Influence of Axial Workpiece Positioning during Magnetic Pulse Welding of Aluminum-Steel Joints*

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Abstract

Magnetic Pulse Welding (MPW) offers a method to economically join similar and dissimilar metals without the need for external physical or chemical binders, while avoiding the adverse heating effects seen in many welding techniques. MPW allows for the fabrication of joints via the harnessing of Lorentz forces, which result from discharging a current pulse through a coil. In the process an outer piece (flyer) is accelerated onto an inner piece (parent), and welding is achieved using propagating impact fronts. There are several geometrical factors to be considered including the flyer-coil distance, the parent-flyer distance, as well as the axial relationship between flyer and coil (working length). Various shapes of the front are possible and each configuration has its own advantages and drawbacks. The goal of this work is to show not only how the aforementioned parameters are related, but also ways to optimize front propagations, which are vital to the welding result. This is done primarily by determining the influence of the working length of tubular MPW specimens. It is shown that for steel-aluminum joints in the given arrangements, three different front regimes exist, which are related to geometrical factors. These results are especially useful to avoid seemingly favorable but nevertheless suboptimal conditions for flyer movement that would reduce weld quality and energy efficiency of the process.

Keywords

Joining by Forming

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1 Introduction

Magnetic Pulse Welding (MPW) is an impact welding process that enables the joining of tubular or flat partners. Through the fast discharge of capacitor banks, a magnetic field is generated in a coil, which leads to eddy currents in the electrically conductive outer (flyer) piece. Both the coil and the work piece generate Lorentz forces, which act in opposing directions, causing the flyer to accelerate towards the inner (parent) work piece. Under adequate conditions, the flyer and parent pieces will form a weld. This process enables the creation of joints of dissimilar materials, such as steel/aluminum and copper/aluminum, which are not easily welded by standard techniques [1].
The properties of the welding front, influenced greatly by the evolution of the flyer deformation and collision, is ultimately the determining factor in welding success. Under the correct conditions a mass flux containing oxides and debris ('jet') is formed, which cleans the surfaces and allows for metallurgical bonding [2]. The two main factors typically considered in joint formation are the collision angle β and the collision velocity v_c. Figure 1 shows a schematic of the welding front, as well as a micrograph of a welding interface.

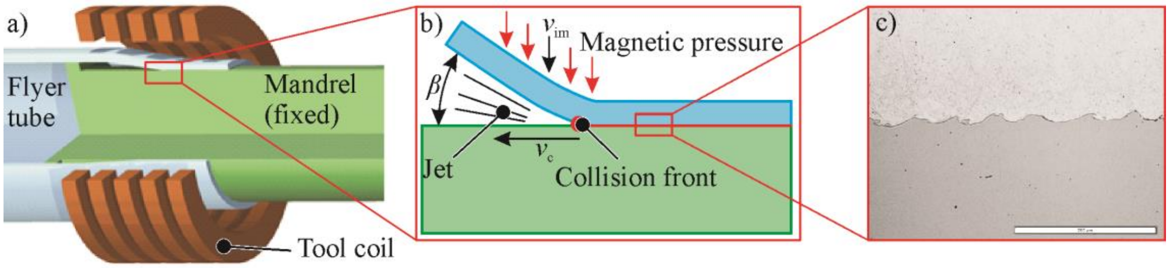

Figure 1: *Magnetic Pulse Welding of tubular work pieces. a) Setup, b) process principle, and c) image of the weld seam (according to [3]).*

The welding front contour is determined by many factors, including the radial relationships between coil/flyer and flyer/parent distance, as well as the axial arrangement of the coil and the flyer (the "working length", l_w). For example, by positioning the flyer edge to extend beyond the coil edge, a two-sided front process can be realized (see Figure 2).

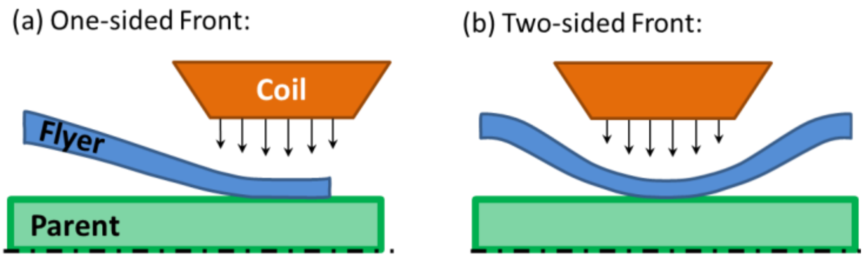

Figure 2: *a) One- and b) two- sided welding, adapted from [6].*

There are advantages to one- or two-front welding processes. As one can imagine, the heavy deformation of the flyer causes shearing forces in the part, which may lead to shearing and tearing of the flyer material above the formed weld. For this reason, a two front process may be advantageous as it creates symmetric forces with opposite directions, counteracting each other globally. However, the energy needed to deform a part along two fronts is higher than a single front, potentially reducing process efficiency and the resulting weld lengths are generally smaller than in a single-front process.

Experiments based on two-front processes have been performed by Kojima et al. [4]. The purpose of this work was an evaluation of the tapering angle of the parent part on the length of resulting welds. Faes et al. [5] reported that the overlap of the field shaper edge and the outer work piece had a significant effect on (tube) welding conditions for copper/brass joints. Working distance of up to 5.5 mm were evaluated on a field shaper with a maximum working zone of 15 mm. No experiments were performed with two-sided fronts and phenomena beyond the occurrence of a weld were not evaluated.

It has been reported by sources such as Zhang [6] that the determination of a one- or two-sided welding process can be done by the axial positioning of the work piece in a coil of maximum working length l_{coil}. If $l_w < l_{coil}$, the process will occur along a single front in which the front edge of the flyer makes impact with the parent, and from there proceeds to collapse via a single front onto the parent. If $l_w > l_{coil}$, a two-front process occurs, in which the flyer impacts the parent in the center of the field shaper/working zone, and collapses outwardly along two fronts. A transition zone between one- and two-fronted processes may exist, for instance with working lengths close to but not exceeding the coil length; however, evaluation of this has not been found in literature. There is also a lack of publications discussing an experimental comparison of one- vs. two-front welding, and no works with in-depth analysis and comparison of the front regimes.

The purpose of this work is to evaluate the effect of the working distance on the features of MPW experiments. This is done by the axial positioning of the flyer piece over the edge of the coil, at the coil edge, and at several positions within the coil. At various positions, the discharge energy was also varied in order to observe if there is a noticeable effect. Simulations were used for comparison and to gain a more in-depth understanding of the process.

2 Experimental Design

2.1 Joining Materials and Tools

Flyer materials consisted of EN AW-6060 (AlMgSi0.5) tubes with an outer diameter of 40 mm and a thickness of 1 mm. The static yield stress of the material was 222 MPa, determined by tensile tests. The parent material was a cylinder of C45-grade steel with a diameter of 33 mm.

A single-turn coil made of a CuCrZr-alloy with a maximum working zone of 15 mm was used for forming. The coil was designed to be able to conduct PDV measurements of flyer deformation, an idea presented by Jäger and Tekkaya [7]. Experiments were conducted on a 32 kJ Bmax pulsed-power generator and workstation. This system has a maximum charging voltage of 20 kV, capacitance of 160 µF, and a discharge frequency of 25 kHz.

2.2 Experiment

Experiments were conducted under fixed flyer-coil and flyer-parent radial distances while varying the axial position of the flyer and the charging voltage. Working distances of 17 (flyer edge placed 2 mm beyond the coil edge), 15, 12, 11, 10, 9, 8, 7, and 4 mm were evaluated. For each working length, the initial charging energy was set at 11.5 kJ and was increased or decreased for select working lengths, depending on initial results. Figure 3a and b show a picture of the experimental set-up and a schematic of the welding set-up/working length distances, respectively. Current measurements were conducted for each trial using a Rogowski coil. After joining, flyers were cut and peeled from the parent in order to expose the interface.

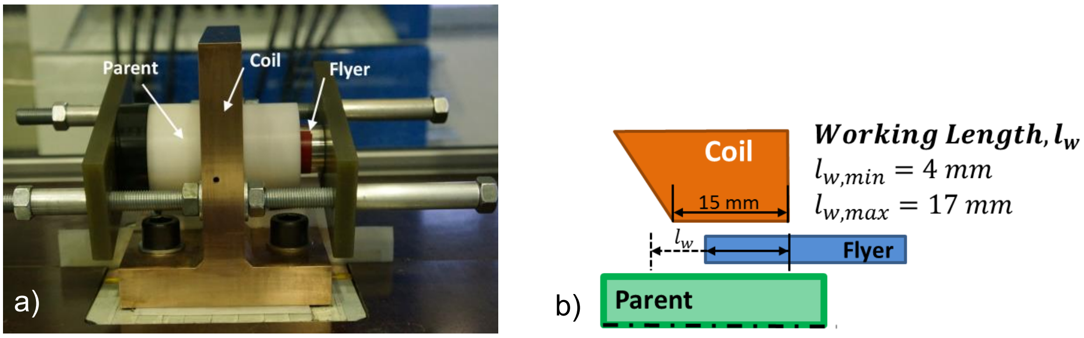

Figure 3: *a) Picture of the experimental setup and b) schematic showing working lengths.*

2.3 Simulation

Due to the high speed and restrictive conditions of MPW, the angles of the welding front are extremely difficult if not impossible to measure directly. For this, coupled mechanical-electromagnetic simulations mirroring the conditions of the experimental part have been conducted. LS-DYNA (Version R 7.0) was used; the electromagnetic fields are computed using a Finite Element Method (FEM), coupled with a Boundary Element Method (BEM) for the surrounding air and insulators (L'Eplattenier et. al [8]). Recorded current curves from the experiments served as input data. The simulations were calibrated based on Photon Doppler Velocimeter (PDV) data obtained by the authors during welding experiments at Bmax in Toulouse, France. The basics of this heterodyne method were described by Strand et al. [9]. This reference contains an in-depth description of the PDV measurement principle and the system properties. In order to adapt the impact velocities in the simulations to the measured data, the Cowper-Symonds constitutive equation (Eq. 1) was used. Here, σ_o' stands for the dynamic flow stress at a uniaxial plastic strain rate $\dot{\varepsilon}$, σ_o is the associated static flow stress and D and q are constants for a particular material [10]. D and q were chosen in a manner, so that the impact velocities of simulations and experiments were comparable.

$$\sigma_o'/\sigma_o = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{1/q} \quad (1)$$

The collision angles β were calculated for selected nodes with the vectors of the velocities in axial and radial direction. For the simplified, time harmonic calculation of the magnetic field intensity between coil edge and flyer, the program FEMM 4.2 [11] was used.

3 Results and Discussion

3.1 Experimental Results - Varied Working Length

By pulse-forming flyer tubes onto parent parts at energies slightly lower than those required for welding or to points for which the weld is weaker than the base material, important details about the rolling process of the flyer can be extracted. By cutting and removing the flyer after pulsing, the surface was able to be observed. This has advantages over other analysis techniques. For example, a push or tension test of welded samples reveals the joint area, but can smear the part interface during removal, and metallographic images of the interfaces show only a very isolated area of the interface. The results of experiments are shown in Figure 4a and b. It can be seen here that for the initial charging voltage of 11.5 kJ, any existing welds broke before the flyer material.

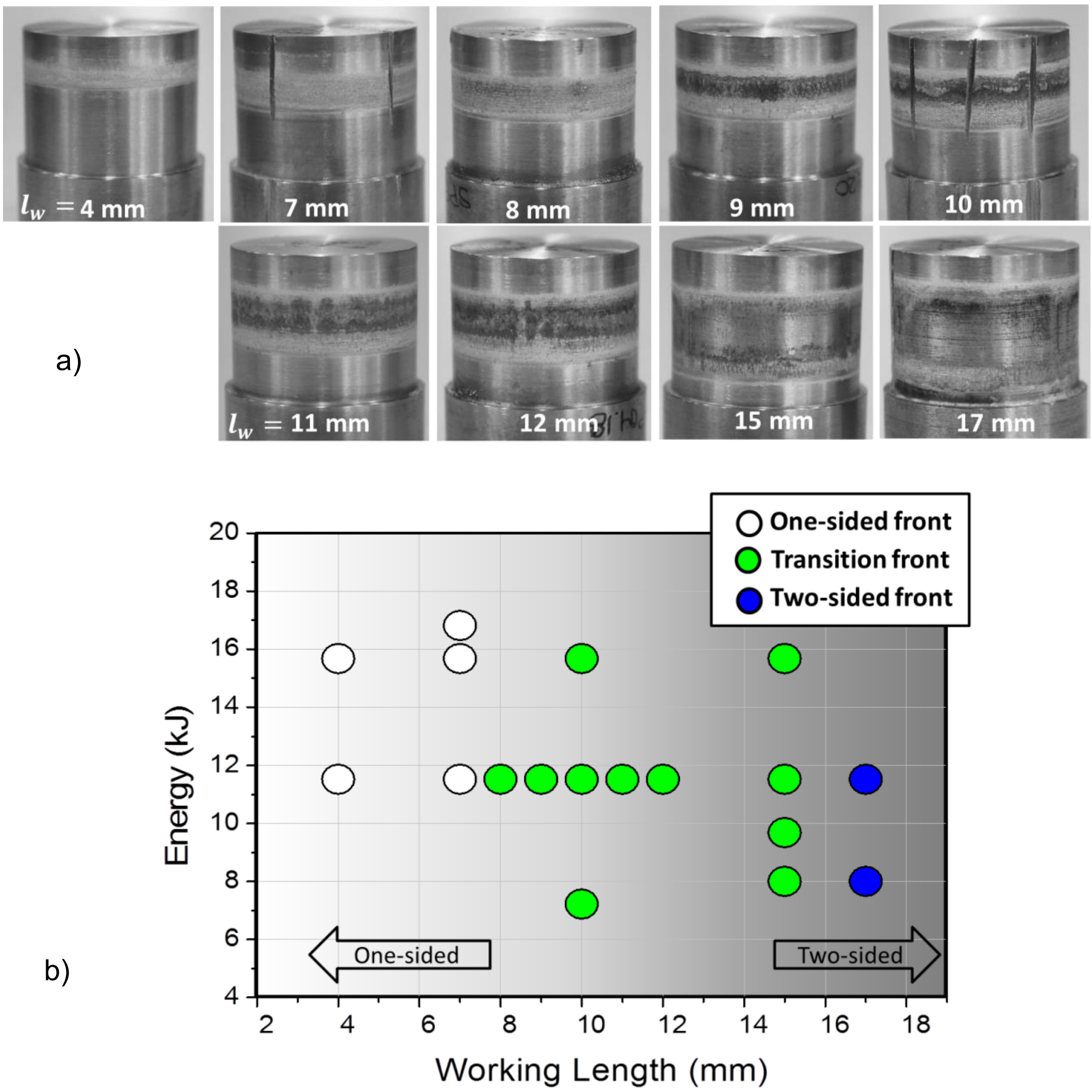

Figure 4: *Overview of welding results: a) images of samples pulsed at constant energy for various working lengths, b) plotted results showing the front-type for each sample.*

As can be seen, in essence three different regimes exist:

A) A one sided front, starting at flyer edge and propagating away from it
B) A transition regime, where (as will by clarified by simulation) the flyer impacts the parent under the correct conditions to create damage or potentially weld at the front of the flyer and near the coil edge, but the area in between contains a grey residue.
C) A two-front process, in which a bowed impact at the center of the coil occurs and two fronts run in opposite directions from this region

Each of the presented regimes leads to distinct surface interface characteristics. Regime A (one front) leads to a short region at the flyer edge, which is clearly seen in Figure 4a for samples with working lengths of 4 and 7 mm.
The other easily recognizable regime is for the working length of 17 mm and corresponds to regime C (two fronts). Here, the parent area near the middle of the coil appears in a similar condition to the state before welding. This is because the initial impact occurred perpendicular to the surface, and the initial pressure of the running fronts was not sufficient to deformation the material interface. The sample surface indicates that the flyer only propagates with high enough pressures for parent deformation as it reached the ends of the coil.
Regime B is present for samples pulsed at working lengths from about 8 mm to about 12 mm. Samples with working lengths of 15 mm are also thought to be included here, as will be seen later. In this regime, grey matter appears between the beginning of the flyer deformation zone and near the opposite coil edge. This matter is due either to low angles, for which the surface is perturbed but no welding occurs, or to non-uniform flyer deformation. If the latter is the case, it is thought that concentration of the magnetic field at the coil edge may cause forces on the flyer exceeding the material strength, leading to early deformation at this point and hindering an existing jet from completely escaping the collision front area. Simulations were performed in order to gain better understanding of this regime.

3.2 Experimental Results – Varied Energy

In order to assure that results presented above could be applied to other charging energies, several working distances were selected for further analysis at higher and lower pulsing energies.
As the energy was changed for a given working length, the width of the distinct areas tended to increase or decrease in accordance with the charging voltage; however, the general interface characteristics remained constant (Figure 5). At higher energies of 15.7 kJ and 16.8 kJ, welding occurred for working lengths of 4 mm and 7 mm, respectively; Figure 6 shows metallurgical analyses of these samples. The increase in welding length in accordance with the working distance is apparent.

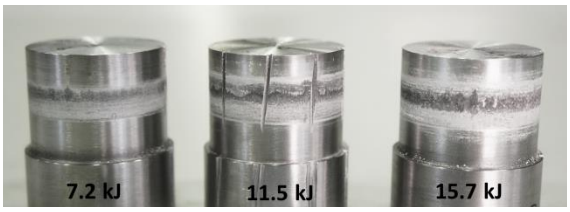

Figure 5: *Samples with 10 mm working length at various energies.*

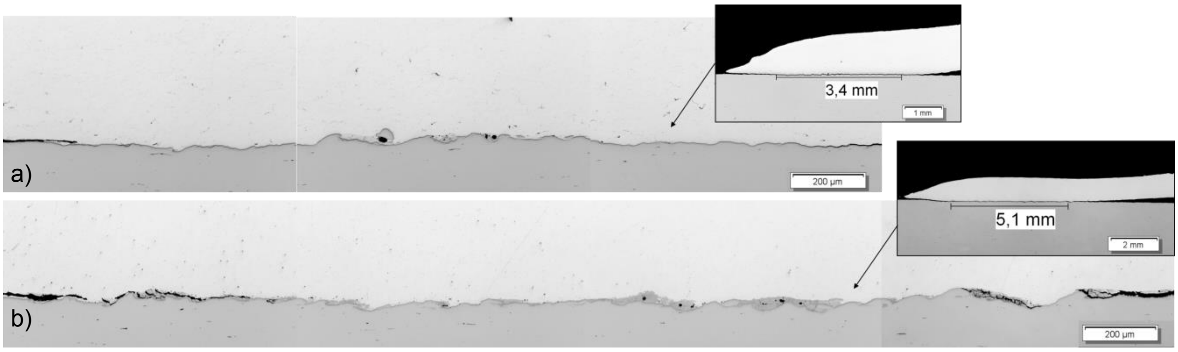

Figure 6: *Overview images and detailed images of samples with working lengths of a) 4 mm and b) 7mm.*

3.3 Simulation

Figure 7a-c shows simulated images of the aluminum tubes at the time of initial impact with the parent part for $l_w < l_{coil}$, $l_w = l_{coil}$ and $l_w < l_{coil}$, respectively. The area of first contact between the parent and flyer part are visible in the simulation. The area appears in the color of the flyer due to a slight immersion of the flyer part into the rigid parent part. The angles at the contact point for each image have also been calculated in order to aid analysis. An exemplary recorded current curve for a charging voltage of 9.7 kJ was used as input for the coupled electromagnetic-mechanic simulation.

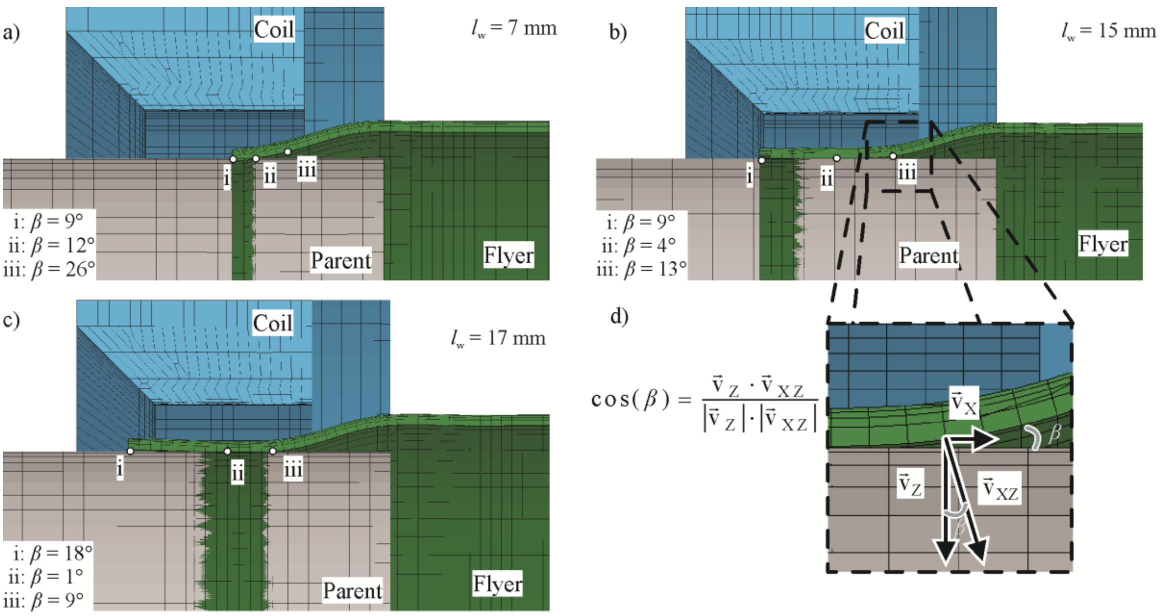

Figure 7: *LS-DYNA simulations of setup with a) $l_w < l_{coil}$, b) $l_w = l_{coil}$, c) $l_w > l_{coil}$, d) Determination of the collision angle β*

Figure 7a and c present clear indications of a one- or two-sided front, correlating with regimes A and C, respectively and match well with the experimental results presented above. At working distances under about 7 mm (half of the coil length), the front is one-sided. This is an indication that the relationship between magnetic pressure at the flyer interface and the material stability is such that the flyer deforms first at the edge, and then

continues along a single, continuous collision front. The simulation in Figure 7c show that deformation for samples placed over the coil working length ($l_w = 17\ mm$) occurs in a bowed manner. If the bow-shape of the flyer was too flat (in this case, a low value of about 1°), it may be that the correct conditions to cause visible damage to the parent were only reached at the edges, in agreement with Figure 4a.
The simulation results shown in Figure 7b are more complicated and may require additional in-depth analysis. As the angular measurements show, the tube near the rear coil edge is slightly bowed towards the parent; this may be an indication of non-uniform flyer deformation leading to jet entrapment, as mentioned earlier. This deformation regime is thought to be very unfavorable not only for potential jet entrapment, but also because of the generally flat characteristics of the front. Both of these would lead to insufficient impact pressures and unfavorable welding conditions.
Through simulations, as well as viewing the interfaces of samples joined under non-welding conditions, it can be seen that positioning the edge of the flyer piece inside the coil/field shaper width does not guarantee a continuous one-sided front process. In order to see if the increase in magnetic field density at the corners of the coil has an influence in the flyer deformation for these trials, an assessment of the magnetic field for various working lengths was performed. Figure 8 presents the simulated effect of the working distance on the magnetic field $H_{tangential}$ for an exemplary harmonic current amplitude of 500 kA at 20 kHz. This shows that the magnetic intensity on the workpiece is inversely related to the working distance and for a working distances $l_w \leq l_{coil}$, the field intensity has a peak at the end of the flyer. However, the process efficiency is not directly inversely proportional to the working distance. Also, it is shown that for this setup the radial position of the flyer piece is far enough away from the coil edge that the increase in magnetic field density at the coil edges does not affect the forces on the flyer.

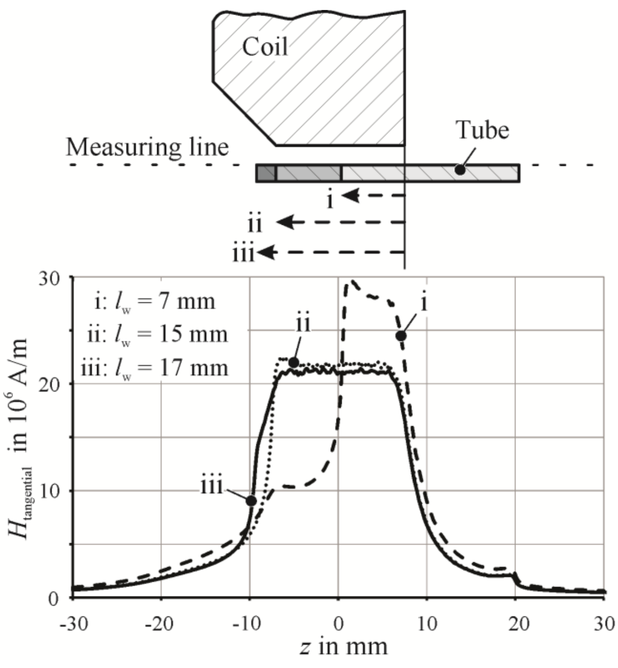

Figure 8: *Axis-symmetric FEMM simulation of the tangential magnetic field intensity* $\boldsymbol{H_{tangential}}$ *at the outer flyer surface for the given setup for different working lengths.*

The results seen above indicate that the magnetic field intensity is relatively even over the part surface, showing a slight increase at the flyer edge. This indicates that flyer acceleration should occur in a uniform manner, beginning with the flyer edge. For transition regime (B), the case is probably such, that the flyer end impacts the sample first, while the rest of the flyer follows in a chiefly flat manner, in slight contradiction with the simulation seen in Figure 7b. Entrapment of the jet is still possible in this case, as projectile particles may impact the flyer or parent surfaces before escaping the joining pair, becoming trapped between flyer and parent and hindering further jetting and welding processes. This, in addition to a flat impact (insufficient angles), is a likely reason for welding failure in regime B. The contradiction between expected flyer deformation based on the magnetic field intensity and the simulation of the flyer deformation requires more in-depth analysis.

Simulation results oppose notions that a longer working length is better in order to increase welding probability/efficiency by harnessing more of the magnetic field. More energy may be used in deformation; however, deformation may occur in a manner unfavorable to welding. Results presented here may be used as a basis for understanding the impact of the working length as well as determining conditions under which partners will weld in MPW. Here, parts with welding distance equal to less than half of the coil length exhibited welding with single-front flyer impact under the given conditions.

4 Conclusions

The presented research has shown three basic regimes for flyer deformation based on its axial position within a MPW coil. If the flyer is placed all the way through the coil, a two-front process ensues in which the flyer contacts the parent first at the coil center, then propagates outwardly. At working distances (in this case) smaller than half of the total coil length, impact between the flyer and parent occurs first at the flyer edge, and propagates along a single front. At working distances between 8 and 15 mm, a transition regime was seen in which the front propagated in either a flat or non-uniform manner. The transition regime is thought to provide sub-optimal conditions for MPW processes. The presented results as well as additional simulation can be used as a basis to establish a more generalized theory of the relations between relative working length and weld result.

In order for a more thorough assessment of the coil-flyer position and deformation relationship, future trials on a coil with a smaller maximum coil working length are planned. This will allow for the investigation of the relationship between the coil length and the working length on the deformation and welding front (for instance, if the features seen in samples joined with $l_w > l_{coil}$ and $l_w = l_{coil}$ are consistent with those investigated here). Additionally, experimental trials on coils with diameters smaller than ∅40 mm are planned in order to see the effect of the part size on the deformation and welding abilities.

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