Increase of the Reproducibility of Joints Welded with Magnetic Pulse Technology Using Graded Surface Topographies

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Abstract

The reproducibility of individual welding methods depends to large extents on the material properties. This is especially the case for impact welding as tests have shown that the surface properties influence the joint formation. With the aim to influence the formation and position of the lower curve of the welding process window, this paper focuses on how the surface topography influences an asymmetrical impact. Additionally, relevant process parameters (e.g. collision speed, collision angle, jet formation) will be included and disturbance contours that are placed transversely to the collision vector will be examined. A high-speed camera was used to measure the collision speed as well as the collision angle. The specific surface topographies were created using belt grinding (cutting with geometrically undefined edges) and laser ablation (non-cutting process, local vaporization of materials through pulsed laser beams). The tests exemplarily show a strong correlation between the surface geometries and the joint. The disturbance contours that were introduced transversely to the collision vector shift the lower weld seam boundary, whereas a reduction of the discharge energy leads to a relative strength of the joint of 1.0.

In sum, this paper offers fundamental insights into the mechanisms of the joint formation when using magnetic pulse welding and shows the influence of the surface topographies on the conflict between relevant procedural parameters and the possibility to shift the lower procedural window.

Keywords

Surface topography, Lower weld seam boundary, Reproducibility

1 Introduction

1.1 Motivation

Constructions with multi-material-design (mixed materials) have long since been established in production of means for transportation, but especially in the automotive and aerospace industries, as they enable a weight reduction of structures. Here, the joining techniques for the joining of mixed materials are of increasing importance, as they have to meet the current and constantly growing future demands on these structures (for example high rigidity and reduction of weight).

Within the field of linear joining techniques for similar and dissimilar materials (e.g. St/Al or Al/Cu) that can be applied without heat and which are an alternative to adhesive bonding, Magnetic Pulse Welding (MPW) is the only option. With a processing time of under 25 µs, especially in serial productions with thin metal sheets (sheet thickness up to 3 mm), MPW enables the production of coalesced joints of similar and dissimilar materials with low distortion and without filler material. The elliptical weld formation can be realized as a short linear seam (Manogaran et al., 2014) or as a seam with a length of up to 3.000 mm (Schäfer and Pasquale, 2011), (Aizawa et al., 2012). Because of its technological and metallurgical advantages, MPW is especially suited for aluminum-steel-joints, which are increasingly requested.

However, the challenge lies in adapting the process to the specific material and constructional characteristics and design. Thus, in order to receive high-quality joints, the process window should take these characteristics into account and should be expanded if possible. Here, the reproducibility of the procedure plays an important role. Although it has been proven that the procedure is reproducible in (Geyer et al., 2014), as well as (Rebensdorf and Boehm, 2015), some issues still remain and show that especially through the influence of the surface topography, the lower process window can be shifted.

1.2 State of the Art and Aim of the Work

Metal welding processes are classified according to the norm DIN 1910:2008 and organized in higher categories. Thus, MPW belongs into the category of pressure welding processes in which coalescent joints are achieved through the movement of mass.

The physical context for impact welding processes can be explained with the basic mechanisms of explosion welding (EXW), as EXW has comparable impact conditions to MPW. This can also be described as an asymmetrical impact welding process. During the impact, the flyer meets the target with a collision angle of β at the collision point/ stagnation point S. The geometrical relationship of the flyer plate velocity (vp) and the collision angle (ß) results in the collision speed (vc) according to Crossland (1982).

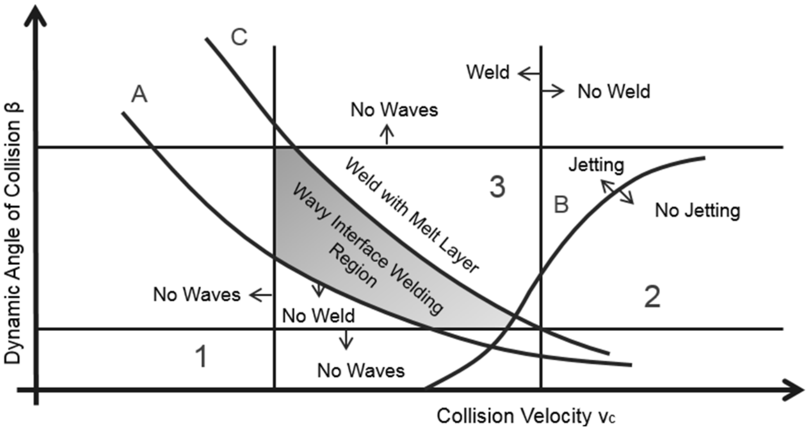

***Figure 1**: General process window for impact welding (experimental investigation of explosion welding) (Crossland, 1982), (Deribas and Zakharenko, 1974), (Walsh et al., 1953), (Mousavi et al., 2013).*

Due to the non-linear behavior of the impact process in MPW, no distinct depiction of the welding process window has been able to established itself. Although similarities to EXW are sought for (Verstraete et al, 2011), the depiction on the β-vc-level is difficult as the angles and velocities vary during impact.

Within the scientific field, there are currently two approaches in dealing with the dependence of the process speed during joint formation in MPW. The first approach assumes that the same procedural limits as for EXW apply in this case too. The second approach, however, presumes that the joint is formed under lower speed and pressure than are known from EXW.

A joint formation using MPW is discussed in (Goebel et al., 2010) in areas of the welding process window in which a joint could not have been formed with EXW. In addition, this publication shows that a joint can be formed with less processing speed than in EXW. In (Goebel et al., 2010), the central element is suggested to be a metastable wave formation process as initiator for the formation of the weld seam, wave initiation in dependence to the Reynold number in (Pai et al., 2013) is also referred to. Göbel et al. prove the difference in the welding process window between MPW and EXW with the help of scientific publications. On the basis of these publications, Göbel et al. assumes that the flyer velocity normal to the target surface is between 30 m/s – 250 m/s. In (Ben-Artzy et al., 2008), however, impact velocities of 250 m/s – 500 m/s were listed from scientific publications and in (Desai et al., 2010) velocities of 400 m/s were presented. These correspond to the velocities of 300 m/s – 650 m/s for EXW as presented in (Goebel et al., 2010) and, therefore, contradict Göbel`s basis of argumentation.

Within the priority program 1640, workgroup 9, of the German Research Foundation (DFG), these theses were taken up and examined. The main focus was on the reproducibility of the Magnetic Pulse Welding technology when the impact is asymmetric and on the influence of the surface topography on the joint formation. Thus, the research focused on specific process variables, collision speed and angle. Here, could be shown the direct effect changes of these variables had on the quality of the weld.

2 Experimental Setup

2.1 Sample Material, Preparation and Testing Methods

To define the real collision speed and angle, a high-speed camera, produced by the company PCO AG, was used. The camera system HSFC-Pro with its four CCD-camera modules allows to take four pictures in 3 ns.

Assumptions were made to define the influencing variables for MPW. The determination of the process velocities was specifically related to the physical conditions for uniformly accelerated motion (formula 1).

$$v_p(t) = \frac{2(s_1 - v_0 t - s_0)}{t} + v_0 \qquad (1)$$

v_P = flyer plate velocity in m/s
v_0 = initial velocity in m/s
s = distance in m
t = time in s

The analytical calculation of the flyer plate velocities results from the geometrical dimensions of the impact conditions and is shown exemplary in figure 2, figure 3 shows the procedure.

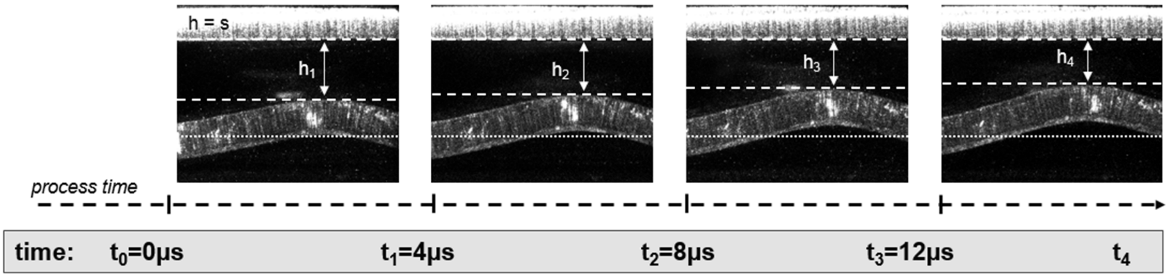

***Figure 2**: Exemplary depiction of the determination of the flyer plate velocities*

The collision angles changed during the process and were evaluated with the help of image correlation (figure 3).

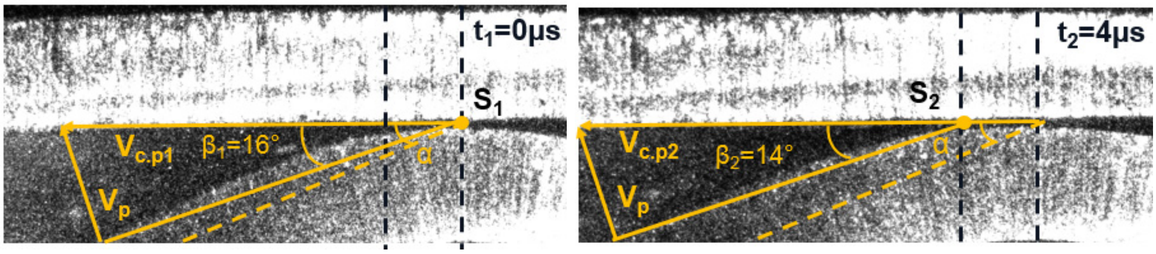

***Figure 3**: Exemplary depiction of the determination of the collision angle*

Subsequently, the calculation of the collision point velocity was done according to Crossland (1982) as follows:

$$V_{cp} = Vp\ \frac{\cos\frac{1}{2}(\beta-\alpha)}{\sin\beta} \tag{2}$$

v_{cp} = collision point velocity in m/s
ß = collision angle
α = set angle before welding

Here, the material combination EN AW-1050 / S235 JR was examined. The aluminum alloy consisted to 99.4% of aluminum and to 0.44% of iron (Fe) as well as to 0.05% of silicon (Si). The mechanical properties included a tensile strength of 109 N/mm² and a yield strength of 102 N/mm². The steel S235JR had, apart from being to 99.3% of iron (Fe), a proportion of 0.22% of manganese. With a yield to tensile ratio of 1.12, the tensile strength was 380 N/mm².

The system BlueWave 48-16 (max. discharge energy of 48 kJ as well as a max. possible impulse of up to 480 kA) with a flat coil of max. 500 kA and web thickness of 10 mm was used for this project (Geyer et al., 2014). For the variation of the parameters, an acceleration distance (s) of 1.0mm to 2.5mm was examined and varied in steps of 0.5 mm. The discharge energy (E) of the capacitors was varied in steps of 2 kJ, ranging from 11 kJ to 17 kJ. To determine the quality of the weld, tensile tests in accordance to the norm DIN EN ISO 14273 were performed. Five welds were examined per test series. The sample dimensions were (100x40x1.5) mm with an overlapping length of 30 mm. The crucial variable for the assessment of the influencing variables was the determined relative strength of the weld (σ) which is based on the dimensions of the weaker material.

Several disturbance variables were taken into account within this research project. For one, the anisotropy of periodic surface irregularities on the flyer, caused by the roller, to the collision vector was varied. Secondly, the kinematic and phenomenological characteristics of the material flow behavior, as caused by disturbance contours that were induced transversely to the welding direction according to (Lysak and Kuzmin, 2012), were also included (figure 4). The roughness on the surface of the target was created with the CleanLaser CL50. Furthermore, laser ablation was performed on the flyer to minimize the influencing variables and the accompanying dispersion.

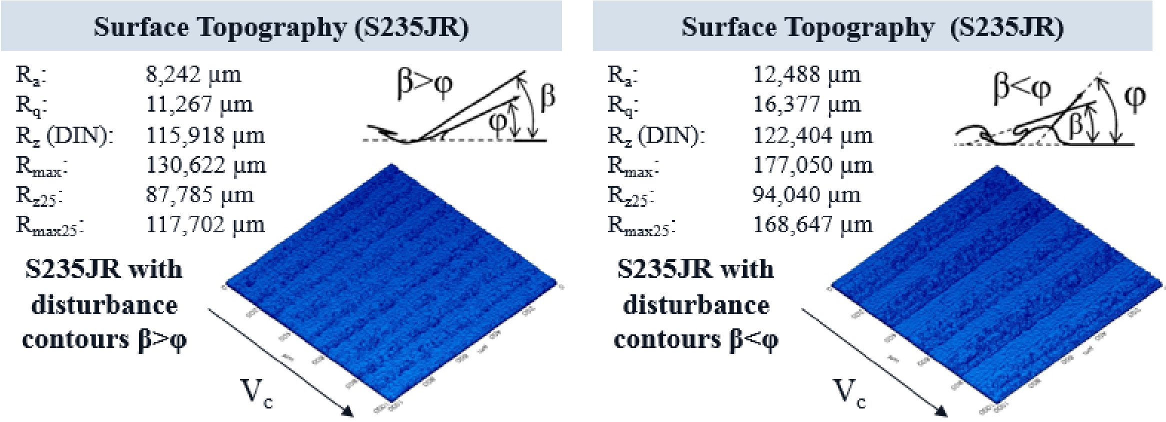

***Figure 4**: Recording of the surface topography, taken with white-light interferometer, MicroProf manufactured by the company Fries Research & Technology GmbH.*

2.2 Magnetic Pulse Welding Process Window

Before examining the processing speed, the influence of the acceleration distance and the discharge energy on the weld was evaluated. Figure 5 (A) shows the results of the direction dependent periodic surface irregularities with 0° (parallel) to the collision vector.

It is striking that when the acceleration distance is 1.0mm and the selected minimal discharge energy is 11kJ, there is a relatively low dispersion of strength. If the acceleration distance is increased to up to 2.5mm, the joint strength decreases. On the other hand, an increase in discharge energy leads to abandonment of the lower welding border.

The acceleration distance of s=1.5mm shows the best results and, thus, the least dispersion, for 11kJ as well as 17kJ.

If the roller direction of the aluminum is changed (90° to the collision vector), the discharge energy of 11kJ is not enough anymore to transgress into the stable process window (figure 5, B).

Even if the energy is increased to 13kJ, an improvement can only be seen at an acceleration distance of s=1.0mm. Within the overall context, an acceleration distance of 1.5mm shows the best results when the discharge energy is varied.

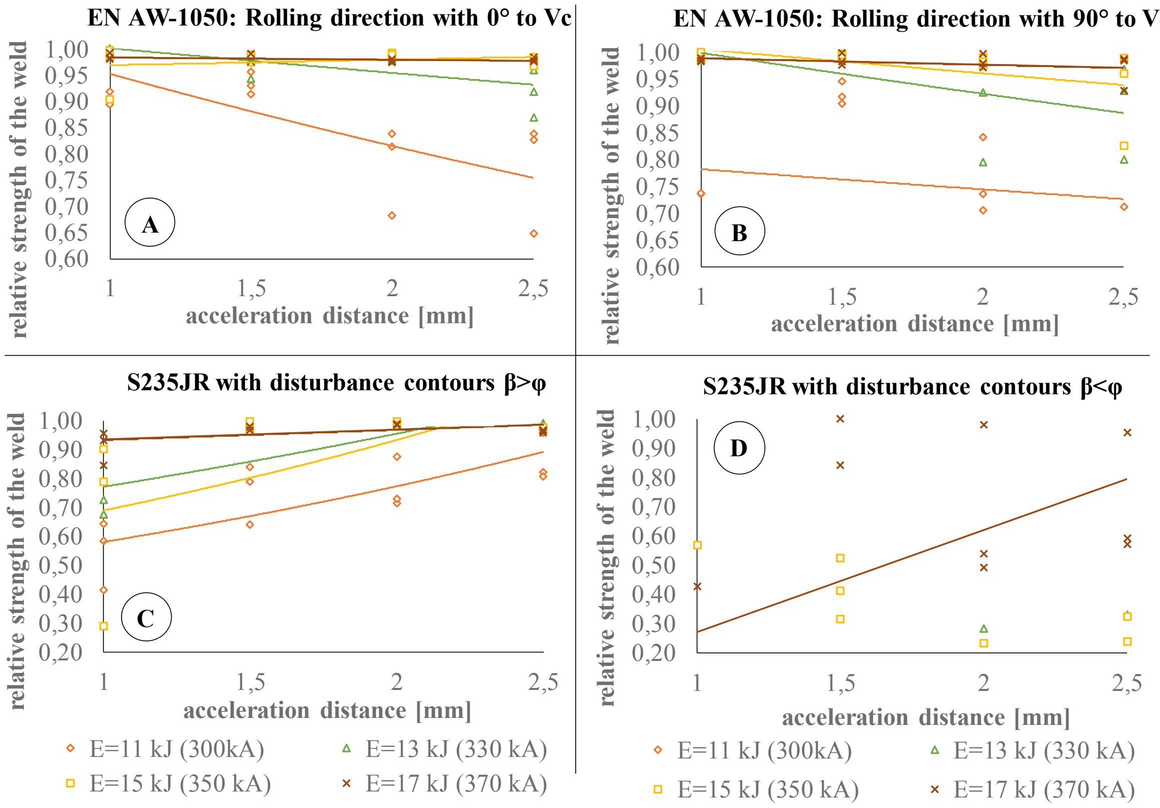

***Figure 5**: Influences on the relative strength of the joint in correlation to the acceleration distance and discharge energy*

This phenomenon became clear, when disturbing contours according to (Lysak and Kuzmin, 2012) were induced. Here, the aluminum alloy EN AW-1050 with surface irregularities, as caused by the roller, with 90° to the collision vector (Picture 5, C) was tested.

Tests that were performed without induced disturbing contours, with low discharge energy and an increased acceleration distance and which resulted in decreased strength (figure 5, C compare figure 5, A), show opposite results as in figure 7. In comparison, the test series E=11kJ showed an increase in strength with increasing acceleration distance. An increase in energy to 13kJ lead to hardly any dispersion and relative strengths σ=1.0.

This effect became clear, when the relation between the critical angle of the induced disturbance contours and the collision angle was changed from β>φ (figure 5, C) to β<φ (figure 5, D). As a result, all test series showed high dispersion and the strengths of the joint only increased at 17kJ with increasing distance.

Besides showing the influence of the process parameters – acceleration distance as well as discharge energy – the results show a direct influence of the non-linear behavior of the impact process in MPW.

3 Experimental Work

3.1 Effects of the Flyer Plate Velocities during Joint Formation

Contrary to the cited scientific publications, the effect of the relative strength of the joint of σ=1.0 was examined, as a realized joint – without direct proof of quality – is not enough to define the effects of the influencing variables.

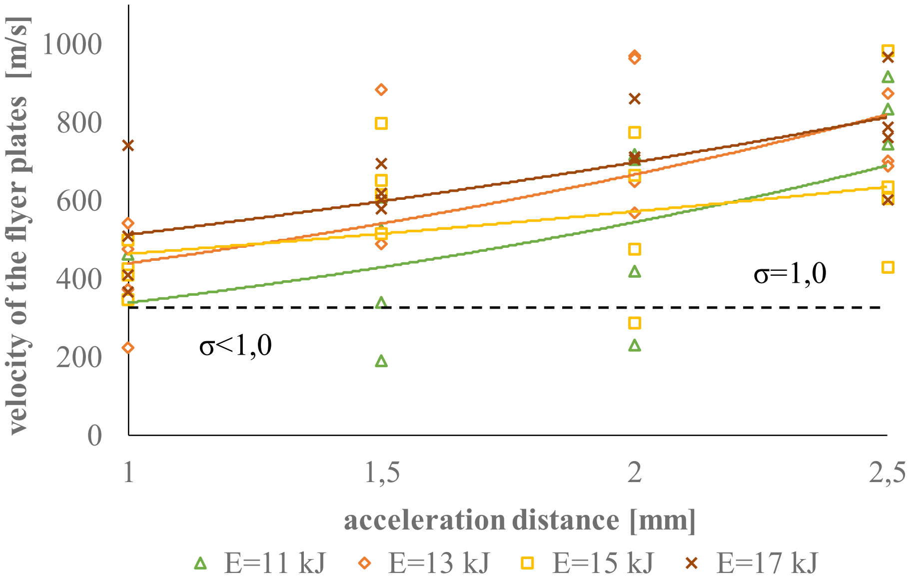

Figure 6: *Influence of the acceleration distance and the discharge energy on the flyer plate velocities*

The tests showed that in order to achieve a strength of the joint of σ=1.0 (comparable to a weaker base material of joining partners), flyer plates velocities of at least 300 m/s had to be achieved. A complete overview of the results of this test series, in correlation to the identified flyer plate velocities, is shown in figure 6.

The necessary flyer plate velocities Vp ≥ 300 m/s do not necessarily lead to an optimal joint. Figure 7 exemplarily shows the fracture surface of S235JR as target. Etching according to Adler clearly shows the actual area of connection to the joining partner aluminum, thus, pointing to failures in the joint. The acceleration distance was 2.0mm and the discharge energy 11kJ. The maximum tensile force was 4.590 N, resulting in a relative strength of the joint towards the weaker base material (EN AW-1050) of 0.67. The strength of the joint was low although flyer plate velocities were 420 m/s.

***Figure** 7: Fracture image analysis of the target S235JR, test series 9.3, Etching according to Adler*

3.2 Effects of the Collision Point Velocity and the Relative Strength (V_{cp} - σ)

Collision point velocities were taken as the basis to define the influence of the processing speed. Figure 8 shows the collision point velocities in correlation to the relative strength of the joint.

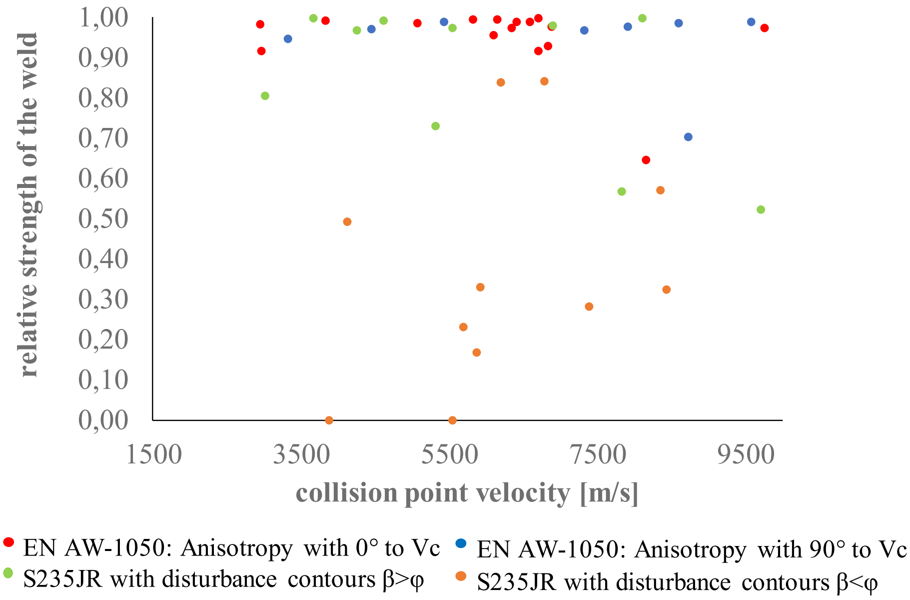

***Figure** 7: Correlation of the collision point velocities with the relative strength of the joint*

Four test series with the respective influencing variables were examined. The results show no direct connection between the collision point velocity and the quality of the joint. Especially when the roughness was such that its angle (φ) was bigger than the collision angle (β) (φ>β), no high strengths of the joint could be realized (figure 8).

3.3 Effects of the Collision Angle and the Relative Strength (β - σ)

The results in figure 9 show the influence of the surface topography. However, the decisive influencing parameter for MPW are not the collision point velocity but the collision angle which constantly changes during the process (see figure 9).

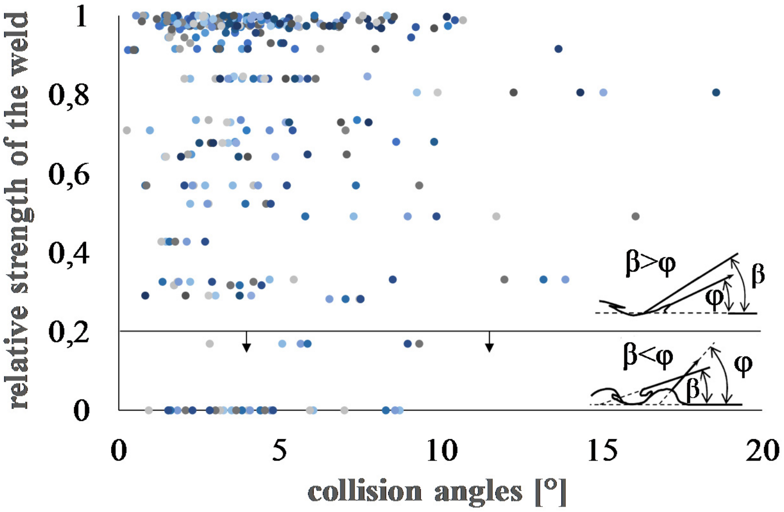

***Figure 8**: Correlation of the collision angle and the relative strength of the joint*

If the collision angle is below the angle of the roughness which needs to be passed, failures in the joint can occur. This information offers a new approach to MPW which has been disregarded in scientific publications so far.

However, this effect can be used; if there is enough information about the exact kind of roughness, wave formation can be realized even for difficult welding combinations such as aluminum and steel. Figure 10 (left) shows a wavy interface without induced disturbance contours transverse to the collision vector. The wavy interface (figure 10, left) was created with an acceleration distance of 2.5mm and a discharge energy of 17kJ. With flyer plate velocities of up to 966 m/s, collision point velocities of 11.237 m/s and collision angles of β ≤ 8,071, the joint achieved a relative strength of 0.98.

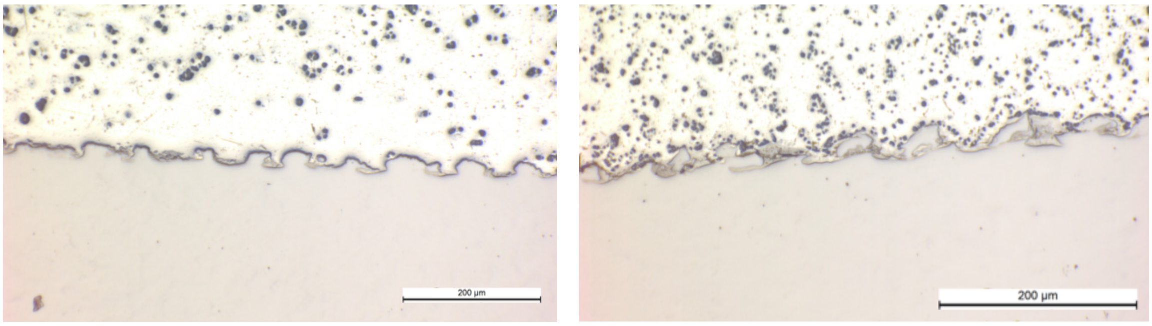

***Figure 9:** (left) EN AW-1050 (0° to Vc) / S235 JR, Pl.-No.: 6962;*
(right) EN AW-1050 / S235JR $\beta<\varphi$, Pl.-No.: 7505

Figure 10 (right), on the other hand, shows a target with a laser structured surface $\beta<\varphi$ (S235JR). The acceleration distance was s=2.5mm and the energy E=17kJ. The flyer plate velocities were 602 m/s, collision point velocities were 4.632 m/s and collision angles were $\beta \leq 9.804$. The relative strength of the joint was 0.97.

These results allow the conclusion that, besides applying specific surface modifications, the interface of the magnetic pulse weld can be adjusted with regard to the surface topography. This allows to prevent critical weld seam irregularities (e.g. joint failures) and, thus, enables to increase the quality of the joint (e.g. waviness in its various forms for fatigue strength stressed parts).

4 Conclusion

These results show at which points good reproducibility can be achieved. Apart from specifically shaping the surface topography, a controlled handling of the process-specific parameters is possible and will lead to high-quality welds. All in all, the following insights could be gained:

- To achieve a relative strength of the joint of $\sigma=1{,}0$, flyer plate velocities of more than 300 m/s are necessary.
- When the acceleration distance is $1.0 \text{ mm} \leq d \leq 1{,}5 \text{ mm}$, collision angles of $5.1° \leq \beta \leq 9.1°$ are realized.
- There is a connection between the relative strength of the joint and the collision angle.
- If the collision angles are from $4{,}8° \leq \beta \leq 10{,}3°$, the resulting interface is wavy (surface topography of target with $0.587 \leq Ra \leq 1.823$).
- Collision point velocities have an indirect influence on the joint formation. However, the collision angle is decisive.
- Optimal process parameters for rel. strength of the joint $\sigma=1$:
  - Flyer plate velocities (v_p): ≥ 695 m/s
  - Collision angle (ß): $6.1° \leq \beta \leq 9.3°$
  - Collision point velocities (v_{cp}): ≥ 6.777 m/s

5 Acknowledgments

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