

Influence of the jet velocity on the weld quality of magnetic pulse welded dissimilar sheet joints of aluminum and steel

Einfluss der Jetgeschwindigkeit auf die Schweißnahtqualität magnetimpulsgeschweißter Blechverbindungen aus Aluminium und Stahl

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The object of this investigation is to determine the influence of the jet velocity on the weld quality of sheet joints produced via magnetic pulse welding. The use of a suitable high-speed camera system enables to observe the jet in detail, to determine its velocity during the collision process and to compare them to the achieved qualities (tensile strength, weld seam characteristics) of the welded samples. The results show that the quality of the weld generally correlates with the jet velocity, however the mere consideration of its velocity proves not to be a promising approach for predicting a specific weld quality. It becomes evident that the jet thickness has to be considered, since quality-critical characteristics of the weld seam appears in greater extent when the jet thickness increases.

Keywords: Magnetic pulse welding / asymmetric impact / jetting / high-speed imaging / weld quality

Gegenstand der Untersuchung ist die Ermittlung des Einflusses der Jetgeschwindigkeit auf die Schweißnahtqualität magnetimpulsgeschweißter Blechverbindungen. Die Verwendung eines geeigneten Hochgeschwindigkeitskamarasystems ermöglicht es, den Jet im Detail zu beobachten sowie seine Geschwindigkeit während der Kollision zu erfassen und diese den erzielten Qualitäten (Zugfestigkeit, Schweißnahtcharakteristiken) der verschweißten Proben gegenüberzustellen. Die Ergebnisse verdeutlichen, dass die Qualität der Schweißverbindung im Allgemeinen mit der Jetgeschwindigkeit korreliert, jedoch erweist sich die alleinige Berücksichtigung seiner Geschwindigkeit als ein nicht vielversprechender Ansatz, um eine spezifische Schweißnahtqualität prognostizieren zu können. Es wird ersichtlich, dass die Jetdicke zu berücksichtigen ist, da qualitätskritische Schweißnahtcharakteristiken in größerem Ausmaß vorliegen, wenn die Jetdicke zunimmt.

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Schlüsselwörter: Magnetimpulsschweißen / asymmetrische Kollision / Jetting / Hochgeschwindigkeitsaufnahmen / Schweißnahtqualität

1 Introduction and aim of investigation

Magnetic pulse welding (MPW) belongs to the collision welding processes and enables as a cold welding process a metallurgical joint for similar as well as dissimilar material combinations without the presence of a pronounced heat-affected zone [1]. Compared to conventional welding processes, in particular fusion welding processes, the metallurgical differences between the metals in case of a dissimilar material combination are no longer decisive for the weld quality, since the process-specific disadvantages (temperature-induced microstructural changes, brittle intermetallic phases, heat distortion, etc.) can be avoided or reduced to an uncritical level [2–3]. This advantage predestines magnetic pulse welding particularly for the realization of a metallurgical joint between aluminum and steel.

In magnetic pulse welding the high-speed collision is based on a strong electromagnetic field that is generated when a high frequency current is conducted through a coil, the welding tool. The magnetic pressure generated between the coil and the so-called flyer accelerates and deforms the flyer across an adjusted distance, *Figure 1a*. The flyer finally collides at velocities above 250 m/s with the fixed joining partner, the target, and performs a rolling movement with an increasing collision angle and decreasing collision point velocity [4–6].

Due to the enormous contact pressure and the resulting plastic deformations during this process, the boundary layers of the joining partners are

transferred at strain rates above 10^4 s^{-1} into the hydrodynamic state and ejected with velocities of several thousand meter per seconds under a certain collision angle from the collision point as a dispersed cloud or a cumulated mass flow, the so-called jet [7–10], *Figure 1b*. The formation of the jet is a necessary condition for a successful joint, since it is associated with a cleaning effect and thus prepares the way to bring the cleaned and oxide-free surfaces to a distance at which the electron exchange and the metallurgical joint takes place [11–14]. Recent investigations in the field of magnetic pulse welding confirm, that in addition to the necessary formation of the jet, its kinetic component plays an important role during the welding process and particularly influence the weld quality [15–17].

Correspondingly, the aim of the presented paper is to determine the jet velocity by means of high-speed imaging during an asymmetric collision process and to investigate the influence on the weld quality for a dissimilar joint of aluminum and steel produced by magnetic pulse welding.

2 Experimental setup

2.1 Magnetic pulse welding and materials

For the welding experiments the pulse generator BlueWave PS48-16 in combination with the sheet welding tool coil B80/10 from PSTproducts was used. The pulse system provides a maximum charg-

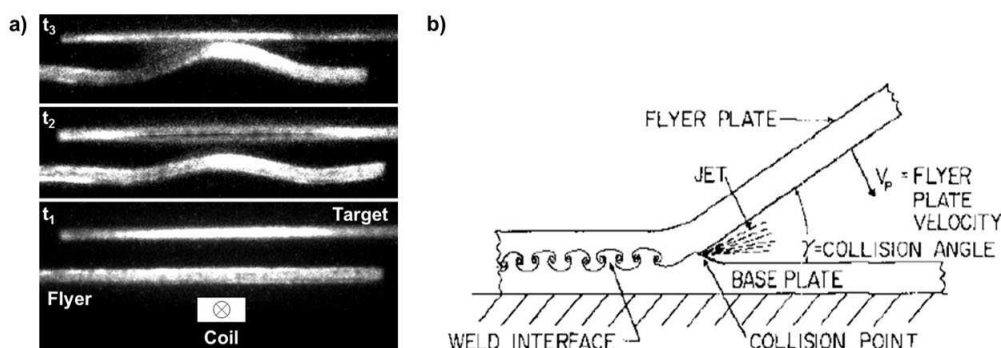


Figure 1. a) High-speed images of the collision process and b) schematic illustration of an asymmetrical impact and the jet ejected from the collision point [10].

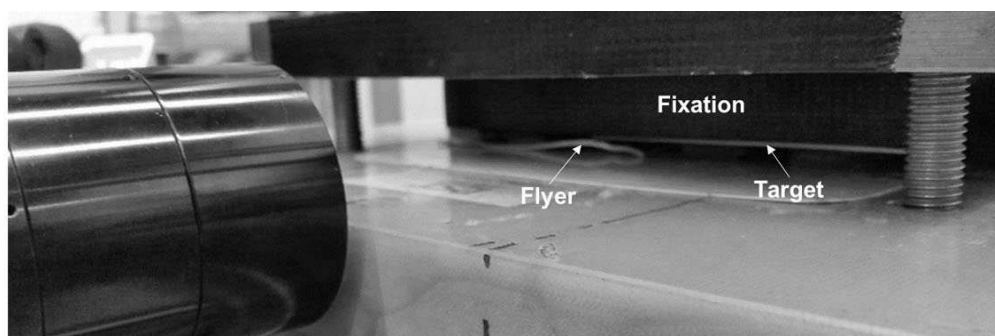


Figure 2. Experimental setup and alignment of the camera system [15].

ing energy of 48 kJ, a maximum charging voltage of 16 kV and the effective part of the sheet welding tool coil was 10 mm wide, 5 mm high and 80 mm long. The tool coil can be operated until a maximum peak current of 500 kA.

The chosen materials were the pure aluminum-alloy EN AW-1050A-H14 and the mild steel S235JR with a sheet dimension of 100 mm × 40 mm × 1.5 mm. The discharge energy was varied between 7 kJ and 15 kJ in 2 kJ steps with corresponding maximum discharge currents between 234 kA and 346 kA. The acceleration distance was varied between 1 mm and 2.5 mm in 0.5 mm steps. Both welding parameters were set according to a full factorial experimental design with 4 repetitions per parameter setup and the joining partners were always positioned with an overlap of 30 mm to each other during the welding process. The aluminum-alloy was always used as flyer and the discharge current frequency was about 19.6 kHz. To increase the welding reproducibility, the flyer and the target were laser ablated and cleaned with acetone prior the welding procedure in the collision area.

2.2 High-speed imaging and jet velocity determination

To observe the asymmetric collision process the image intensifier camera HSFC-Pro from PCO was used. The system enables the acquisition of four images per three ns, whereby the number of images is limited to four or eight. In this investigation eight images were captured with a resolution of 1280 pixels × 1024 pixels. Furthermore, the camera system was equipped with an optical 640 nm bandpass filter and was aligned to the collision area in such a

way that it looked through the set acceleration distance between the two joining partners and was illuminated with a diode laser positioned behind the fixation, *Figure 2*. The diode laser was the CAV-ILUX Smart from Cavitar, operating with a power of 400 W and a wavelength of 640 nm.

In order to determine the velocity of the jet, two images according to the chronological sequence of the collision process were compared to each other and the distance travelled by the jet during these two images was determined, *Figure 3*. Considering the time difference of the two images, the velocity of the jet was finally calculable.

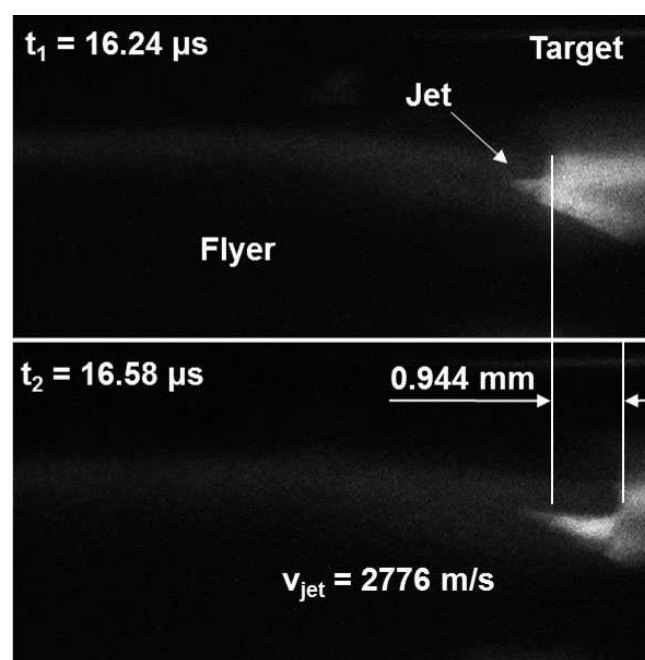


Figure 3. Exemplary illustration of the jet velocity determination.

2.3 Testing and weld seam observation

In order to quantify the weld quality, three samples per parameter setup were destructively tested by tensile shear testing according to DIN EN ISO 14273 and the determined maximum tensile forces were used for evaluation. In case the tested samples failed in the weld seam and not in the weaker base material (EN AW-1050A-H14), the weld seam formation in the collision area of the target was observed. In addition, cross sections were made with the fourth sample of each parameter set to observe the interface. The observation of the weld seam characteristics was performed with the light microscope DM2700 from Leica Microsystems.

3 Results and discussion

3.1 Tensile forces

The comparison of the achieved tensile forces depending on the welding process parameters showed, that at constant acceleration distance the maximal tensile force increases with increasing discharge current, whereby an increasing acceleration distance decreases the maximum bearable force of the weld, *Figure 4*. At an acceleration distance of 1 mm, the failure of the weaker EN AW-1050 A-H14 ($F > 6700$ N) was reproducibly adjustable with discharge current of 296 kA. As the accel-

eration distance increases higher discharge currents were required to reach this limit again, whereby a reproducible failure of the aluminum at an acceleration distance of 1.5 mm was only achieved with a discharge current of 346 kA. At acceleration distances of 2 mm and 2.5 mm, the maximum applied discharge current of 346 kA was not sufficient to accomplish this. It should be noted, at an acceleration distance of 2.5 mm successful welding was only realized above discharge currents of 234 kA.

The generated welding process window is relatively similar to those observed in previous investigation, where the negative influence of an increased acceleration distance ($d \geq 2$ mm) on the lower welding limit and weld seam strength was also found [18].

3.2 Jet velocity and weld seam characteristics

The high-speed images revealed that the jet was mainly thrown out from the collision point as a cumulative mass flow and steadily decreases in speed during its movement in the closing gap between the joining partners while its thickness increases. This is in good agreement with previous investigation [7].

The comparison of the measured maximum jet velocity at the beginning of the impact process depending on the applied welding process parameters showed that at constant acceleration distance the jet velocity increases with an increasing discharge cur-

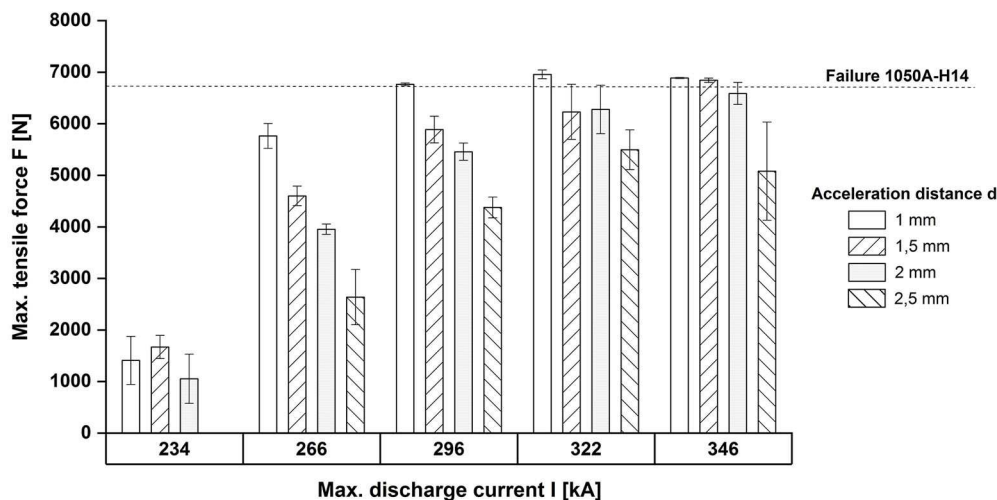


Figure 4. Maximum tensile force depending (mean value, standard deviation) on maximum discharge current and acceleration distance.

rent, *Figure 5*. For example, at acceleration distance of 1 mm the average jet velocity starts with 1781 m/s at discharge current of 234 kA, increases to 2831 m/s at 296 kA and finally achieves an average velocity of 3463 m/s at the maximum applied discharge current of 346 kA. The acceleration distance could not be attributed to a definite tendency with regard to the jet velocity, but rather to the jet thickness, which was at the beginning of the collision process due to the very small gap between the joining partners in the immediate vicinity of the collision point not determinable in a satisfying degree. Nevertheless, the images taken at a later stage of the collision process showed, that the jet thickness increases at constant discharge current with increasing acceleration distance during the ongoing movement of the flyer, *Figure 6*. In addition, the depicted images illustrate that with an increasing acceleration distance an increase of the collision angle was present at the time of its first appearance.

Regarding the achieved tensile forces of the samples showed, that the tensile force again strongly correlates to the jet velocity, whereby this correlation also changes with increasing acceleration distance and in particular scatters at acceleration distance of 2.5 mm, which makes it finally impossible to predict a definite strength from a specific jet velocity [7], *Figure 5*. In addition, a shift of the jet velocity required for successful welding (lower welding limit) took place at an acceleration distance of 2.5 mm. While welds were realizable at an acceleration dis-

tance of 1 mm with jet velocities of 1727 m/s and at acceleration distance of 1.5 mm and 2 mm with approximately 1835 m/s, no welds occurred at an acceleration distance of 2.5 mm even at jet velocities of 1673 m/s. Only an increase of the discharge current to 266 kA and thus of the impact velocity enabled to achieve successful welding with jet velocities of 2321 m/s. A possible explanation for the shift of the lower welding limit is delivered from the increased jet thickness. Assuming that at the beginning of the jet formation more surface particles are actually involved due to the increased collision angle, it is plausible under consideration of the total energy budget (kinetic energy of the flyer) that the jet velocity decreases as a result of its increased mass [13]. The raise of the impact velocity, in this case through an increased discharge current, finally enabled to accelerate the additional mass to the velocity necessary to leave the closing gab without being trapped and thus interrupting the interaction of the cleaned and oxide-free surfaces or more precisely to a velocity above the collision point velocity.

Furthermore, a shift of the jet velocity required to achieve a reproducible failure of the weaker aluminum took place to higher levels as the acceleration distance increased. Tensile forces above 6700 N were reproducible with jet velocities of 3103 m/s at an acceleration distance of 1 mm, with 3321 m/s at 1.55 mm and with 3500 m/s at 2 mm. At an acceleration distance of 2.5 mm the maximum measured jet velocity of 3838 m/s, which was not sufficient to

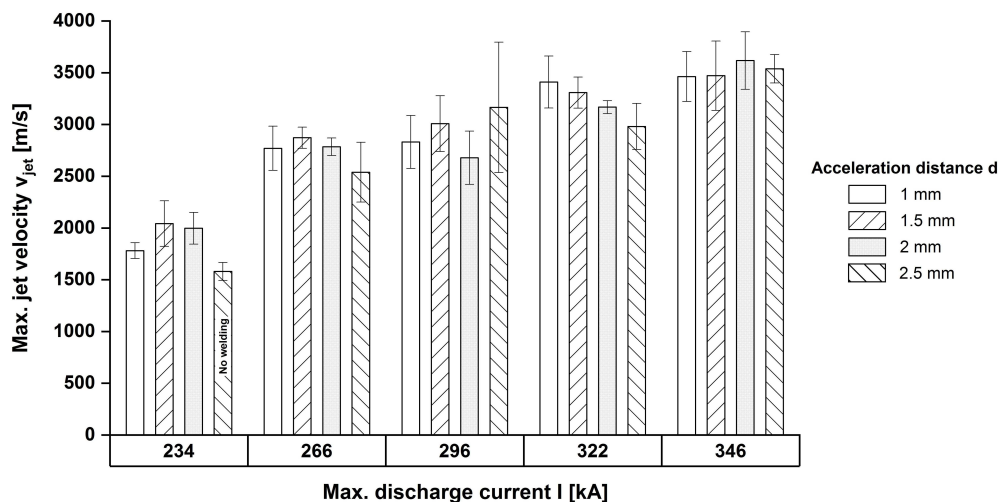


Figure 5. Maximum jet velocity (mean value, standard deviation) depending on maximum discharge current and acceleration distance.

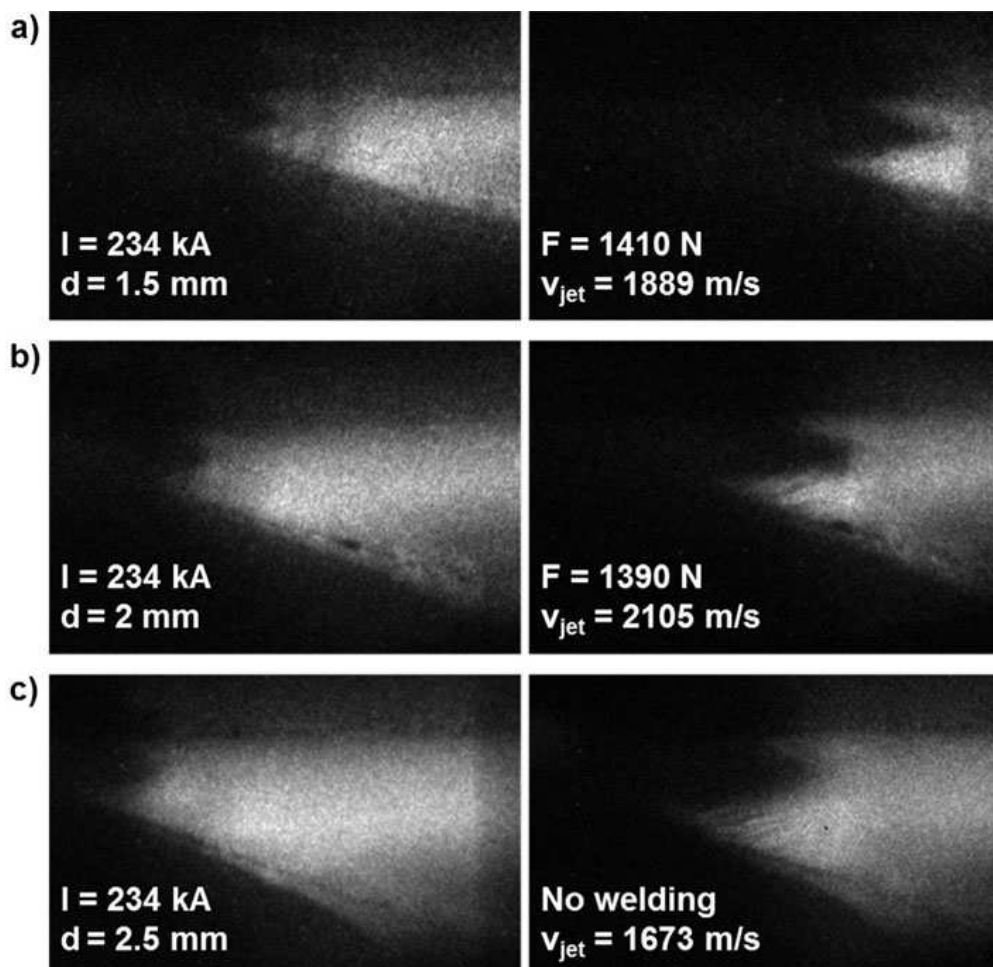


Figure 6. High-speed images at the lower welding limit of selected samples.

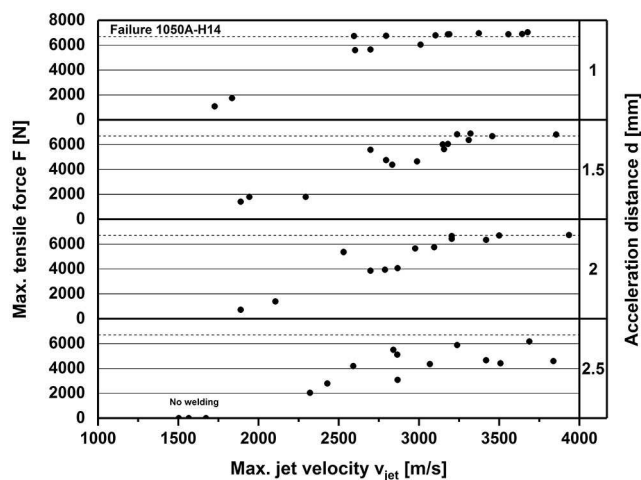


Figure 7. Tensile force depending on maximum jet velocity for different acceleration distances.

reach this target limit. The analysis of interface, which only appeared turbulent wavy above a dis-

charge current of 296 kA, revealed that despite relative similar jet velocities melt pockets behind the well-known Kelvin-Helmholtz instabilities in the middle area of the weld seam width W_2 and in particular the intermediate layer at the beginning of the weld seam formation W_1 appeared in a greater and strength critical extent when an increased acceleration distance was used [19–22], *Figure 8*. The intermediate layers of a sample welded with a discharge current of 346 kA and an acceleration distance of 1 mm were isolated from each other and did not exceed a thickness of 3 μm , *Figure 8b*, while by far continuous (500 μm) and partly cracked intermediate layer with a maximum thickness of 15 μm was found at the beginning of the weld seam formation at an acceleration distance of 2.5 mm, *Figure 8c*. The taken fracture images finally revealed the global impact of the increased layer thickness on the formation of the mainly force-absorbing part of the weld seam, *Fig-*

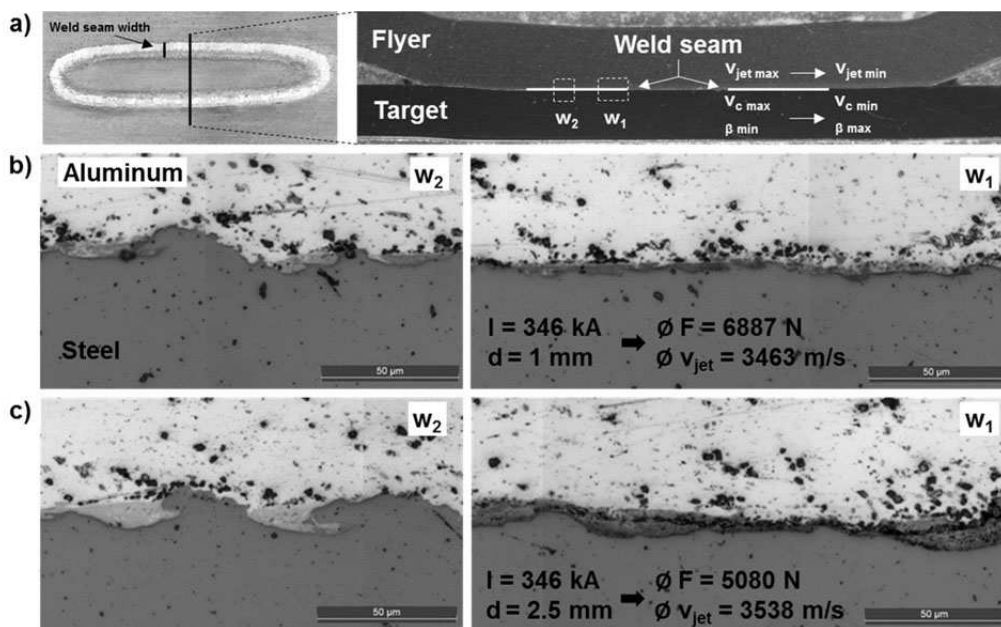


Figure 8. a) Schematic illustration of the investigated positions and b), c) interface of selected samples.

ure 9. Here again, despite similar jet velocities critical irregularities such as incompletely shape and in particular an inconstant width (weld seam width) of the elliptical ring, occurred in greater extend, strongly indicating an uneven load absorption during the tensile shear test for the samples welded with an increased acceleration distance [18], Figure 9c, d. Obviously, the jet thickness has to be considered to deliver an explanation approach. As the jet thickness raised with increasing acceleration distance, the intermediate layer at the beginning of the weld seam formation probably appears in a greater degree due to the unfavorable combination of an increased jet thickness

and the maximum collision point velocity at the beginning of the collision. Considering this assumption, the shift of the limit at which the weaker aluminum fails as well as the increasing scattering between the jet velocity and the tensile force could be related to the extent to which the jet or at least a part of it is trapped between the joining partner influencing the bond formation negatively through an increased local heat input or maybe even inhibiting it completely. Although this approach cannot be clearly confirmed by the available results, it is supported by the superior weld quality achievable when performing magnetic pulse welding in vacuum, where the reduced air re-

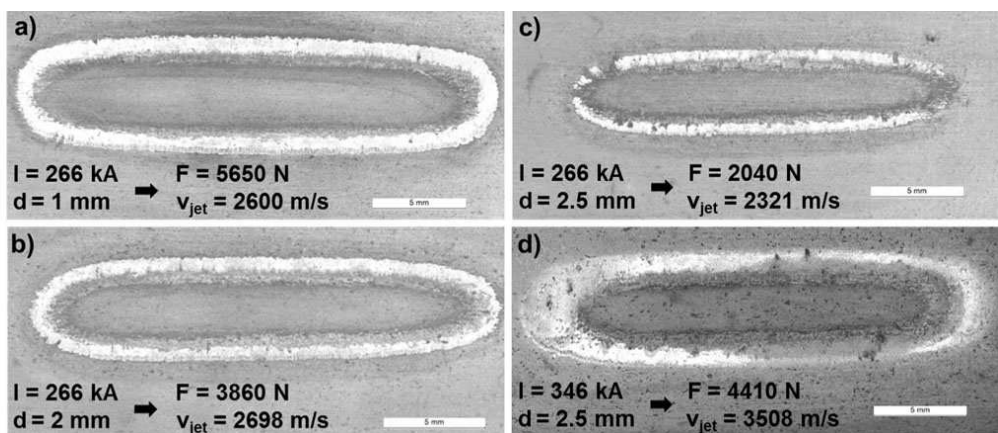


Figure 9. Fracture image of selected samples after the tensile shear test [15].

sistance enables the jet to leave the closing gab at much higher velocity and as a thinner mass flow [7, 16–17].

4 Summary

In this paper, the influence of the jet velocity on the weld quality of magnetic pulse welded sheet joints was investigated by means of high-speed imaging. The acquired images showed that the jet was mainly ejected from the collision point as a cumulated mass flow, traveling with decreasing velocity and increasing thickness between the closing gab of the joining partner. The comparison of measured maximum jet velocities confirmed that the weld seam strength in general correlates with the jet velocity, which can be maximized by an increasing discharge current. However, the mere consideration of the jet velocity to predict a definite strength or weld seam quality is not possible. The jet thickness, increased with a steadily increasing acceleration distance, plays an important role for welding (lower welding limit) and particularly influence the correlation between the jet velocity and the weld quality negatively, since quality-critical weld seam characteristics (increased intermediate layer, cracks, voids) appeared in a greater extent. It is concluded that an increased thickness promotes the possibility that the jet or at least a greater part of it to be trapped at the early stage of process due to the maximum collision point velocity and thus influencing the bond formation negatively or maybe even inhibiting it.

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