Identification of additional process parameters for impact welding and their influence on the process window

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Abstract

Impact welding in general facilitates the metallurgical bond even between dissimilar metals due to the lack of extensive heat input. It thus offers superior joint properties such as a good mechanical strength. However, in contrast to fusion welding, the fundamentals are not fully understood. As a direct consequence, not all influencing process parameters are known or quantified yet. However, this is crucial in order to further comprehend, develop and optimize the process. The objective of this study is to investigate the influence of the surrounding gaseous medium on the weld strength as additional parameter. This issue has been discussed in earlier publications of other researchers already, though without any consistent conclusion yet. The results of this study show that a lower gas density results in higher weld strength, whereas higher densities may even inhibit the joint completely at identical impact velocities. High speed images of the electromagnetic pulse welding process indicate that this might be caused by the jet which is obstructed by the ambient gas atmosphere on its way out of the impact area. The higher the density, the slower the visible jet is. Thus, superficial material of the workpieces and contaminants cannot leave the welding area and hinder its formation instead.

Keywords

Impact welding, process window, jetting, high speed imaging, ambient gas atmosphere

1 Introduction

Impact welding offers unique advantages regarding the joint properties, especially the superior mechanical strength and ductility, helium tightness and non-detectable electrical resistance (Schäfer and Pasquale, 2010). These properties apply to both similar and even dissimilar metal combinations, enabling a wide variety of applications. The utilization of impact welding as explosion welding can be traced back until 1944 (Carl, 1944), electromagnetic pulse welding followed in the 60s (Demichev, 1992). However, even the basic process mechanisms are still barely understood, for example the initiation and evolution of the wavy interface. Fluid effects (Lysak and Kuzmin, 2012) and shock wave effects (Ben-Artzy et al., 2010) are discussed in literature. It requires often time- and money-consuming experimental investigations to identify the robust process window, which is absolutely mandatory for the industrial mass production of components. Depending on the experience, empirically found guidelines are known which can shorten this process. But the objective persists to find valid design rules similar to those from arc welding for example. This has not been achieved yet, possibly because not all process parameters have been found yet. The high process velocities, which can reach several thousand metres per second, used to be responsible for the limited observability and thus limited understanding of the process. With the help of pulse generators with exactly synchronized and triggered switches in combination with special high speed cameras, detailed images during the process and inside the impact area can be captured and evaluated (Pabst and Groche, 2016).

The normal impact velocity between the two workpieces starts at roughly 200 m/s and may reach many hundred metres per second. The required angle between the workpieces is in the range of some degrees up to approximately 30° or even more. The triangular gap between the two workpieces to be joined thus closes at velocities of several thousand metres per second, depending on angle and impact velocity. Under these extreme conditions, high strain rates and high pressures, the so-called jet is formed and ejected from the closing gap. It contains superficial material such as contaminants or oxides, leaving pure metallic surfaces behind to be pressed together during the impact. There is a broad consensus that this jetting is crucial for the formation of a bond. Several analyses on the jetting have been conducted in the past, mainly regarding its composition depending on the involved alloys and the process parameters, for example in (Kakizaki et al., 2011), (Miller, 1998) and (Stern et al., 2015). The objective of this study is to find a correlation between the jet velocity and the joint properties, which is the mechanical weld strength for these investigations. It is assumed that the weld strength is proportional to the size of the welded area. Apart from already known parameters, the focus of this study is on the influence of the ambient gas atmosphere on the jetting and its effect on the joining process and the joint properties. This has been done in earlier works already, however without any consistent outcome. In (Bergmann et al., 1966), the joint properties increase only slightly in vacuum, despite a measured jet velocity which is almost twice as high as under ambient atmosphere and pressure. According to (Groschopp et al., 1987), the normal impact velocity is twice as high in vacuum, also leading to an only slight increase in mechanical properties. The most recent publication also states that the weld quality increases in vacuum, but without a higher normal impact velocity (Buijs, 2010). According to Koschlig et al. (2008), the supersonic acceleration and compression of the ambient gas in the closing gap can produce temperatures of up to several thousand kelvins.

2 Experimental setup

2.1 Tool coil, pulse generator and specimens

The experimental works have been carried out with the help of a PSTproducts industrial pulse generator, a standard sheet welding tool coil and an image intensifier camera from PCO. The pulse generator “PS32-16” provides a maximum charging energy of 32 kJ and a maximum charging voltage of 16 kV. The effective part of the tool coil has a cross section of 5 x 5 mm² and a length of 130 mm. The camera is synchronized with the trigger signal for the pulse switches and takes the images after an adjusted delay after the first contact between flyer and target. This delay depends on the discharge current, because the flyer reaches the target after a different time due to different impact velocities.

The material used for these basic investigations is commercially pure aluminium (99.5 %, EN AW-1050A) in condition H14. The tensile strength is about 118±3 N/mm². The deviation depends on the rolling direction, which however is not considered here because it has shown that there is only a minor and thus negligible effect. The specimens’ size is 40 mm x 40 mm x 2 mm. Two sheets are welded with an air gap of 2 mm. The target is supported and clamped to the tool coil with a steel block. Flyer and tool coil are separated by a 0.35 mm thick electric insulation. The specimens are inside an acrylic glass housing that can be evacuated. The experiments are performed at discharge energies between 11 kJ and 20 kJ, which equals peak discharge currents between 252 kA and 357 kA. The discharge current frequency is 20 kHz for this system.

2.2 Image acquisition

An image intensifier camera is used to study the impact. The camera “hsfc pro” from PCO is capable of capturing 300 million frames per second at a resolution of 1280 x 1024 pixels, however with a maximum frame number of up to eight. The light source is a red pulsed 400 watts laser “CAVILUX Smart” from Cavitar. The camera is equipped with an optical bandpass filter and thus captures the laser light only, but barely the process light. A long distance microscope enables a spatial resolution of 5.7 µm per pixel in this case at a safe distance from the process and the tool coil of about 120 mm. The light path passes the specimens through the air gap parallel to the weld seam. As the setup is symmetrical, only one half is filmed. This is shown in Fig. 1. An exemplary camera image is shown and explained in Fig. 2. The jet can be identified clearly.

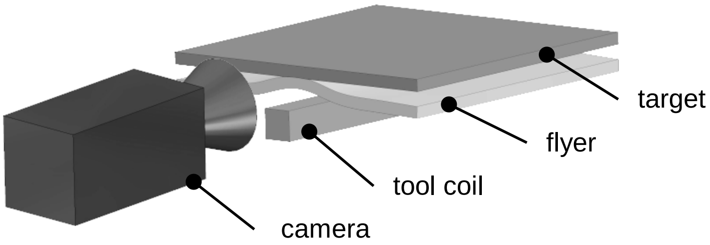

Figure 1: *Optical setup for the experiments.*

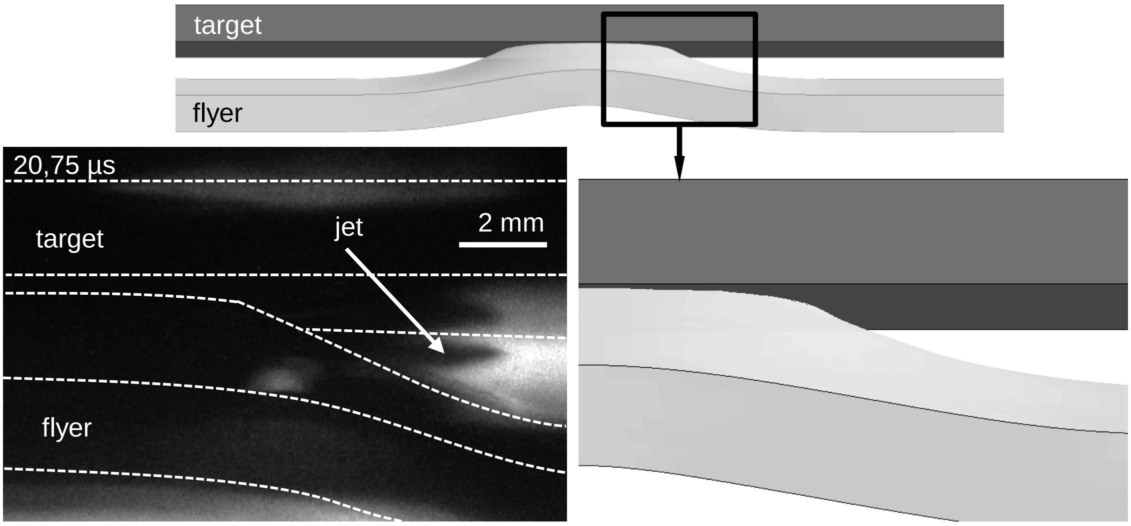

Figure 2: *Description of the camera images.*

The calibrated camera enables to measure exact distances as long as they are in focus. This allows an exact determination of the velocities. Fig. 3 illustrates the measurement of the jet velocity at ambient air and in vacuum for identical peak discharge currents. Taking into account the different frame delays, the jet velocity is about 2120 m/s in air and about 3860 m/s in vacuum.

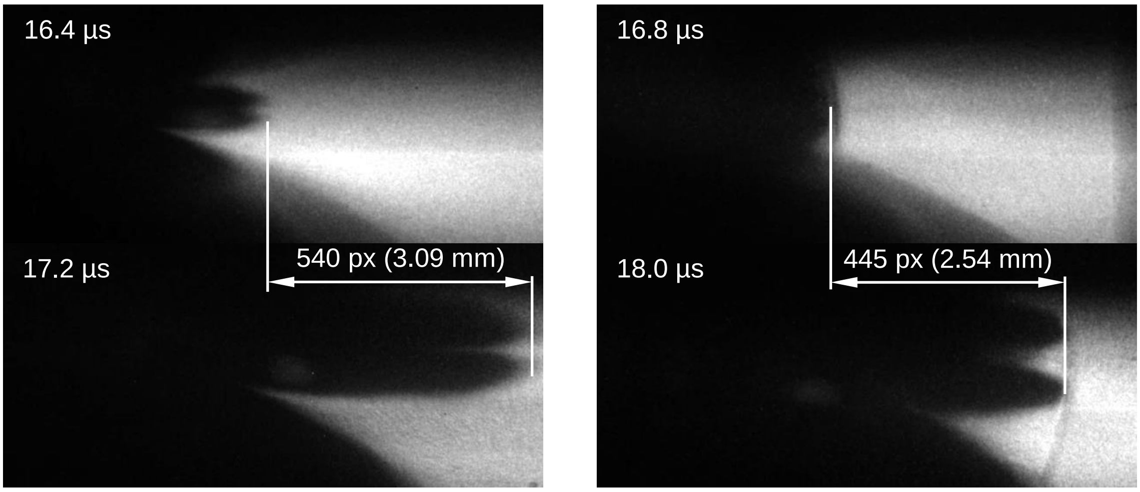

Figure 3: *Velocity measurement with the help of the camera images.*

2.3 Weld shear strength

The strength of the welded specimens is determined by shear testing. With the given dimensions and tensile strength of the aluminium, a maximum shear strength of about 9500 N can be expected. This is of course a theoretical value only, because the weld area is not homogeneous for this setup which leads to stress concentrations. In addition, both the target and especially the flyer experience plastic deformation. The tensile test is depicted schematically in Fig. 4 (left). The potential joint area is shown on the right in Fig 4. It appears as white and is 0-shaped.

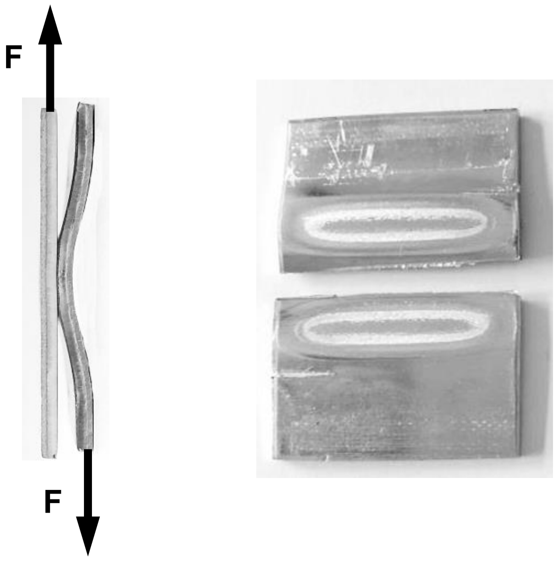

Figure 4: *Schematic illustration of the shear test.*

3 Results

3.1 Normal impact velocity

The first result refers to the normal impact velocity of the flyer onto the target. It is measured with the help of high speed images just before the first contact between flyer and target. As expected, no difference could be measured between ambient pressure and vacuum. This is plausible due to the fact that the volume of displaced solid material and ambient gas is roughly identical, but the density differs by a factor of more than 2000. The measured normal impact velocities are given in Table 1. The accuracy is in the range of ±6 m/s.

Discharge current	252 kA	275 kA	297 kA	318 kA	338 kA	357 kA
Normal impact velocity	290 m/s	312 m/s	340 m/s	363 m/s	386 m/s	410 m/s

Table 1: *Discharge currents and corresponding normal impact velocities.*

3.2 Jet velocity

The maximum shear force for different jet velocities is given in Fig. 5. It is obvious that a given jet velocity does not correlate with a specific weld strength. Specimens at both ambient pressure and in vacuum reach a peak strength, which is close to the theoretical maximum. The specimens fail close to the joint area here, whereas the weld fails at all lower discharge currents. The specimens’ strength cannot increase any further, but surprisingly decreases slightly at higher discharge currents. This might be caused by shock damage especially in the target sheet due to the stronger impact of the flyer. The plastic deformation of the flyer sheet also increases.

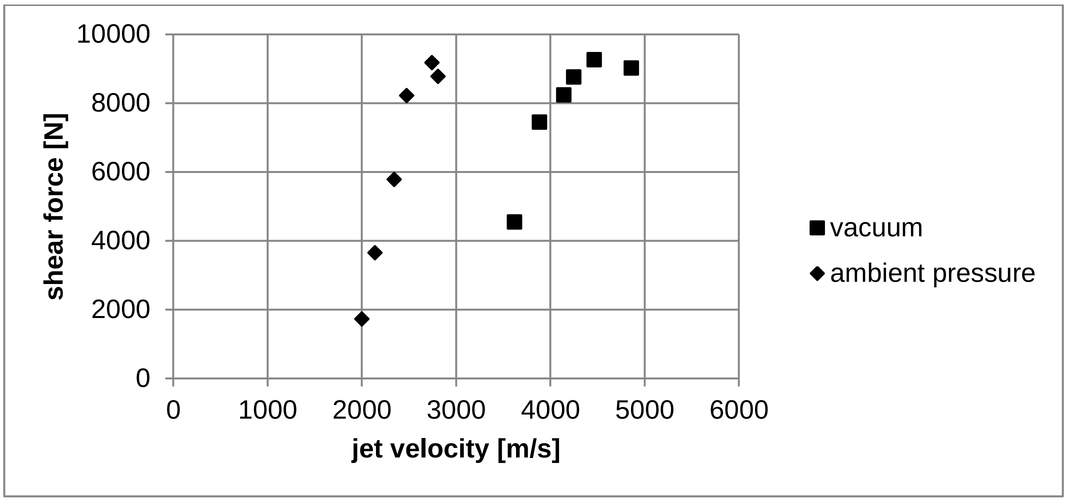

Figure 5: *Shear force depending on the jet velocity for vacuum and ambient pressure.*

The formation of the jet depends on the flow of material in the impact area. This flow of material again depends on the macroscopic deformation of the specimens. It has been shown that this deformation is not significantly influenced by the density of the ambient gas. As a consequence it can be expected that the formation of the jet as well does not depend on the ambient medium. However, an ambient gas with lower density simplifies the ejection of the jet. Otherwise, the jet is hindered, remains in the joint area and inhibits the bond formation.

3.3 Micrographs

It shows that welds in vacuum reach higher strengths than under ambient pressure, which leads to the assumption that the size of the welded area has to be different. Fig. 6 shows the direct comparison between the two welded samples welded at 297 kA in vacuum and ambient pressure. For reasons of simplification, only one half is shown here, because the samples are symmetrical. The area of the first impact is located on the left in Fig. 6. Please note that the weld size might not be the same across the whole specimen size.

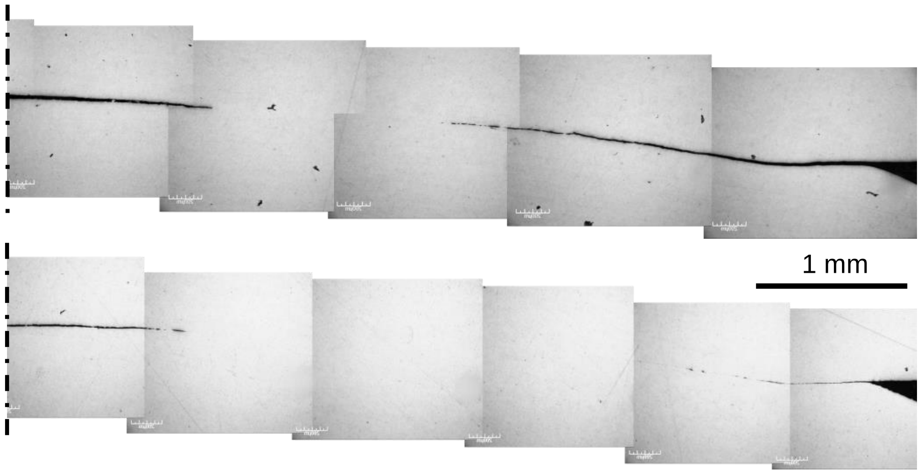

Figure 6: *Micrograph of the joint area for ambient air (top) and vacuum (bottom).*

The weld width alone cannot be used to predict the strength of the weld. Judging from the welded area, which appears to be twice as large in vacuum than at ambient air, the comparably moderate increase in shear strength from 5780 N to 8235 N cannot be explained. Two reasons are possible: The width of the weld length is probably not constant across the complete surface, as already mentioned. Furthermore, in optical microscope images, kissing bonds often cannot be identified. Thus the actually welded area might be smaller than it appears to be here.

4 Discussion

It has been shown that it is possible to correlate the density of the ambient gas with the jet velocity and the strength of the weld. However, there is no direct or even linear correlation.

The increasing weld width and strength can be explained as follows: The jet is initiated at an early stage of the process. The collision point and thus the jet move very fast within this period (Groche et al., 2014). Consequently, any ambient medium decelerates the jet and makes the particles stay in the impact area where they inhibit the bond formation. This is why the weld starts earlier in vacuum. After this early stage, the jet velocity decreases and its weight increases. In this stage, there is no large difference between vacuum and ambient pressure. During the final stage, the jet velocity still decreases, whereas its weight still increases. The air drag decelerates the jet so much that the particles cannot escape the closing gap until it eventually closes completely. This has been shown with the help of microscopic investigations in (Pabst and Groche, 2016).

Furthermore, a critical analysis is advisable, especially regarding the relevance of the jet velocity as process parameter in general. The jet is measured largely outside the joint area and thus after the welding process. This means that large portions of the bond have already been created. However, there is a strong correlation between jet velocity and shear strength. Moreover, further experiments have shown that there seems to be a minimum jet velocity of around 2000 m/s below which no joint is possible, which seems to be irrespective of the surrounding gas.

The results suggest that the extension from the measured jet velocity to its power or kinetic energy at a certain point of time could be a more relevant parameter. It is possible that the diagram of the shear force versus the jet power would be one single line. It must be kept in mind that even the jet power can only be an effect of the differing joint formation mechanisms, but not the root cause.

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