

Incremental magnetic pulse welding of dissimilar sheet metals

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Abstract. Magnetic pulse welding is a solid state welding process using pulsed magnetic fields resulting from a sudden discharge of a capacitor battery through a tool coil in order to cause a high-speed collision of two metallic components, thus producing an impact-welded joint. The joint is formed at room temperature. Consequently, temperature-induced problems are avoided and this technology enables the use of material combinations, which are usually considered to be non-weldable. The extension of the typically linear weld seam can easily reach several hundred millimetres in length, but only a few millimetres in width. If a larger connected area is required, incremental or sequential magnetic pulse welding is a promising alternative. Here, the inductor is moved relative to the joining partners after the first weld sequence and then another welding process is initiated. Thus, the welded area is extended gradually by arranging multiple adjacent weld seams. This paper demonstrates the feasibility of incremental magnetic pulse welding. Furthermore, the influence of important process parameters on the component quality is investigated and evaluated in terms of geometry and micrographic analysis. Moreover, the suitability of different mechanical testing methods is discussed for determining the strength of the individual weld seams.

Keywords: Manufacturing process, Welding, Magnetic pulse welding

1 Motivation and principle of incremental magnetic pulse welding

Industrial manufacturing is more and more influenced by social, ecological, and health aspects. Politics supports this trend by establishing corresponding national and international laws and agreements such as the 2020 Climate & Energy Package [1] or the Agenda 2030 [2]. Saving energy and resources as well as reducing emissions are essential aspects of this development. Regarding product design and manufacturing, this specifically means that one major focus has to be placed on reducing weight by consistently implementing lightweight design concepts e.g. multi-material design [3].

When choosing product materials, technological properties and weight reduction potential, but also availability and costs of specific materials are decisive. Furthermore, it is essential to consider the readiness of cost-efficient joining technologies suitable for the specific material or material combination. Conventional joining technologies, i.e. usually thermal ones such as gas metal arc welding or resistance spot welding often reach their limits when it comes to multi-material combinations. [4]

Magnetic pulse welding (sometimes also called electromagnetic pulse welding) is a technology offering a high potential, especially for joining dissimilar

materials, including material combinations which are usually considered to be non-weldable. Feasibility has been proven for material combinations aimed at e.g. car body manufacturing such as aluminium and steel [5, 6], including stainless steel [7] and press hardening steel (see Fig. 1). In addition, feasibility was verified for material combinations which are of special interest for applications related to electrical engineering or heat transfer and conduction such as aluminium and copper [8]. Fig. 1 shows examples of joints produced by magnetic pulse welding of similar and dissimilar sheet metals at Fraunhofer IWU.



Fig. 1. Joints produced by magnetic pulse welding of similar and dissimilar materials

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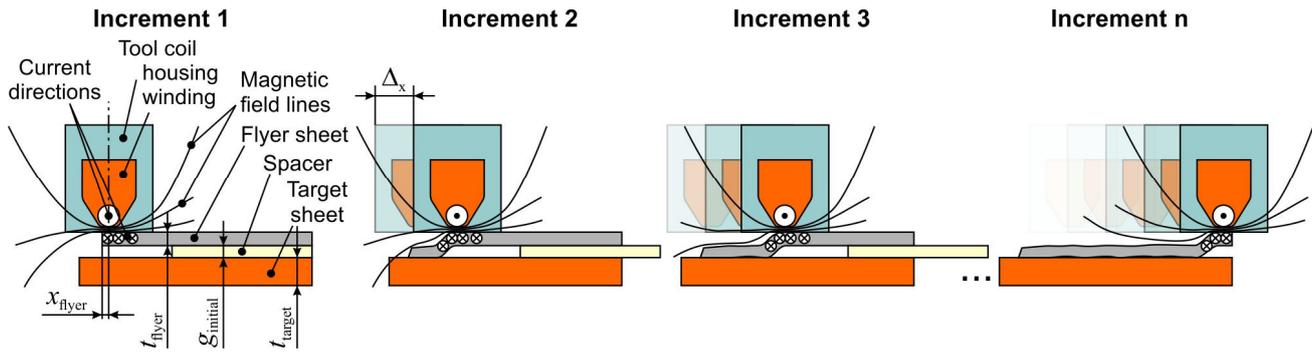


Fig. 2. Principle of incremental magnetic pulse welding

The process of magnetic pulse welding was initially suggested and patented by Lysenko et al. in 1970 [9]. This technology is an impact-based welding technique which features some similarities with the well-known explosive welding or cladding techniques. However, magnetic pulse welding is significantly less critical with regard to safety, which makes it much easier to implement it into an industrial environment.

In order to perform the process, the flyer – i.e. the accelerated joining partner – and the target – i.e. the static joining partner – are positioned with a defined initial gap between them and the flyer is accelerated by electromagnetic forming [10]. This means that a capacitor battery is charged to an application-adapted charging energy and discharged through a so-called tool coil or inductor. As a consequence, damped sinusoidal current flows through the tool coil and induces an according pulsed magnetic field, which in turn induces a time-dependant current in the workpiece – i.e. in the flyer sheet – which is directed opposed to the coil current. Lorentz forces occur due to the interactions of the currents and the magnetic field, which accelerate the flyer to velocities of up to several hundred meters per second within a few microseconds. The flyer movement is directed away from the tool coil and towards the target. After overcoming the initial gap, flyer and target are involved in a high-speed collision. If the collision parameters (impact velocity and impact angle) lie within a process window, which is specific for the material combination, an impact welded joint is generated [11]. In contrast to classic welding techniques, magnetic pulse welding forms the joint at room temperature without significant heating of the parts, thus avoiding temperature-induced problems such as thermal softening or the formation of continuous intermetallic or oxidic phases deteriorating the weld quality.

Due to the setups typically used for the process, the weld seam is usually of linear shape either along the circumference of tubular components, or along the edges of joint sheet metal parts. The extension of such weld seams can easily reach several hundred millimetres in length, but their width is limited to a few millimetres.

However, in some applications it is necessary to have a larger connected area of the joining partners, e.g. in order to achieve better electrical or heat conducting properties. In these cases incremental magnetic pulse welding is a promising alternative. In this process variant

the tool coil is moved relatively to the joining partners after the first magnetic pulse welding sequence and then another welding process is initiated (see Fig. 2). In doing so, the extension of the joint area can be extended gradually by arranging multiple adjacent weld seams. Feasibility of the principle extension of an electromagnetic forming process by applying an incremental or sequential approach has been proven for a structuring process in [12], for a simple 3D-shaping process in [13] and for a more complex 3D-shaping process of large sheet metals in [14]. For tube welding processes, first investigations were carried out regarding incremental magnetic pulse welding in [15], but up to now, the transfer to magnetic pulse welding of sheet metal has not been studied.

2 Procedure of analysing incremental magnetic pulse welding

2.1 Reference of single sequence magnetic pulse welding

In this analysis the reference used was a conventional magnetic pulse welded joint consisting of one single weld sequence. In particular, in this reference a one millimetre thick flyer sheet made of EN AW-1050 was welded to a two millimetre thick target sheet made of Cu-DHP. Suitable process parameters guaranteeing high weld quality were chosen based on the results of a detailed study quantifying the influence of important adjustable process parameters on quality criteria of the resulting weld such as transferable force, electrical and thermal conductivity, and width of the weld seam [11]. Specifically, the following values were chosen:

- Capacitor charging energy $E=30$ kJ
- Initial gap between flyer and target $g_{\text{initial}}=1$ mm (see Fig. 2)
- Relative position of tool coil and flyer $x_{\text{flyer}}=2$ mm (see Fig. 2)

2.2 Parameters of sequential welding

In the sequential welding tests, for the first weld sequence the same process parameters were applied as in the single sequence reference. Then further weld sequences were added using the same capacitor charging energy. This paper specifically investigates and evaluates the influences of different numbers of

sequences n , on the one hand, and different relative movements of coil and joining partners Δx , on the other hand, on the component quality in terms of geometry, micrographic analysis, and mechanical strength.

Parts with $n=2$ sequences, $n=3$ sequences, and $n=5$ sequences were examined. The considered relative movements of $\Delta x=9$ mm, $\Delta x=13.5$ mm, and $\Delta x=18$ mm were selected, taking into consideration the cross section geometry of a typical single sequence weld. Fig. 3 shows that for these kinds of welds, the contact area of the two sheets is approximately 9 mm followed by the slope geometry of the flyer, which extends approximately for another 9 mm. This means that the gap between flyer and target is similar to the initial gap width between flyer and target in the first weld sequence at a distance of 18 mm to the flyer edge.

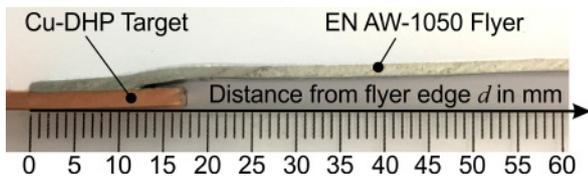


Fig. 3. Cross section of a typical joint produced by magnetic pulse welding

3 Characterisation and evaluation of the joining result

3.1 Thickness of the welded specimens

A significantly simplified approach for estimating the overall thickness of the welded part is adding the nominal thicknesses of the joining partners. In the example regarded here, this leads to a value of 3 mm for the total width. However, it is well known that both – flyer and target – can undergo significant changes in thickness due to the impact and the corresponding severe plastic deformation of the joining partners, which seems to be an indispensable prerequisite for magnetic pulse welding. This in turn influences the thickness of the part produced by magnetic pulse welding [8]. The deformation and the resulting thickness of flyer and target significantly depend on density and strength ratio of the joining partners. As exemplarily shown in Fig. 4, the impact of a copper flyer onto an aluminium target causes significantly more deformation of the target than the impact of an aluminium flyer onto a copper target.

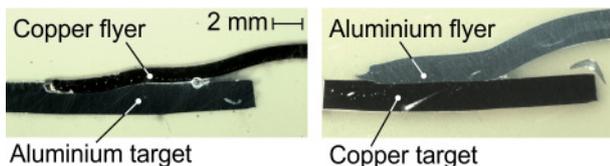


Fig. 4. Resulting cross sections of magnetic pulse welding of a copper flyer to an aluminium target (left) and vice versa (right)

Considering e.g. the application of the process in manufacturing of components related to heat transfer, essential aspects include the contact properties. Therefore, the flatness of the contact surfaces used to

introduce the heat, which is closely related to the thickness distribution is important. Thus, the thickness distributions have been examined regarding different sheets produced by sequential magnetic pulse welding and a reference specimen manufactured by single sequence magnetic pulse welding. As shown in Fig. 5, each single weld sequence can easily be recognized in the thickness plots, as it causes a local thickness minimum. Consequently, at least one surface of the resulting part produced by sequential welding features more or less distinctive waviness. This waviness is augmented by an increase of the coil movement relative to the position of the joining partners in-between two subsequent joining sequences.

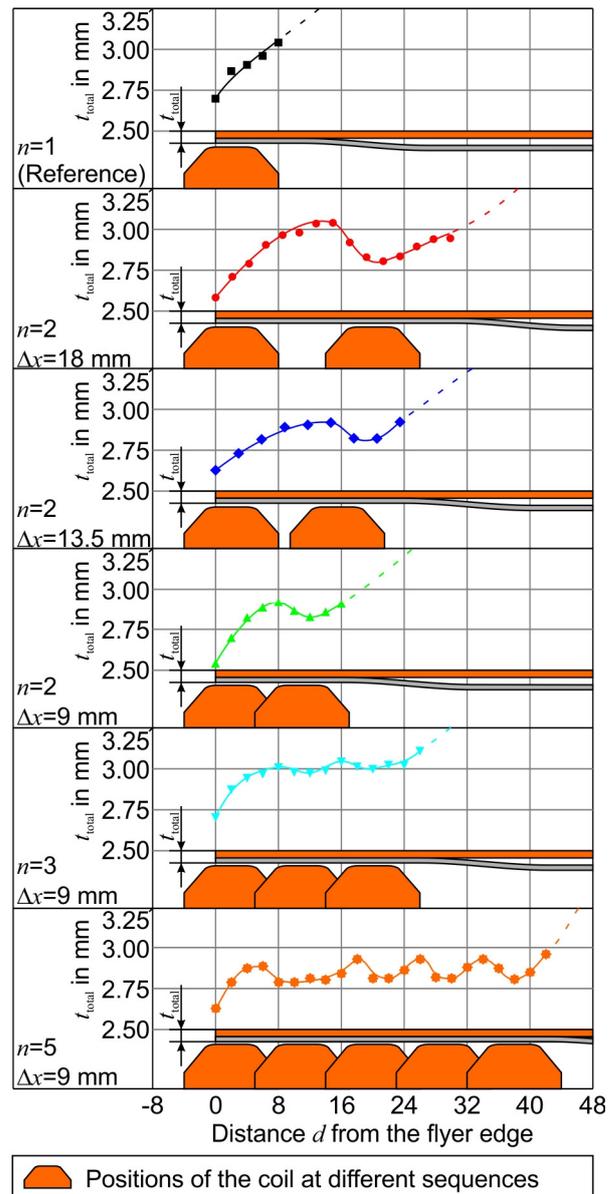


Fig. 5. Coil positions and corresponding thickness distributions of specimens produced by single sequence and incremental magnetic pulse welding

3.2 Microstructural investigations of the welded specimens

Another important evaluation criterion for joints produced by magnetic pulse welding is the extension of the welded area, which is directly related to the conductivity of the weld and the force, which can be transferred via the weld [11]. Obviously, it is desirable to maximise the extension of the welded area. Therefore, influences of the different parameters on the welded areas in sequential magnetic pulse welding were analysed. Welded areas are frequently characterised by a more or less distinctive wavy structure of the interface between the two joining partners. Sometimes they even feature vortexes, while non-welded sections feature a gap or a shattered structure (see Fig. 6).

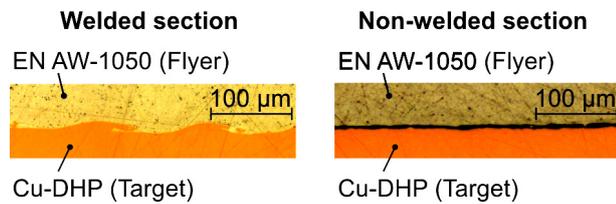


Fig. 6. Exemplary micrographs of welded and non-welded sections

As shown in Fig. 7, all specimens produced by incremental magnetic pulse welding feature multiple welded areas. As expected, the number of welded areas and the total length of the welded area l_{total} , i.e. the sum of the individual lengths of all welded areas, rise with an increasing number of sequences. The total weld lengths indicated in Fig. 7 are mean values calculated from all experiments performed with the parameter set, while the local distributions of the weld extensions represent one specific test case and consequently may slightly deviate from the mean value.

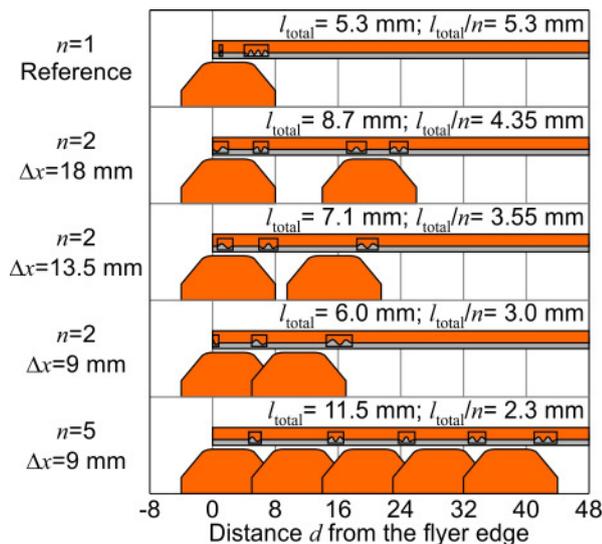


Fig. 7. Coil positions and corresponding welded areas of specimens produced by sequential magnetic pulse welding

The direct comparison with the positions of the coil during the different weld sequences allows attributing the individual welded sections to the different weld

sequences. It is most likely that all welding areas at a distance $d \leq 10$ mm from the flyer edge can be attributed to the first weld sequence. The differences in the welding area for this sequence can probably be attributed to slight inaccuracies in the manual positioning of the specimens in relation to the tool coil and in the flatness of the parts resulting in slight deviations of x_{flyer} and $g_{initial}$.

For the specimens welded with two sequences all further welded areas can be attributed to the second weld sequence. For the specimen with five welding sequences, the weld area at a distance of approx. 25 mm from the flyer edge can be attributed to the third welding sequence, while the welded areas at a distance of $d \approx 34$ mm and $d \approx 42$ mm can be attributed to the fourth and fifth welding sequence.

This shows that in the ideal case, two welded areas at both sides of the coil result from one single welding sequence. This is the case for the first welding sequence in nearly all specimens. In contrast, most of the further welding sequences lead to only one single welded area. The reason for this probably lies in the fact that there is only a very small distance between flyer and target in the area close to the preceding welding sequences. This means that especially for processes with small relative movement of coil and joining partners in-between two subsequent joining sequences, the available acceleration distance for the flyer is very small at the side facing the preceding welding sequence. Therefore, the collision velocity necessary for magnetic pulse welding cannot be reached as it is in the range of 300 m/s for this specific material combination, [8]. If the relative movement of tool coil and workpiece is sufficiently long so that the initial distance between flyer and target is approximately the same as in the first welding sequence, the acceleration is more effective. Consequently, the collision conditions are more beneficial so that two welding areas result again from one welding sequence. In the considered examples this is the case for a relative movement of tool coil and joining partners of $\Delta x = 18$ mm. These correlations explain to some extent the tendency of an increasing total weld length per welding sequence l_{total}/n with increasing relative movement Δx , which is illustrated in Fig. 7. Here mean values are represented which were calculated from all experiments performed with the specific parameter set.

3.3 Discussion of mechanical characterisation methods for specimens produced by sequential magnetic pulse welding

3.3.1 Lap shear test

The lap shear test is a frequently applied mechanical test for characterising the mechanical quality of joints produced by single sequence magnetic pulse welding, see e.g. [5, 7, 16, 17, 18]. For this purpose, either simple rectangular or waisted specimens are used, similar to those used in a conventional tensile test, but featuring the joint produced by magnetic pulse welding in the centre of the specimen, and the test is carried out in a standard testing machine.

As already shown e.g. in [11] for single sequence welds, the strength of a joint produced by magnetic pulse

welding can exceed that of the base material, causing failure in the base material and not in the joint. Only low quality welds fail in the weld area, so that the failure type can be regarded as an evaluation criterion for a high-quality joint. In Fig. 8 the difference is shown based on a copper aluminium joint failing in the joint and in the flyer base material, respectively. In this sample the flyer is the weaker base material. The reason for this is that the copper sheet features remarkably smaller thickness compared to the aluminium base material. Therefore, the aluminium sheet can transfer higher forces although its material strength is lower compared to the copper material.

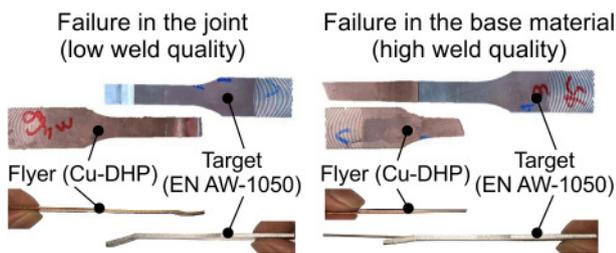


Fig. 8. Failure cases in lap shear tests of joints produced by single sequence magnetic pulse welding

However, the lap shear test can only provide an overall evaluation of the complete welding zone. Thus, the informative value is expected to be limited with regard to testing of parts produced by incremental magnetic pulse welding. Differentiated conclusions regarding the contribution of the individual weld sequences to the overall transferable force will not be possible because in this test setup the complete welded area is always loaded, since the forces are applied at the two opposing ends of the weld zone. Thus, even if only one weld sequence is of high quality, failure will occur in the base material, and minor quality of the other welds cannot be detected at all.

3.3.2 Peel test

In contrast to the lap-shear test, forces are applied perpendicular to the welded zone at only one end of the welding zone in the peel test. Theoretically, this should allow testing one weld sequence after the other and drawing conclusions regarding the quality of each individual weld seam. Therefore, the end of welded sheets were bent 90° and peel tests were performed on the prepared specimens in a conventional testing machine (see Fig. 9).

However, the regarded welded sheets feature significantly different material strength and stiffness. The bending stiffness of the copper sheets is approx. 1.8 to 2.8 times as high as that of the aluminium sheet due to the higher Young's modulus and thickness in this joining example. As shown above, the thickness of the joining zone is remarkably higher than that of the base materials, which also implies that the stiffness is even higher here. At the same time the quasistatic yield strength of the copper target is approx. 1.8 times as high and the quasistatic tensile strength is even 2.3 times as high as the corresponding values of the aluminium flyer. As a consequence, no remarkable elastic or plastic deformations occur in the copper base material or in the deformation zone, while the aluminium base material is strongly bent. Finally, bending failure occurs in the aluminium base material close to the welding zone. Some qualitative deformation stages of the testing process are shown in Fig. 9. They clearly show that this kind of test is not suitable for joints produced by magnetic pulse welding – neither single sequence nor multiple sequence welds – of different materials or different sheet thicknesses. However, the test might lead to meaningful results in cases of welds with similar sheet metal parts.

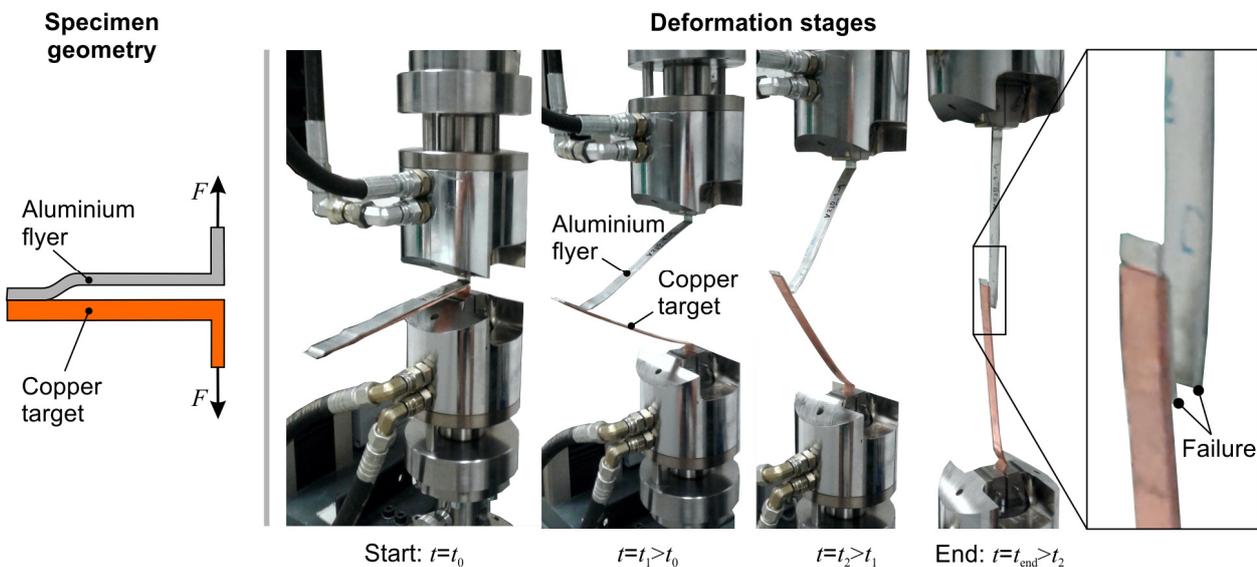


Fig. 9. Specimen geometry and deformation stages in peel tests

3.3.3 Chisel test

In spot welding, in addition to the peel test the so-called chisel test is another established way for characterising the joint quality by applying the test force on one side of the joint [19]. Thus, a similar test was tried here. Fig. 10 shows setup, specimen geometry, representative deformation stages and a typical tested specimen. Tests were carried out on six reference parts produced by single sequence welding and six sequentially welded specimens.

These tests used only specimens with a number of sequences of $n=3$ and a relative movement of $\Delta x=9$ mm. As known from the investigations of the microstructure, these specimens provide relatively short weld lengths; consequently the expected transferable force is relatively low. This means that choosing this parameter set will allow a worst-case estimation of the weld strength. During the tests, the force and the displacement of the moving chisel were recorded, and the failure type was analysed after the test.

Similar to the lap shear tests, also for these tests occurring failure cases can be differentiated between failure in the joint (i.e. detachment of the joint) and failure in the weaker base material (i.e. the aluminium flyer material). Fig. 10 shows an exemplary sequentially welded specimen featuring both failure types for different weld sequences. In case of failure in the joint, the two sheets are separated without any major damage. Only slight particle residues from the aluminium flyer can be detected on the copper sheet. In case of failure in the base material, the adherence of the two dissimilar material sheets to each other is so high that no separation of the materials occurs. Instead, shear failure of the aluminium base material occurs, although the chisel used in these tests does not feature a sharp, but a rounded edge with a radius of 1 mm.

In the reference case using welding with one single magnetic pulse welding sequence, all tested specimens failed in the aluminium base material. This proves that the set of process parameters resulting in high quality welds in terms of lap shear strength, electrical conductivity of the joint, and length of the welded area [11] also leads to high quality in terms of the acting loads during the chisel test.

In case of the specimens produced by incremental magnetic pulse welding it is important to consider that

the weld sequences were tested in reversed order due to the setup, specifically the orientation of the specimen. This means that the welding sequence that was produced first was the last one to be tested, while the welding sequence that was produced last was the first one to be tested. In most cases the welding sequence tested first already failed in the base material. In this case further testing of the other welding was not possible any longer, because no suitable force application area could be created for the chisel in order to test the further sequences. For two specimens, the first and second tested welding sequences failed in the joint. However, here the welding sequence that was tested last (i.e. the sequence, which was welded first) failed in the base material. The thickness measurement of these specific specimens has shown that the thickness values in the area of the weld sequences failing in the joint are slightly (i.e. up to two tenths of a millimetre) higher compared to most of the other specimens. This suggests that shortcomings in terms of weld quality can also be detected via the thickness distribution.

Fig. 11 shows three distinctive areas featured by force-displacement measurements during the chisel test of the specimens produced by single sequence magnetic pulse welding. An initial slight increase of the force up to approx. 200-400 N is followed by a much steeper rise up to approx. 2500 N, before a similarly steep drop of the force occurs. This principle shape corresponds to the deformation of the specimen. This deformation is characterised by elastic-plastic bending of the free flyer end at the beginning of the test. The increasing slope of the curve characterises the transition from plastic bending to shearing. Finally, necking of the aluminium flyer causes the force to drop again until failure occurs.

As expected, force-displacement measurements taken for specimens produced by incremental magnetic pulse welding with material failure in the weld sequence, which were tested first, have the same principle shape. The forces measured during elastic-plastic bending are on a similar level as the reference specimen, but the force achieved during shearing of the aluminium is approx. 30% lower than in case of the single sequence welding.

For specimens featuring base material failure in the first weld sequences and joint failure in the other weld sequences, distinctive drops of the force values can be detected in the measurement curve. These can be

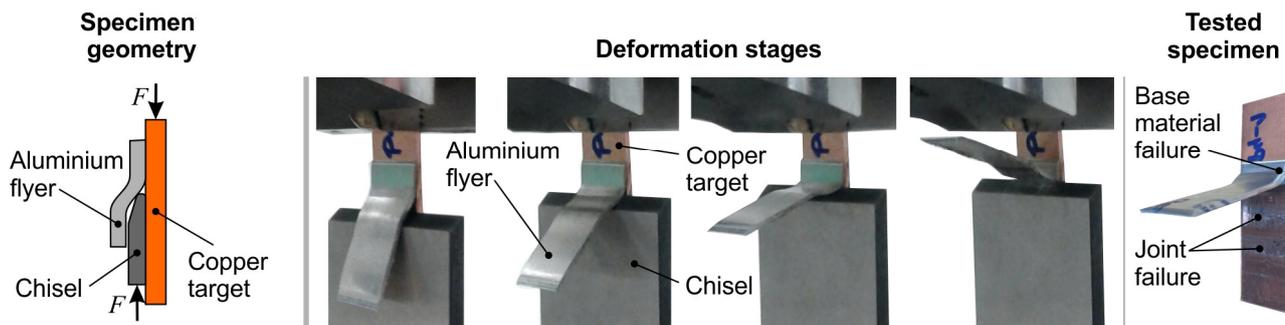


Fig. 10. Specimen geometry and deformation stages in chisel tests

attributed to the detachment of the weld. However, the force peaks related to failure in the joint do not exceed values of approx. 400-450 N. As this is one magnitude lower compared to the maximum force values measured during the tests, it can be concluded that such low quality joints do not significantly contribute to the overall strength of the incremental weld. In contrast, the measured forces during shearing of the aluminium base material in the first weld sequence was on the same level as the single sequence weld, proving that the subsequent welding processes do not deteriorate the quality of the earlier sequences.

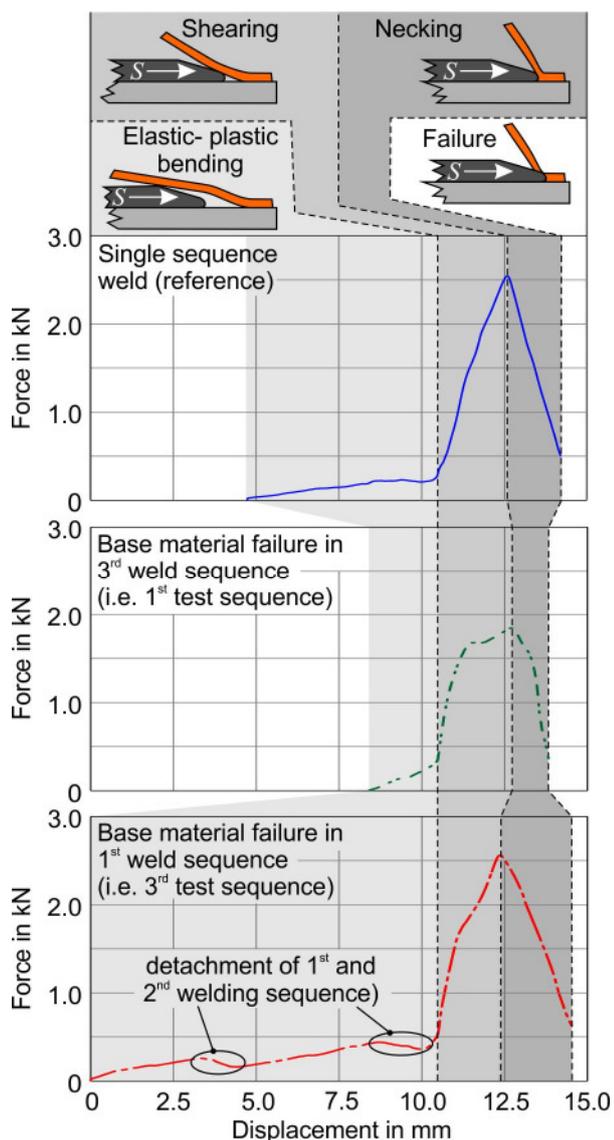


Fig. 11. Typical force displacement curve measured during chisel tests

4 Summary and conclusions regarding the process design

Magnetic pulse welding offers important advantages for manufacturing dissimilar material joints, which cannot be realised by conventional techniques, but the width of the typically linear weld seam is limited to a few millimetres. Larger joint areas can be realised by incremental magnetic pulse welding. Here, multiple weld

seams are arranged next to each other by performing several weld sequences and moving tool coil and joining partners relative to each other in-between the sequences.

The feasibility of this new process variant was proven and a basic analysis of the process was carried out for copper aluminium joints. In addition to the typical process parameters known from single sequence magnetic pulse welding, additional parameters significantly influence the resulting joint quality in the incremental approach. These are specifically the relative displacement of tool coil and joining partners between two subsequent sequences and the number of weld sequences necessary to join a defined area.

Measurements of the thickness distribution have shown that decreasing relative movement of the tool coil to the joining partners decreases thickness variations and consequently waviness of the part's surface. However, for short relative movement of tool coil and workpiece the conditions for welding are less favourable since the gap width between flyer and target in direct proximity to the preceding weld seam hardly allows for reaching the flyer velocity required for welding. Therefore, the extension of the weld is only small and due to the direct relation to the corresponding transferable force, the mechanical strength is also low. In extreme cases magnetic pulse welding will not be possible any longer. Thus, a compromise has to be found depending on the requirements related to flatness of the part, on the one hand, and required mechanical strength of the weld, on the other hand.

If high mechanical strength is required, the relative movement must be long enough to guarantee an initial gap width similar to that of a high quality single sequence weld for all weld sequences. In the specific case regarded here, this means a relative movement of at least 18 mm.

If flatness of the part is of major importance as it is the case e.g. in heat transfer elements, the relative movement should be as short as possible. However, this obviously leads to an increase of the number of weld sequences required to connect a specific area, implying higher effort and cost in manufacturing. For the specific case regarded here, a relative movement of $\Delta x=9$ mm seems to be a lower boundary. Mechanical load tests for this value have shown that high weld quality characterised by failure in the base material can basically still be achieved for all sequences of a part produced by incremental magnetic pulse welding. However, the transferable force of the subsequent weld sequences and the robustness of the process tend to be lower compared to single sequence magnetic pulse welding. On the other hand, variations of the thickness are relatively low.

If both high strength and good flatness of the part is required, a two-stage process might be a solution. In this case incremental magnetic pulse welding must be carried out with long relative movement of the coil and the joining partners in order to optimise the weld quality of the individual weld sequences, while accepting that the flatness of the part has to be improved in a second manufacturing step. The improvement might be achieved by levelling buckles via electromagnetic forming steps in-between the individual weld sequences. For this

operation the same tool coil already applied for the magnetic pulse welding process might be used again, so that no additional equipment is required. However, this procedure will probably not lead to an ideally flat surface. Therefore, milling of the welded surface can be expected to be the best option for flattening it, if geometrical requirements are very high.

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