Process Analysis and Physical Simulation of Electromagnetic Joining of Thin-Walled parts

V. Psyk[1], G. Gershteyn[2], O. K. Demir[1], A. Brosius[1], A. E. Tekkaya[1], M. Schaper[2], F.-W. Bach[2]

[1]Institute of Forming Technology and Lightweight Construction, Technische Universität Dortmund, Germany
[2]Institute of Materials Science, Leibniz Universität Hannover, Germany

Abstract

To avoid typical problems when connecting different metallic materials as aluminum and titanium as e.g. the formation of intermetallic phases, electromagnetic welding represents an alternative technology to conventional (i.e. usually thermal) joining processes. Although feasibility and potential of this technique are already proved, the fundamental correlations of part- and process-parameters have not yet been investigated systematically. As an approach to examine these, the performance of model experiments and supplementary technological tests is suggested. The resulting connection quality is evaluated using metallographic methods.

Keywords

Electromagnetic welding, Model experiment, Metallographic evaluation

1 Introduction and Principle of Impulse Welding

The demand for implementing lightweight construction concepts e.g. in the automotive or aircraft industry has been steadily increasing over the last years. A constructive approach to reduce the product weight can be realized by decreasing the number of part components by combining their functions. However, following this approach leads to a higher complexity of the remaining components, because they now have to fulfil different and sometimes contradictory functions [1]. Thus, in many cases, the application of one single material is no longer sufficient, and a sophisticated material mix realizing the desired technological characteristics is required. It could e.g. be necessary to combine the corrosion resistance and strength of steel or titanium with the high electrical and thermal conductivity of aluminum or copper. When connecting these materials, the application of conventional (i.e. usually thermal) joining technologies often implicates problems, because at elevated temperatures in the range of 300°C and more, titanium shows a high affinity to the atmospheric gases oxygen, nitrogen and hydrogen. The chemical compound of titanium and these gases results in metalloid phases, which are extremely hard and brittle, so that part failure can occur. For this reason, autogenous welding is not applicable at all for titanium and titanium alloys. And even shielding gas arc welding technologies as MIG or WIG make special preconditions necessary, as e.g. the application of particularly pure gases, the maintenance of the shielding gas atmosphere even during the cooling-down of the part, and a careful preparation of the welding seam [2].

The welding of dissimilar materials as e.g. the combination of titanium and aluminum is even more difficult, because, here, the forming of intermetallic phases as TiAl3, TiAl2, TiAl, and Ti3Al, which also reduce the ductility of the material significantly, has to be avoided. Therefore, only special technologies as friction welding, which often results in reduced strength of the welding seam compared to the base material, or, in case of thin sheets, laser welding can be applied. Large and even connections of titanium and other metallic materials are often realized by means of explosive cladding [2], but, here, restrictions due to occupational safety have to be considered. Therefore, the development of innovative technologies suitable for the joining of these material combinations is necessary.

Here, one promising technology is electromagnetic forming (EMF), which can be used for forming operations as well as for the production of force-fit, form-fit, and welded material joints. EMF is a non-contact high-speed forming technology using the energy density of pulsed magnetic fields in order to apply a so-called magnetic pressure to workpieces made of electrically highly conductive materials. As soon as the resulting stresses in the workpiece exceed the yield stress of the material, plastic deformation starts. Depending on the geometry and setup of workpiece and tool coil, the technology can be used to compress or expand tubes and hollow profiles as well as to form flat or preformed sheet metal parts. A detailed description of the process principle and the pressure development is given in [3].

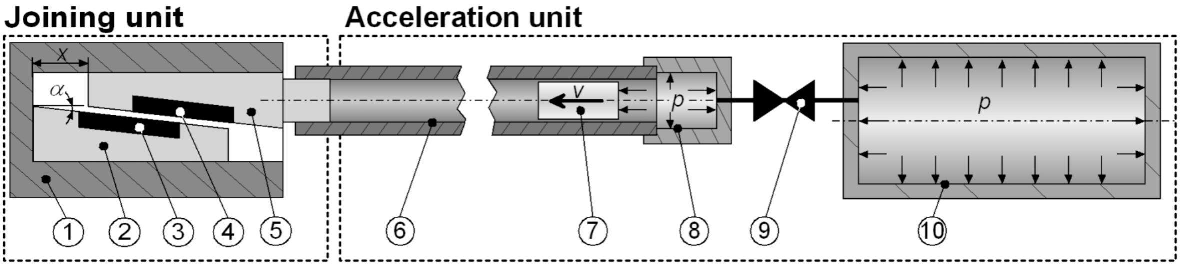
First approaches to use EMF in order to weld components were already realized in the nineteen-sixties [4]. At that time, the analysis focussed on the processing of tubular semi-finished parts while over the last years, investigations regarding sheet metal components have increasingly been carried out [5, 6]. For electromagnetic welding, the two joining partners are positioned at a defined distance and angle. Analog to explosive bonding, one partner is accelerated so that the two components approximate each other in the range of inter-atomic distance causing a bonding process on atomic scale. During collision, the workpieces are brought to a highly viscous liquid condition so that a wavy contact area is formed which can be laminar or turbulent [7]. The process is usually carried out at room temperature. Heat is produced only directly in the collision zone, i.e. there is no large-area heating of the workpiece. The weld seam is built within microseconds and no additive is required [8]. The feasibility and the potential of electromagnetic welding was already shown in several international publications, but, nevertheless, the fundamental correlations of part- and process-parameters responsible for the onset and formation of the connection development have not yet been investigated systematically [8, 9].

One explanation might be the complexity of the interdependencies between workpiece, tools/equipment, and process parameters during electromagnetic forming. The possibility to directly adjust process parameters is usually limited to the choice of the capacitor charging energy, while e.g. the temporal course and the local distribution of the magnetic pressure and the resulting forming velocity are significantly influenced by the process setup and the equipment.

2 Investigations on a Model High-Speed Joining Experiment

2.1 Principle and Experimental Setup

In order to allow a basic analysis of the significance and influence of separate parameters describing the collision, a model experiment was built up at the Institute of Materials Science, Leibniz Universität Hannover (IW). The principle setup of this high-speed joining device consists of a joining unit and a pneumatically driven acceleration unit as schematically depicted in Figure 1. At the process beginning, the pressure chamber (10) is pressurized and a mass (7) is positioned at the end of the acceleration tube (6) that is connected to the acceleration chamber (8). Opening a high speed valve (9) pressurizes the acceleration chamber and a section of the acceleration tube so that the mass is sped up through the tube and bounces against the dynamic support (5) carrying the dynamic joining partner (4). The impact leads to a sudden relative movement (x) in the magnitude of some millimetres between the joining partners, which results in a welding process, provided that the chosen process parameters are suitable. In this way, the impact velocity of the mass, which is expected to be a decisive aspect, can be influenced via the dimensioning of the mass and/or via an adaptation of the initial pressure in the pressure chamber.



1 - Mounting device
2 - Static support
3 - Static joining specimen (length: 30 mm; width: 8 mm; thickness: 0.1 mm)
4 - Dynamic joining specimen (length: 30 mm; width: 8 mm; thickness: 0.1 mm)
5 - Dynamic support (weight: 0.337 kg)
6 - Acceleration tube (length: 1000 mm)
7 - Mass (weight: 0.052 kg)
8 - Acceleration chamber
9 - High-velocity valve
10 - Pressure chamber (volume: 0.05 m^3; max. pressure: 1.6 MPa)

***Figure 1**: Principal setup of the high-speed joining device*

2.2 Evaluation of Welding Quality Achieved Using the Model Experiment

In order to investigate the influence of the impact velocity, experiments regarding the weldability of titanium and aluminum were carried out using the described high-velocity joining setup. For this purpose, aluminum (Al99.5) and titanium (TiAl6V4) samples with a size of 30 mm x 8 mm and a thickness of 0.1 mm were prepared by milling a rib profile. The surfaces were sanded in order to remove oxides and cleaned using acetone. The aluminum samples were positioned as static joining specimen in the static support while the titanium samples were mounted to the dynamic support which was positioned at a distance (*x* compare Figure 1) of 5 mm in relation to the static support. The application of different initial pressures caused impact velocities in the range of 10 m/s up to 130 m/s, while the impact angle α was 5° in all trials.

The evaluation of the joining quality was done at IW using metallographic methods. These investigations showed that for velocities in the range of 10 m/s up to 25 m/s, no bonding on atomic scale could be achieved, whereas in case of higher impact velocities, at least sections of the specimens were impact welded. In Figure 2 representative micrographs are shown. Here, the contact area of specimens, joined with an impact velocity of approximately 30 m/s, approximately 100 m/s, and approximately 130 m/s is compared and it is clearly shown that an increase of the impact velocity leads to a higher ratio of the welded area and contact surface, an effect which is comparable to the material behaviour during explosive welding (compare [10, 11]). Statistic interpretations of the microstructural data suggest a linear correlation between this ratio and the impact velocity in the regarded span of values (compare Figure 2), but to be able to make a more reliable conclusion, additional experiments are required.

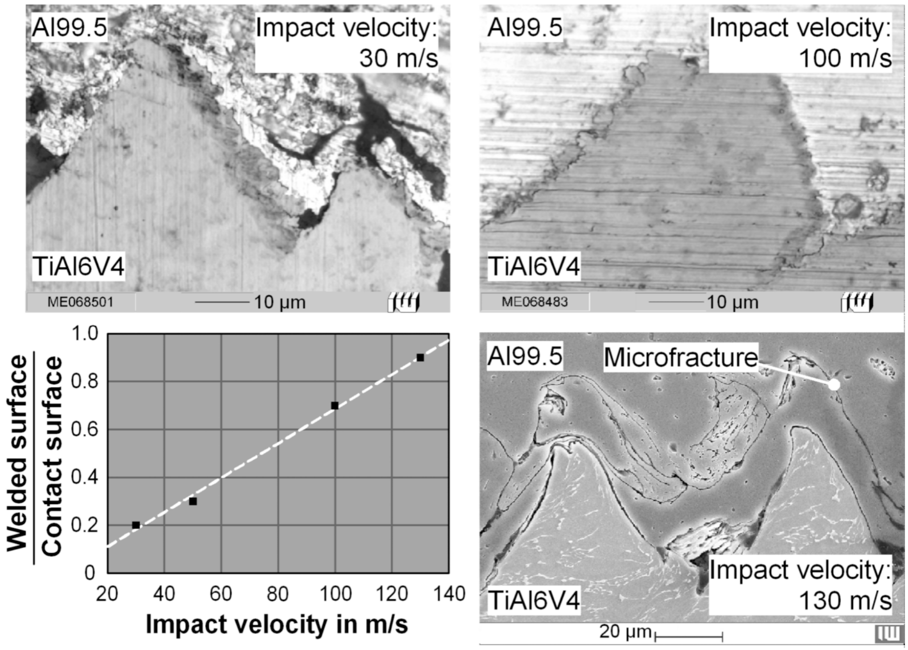


***Figure 2**: Influence of different impact velocities on the contact area of joined specimens*

However, when evaluating the welding quality, the proportion of the welded area is not the only criterion that has to be taken into account. Considering e.g. the intactness of the microstructure in the contact area, the micrograph of the joint area produced with an impact velocity of approximately 130 m/s shows microfractures in the aluminum running approximately parallel to the contact surface of the two joining partners. This effect indicates a deterioration of the joining quality, if a critical value of the impact velocity is exceeded. Thus, with respect to the microstructural investigations, it can be concluded that there exists an optimum value for the impact velocity that is high enough to maximize the ratio of the welded area and contact surface but not too high, in order to avoid any damage of the microstructure. For the regarded material combination and setup, this optimum is between 100 m/s and 130 m/s.

Another evaluation criterion for the welding quality is given by the resulting phases in the joining area. In order to determine if metalloid or intermetallic phases are formed in the joints produced by using the high-velocity joining device, polished and etched specimens were investigated by means of an energy dispersive x-ray (EDX) and microanalysis. This method allows the detection of the element distribution in the welding area. As shown in Figure 3 the titanium and the aluminum base material can be distinguished and an extremely thin titanium-rich transition area of less than 1 µm thickness can be detected in-between the two. According to [12], intersection layers consisting of different phases in this magnitude can be regarded as subcritical and will not deteriorate the joint quality significantly.

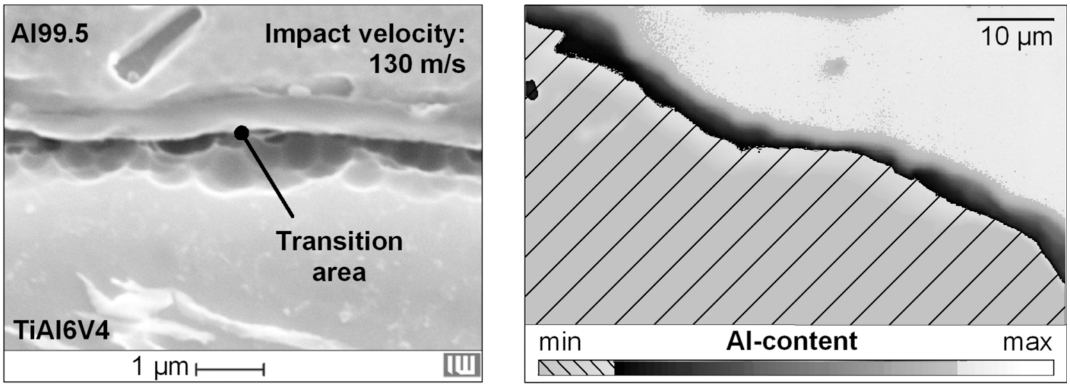


***Figure 3**: Phases in the transition area of joined aluminum and titanium samples*

3 Investigations on Electromagnetic Forming

3.1 Setup and Process Dimensioning of the Electromagnetic Compression

In the next step, comparative technological experiments applying the electromagnetic compression process were carried out. For this purpose, aluminum (Al99.5) tubes with a diameter of 20 mm and a wall thickness of 1 mm, produced by turning, were sanded in order to remove oxide films and cleaned in acetone using an ultrasonic cleaning device. Titanium (TiAl6V4) tubes with an outer diameter of 15 mm and a wall thickness of 2.5 mm were prepared in an analog manner and the aluminum and the titanium tubes were positioned coaxially in the compression coil so that the initial gap width between the two joining partners was 1.5 mm.

In order to achieve an impact velocity of approximately 100 m/s, which was determined as a desirable value in the model experiments, suitable process parameters have to be chosen. As already mentioned, the capacitor charging energy is the only directly adjustable variable. For this reason, preparative investigations on the correlation between this value and the resulting deformation behaviour for the regarded setup were carried out. Exemplary results are shown in Figure 4.

In free forming operations (i.e. without a joining partner inside), the time-dependent radial displacement of the smallest cross section of the aluminium tube, which is typically located in the middle of the tool coil, can be quantified applying an optical measurement system based on the shadowing principle as described in [3]. By differentiating the displacement over time curve, the time dependent forming velocity can be determined and it can be associated to the according radial displacement. Provided that the parameters of the workpiece and the applied equipment (tool coil and forming machine) are the same, it can be assumed that the impact velocity of the middle cross section during an electromagnetic joining process is approximately the same as the forming velocity in a free electromagnetic compression at that special radial displacement (here 1.5 mm). However, this measurement technique is limited to recording the displacement of the smallest cross section of the tube, and the measurement uncertainty rises with increasing workpiece deformation and the related increasing wrinkling effect during free electromagnetic compression (compare photos in Figure 4). For the current investigations, it can be concluded that in case of an initial gap width of 1.5 mm between the joining partners, the impact velocity of the smallest cross section amounts to 100±15 m/s in case of 500 J charging energy and 80±10 m/s in case of 400 J.

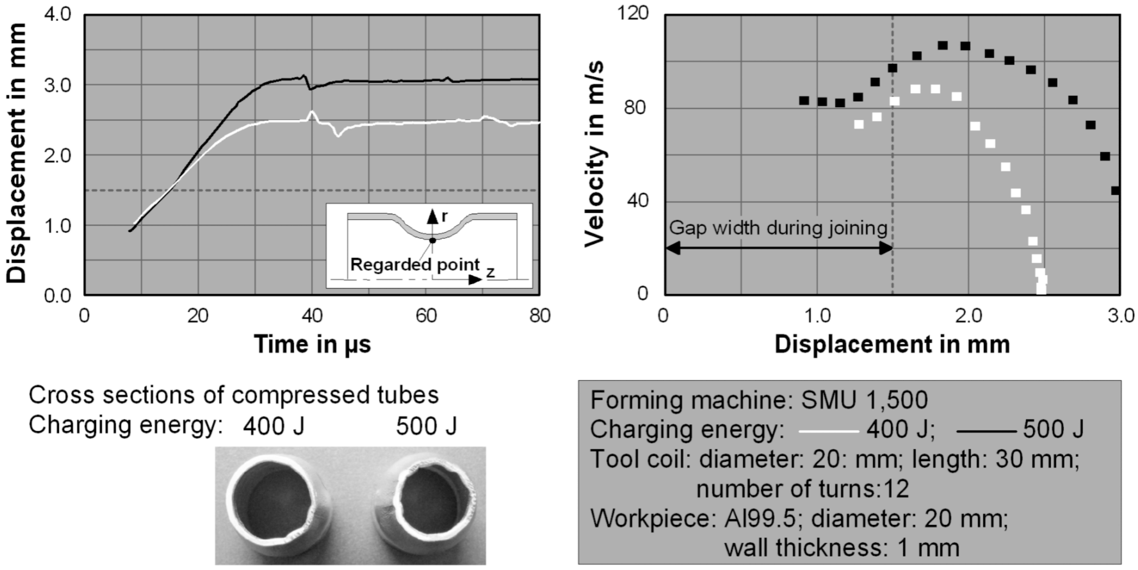


***Figure 4**: Displacement courses and corresponding radial velocities in free electromagnetic compression experiments applying different charging energies*

3.2 Evaluation of Welding Quality Achieved by Electromagnetic Forming

Considering these measurements, first electromagnetic joining experiments with a capacitor charging energy of 500 J and comparative tests applying higher energies of 1,000 J and 1,500 J were performed. It turned out that the charging energy of 500 J caused a joint merely basing on force-fit, i.e. an elastic plastic bracing of tube and mandrel (compare [14]) and no bonding on atomic scale occurred. However, in case of higher charging energies (1,000 J and 1,500 J), welding could be realized at least locally.

Micrographic investigations done by IW show that considering the axial length of the interface between aluminum and titanium, zones of different joint qualities can be identified, which are representatively shown in Figure 5. For both charging energies, a minor joint quality (characterised by gaps between the joining partners) occurs in the middle of the compression area ($z \approx 0$ mm), although small adhesions of material particles welded on each other can be found. The length of this region spans 4 mm in both directions from the middle of the compression area in case of a charging energy of 1,000 J, and 2-3 mm in both directions in case of 1,500 J charging energy. This zone is directly followed by an area of high joining quality characterized by a wavy interface between the two materials. In case of 1,500 J charging energy, this zone continues to the end of the compression area, i.e. for a length of approximately 10 mm, and the transition between aluminum and titanium is extremely narrow (width 0.5-1 µm), while in case of 1,000 J charging energy, the length of this area is only about 2 mm and also the transition is slightly wider (2-3 µm). Subsequent to this high-quality joint zone, another region, characterized by a strongly inhomogeneous layer in-between the aluminum and the titanium, can be identified in case of the lower charging energy. This area extends to the end of the compression zone and, again, indicates an inadequate joining quality.

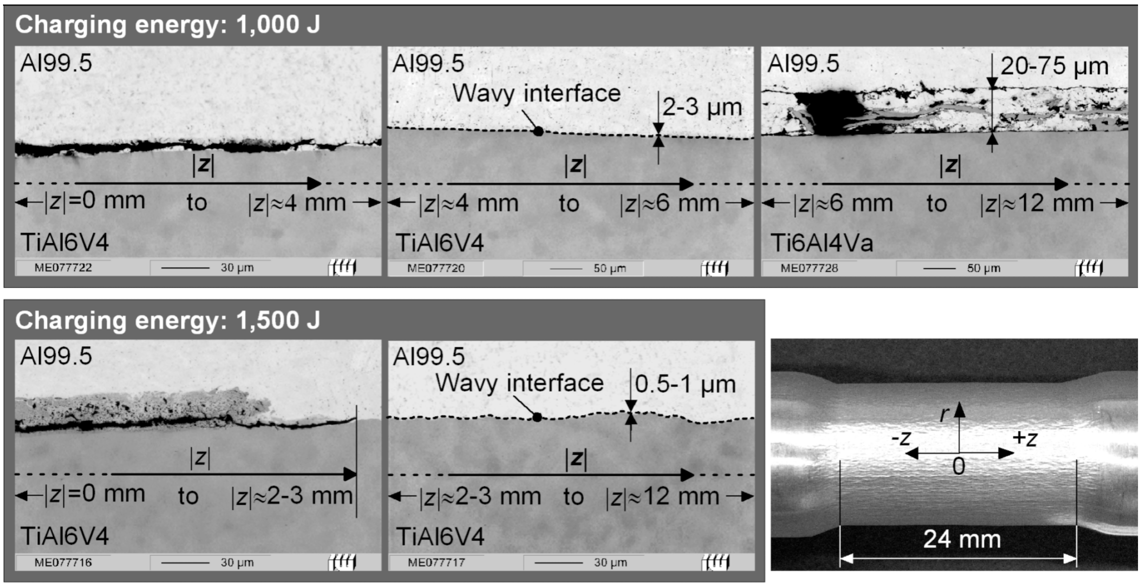


***Figure 5**: Microstructural state of joints produced by EMF*

One possible explanation for the described condition of the joints could be given considering the axial distribution of the workpiece velocity $\vec{v}_{wp}$ associated to the corresponding impact angle α_{impact}. In Figure 6, the qualitative axial distribution of the impact velocity and the angle between the joining partners, determined by an FE-analysis, is shown. Considering the experimental results described above, the impact velocity for a charging energy of 500 J is in the range of 100 m/s for z-values close to the centre of the compression zone (i.e. in the region of $z \approx 0$ mm) and decreases for higher z-values. On the other hand, it is obvious that especially for small z-values the impact angles are much higher during the electromagnetic compression tests than the 5° chosen for the model experiments. This derivation between the technological tests and the model experiment is a reasonable explanation for the absence of any bonding on atomic scale in case of using 500 J charging energy during electromagnetic compression.

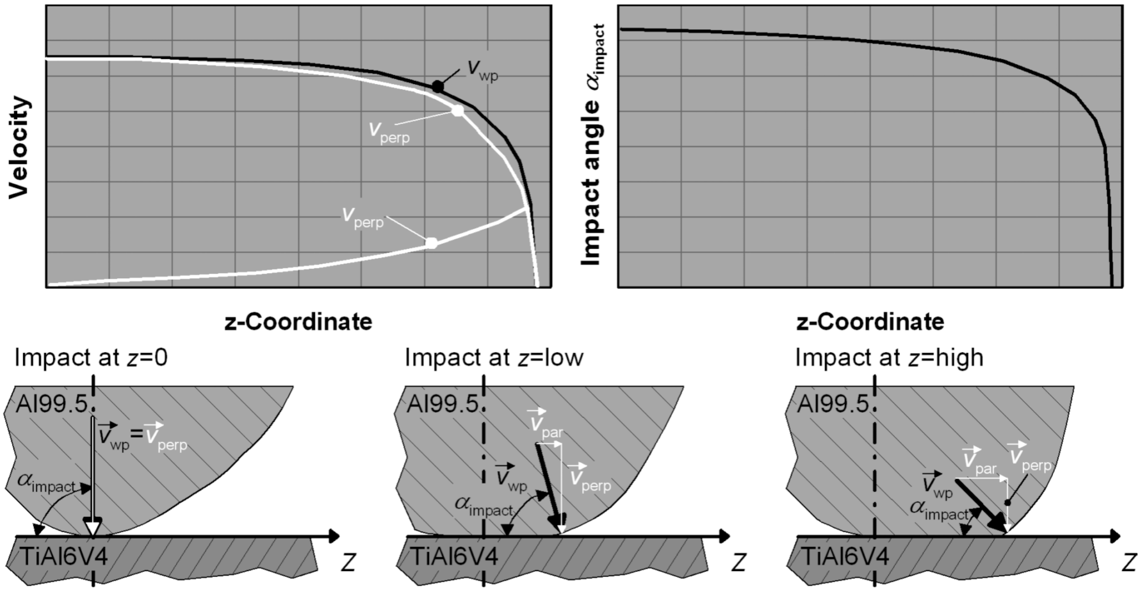


Figure 6: Distribution of impact velocity and angle along the workpiece axis

Regarding the condition of the joints in case of higher charging energies and the described zones of different welding quality, a possible explanatory approach can be given considering the velocity components parallel $\vec{v}_{par}$ and perpendicular $\vec{v}_{perp}$ to the joining interface and the surface of the inner joining partner, here the titanium tube, respectively. These values can be calculated on the basis of the local workpiece velocity and the corresponding impact angle. They are also qualitatively shown in Figure 6.

In the center of the compression area, the highest workpiece velocity, which is much higher than 500 m/s, here, occurs. Due to the extremely high impact angle (90° in the center) the corresponding perpendicular velocity components are high, too, while the parallel ones are very low (0 m/s in the center). This means that the high impact forces and pressures, which are mainly determined by the perpendicular velocity, are very high, but there the relative movement between the joining partners, which depends on the parallel velocity components are extremely low. This combination seems to be unsuitable for the generation of proper welds. For higher values of $|z|$, the workpiece velocity decreases and, due to the likewise decreasing impact angle, the parallel velocity component and thus the relative movement between aluminium and titanium rise. Thus, matching conditions, resulting in the described high joining quality, could be realized. In case of the lower charging energy (1,000 J), the combination of low impact angles and lower workpiece velocities lead to lower perpendicular and parallel velocity components, compared to the sample compressed with 1,500 J. This, again, seems to be a disadvantageous parameter constellation, and an unfavourable welding quality for $|z|$-values of 6 mm and higher occurs. This approach suggests that not only high workpiece velocities are required for the generation of good welding properties, but also matching conditions of local impact velocity and angle have to be granted. In order to determine such parameter constellations, the model experimental setup can be used, because thereby the impact velocity and impact angle can easily be modified separately.

4 Summary and Outlook

Summarizing, it can be said that the model high-velocity joining setup as well as the electromagnetic compression process in general are suitable for impact welding aluminum (Al99.5) and titanium (TiAl6V4). In the model experiment, the impact is realized between small rectangular samples applying a selectable impact angle and velocity. Microstructural investigations have shown that an optimum value of the impact velocity can be identified, which is high enough to maximize the ratio of welded area and contact surface but not too high, in order to avoid any damage of the microstructure. In the regarded case, this optimum is in the range of 100 m/s for an impact angle of 5°. Investigations of the transition area between aluminum and titanium have shown that this area is extremely thin, proving an advantage of the impact welding process in comparison to thermal joining technologies.

In addition, technological joining tests were carried out using the electromagnetic compression setup. A microstructural evaluation of the resulting welding quality has shown that it is inhomogeneous along the tube axis. An explanation for this effect is suggested, considering the velocity components parallel and perpendicular to the impact surface, which can be calculated on the basis of the impact velocity value and the angle between the joining partners. This approach proposes that in order to establish a proper weld, high workpiece velocities only are not sufficient, but also matching parameter conditions, taking the distribution of the impact velocity and angle along the workpiece axis into account, have to be provided.

For the determination of suitable parameter constellations, the model experiment is advantageous, because here, impact velocity and impact angle can be modified easily and, what is even more important, separately. Thus, numerous additional model experiments are planned, which will also involve the use of different specimen materials and thicknesses. First spot checks applying samples with a thickness of 500 µm have already shown that in this case higher impact velocities are required than in case of the 100 µm thick specimens. In order to transfer the results from these investigations to the electromagnetic welding process, parallel research work regarding the process analyses of this technology is planned. In order to determine the axial distribution of the impact velocity and angle quantitatively, a coupled electromagnetic and mechanic finite element analysis (FEA) following the style of BROSIUS as described in [13] shall be accomplished. Thus, both approaches will be exploited complementarily in order to allow a target-oriented process dimensioning for the electromagnetic welding technology.

References

[1] *Kleiner, M.; Geiger, M.; Klaus, A.:* Manufacturing of Lightweight Components by Metal Forming, Annals of the CIRP "Manufacturing Technology", 53rd General Assembly of CIRP, Vol. 52/2, Montreal, Kanada, August 24-30, 2003, pp. 521-542.

[2] *N.N.:* Hinweise zum Schweißen von Titan und Titanlegierungen, http://www.isoarc.ch/Info_Datenbank/Hinweise_zum_schweissen_von_Titan.pdf Deutsche Titan, 2000.

[3] *Beerwald, C.:* Fundamentals for Process Dimensioning and Design of Electromagnetic Forming (in German), PhD.-Thesis, Dortmund, Germany, 2004.

[4] *Lysenko, D. N.; Ermolaev, V. V.; Dudin, A. A.:* Method of pressure welding, Patent US 3520049, 1970.

[5] *Aizawa, T.; Okagawa, K.; Henmi, N.:* Impulse magnetic pressure seam welding of aluminium, copper and steel sheets, Proceedings of the 7th Int. Conf. on Theory of Plasticity (ICTP), 28.-31. October 2002, Yokohama, pp. 1687-1692, 2002.

[6] *Aizawa, T.:* Magnetic pressure seam welding method for aluminium sheets, Journal of Light Metal Welding and Construction, Vol. 41-3, pp. 20-25, 2003.

[7] http://www.iwf.tu-berlin.de/fachgebiete/wzm/forschung/forschung8/schweissen, state: 14.01.2008.

[8] *Shribman, V.; Tomer, Y.:* Magnetic pulse technology for improved tube joining and forming, In: Tube & Pipe Technology, 2006, S. 91-95.

[9] *Kore, S. D.; Date, P. P.; Kulkarni, S. V.:* Effect of process parameters on electromagnetic impact welding of aluminum sheets (2006), doi: 10.1016/J.ijimpeng.2006.08.006.

[10] *Deribas, A. A.:* Strengthening mechanisms and Explosive welding, Novosibirsk, 1980, p.222.

[11] *Grignon F., Benson D., Vecchio K.S., Meyers M.A.:* Explosive welding of aluminum to aluminum: analysis, computations and experiments, Int. J. of Impact Engineering 30, pp. 1333–1351, 2004.

[12] *M. Kreimeyer, F. Wagner, I. Zerner, G. Sepold:* Laser beam joining of aluminium with titanium with the use of an adapted working head (in German), Löt '01, Aachen, DVS-Berichte, Band 212, DVS-Verlag Düsseldorf 2001, pp. 317-321.

[13] *Brosius, A.:* A method for the Determination of Strain-Rate-Dependent Flow Curves by Means of Electromagnetic Tube Forming and Iterative Finite-Element-Analyses, (in German), PhD.-Thesis, Dortmund, Germany, 2005.

[14] Al-Ahmad, N.: Das Fügen rotationssymmetrischer Formelemente durch Umformen mit Impulsmagnetfeldern. Dissertation Ingenieurhochschule Zwickau 1980.