Process Model and Design for Magnetic Pulse Welding by Tube Expansion[*]

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Abstract

In this paper a design methodology for magnetic pulse welding processes is presented. To examine fundamental correlations of part- and process-parameters, a model experiment is used. Different impacting conditions are tested and the effect on the joint quality is evaluated by metallographic analysis. Conclusions regarding suitable impacting parameters are drawn. Electromagnetic expansion tests are carried out in parallel with the aim of adjusting the impacting parameters via typical process parameters. Therefore, the forming velocity is measured online and the impacting angle is varied via the geometry of the joining zone. To verify that the tendencies observed in the model experiment occur also in magnetic pulse welding, the influence of the impacting parameters on the joint quality is investigated for magnetic pulse welded tubes, too. Finally, the results of both investigation paths are combined and serve as a basis for target-oriented design of magnetic pulse forming processes.

Keywords

Magnetic pulse welding, model experiment, metallographic evaluation

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1 Introduction

In these days an enterprise's reputation and position at the market does not depend on the product quality and image exclusively but politics and society demand for more efficient and economical products especially because of the steadily shrinking resources and for reasons of environmental protection [1]. These requirements concern the whole life cycle of a product [2]. Consequently, the ecological footprint, which evaluates the ecological effects of an activity or product, has become an important characteristic for many institutions and companies [3].

This affects especially but not exclusively the mobility industry. Here, the development of new and improved driving concepts as hybrid and electric ones are an important step to reduce emissions, but also the consequent implementation of lightweight construction concepts significantly contributes to reducing the ecological footprint [1]. These concepts include among other aspects weight reduction via substitution of conventional materials by typical light weight materials as e.g. light metal alloys and fibre-reinforces plastics. According to [4], maximum effect can be achieved if the best fitting material with regard to the special load and function is applied for every component. Although there are some impressive examples for multi-material design as the Audi R8 Spyder and the Boeing 787 Dreamliner, such implementation examples are far away from being the standard. One reason is that the joining of dissimilar materials still leads to severe problems when applying conventional i.e. usually thermal joining technologies as welding and soldering. While connections of metal to non-metal components are normally not possible at all, even joining of some similar and especially of dissimilar metallic components entails difficulties and can lead to microstructural defects as softening or formation of oxidic or intermetallic phases [5].

To avoid these problems, solid state welding techniques can be applied, because they are carried out without large heating and melting of the workpiece. Among these techniques magnetic pulse welding is a promising example, because it can be used for connecting profile shaped as well as sheet metal components of similar and dissimilar metallic materials at room temperature and without additives and it can be automated easily [6].

2 Principle of and Design Strategy for Magnetic Pulse Welding

Analogue to electromagnetic forming, magnetic pulse welding uses the energy density of pulsed magnetic fields to exert a so-called magnetic pressure to workpieces ideally made of an electrically highly conductive material and accelerate them accordingly without mechanical contact. More detailed information about the process principle and variants of electromagnetic forming is given e.g. in [6]. In magnetic pulse welding the accelerated workpiece approximates the joining partner at very high velocity in the magnitude of 10^2 m/s to atomic distance. During collision the joining partners behave like highly viscous fluids and – provided that the process parameters are adequately chosen – an intermetallic joint characterized by a typically but not necessarily wavy weld seam results. Magnetic pulse welding was mentioned in literature for the first time in the patent by Lysenko et al. [7].

To allow metallic bonding, similar to explosive welding also in magnetic pulse welding the impacting parameters – i.e. especially the impacting angle and the impacting velocity – are of significant importance. If they are properly chosen, a so-called jet effect occurs leading to a self cleaning of the joining partners' surfaces and thus to highly reactive surfaces, which abet the formation of a weld.

Despite of the process benefits, up to now industrial use is limited to a few applications. This is probably due to the fact that currently there are no design guidelines for magnetic pulse welding neither considering the components nor the process itself. The major obstacle complicating the generation of such guidelines is that in magnetic pulse welding the impacting parameters influencing the formation of the weld cannot be adjusted directly but result from a complicated set of interacting process-, equipment-, and workpiece-parameters. To handle this complex problem, the design strategy suggested in [8] and [9] is applicable.

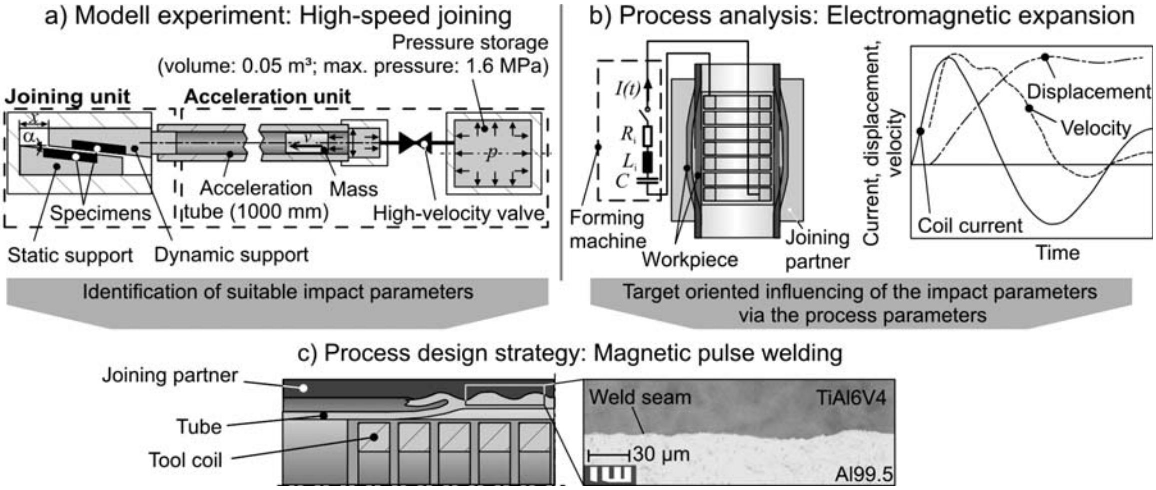


***Figure 1**: Process analysis and design strategy for magnetic pulse welding [9]*

As illustrated in Figure 1 in this strategy the problem is subdivided according to two parallel analysis paths and a subsequent synthesis:

a. Suitable impacting parameters are identified at the Institute of Materials Sciences, Leibniz Universität Hannover using a model experiment allowing direct and separate adjustment of impacting angle and velocity.
b. Strategies for adjusting the impacting parameters via the process parameters (including equipment and workpiece related parameters) are deduced from a process analysis carried out at the Institute of Forming Technology and Lightweight Construction, Technische Universität Dortmund. Considering electromagnetic tube compression and sheet metal forming, these correlations have already been largely investigated [10-12], so that in the current work the focus is set on electromagnetic expansion.
c. The results of these analyses are combined and conclusions regarding the process design strategy for magnetic pulse welding are drawn in cooperation of the two institutes.

3 Model experiment

The setup of the model experiment for high-speed joining is shown in Figure 1a. A detailed description of the setup and the process principle can be found e.g. in [9], so that in the following only the most relevant aspects with regard to the impacting parameter adjustment are described before focussing on the experimental results.

3.1 Adjustment of the impacting parameters

In the model experiment the specimens are fixed to the static and the dynamic support – two tapered components whose tapering angle directly corresponds to the impacting angle. Thus, the impacting angle can be varied stepwisely by using different supports.

The impacting velocity is the dynamic support's velocity during collision. It can be adjusted via the pneumatic drive of the machine and depends on the applied mass. The energy source in the setup is pneumatic pressure storage. Opening the high-velocity valve releases the pressure und accelerates a mass to a velocity v_m. The mass flies through an acceleration tube until it impacts to the dynamic support. The kinetic energy of the mass is partly transferred to the support, which is accordingly accelerated to a velocity v_s and impacts with the static support. The transfer of the kinetic energy and the according impulse depends on the mass properties. If the mass weight is too small it bounces from the dynamic support without significantly accelerating it. Therefore, in many cases increasing the mass weight improved the welding quality. Moreover, the mass material must not be too soft because otherwise the kinetic energy of the mass is transferred to deformation energy. For example in case of lead masses – which appeared to be well-suited because of their high density and weight – large plastic deformation of the mass occurred, and consequently the efficiency of the support acceleration was reduced. On the other hand, the acceleration tube might be damaged if the mass is too hard. Experience has shown that in many cases brass is a well suited mass material. During the experiments the impacting velocity was measured by an optical technology [9].

3.2 Investigation results

In the experiments different material combinations have been regarded. The impacting angle and velocity were varied and the resulting joints were evaluated by metallographic analyses. In the following, general influences are shown on the basis of representative joining results and suitable impacting parameters for different material combinations are listed in Table 1. Thus, the essential investigation results of this analysis path are excerpted.

In Figure 2 the influence of the impacting angle is shown on the example of different copper-copper and aluminium-aluminium joints. It can be seen especially in the first row, which gives a good overview of nearly the complete joining area, that an impacting angle of 3.5° leads to the best joining result while the weld quality is lower in case of 2° and 6° angles. In the following rows a larger magnification was used to give a more precise view of the weld seam. However, in these pictures it was not possible to consider the complete joining area. Therefore, the area of highest welding quality was chosen in order to compare different specimens.

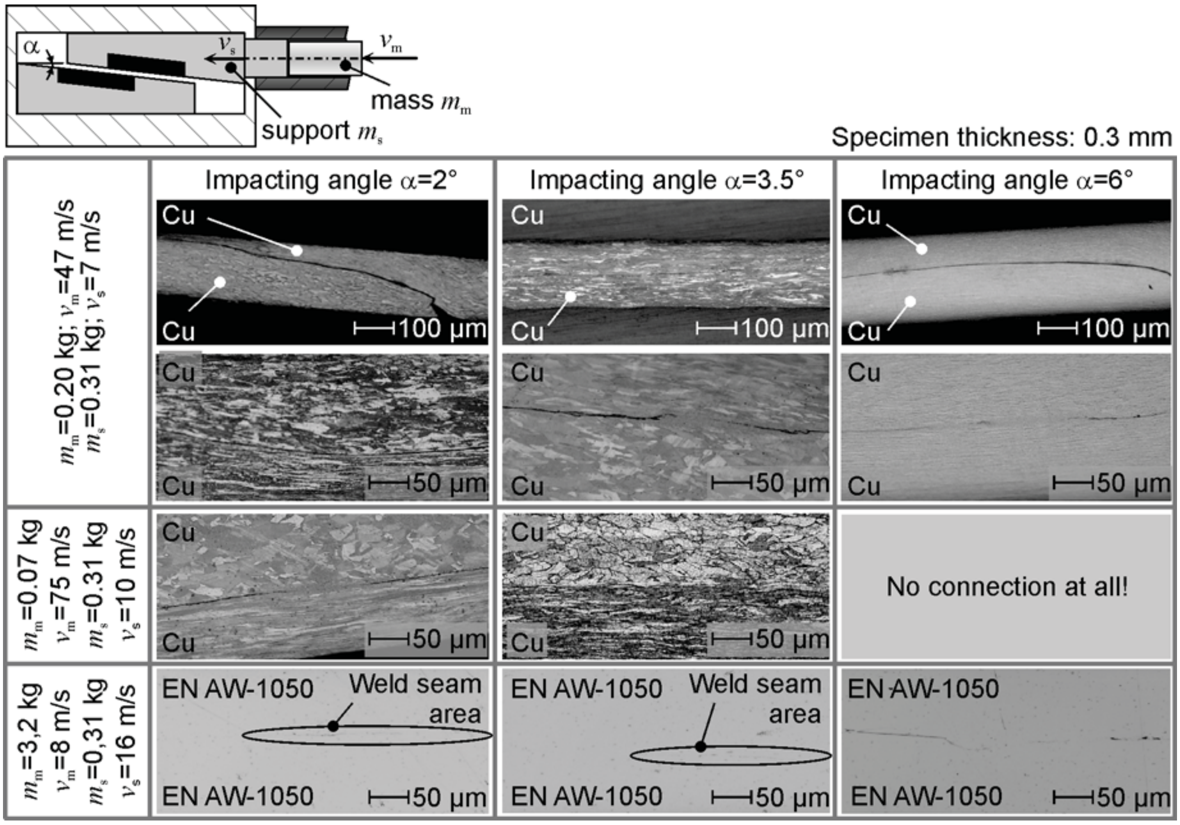


***Figure 2**: Exemplary joining results achieved with the model experiment*

Workpiece material		Mass parameters			Support parameters		Impacting angle	Welding quality*
Specimen I	Specimen II	Material	Weight m_m in kg	Velocity v_m in m/s	Weight m_s in kg	Velocity v_s in m/s		
Copper annealed	Copper annealed	Brass	0.2	47	0.31	7	3.2	+
Copper hard	Copper annealed	Brass	0.056	89	0.31	6	3.2	+
Copper hard	Copper hard	Brass	0.2	47	0.31	7	6	o
EN AW-1050	EN AW-1050	Steel	3.2	8	0.31	16	3.2	++
DC06 hard	EN AW-6060	Steel	3.2	8	0.31	16	3.2	o
DC06 annealed	EN AW-6060	Lead	0.59	27	0.31	16	3.2	+
DC06 annealed	TiAl6V4	Brass	0.56	49	0.25	29	3.2	+

* welded area: ++: >75-100% +: >50-75% o: >25-50% -: >0-25% welded --: no welding at all

***Table 1:** Impacting parameters and resulting weld quality for different specimen materials*

Comparing the rows two and three shows that higher support velocity can influence the welding quality in different directions depending on the impacting angle. For a small impacting angle (α=2°) a slight increase of the impacting velocity (v_s) from 7 m/s to 10 m/s has no significant influence on the joint quality. Contrary, for the 3.5° angle the same slight increase of the velocity effects a remarkable improvement of the joint quality and for the 6° angle it has a negative influence to that extend that a welding is no longer possible.

The last row shows that the effect of the impacting angle is similar in case of aluminium-aluminium joints but it is much more indistinct, here. Additional investigations proofed the same for differently heat-treated copper and for aluminium-steel joints.

Moreover, the comparison of the different materials shows that welding softer materials is easier, requires lower impacting velocities, and leads to higher weld qualities than harder material combinations. Welding a soft material to a hard one resulted in a middle-rate quality as shown in Table 1.

4 Electromagnetic Expansion

The electromagnetic expansion tests were carried out using a pulsed power generator SMU1500 by Puls-Plasmatechnik, Dortmund featuring maximum charging energy of 1.5 kJ, maximum charging voltage of 6.1 kV, a capacitance of 80 µF, an inner inductance of 75 nH and an inner resistance of 6.8 mΩ, resulting in a short circuit frequency of approx. 67 kHz. An expansion coil by Poynting GmbH, Dortmund was mounted to this machine. The coil has an outer diameter of approx. 36 mm and consists of 13 turns distributed over a length of 27 mm. The specimens were tubes made of EN AW-1050 with a nominal outer diameter of 40 mm, a nominal wall thickness of 2 mm, and a nominal length of 100 mm joined to hubs of different geometries made of EN AW-1050.

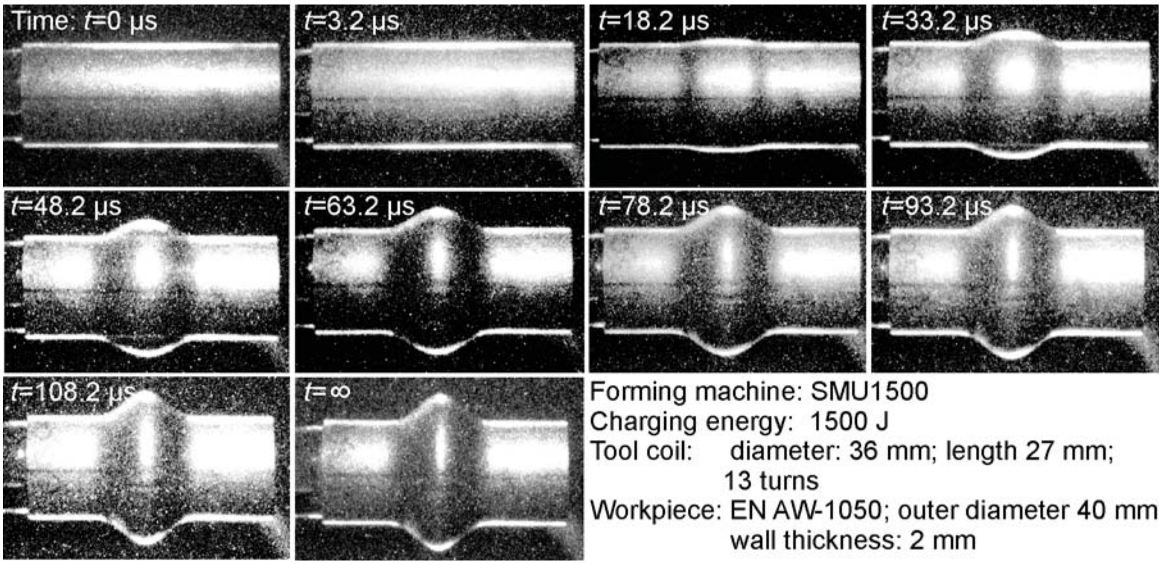
4.1 Determination of Current, Magnetic Pressure, Displacement, and Forming Velocity

Before focussing on magnetic pulse welding, the free electromagnetic expansion process (i.e. without a joining partner) is investigated with the aim of analyzing correlations between adjustable process parameters and resulting impacting parameters. The impacting velocity corresponds to the forming velocity at the moment of collision and the impacting angle depends on the workpiece contour at the moment of impact. Considering free forming is a passable simplification, here, because until collision the workpiece in a welding process will be deformed in the same way as in free forming.

The workpiece displacement was determined using two complementary optical measurement techniques: a high-speed camera HSFC-PRO by PCO and a measurement based on the partial shadowing of a light beam due to the workpiece deformation [12]. The strength of the high-speed camera is that information about the complete workpiece contour can be gathered at discrete moments while the shadowing principle leads to a continuous measurement of the displacement of individual surface points. For verification purposes the final workpiece contour was measured using a coordinate measurement machine after the forming. The forming velocity was calculated by differentiating the displacement-time-curves.

The camera system HSFC-PRO consists of four channels and each of them can take two pictures. Moreover, taking additional photos before and after forming is possible. Thus, a complete set of photos consists of ten pictures as exemplarily shown in Figure 3.

In the following the notation $t=\infty$ is used to indicate measurement data taken after the forming process is finished because an exact temporal correlation is not possible.



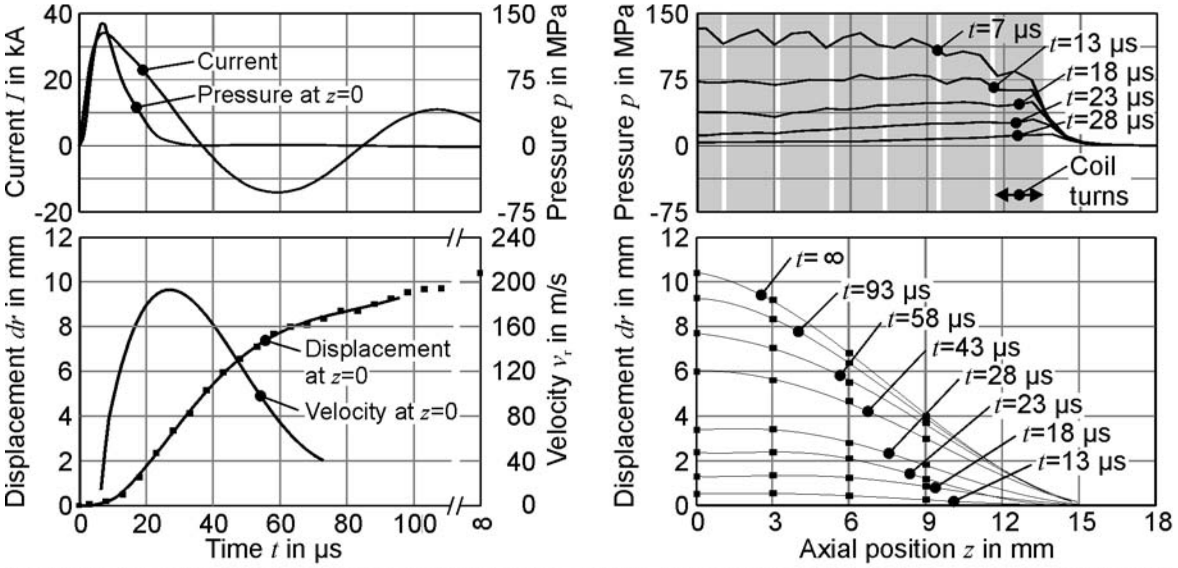
Forming machine: SMU1500
Charging energy: 1500 J
Tool coil: diameter: 36 mm; length 27 mm; 13 turns
Workpiece: EN AW-1050; outer diameter 40 mm wall thickness: 2 mm

***Figure 3**: Set of high-speed photos taken during an electromagnetic expansion process*

To get more detailed information about the forming stages it is possible to focus on a shorter time interval and compose the complete deformation course from pictures taken in different experiments. Tests have shown that the repeatability is sufficiently high to justify this procedure especially in the time-sequence relevant with regard to the subsequent joining tests. In case of large deformations and especially if cracking occurs, material inhomogeneities in the semi-finished parts influence the contour significantly, so that the repeatability is not guaranteed any longer.

In Figure 4 exemplary measurement results of the acting loads – characterized by coil current and resulting magnetic pressure – and the resulting workpiece deformation – quantified via displacement and velocity of the workpiece surface – are shown. According to [12] the magnetic pressure can be used as an abstract description of the acting loads which does not include any equipment- or setup-related parameters. The calculation of the magnetic pressure is based on a finite element simulation of the magnetic field carried out with the special purpose FE-programm FEMM by David Meeker [13], here. To consider interdependencies between the magnetic pressure and the workpiece deformation, the pressure was calculated for a short time-interval only. Then the workpiece contour was updated according to the measured deformation.

By comparing the temporary development of the curves it can clearly be recognized that due to the strong deformation of the workpiece the pressure collapses faster compared to the first half-wave of the coil current – a behaviour well known from electromagnetic sheet metal forming (e.g. [6, 12]) – and that no noteworthy pressure is exerted during the subsequent half waves of the current. As long as the pressure acts, the workpiece is accelerated. After the decay of the pressure inertia effects continue the deformation but at decreasing velocity. Considering the forming stages, it can be recognized that the displacement of the surface points in the middle area of the coil (i.e. for z-values of about 0-6 mm) is almost parallel to the initial geometry as already observed in [9] for a different expansion coil and another workpiece material. Further measurements have shown that the general tendencies described above can also be noticed for other charging energies. As expected, the maximum values for the current and the pressure as well as for the displacement and the velocity increase with increasing charging energy.



Forming machine: SMU1500; Charging energy: 1500 J; Tool coil: diameter: 36 mm; length 27 mm; 13 turns; Workpiece: EN AW-1050; outer diameter 40 mm; wall thickness: 2 mm

***Figure 4**: Exemplary acting loads and according workpiece deformation*

4.2 Joining by Electromagnetic Expansion

To verify that the tendencies observed during the experiments with the model setup can be transferred to the electromagnetic welding, technological joining experiments were carried out. In these tests the setup for the free electromagnetic forming was completed by hubs made of EN AW-1050, which were positioned in the middle and oriented coaxially with the tool coil and the tubular specimens (compare Figure 5). To influence the impacting velocity and angle, the capacitor charging energy was varied and different hub geometries were regarded. Hub angles of 0°, 3° and 5° were considered. Impacting velocities in the range of approx. 100 m/s up to approx. 200 m/s could be realized in the centre of the joining zone, i.e. in the region close to z=0. In this area the impacting velocity corresponds to the according forming velocity at the relevant gap width measured during the free forming experiments. To ease the interpretation of the measurement data, the forming velocity is plotted over the displacement in Figure 5. For higher z-values significant deceleration effects have to be considered due to the partial contact of tube and hub in the centre area so that the velocity measurement from the free forming cannot be transferred to the joining process, in those areas.

After joining, all specimens were axially cut by eroding to avoid influencing the potential weld seam. It turned out that for nearly all parameter combinations at least local welding took place somewhere in the specimen preventing a direct complete separation of tube and hub after cutting. However, the subsequent micrographic analysis revealed significant differences in the welding quality – i.e. mainly the extension of the welded area – and thus the specimens were rated according to their individual performance.

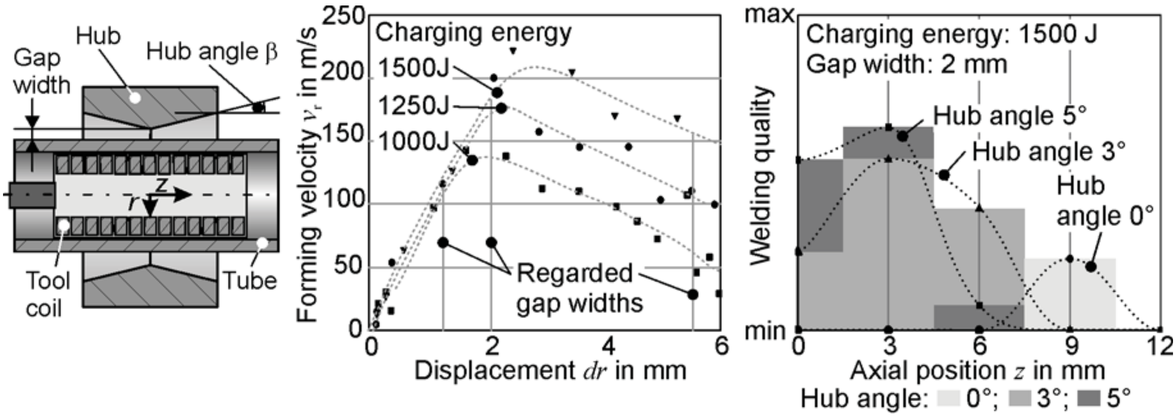


***Figure 5**: Setup for electromagnetic welding tests, impacting velocity depending on gap width and welding quality for different hub angles*

Based on this classification it was proofed that similar to the model experiments also here the best result were achieved for the hub angle of 3°. In Figure 5 the percentage of the welded area in the regarded cross sections is plotted over the axial length of the joined specimens exemplarily for an impacting velocity of approx. 186 m/s at z=0 mm. In doing so, the overall welding quality can be evaluated by trend by comparing the area under the individual curves. Additionally, information about the position of the welded area is contained. In this special case the overall quality of the hub with the 5° angle is only slightly lower than the one with the 3° angle but there are several other examples where this difference is much more pronounced. However, here the dependency of the weld position on the hub angle is very distinctive. It is obvious that in case of the 0° hub angle the welded area is located close to the end of the tool coil. Taking into account the forming stages presented in Figure 4 it can be recognized, that in this area the contour of the deformed workpiece is not parallel to the initially cylindrical geometry any longer and thus the impacting angle does not correspond to the 0° hub angle but it is wider. With increasing hub angle the position of the weld is moved towards the middle of the coil although the curves still feature a local minimum at z=0 mm.

Considering the impacting velocity, no clear tendency can be deduced from these experiments although earlier investigations have shown that an optimum velocity leading to the best welding quality exists [8, 9]. This suggests that at least in the range of values regarded here and for this specific material combination the impacting angle seems to be much more decisive than the velocity.

5 Summary and Conclusion

A process design strategy for magnetic pulse welding suggested in [8, 9] has been verified for further materials and process parameters. The influence of different impacting parameters – more precisely the impacting angle and velocity – was investigated fundamentally by a model experiment and suitable impacting parameters for welding different material combinations have been identified. In parallel the electromagnetic expansion process was analyzed to reveal basic correlations between the adjustable process parameters, the acting loads – characterized by the coil current and the magnetic pressure –, the resulting workpiece deformation – characterized by the forming stages and the velocity –, and the according impacting parameters during magnetic pulse welding. The comparison of model experiment and technological investigations shows that the general trends regarding the impacting parameters' influence on the weld are transferable and concerning the impacting angle even the quantitative values are similar. However, the required impacting velocities during magnetic pulse welding are significantly higher than in the model experiment. This might be attributed to the differencies in the specimen size and the impacting mass. In the model experiment specimen size and welding zone are drastically smaller, but the impacting masses – also including the mass of the supports – are much higher.

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