequently accelerates the tube towards the parent part until they collide (b). For certain favorable radial impact velocities v_r and angles β between both parts at the collision line that travels with the axial velocity v_c, a so called jet is formed. This mass flux contains oxides and surface debris of both joining partners and leaves two juvenile and activated surfaces. Under the high impact pressure welding takes place (c) (Deribas et al., 1975).

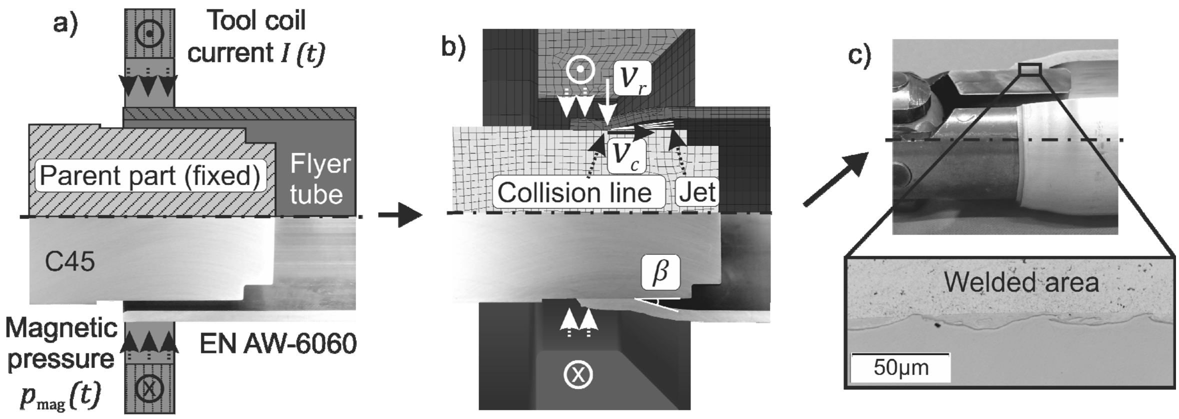


***Figure 1**: Magnetic Pulse Welding of cylindrical parts with a) positioning of flyer tube and parent part in the tool coil, b) forming and joining process, c) macroscopic and microscopic view on the cross section of the welded area*

Welding windows show radial impact velocities v_r and angles β that will lead to a welded area (Kapil and Sharma, 2015). This data can be evaluated experimentally or with the help of high velocity impact simulations, as e.g. Cuq-Lelandais et al. (2014) showed. They are valid for the base materials and in most cases do not take surface coatings into consideration. Coatings that are used to improve corrosion resistance or to reduce wear are typically applied on the semi-finished part. This means, every following production step has to cope with these additional layers. Especially in large-scale production, where MPW is nowadays a viable option, an extra process to remove the coating at the joining zone would increase the effort and costs.

The idea of this investigation is to gain an insight which typical industrial coatings are favorable or unfavorable for MPW weld quality. Assuming that other non-fusion welding techniques are influenced likewise, a short literature review is carried out first and reveals three types of interaction between the coatings and the joining partners:

I. Brittle surface coatings: Under high deformation, the layer fractures and the underlying surfaces are welded together due to the high pressure (e.g. Cold roll welding: Zhang and Bay, 1997). A direct welding on these coatings is also possible, but the coating can delaminate (Schäfer et al., 2011).

II. Thick and ductile layers: The layer absorbs a significant portion of the kinetic energy from the flyer during collision (e.g. Explosion welding (EXW): Manikandan et al., 2008).

III. Thin and ductile layers: Although not discussed in literature, thin layers (e.g. only few µm) would still retain chemical features but should probably influence the deformation behavior or the welding process much less than type II.

This paper aims at all three types and will expand the knowledge regarding compatibility of MPW with different coatings as well as the behavior of these surface layers within the process. Therefore, representative industrial coatings are chosen for both joining partners. Additionally, the influence of the pulse generator's discharge frequency is investigated for all coatings listed in **Table 1**.

Type	Flyer	Parent part
I. Brittle	Anodized, hard anodized	Zinc, nitrated
II. Thick, ductile	-	Nickel
III. Thin, ductile	Acid passivated, chromated	Nickel, chrome

***Table 1**: Typical coatings for flyer and parent part investigated in the present study*

2 Experimental Design

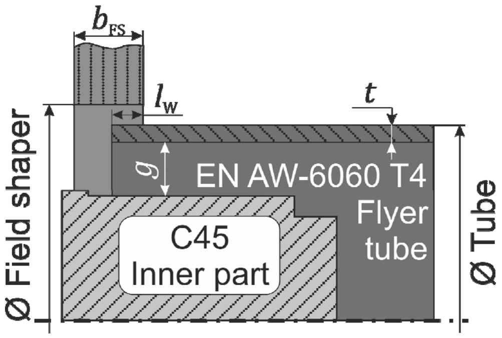
2.1 Joining Materials and Tools

The experimental investigation of the effect of different surface coatings on the pulse welding process is carried out on two pulse stations as shown in **Table 2.**

Setup	High Frequency	Low Frequency	Unit
Pulse generator	Bmax MPW50/25	Maxwell-Magneform 7000	-
Capacity	160	362	µF
Maximum charging energy – E	32	12	kJ
Discharge frequency with coil and workpieces - $f_{\text{discharge}}$	20	7	kHz
Coil design	Single turn	8-turn with field shaper	-
Ø Field shaper (see Table 3)	42	41	mm

***Table 2**: Comparison of the pulse generators and tool coils*

The experimental setup is depicted in **Table 3**: the width of the field shaper, the working length and the outer diameter of the tube are fixed for all experiments. Varying parameters are the flyer thickness which is changed from $t = 1.5$ mm to $t = 2.0$ mm after half of the experiments, and the gap size g which is set to 1.5 mm and 2.0 mm for both thicknesses. Since the gap is equivalent to the acceleration distance of the flyer, a value of 2.0 mm will lead to higher impact velocities than $g = 1.5$ mm. Furthermore, the collision angle β will decrease with a smaller gap.



Definition	Applied values [mm]
Width field shaper - b_{FS}	10.0
Working length - l_W	6.0
Ø Tube	40.0
Gap – g (with corres-ponding Energy E)	1.5 (10.2 kJ); 2.0 (9.6 kJ)
Thickness - t	1.5; 2.0

***Table 3**: Geometrical definitions in the experimental setup*

Based on the descriptions given in the introduction, **Table 4** exemplifies the surface coatings that were applied either on the outside of the parent part or on the inside of the flyer tube. To limit the number of surface combinations, all coated flyer tubes are joined to the as-received conditioned steel parts and the as-received aluminum tubes to the coated steel parts. The aim of the acid passivation is to reduce the native oxide layer on the aluminum and preserve this condition with a special passivation until it is joined in the MPW process. The objective is to extend the welded length compared to Al-Pure.

Parent part – C45 (St)		**Flyer tube – EN AW-6060 (Al)**	
C45, normalized, surface polished (Ra = 1)		EN AW-6060, T66, heat treated (one hour at 500°C)	
Property	**Name**	**Property**	**Name**
As-received condition	St-Pure	As-received condition	Al-Pure
Electroplating nickel 5 µm	St-Ni5	Anodized 5 µm	Al-An5
Electroplating zinc 5 µm	St-Zn5	Anodized 10 µm	Al-An10
Electroplating zinc 10 µm	St-Zn10	Hard anodized 15 µm	Al-HAn15
PVD nickel vanadium 2.5 µm	St-PVD Ni2.5	Chromated	Al-Cr
PVD chrome 1.5 µm	St-PVD Cr1.5	Acid passivated	Al-AP
Nitrated	St-N		

***Table 4**: Explanation of surface coatings for steel and aluminum*

2.2 Experiment and Evaluation

Every uncoated part is cleaned in acetone to remove passivation oils and dirt before each welding experiment. Afterwards, both parts are positioned and fixed as indicated in Table 3 and the energy level is set to 10.2 kJ for a gap of 1.5 mm and 9.6 kJ for 2.0 mm, since these are the minimum values to achieve welding at the Maxwell pulse generator. These energy levels are also set at the Bmax pulse generator to guarantee comparability.

The radial deformation velocity of the tube is measured with the PDV-system in the opposite direction of the field shaper's slot with an axial offset of 1.0 mm to the deformed edge of the flyer tube (Jäger and Tekkaya, 2012). After the joining process, flyers are cut once in axial direction to release the compressed tube. If it separates from the parent part during this procedure, the welding has not been successful. In the other case, the samples undergo further mechanical testing as suggested by Shribman (2006) in **Figure 2**. For the tests, stripes with a width of 5.0 (±1.0) mm are cut from the cylindrical part.

With the help of a peel test it is possible to identify the axial position x, where the weld strength is higher than the strength of the base material aluminum and fracture occurs. This value can be interpreted as weld quality along the welding front. The peel test is performed at four positions to the field shaper's slot: 45°, 135°, 225° and 315°. If the samples are not welded or fail during preparation, the value is defined to be zero.

The shear test reveals the shear strength of the welded area A and takes the mechanical properties of the surface coating between both parts into consideration. After the shear test the area A is measured and divided by the applied force F_{max} which gives the shear strength. This is done at four positions in relation to the field shaper's slot: 0°, 90°, 180° and 270°. In addition metallographic analysis is performed on selected samples to identify the location and length of the welded areas. Therefore polished cross sections are prepared for the 90°-position to the field shaper's slot on samples that were not used for the shear test.

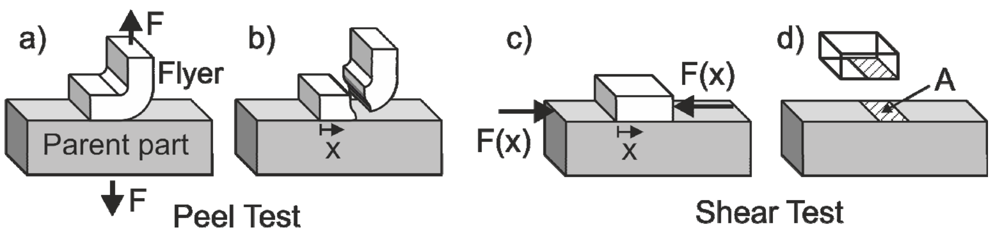


***Figure 2**: Mechanical testing methods for MPW-samples a) during and b) after peel test and c) during and d) after shear test*

3 Results

3.1 Experimental Results

The deforming behavior of the flyer tube strongly depends on the discharging frequencies of the electrical circuits and thus the pulse generators. If the charging energy is the same, it is obvious that a higher discharging frequency leads to higher flyer accelerations, earlier collisions and higher impact velocities. **Figure 3** shows these effects based on the measured velocities and collision times for all four geometrical combinations of the uncoated aluminum tubes. Furthermore, a gap of 2.0 mm leads to higher impact velocities compared to 1.5 mm since the acceleration distance is longer. The wall thicknesses have only a small influence on the impact velocity, since the difference between the rigidity of the tube walls is small compared to the magnetic pressure. It was also found that the coatings on the aluminum tube do not affect the acceleration behavior, which is an important requirement for the comparison of the experiments. Using the uncoated parts as references, welding with the same energy was achievable at both discharging frequencies for nickel- and chrome-plated steel parts as well as acid passivated and chromated aluminum tubes. Nitrated and electroplated zinc steel parts and nearly all kinds of anodized tubes were not weldable with the chosen parameters. Within this study, welding of anodized aluminum was only possible for a wall thickness of 1.5 mm with high impact velocities and gaps of 1.5 or 2.0 mm.

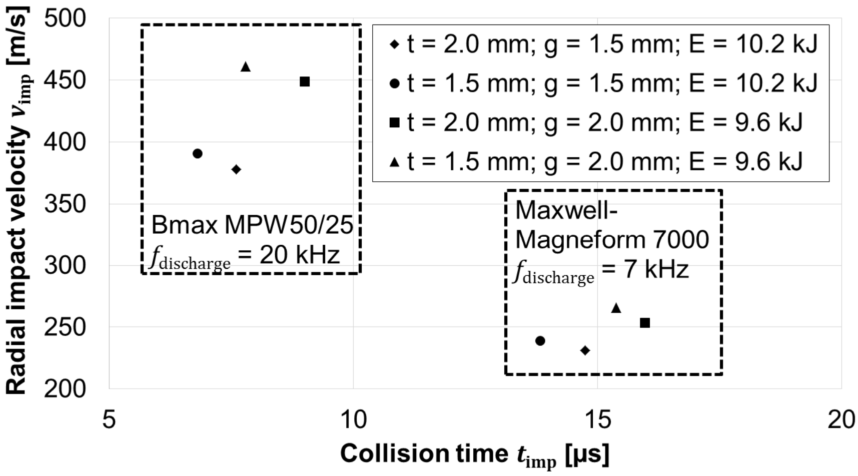


***Figure 3**: Radial impact velocities and collision times for 4 experimental setups and two MPW-machines*

The results of the mechanical testing and the metallographic analysis of the welded samples with a wall thickness t = 1.5 mm and a gap of g = 1.5 mm are plotted in **Figure 4**. The horizontal bars show the position and length of the welded zones in relation to the flyer edges optically measured in the cross section. Furthermore, the failure positions in the base material aluminum during the peel tests are plotted with quadrangles and the corresponding standard deviation. If the standard deviation exceeds the welded area, at least one peel test failed in the weld and not in the base material. Using the uncoated sample as a basis, it can be observed for the coatings in Figure 4 that:

1. **Electroplated nickel clearly enlarges the welded zone**. Due to the deformation of the flyer edge it is possible that welding starts 0.3 mm before the reference point x = 0 and reaches more than 9.0 mm in length. This phenomenon occurred for all investigated wall thicknesses and gaps.
2. The beginning of the welded zone for anodized parts was shifted to 2.0 mm or more, whereas all other coatings show no difference compared to the uncoated sample.
3. The failure position during peel test was located in the last third of the welding for PVD-chromated cylinders and acid passivated and chromated aluminum tubes under high impact speed as well as electroplated nickel parts at both impact velocities.
4. Welding with lower impact velocities **shifted the failure** position for PVD-chromated parts into the first third of the weld and affected a higher spreading.

5. In case of PVD-nickel-plated steel parts, the lower impact velocity improves the weld quality but shows also a high deviation.
6. 5 µm anodized aluminum was only weldable with high impact speeds. Although a wavy interface was achieved, the preparation for the peel test always destroyed the joined zone, suggesting a **strong detrimental effect of anodization**.

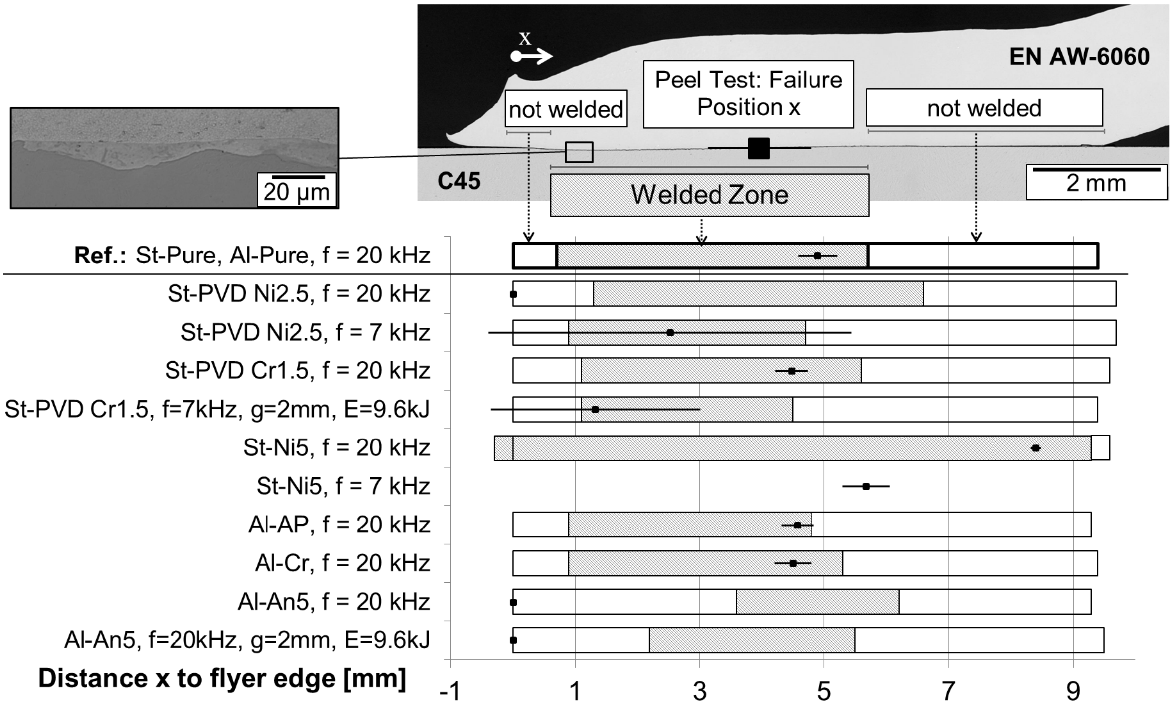


Figure 4: *Welding Results for g = 1.5 mm, t = 1.5 mm and E = 10.2 kJ*

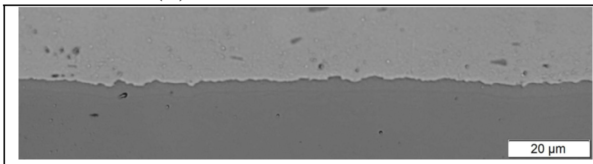
The shear strengths of the welded areas were evaluated for all welded samples with t = 2.0 mm and g = 2.0 mm. Compared to the shear strength of the uncoated sample with 153 MPa, chromated aluminum tubes have an **increased strength** of 162 MPa. St-PVD Cr1.5 at low impact speeds and St-Ni5 at high impact velocities decrease the shear strength to 120 MPa, whereas the other coatings showed almost no difference compared to the uncoated sample.

3.2 Metallographic Results

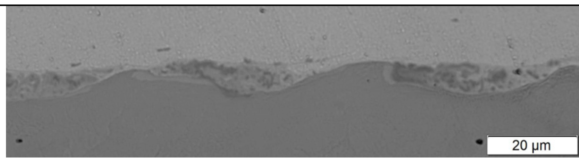
The metallographic study of selected specimens in **Table 5** shows that:

1. There is a noticeable influence of the impact speed on the weld interface. A comparison between the PVD-nickel-plated steel parts suggests that with increased impact velocity (a vs. b), the height of the formed waves increases. The coating is deformed heavily at the wavy interface (b). This can be found with all welded samples except St-Ni5 (d), where the middle section stays smooth.
2. Except for the PVD-chromed (e) and electroplated nickel (c) parts all samples show areas before and after the welded zone that were bonded first and **separated again** during the joining process as the crack propagation and welded fragments on both base materials show (g).

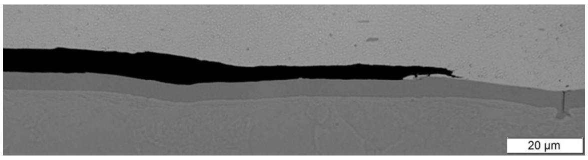
3. The anodized layer of 5 µm is included in the wavy interface in the first half of the welded zone (i). For a welding gap of 1.5 mm it is also embedded until the end of the weld. For a gap of 2.0 mm the layer is completely removed so that the juvenile steel and aluminum surfaces come into contact (j).
4. The nitrated steel's surface fractures at the collision point, is partially removed, but not welded (h).



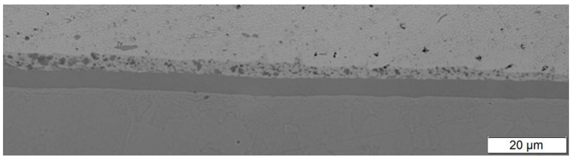
a) St-PVD Ni2.5 (f = 7 kHz): Smooth middle section



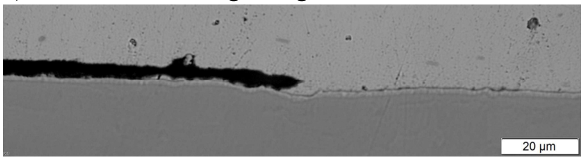
b) St-PVD Ni2.5 (f = 20 kHz): Wavy middle section



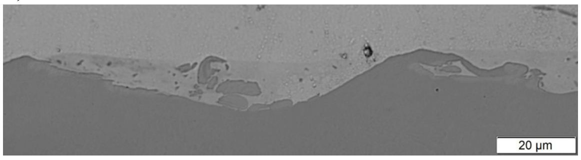
c) St-Ni5: Smooth beginning section



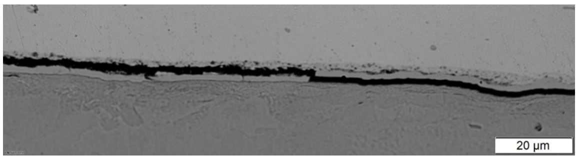
d) St-Ni5: Smooth middle section



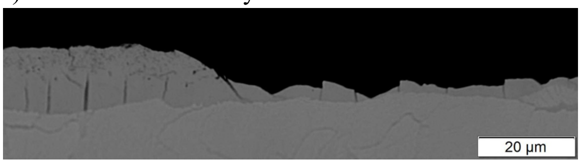
e) St-PVD Cr1.5: Stable beginning section



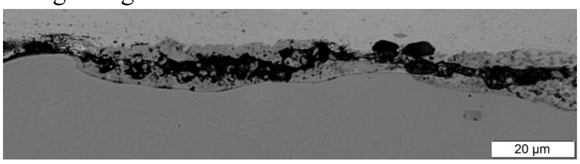
f) St-PVD Cr1.5: Wavy middle section



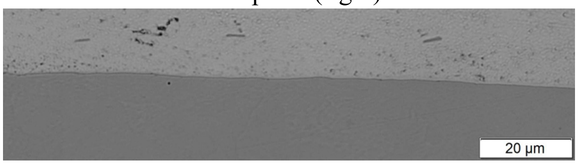
g) St-PVD Ni2.5: Welded, but fractured section at beginning



h) St-N: Nitrated layer: fractured (left) and partly removed at collision point (right)



i) Al-An5 (g = 2.0 mm, E = 9.2 kJ): Wavy section at beginning with embedded anodized layer



j) Al-An5 (g = 2.0 mm, E = 9.2 kJ): Smooth middle section without anodized layer

Table 5: *Polished cross sections of selected samples with* $g = 1.5$ *mm,* $t = 1.5$ *mm,* $E = 10.2$ *kJ,* $f = 20$ *kHz, welding direction: left to right, scale bar length = 20 µm*

4 Discussion

Based on the metallographic observations and the models presented in the introduction it can be predicted that:

1. Brittle surface coatings ("Type I") on the flyer tube can strongly be fragmented by the deformation. In the first part of the joining zone, they are embedded in the weld interface which is bad for welding. Using larger collision angles respectively larger gaps of 2.0 to 2.5 mm helps to remove the fragments by the jet and enables the welding of anodized parts with a layer thickness of 5 µm. Anodization layers of more than 10 µm are not removable by the jet in the given configuration. Brittle coatings on the parent part are

only partly fragmented or delaminated, but not removed by the jet completely. They are unfavorable for the MPW-process in the given configuration.

2. Thick and ductile layers like 5 µm electroplated nickel, ("Type II") seem to absorb a part of the collision energy as described in certain EXW-articles, e.g. by Manikandan et al. (2008). Probably, they also increase the diffusivity. While the uncoated sample shows welding and waves, coated samples show no waves at the same collision conditions. Increasing the impact velocity brings the wave formation back.
   The layer can be used to generate longer weld seams with the same amount of energy. Due to the partial absorption of the collision energy, the elastic forces of the compressed tube are reduced. Thus, internal disruptions ("spallation") that are common in uncoated samples before and after the final weld seam can be avoided with this coating.
3. Thin and ductile surface layers ("Type III") on the parent part are hard to remove by the jet due to the smaller global deformation compared to the flyer tube. It can be stated that ductile and deformable coatings like nickel or PVD-chrome can be embedded in the weld interface without deterioration of the weld quality.
4. The measured impact velocities for discharging frequencies of 20 kHz are approximately 460 m/s, whereas the flyer part in the MPW-setup with the bigger current rise time reaches an impact speed of only 270 m/s. Using the welding window from Cuq-Lelandais (2014) in the v_r-β-plane, it can be seen that for the same collision angle β, a higher impact speed leads to a wavy interface. Peel and shear tests showed an influence of the surface coating and impact velocity on the joint strength. To study these correlations, further material testing as well as a deeper metallographic analysis is necessary. In general, the welding results are almost independent from the wall thicknesses and gaps, whereas the discharging frequency has a major influence.

5 Conclusion

This paper investigates the influence of the surface coating on the welding result during MPW of tubular parts. Using the same amount of energy, two pulse generators with different discharging frequencies are used to join aluminum flyer tubes (EN AW-6060) on steel cylinders (C45). The difference in the acceleration behavior leads to impact velocities of 230 to 270 m/s for the 7 kHz pulse-station and between 400 and 450 m/s for the 20 kHz pulse-station, depending on the wall thickness and the acceleration gap. Three types of surface coatings are defined and systematically investigated in the MPW process:

I. Brittle surface layers: Anodized layers on the flyer part fracture because of the global deformation, but are detrimental for MPW when they stay in the welding interface. To avoid this, welding parameters like the gap must be adapted. Brittle coatings on the parent part (nitrated or zinc-coated surfaces) are strongly fragmented and delaminate from the parent part's base material, too. Due to the lower global deformation of the parent part, the coatings are difficult to remove and thereby detrimental for MPW. Since these coatings are of great importance in industrial production further investigations especially for zinc are necessary.

II. Thick and ductile layers: 5µm electroplated nickel shows a very good performance during MPW and **can even double the weld length** with the same amount of energy compared to uncoated surfaces. It influences the local deformation behavior due to the kinetic energy loss of the flyer part and reduces wave formation. A wavy interface can be generated with higher impact velocities, but this is not mandatory since the high strength of waveless joints already leads to failure in the base material. A more economic exploitation of the effect would be to reduce the energy in the MPW-process and counteract the decreasing weld length with an interlayer like nickel. Consequently, **pulse generators can be downsized and the tool coils life increased**.

III. Thin and ductile coatings: PVD-nickel, PVD-chrome on the parent part (steel) as well as acid passivated and chromated surfaces on the aluminum tube are deformed and are uncritical for a good welding result.

Acknowledgments

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