Investigations on Shock Waves during Collision Welding

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Abstract

Collision welding is a joining process that bases on the high speed impact between two joining partners. Caused by the dynamic behaviour (welding time < 10 µs), the investigation of the actual process is associated with a high technical effort. Therefore, the basic mechanisms of the process and a possible interaction have not yet been conclusively clarified.

In previous experiments on a model test rig for collision welding, indications have occurred on some high-speed images that could be characterized as shock waves. This paper describes the set-up of a Background-Oriented-Schlieren system (BOS) and its integration in the existing test rig for a closer examination of the occurring phenomena. The first aim was to increase the visibility of the occurrences in the medium surrounding the collision. As a result of the commissioning, it can be stated that shock waves were detected and propagate at supersonic speed. However, these do not only originate from the closing gap, but there is also an interaction between the colliding samples and the set-up environment.

Keywords

Collision Welding, Shock Waves, Background-Oriented-Schlieren

1 Introduction

Collision welding is a joining technology that becomes more interesting under the aspect of increasing electro mobility and light weight construction. The reason for this is the growing use of multi-material-assemblies, as collision welding allows joining dissimilar materials (e.g. aluminium/steel or aluminium/copper) that cannot be joined by fusion welding (Aizawa et al., 2007). However, due to the lack of understanding the welding mechanisms of collision welding, most of the production processes still have to be designed experimentally. For a deeper study of the subject, an innovative test rig was developed at TU Darmstadt. This system enables the investigation of collision by means of an image intensifier camera (PCO hsfc pro) under constant process parameters (Pabst et al., 2014). Like the other collision welding techniques, the test rig's process principle is based on the collision of two joining partners (flyer and target) at high relative velocity v_i and a specific collision angle β. The collision point velocity v_c is calculated to enable a comparison of the process window with other setups.

During the investigations, some of the images showed phenomena that can be characterized as shock waves caused by the impact between the specimens. However, they are not present in every experiment and occur in different locations, e.g. in the closing gap or at the backsides of one or both specimens. The latter could also be caused by spalling particles due to the impact of the specimens. **Fig. 1** shows an exemplary constellation (white arrows).

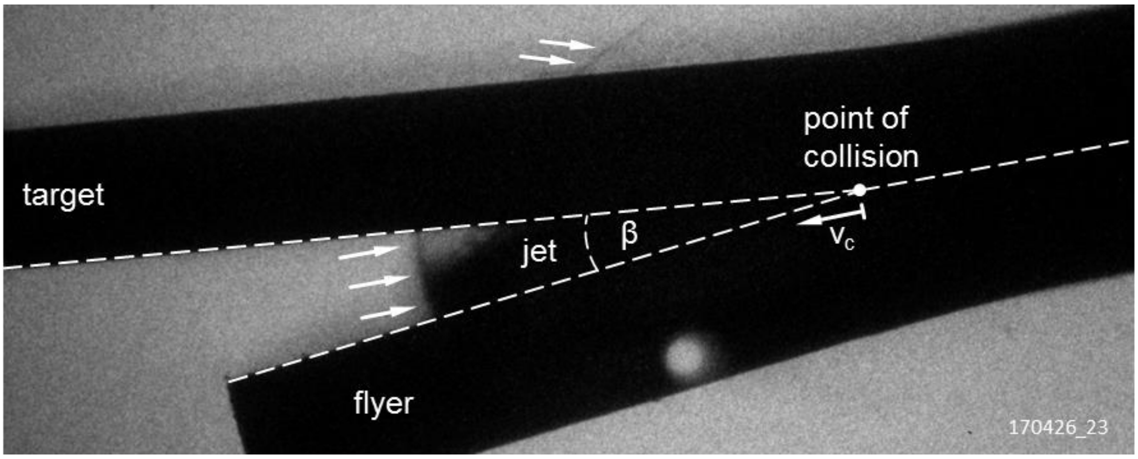

Figure 1: *Process image at the test rig taken with the INFINITY K2 DistaMax lens, arrows indicate occurring phenomena inside the closing gap and on the backside of the upper specimen*

In literature, the generation of the so called jet is crucial for the formation of the bond (Zlobin, 2002). It is formed by the near-surface layers of the welding partners and prepares the surfaces for the bond formation. Hence, several investigations on the behaviour and consistence of the jet have been carried out (e.g. Cowan and Holtzman, 1963, Bergmann et al., 1966, Watanabe and Kumai, 2009). Pabst and Groche (2018) showed that the jet velocity and also its shape depend on the atmosphere's density and it affects the bond strength. Considering this fact and looking at Fig. 1 the question arises whether the shock waves in the gap have an influence on the jet and thus an effect on the formation and quality of the bond. Furthermore, shock waves separate two fluid regions with different conditions which can be described by density, pressure, velocity and temperature before and after the shock wave. Especially the temperature in the gap is of particular interest. It can provide information on the heating of the bond zone and hence, the jet. Sharafiev et al. (2016) determined a high local temperature rise due to columnar grain growth in the bond zone. Knowledge of the temperature distribution could therefore contribute to a better understanding of the energetic mechanisms of bond formation in collision welding. Moreover, some studies see shock waves reflected on the backsides of the joining partners as a trigger for wave formation (Ben-Artzy et al, 2010). In this context, the examination of the shock waves alternating from the specimen's backside could help to prove or disprove this theory.

For further investigations of this phenomenon, the visualization of the flow and the density distribution between and around the specimens is a suitable option respecting the experimental conditions of the test rig. Hence, the present paper describes the integration and the commissioning of an optical setup in the existing test rig to detect the flow conditions, visualize the shock waves and make a first attempt to measure the density distribution.

2 Integration of an Optical Density Measurement System in Collision Welding

As described above, a model test rig is used for experimental investigations of the bonding mechanisms in collision welding. The test rig in the current configuration is described in Groche et al. (2017). Two rotors turn in the same direction with a phase offset. Specimens are mounted on one end of each rotor. After the run-up of the motors, the phase offset becomes compensated within a single revolution and the specimens collide in the middle between the two rotor hubs. The camera is arranged in such a way that the collision of the samples can be observed laterally. This allows a close observation of the processes in the closing gap. Four or eight images can be taken per experiment with a minimum exposure time of 1 ns. A pulsed laser with an output power of 400 watts and a wavelength of 640 nm in incident or transmitted light configuration is used for a sufficient illumination. A script written in MathWorks MATLAB reads out the angle between the colliding specimens for each image.

In order to integrate an optical method to visualize the flow, the main techniques, namely Interferometry, Schlieren and Shadowgraph technique, have been examined with regard to their suitability. All of these techniques are based on the Gladstone-Dale relation:

$$(n-1)/\rho = const. \tag{1}$$

which shows the linear relation for gases between the refractive index n and the density ρ. If the density changes, the refractive index changes as well. This enables a high local and temporal determination of density differences in media and flow fields based on phase differences. (Panigrahi and Muralidhar, 2012)

In order to find a technique which can be integrated in the current test rig configuration, a Background-Oriented-Schlieren (BOS) system proved to be the most suitable solution. This method has been developed to simplify the optical Schlieren system by reducing the optical elements to a camera and a structured background (Meier, 2002). For the determination of the distraction, an image distorted by Schlieren and an undistorted image as reference are numerically compared which allows a two-dimensional detection of the density distribution. Due to the increasing performance of computers, this optical measurement method has been used more and more frequently in the last decade (Dalziel et al., 2000; Richard and Raffel, 2001). Moreover, BOS has already been proved as an adequate technique for the investigation of shock waves that move with 1500 m/s in water (Yamamoto et al., 2015).

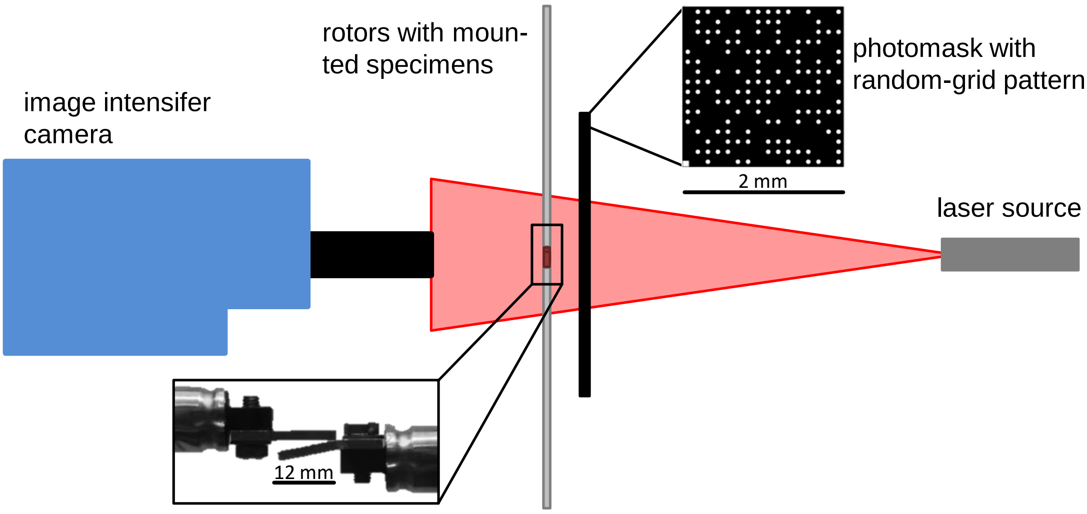

Figure 2: *Plan view of the test rig with the integrated BOS setup; collision of the two specimens in front of the laser illuminated photomask and observed by the image intensifier camera*

Fig. 2 shows the implementation of the BOS system in the test rig. A photomask with a random-grid dot-pattern is utilized as a structured background that is arranged closely behind the colliding specimens. The dots are penetrated by the laser behind them, creating an illuminated background for the colliding specimens. In addition, the portion of the laser light radiating through the dots is sufficient to illuminate the specimens. Since two lenses with different optical length (INFINITY K2 DistaMax Long-Distance Microscope (LDM) and ZEISS Milvus 2/100M) are used for process observation, two photomasks with different diameters (0.06 mm and 0.08 mm) close to the camera's resolution were developed to ensure a high sensitivity of the system (Meier, 2002). The background is focused for a precise evaluation of the flow. In order to achieve the highest possible depth of field, the aperture of the lenses is closed to such an extent that the exposure is still sufficient. However, **Fig. 3** shows that the LDM in particular has a very small depth of field and the specimens are no longer sharply displayed. In addition, diffraction occurs at the edges of the specimens. With the ZEISS Milvus, these effects are less noticeable. However, strong vignetting occurs.

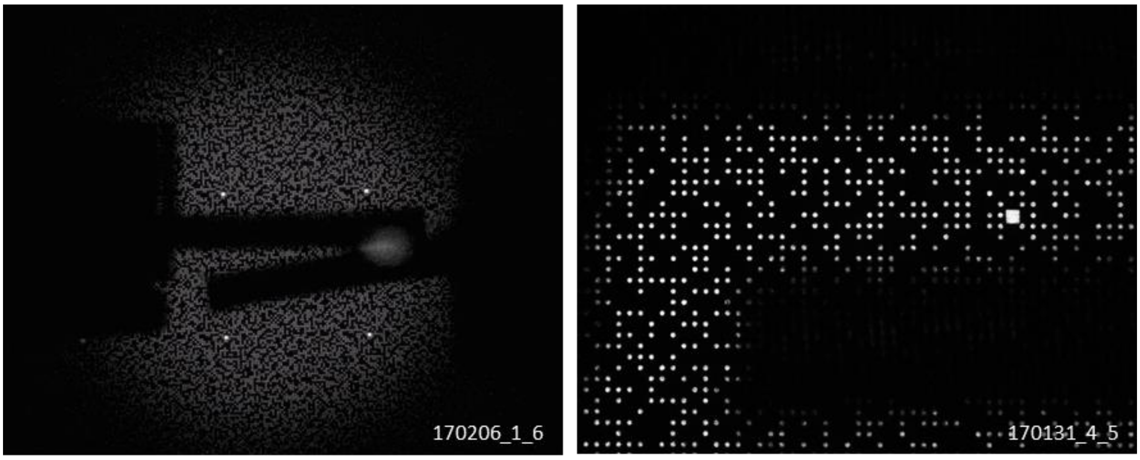

Figure 3: *Images taken focusing the background; overview image with ZEISS Milvus (left); magnification of the gap with INFINITY K2 Diastemas (right)*

In order to analyze the flow, a reference image is first taken for each of the four camera channels in order to exclude erroneous displacements due to misalignment of the optical components. After the experiments have been carried out, the images are examined regarding the background distortion. The displacement of the dots can be calculated using programs to determine velocities in particle flows, called particle image velocimetry (PIV) (Meier, 2002). Murphy and Adrian (2011) have already successfully used PIV for the investigation of shock waves in microscale of 2 mm in a Schlieren setup.

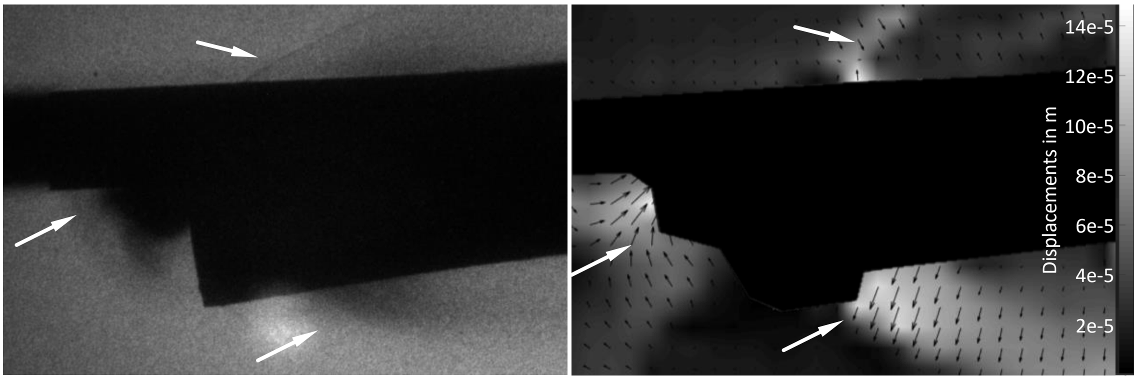

Figure 4: *Comparison of a high-speed image of the process (left) and a calculated BOS-image (right); white arrows indicate compared areas, bright areas represent areas with high density gradients*

The flow distortions in the present paper have been analyzed by the MathWorks MATLAB basing software PIVlab (Thielicke and Stamhuis, 2014). The software determines the direction and amount of the displacement vectors (see **Fig. 4**) and presents them in several representations. Different algorithms process the raw data previously and areas that cannot be evaluated (e. g. the samples or their mounts) can be excluded manually by masks. By means of the distances between camera lens, investigating area and background and the focal length of the lens, the displacement can be correlated with the local density gradient (Meier, 2002). Thus, it is possible to determine the density fields by integrating the matrix of displacements. Only the constants of the integration term have to be identified, which can be done by calibration.

3 Results of the Commissioning and Discussion

The initial results of commissioning are shown in the following and the relevant findings are discussed. First of all, it can be stated that the application of the BOS system in the test rig extends the investigation opportunities regarding the interaction of the joining partners and the surrounding atmosphere. The two lens setups allow the investigation of the phenomena in the area of the closing gap on the one hand and in the area around the specimens and their mounts on the other.

Thus, considering the comparison of the high-speed image and the calculated BOS-image in Fig. 4 taken with the LDM, it can be seen that the visibility of the processes in the surrounding medium is enhanced. The detachment from the upper specimen is also apparent in the BOS image. In addition, it can be seen that displacements and thus the density gradients increase from both sides and converge on a plateau in the form of the assumed shock wave. The BOS image also shows that a region of increased density is running ahead of the jet, where the ambient air probably is compressed from the closing gap. Furthermore, an area of increasing density can be observed under the lower specimen in the BOS-image which is not displayed in the regular high-speed image. This suggests that a compression of the solid specimen was emitted to the ambient medium like above, but the energy was not sufficient to generate a shock wave like above. This can be attributed to the different collision conditions between flyer and target. However, it must be taken into account that the two-dimensional images represent three-dimensional processes and that the medium can also escape from the gap laterally, which can distort the measurement.

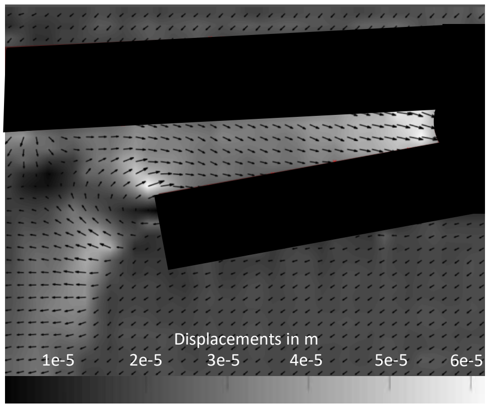

Figure 5: *BOS-image of the closing gap; density increase indicated by displacements inside the gap to the collision point and a vortex on the edge of the lower specimen*

The previously discussed images show the collision process at a late stage. Looking at a BOS image of the same experiment at an earlier time (see **Fig. 5**), it can be seen that there is no shock wave in the gap at this experimental configuration. It should be noted that the area where the jet takes place must be cut out of the evaluation region by a mask, as it is impossible to detect the displacement close to the collision. An additional factor to be taken into account is that the edges of the specimens have to be excluded from the evaluation, due to diffraction and therefore, the evaluable area has to be reduced. Nonetheless, it can be stated that the density gradient increases towards the collision point. Furthermore, it can be observed that the escaping medium is deflected downwards, possibly caused by the formation of a channel through the upper specimen mount. It is more compressed at the edge of the lower specimen, probably due to a vortex formation. The medium in the peripheral areas of the field of view is not affected by the emerging phenomena and almost no displacement can be noticed. The minor changes are either due to the moving rotors or to a measurement noise.

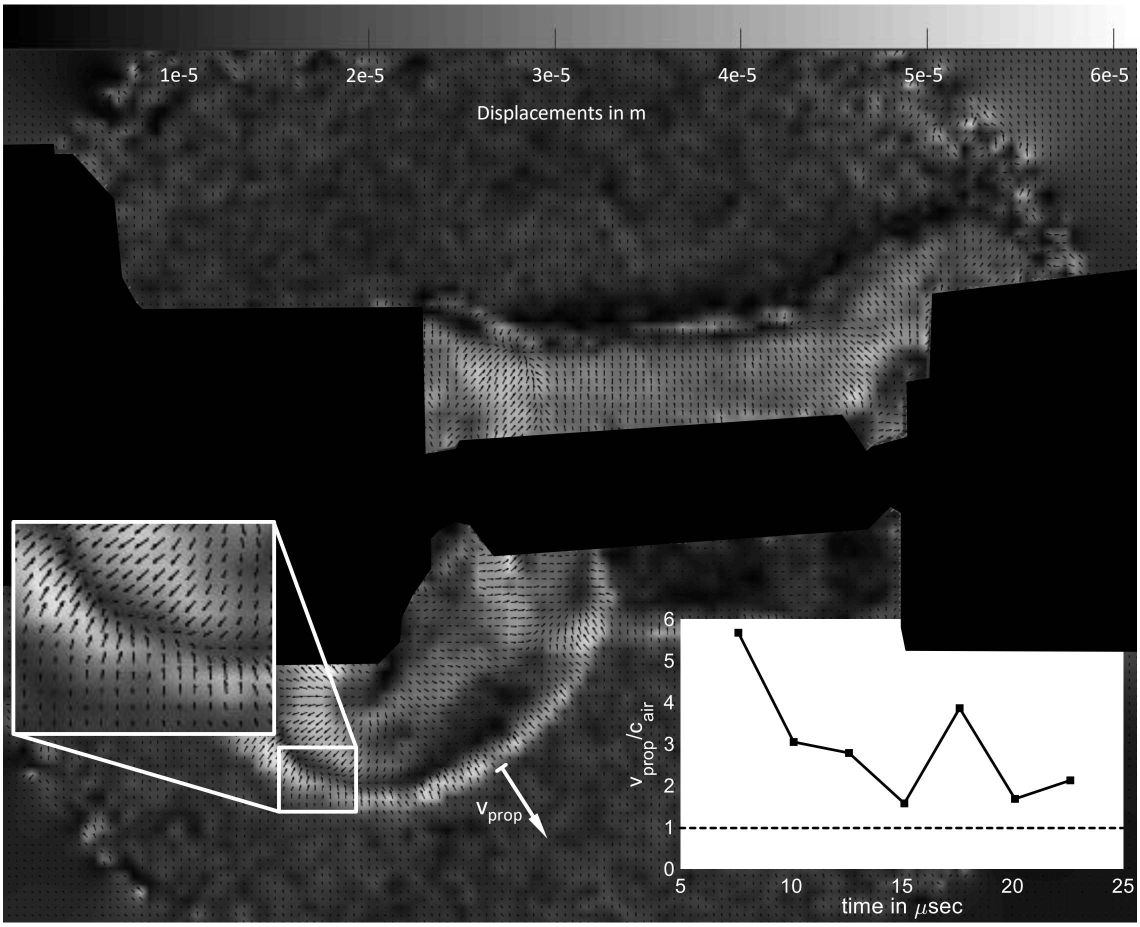

Figure 6: *BOS-image taken with the ZEISS Milvus lens showing the propagation of the shockwaves after the collision; diagram: propagation velocity in relation to the velocity of sound in air*

Fig. 6 shows a BOS image taken with the ZEISS Milvus lens. The collision welding process has already been completed, but the specimens have not yet been torn off at the predetermined breaking point. Multiple compressions move away from the collided specimens. The compressions that spread out circularly from the closing gap and finally subside are remarkable. As on the LDM images, the increasing density gradients from both sides with an intermediate plateau indicate shock waves (see detail in Fig. 6). According to Krehl (2009), shock waves cause a sudden change of pressure, density, particle velocity and temperature. They also move faster than the speed of sound of the medium. Therefore, the radial distances of the compression were measured in an area of constant propagation and their velocity was calculated using the time difference between the exposures. In relation to the speed of sound in air, it is shown that the compression spreads at supersonic speed, demonstrating that it is actually shock waves. Their speed tends to decrease, but increases again temporarily. A possible explanation for this could be a fusion with another shock wave propagating from the back of the specimen or by influencing the measurement by the sideways escaping medium, which propagates in the direction of the optical axis.

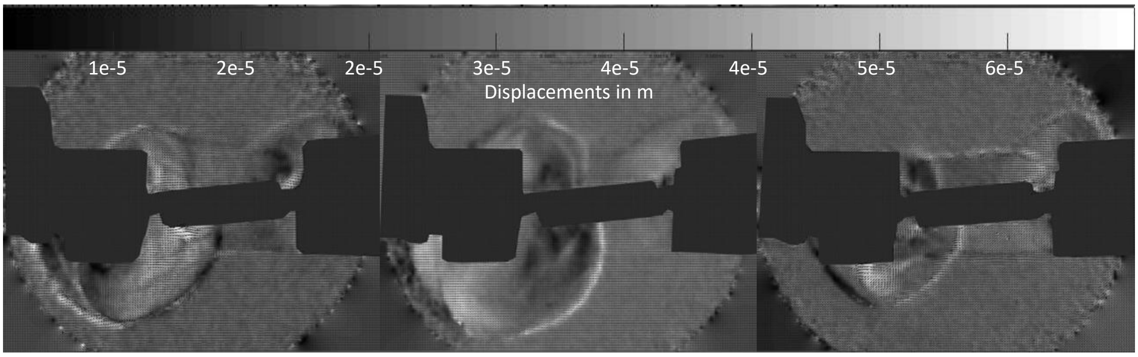

Figure 7: *Comparison of the accuracy of the measurement system by three experiments at the same time of exposure*

In order to check the accuracy of the measuring system, several tests were carried out, subjected to the same conditions. **Fig. 7** shows three experiments at the same recording time. While the first two shots show comparable qualitative results, the third one is rather different. The reason for this can be a deviating collision angle between the experiments which leads to a change in the propagation speed of the compression. The collision angle can only be set exactly before the collision, but due to the focusing on the background it cannot be measured during the experiment. Experience has shown that, due to elastic effects, the angle reduces slightly with a certain amount of variation at the beginning of the collision.

4 Conclusion and Outlook

A Background-Oriented-Schlieren system has been integrated into the existing test rig for collision welding. The first results from the commissioning process showed that the movements of the flow of the surrounding medium and the qualitative density gradient distribution can be determined by this device. The expected shock waves can be clearly identified by the density gradient progression and by their supersonic propagation velocity. Furthermore, it was found that the quality of the investigations in the gap strongly depends on the angle of collision and optical effects.

The measuring system should be calibrated to determine the conditions, especially the temperature, behind the shock waves on the basis of the density in front of them. However, the combination of the Gladstone-Dale relationship and the law of refraction of Snellius failed, as the actual width of the medium must be known. To assume it as specimen’s width is also inappropriate because due to the geometric relations small deviations of the width result in high changes of the calculated density. In future, further approaches for calibration will be investigated. The application of a standard Schliere is considered to be promising (Settles, 2001). A transparent object with a known density is used for this purpose, whereby the constants for integration of the density gradients can be determined by means of the known density of air.

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References

Aizawa, T., Kashani, M., Okagawa, K., 2007. Application of magnetic pulse welding for aluminum alloys and SPCC steel sheet joints. *Welding Journal, 86* (5), pp. 119-124.

Ben-Artzy, A. Stern, N. Frage, V. Shribman, O., Sadot, 2010. Wave formation mechanism in magnetic pulse welding. International Journal of Impact Engineering (37), pp. 397-404.

Bergmann, O. R., Cowan, G. R., Holtzman, A. H., 1966. Experimental evidence of jet formation during explosion cladding. *AIME MET SOC TRANS* 236 (5), pp. 646-653.

Cowan, G. R., Holtzman, A. H., 1963. Flow configurations in colliding plates: explosive bonding. Journal of applied physics, 34 (4), pp. 928-939.

Dalziel S., Hughes G.O., Sutherland B.R., 2000.Whole-field density measurements by esynthetic schlieren. Exp Fluids 28 (4), pp. 322–335.

Groche, P., Becker, M., Pabst, C., 2017. Process window acquisition for impact welding processes. Materials & Design, 118, pp. 286-293.

Krehl, P. O., 2008. *History of shock waves, explosions and impact: a chronological and biographical reference*. Springer Science & Business Media.

Meier G., 2002. Computerized background-oriented schlieren. Exp Fluids 33 (1), pp. 181–187.

Murphy M.J., Adrian R.J., 2011. Piv through moving shocks with refracting curvature. Exp Fluids 50 (4) pp. 847–862.

Groche, P., Wagner, M. X., Pabst, C., Sharafiev, S., 2014. Development of a novel test rig to investigate the fundamentals of impact welding. *Journal of Materials Processing Technology, 214* (10), pp. 2009-2017.

Pabst C., Groche P., 2018. Identification of Process Parameters in Electromagnetic Pulse Welding and Their Utilisation to Expand the Process Window. International Journal of Materials, Mechanics and Manufacturing vol. 6 (1), pp. 69-73.

Panigrahi, P. K., Muralidhar, K., 2012. Schlieren and shadowgraph methods in heat and mass transfer (Vol. 2). New York: Springer.

Richard H, Raffel M, 2001. Principle and applications of the background oriented schlieren (bos) method. Meas Sci Technol 12 (9), pp. 1576-1585

Settles, G. S., 2001. Schlieren and shadowgraph techniques- Visualizing phenomena in transparent media (Book). Berlin, Germany: Springer-Verlag GmbH.

Sharafiev, S., Pabst, C., Wagner, M. F., Groche, P., 2016. Microstructural characterisation of interfaces in magnetic pulse welded aluminum/aluminum joints. In IOP Conference Series: Materials Science and Engineering (Vol. 118, No. 1, p. 012016).

Thielicke and Stamhuis , 2014. Thielicke, W. and Stamhuis, E.J., 2014. PIVlab – Towards User-friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB. Journal of Open Research Software 2 (1).

Yamamoto, S., Tagawa, Y., Kameda, M., 2015. Application of background-oriented schlieren (BOS) technique to a laser-induced underwater shock wave. Experiments in Fluids, 56 (5), pp. 93.

Watanabe, M., Kumai, S., 2009. High-Speed Deformation and Collision Behavior of Pure Aluminum Plates in Magnetic Pulse Welding. In: Materials Transactions, Vol. 50, pp. 2035-2042.

Zlobin, B. S., 2002. Explosion welding of steel with aluminum. *Combustion, Explosion, and Shock Waves, 38* (3), pp. 374-377.