MAGNETIC PULSE WELDING

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Abstract The contemporary construction industry is evolving with a rapid pace and is pushing technological boundaries. Together with that progress new requirements on joints and joining techniques are imposed. This paper describes our research concerning an advanced joining technique, the Magnetic Pulse Welding process (MPW).
The first part of this article briefly describes the MPW process and summarizes the differences with respect to conservative welding techniques. Secondly an analytical model of the process will be investigated on accuracy. This model was developed by the manufacturer of the MPW machine used at the Belgian Welding Institute. Further a description is given of the methods which are used to investigate the experimental joints. After describing the recently performed experiments, finally an overview will be given depicting the work that will be carried out during the rest of this master thesis.

Keywords Magnetic Pulse Welding, MPW, analytical model, testing methods, experiments

1 INTRODUCTION

1.1 The principle

Magnetic Pulse Welding is a cold welding process which uses high velocity impact to join two parts. The process can be compared to explosion welding but using magnetic force to accelerate the object instead of explosives. Unlike conventional welding processes no melting is involved and thus no major changes in material properties take place. The working principle is based on the theory of the Lorentz force, dictating that an electrically charged particle, moving in a magnetic field, undergoes a force normal to the direction of the magnetic field and to the direction of movement:

$$F = q\ (\vec{v}\ x\ \vec{B}) \qquad (1)$$

With: *F* is the force (in Newton), *q* is the electric charge (in coulombs), *B* is the magnetic field (in Tesla) and *v* the speed of the particle (in m/s). The force exerted by an electric field has been neglected since no significant electric field will be present in this application.
The main components of the welding machine can be schematically depicted as shown in Figure 1 .

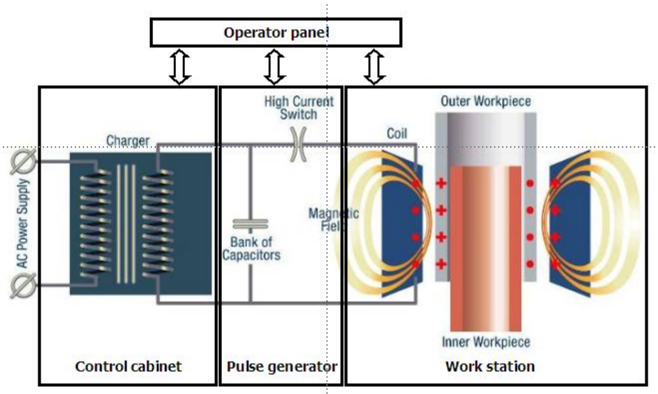

Figure 1: System schematic [1]

First a bank of capacitors is charged to an energy level chosen by the operator. Once the bank is fully charged the high current switch can be closed, sending a current through the coil. This current will induce a magnetic field in the coil. To concentrate the magnetic field in the desired region, a field shaper is placed inside the coil. The changing magnetic field will induce eddy currents in the outer work piece, also named the flyer tube. Further due to the shielding effect of an electrical conductor the flyer tube will prevent the magnetic field of passing through. So considering the Lorentz Force, the magnetic field outside the flyer tube will exert a force on the flyer tube due to the eddy currents, thrusting the tube inward in radial direction. The high velocity of the inward motion and thus the high-energy impact between outer and inner work piece will result in a cold weld.

1.2 MPW versus conservative welding techniques

The main advantages of MPW can be summarized as follows: [1] [2]

- Since it is a cold welding process no heat affected zone, HAZ, is present. All original material properties reached by heat treatment or not, are maintained.
- It enables the possibility of joining dissimilar materials.
- No preparation of the parts is required. The parts do not have to be cleaned or degreased.
- No post weld finishing or cleaning has to be carried out.
- Possibility of a high degree of automation.

Its main disadvantages are:

- Only electrically conducting materials can be used as flyer material.
- The parts must overlap to generate the joint.

2 THEORETICAL CONSIDERATIONS

2.1 Analytical model

An analytical model is essential to gain insight in the parameters governing the MPW process, and to make a quick estimation of the required value of these parameters to obtain a successful weld. However it is not straightforward to develop an accurate set of equations that is able to accurately model the MPW process.
The discharge current is a damped sinusoidal wave, which results in a time-dependent magnetic pressure. If a field shaper is used to increase the amplitude of the magnetic field, the pressure will theoretically be a function of axial and circumferential position, as well as time. Furthermore, complex deformation behaviour of the tubular work-pieces and high speed deformation both add to the problem of finding equations that have reasonable accuracy, as well as sufficient simplicity.

2.1.1 Pulsar model

We investigated an analytical model developed by the manufacturer of the welding machine (Pulsar), which should allow users to choose the process parameters needed to attain a good weld. The structure of this model is essentially correct. However, a multitude of simplifications result in decreased accuracy of the model.
The collision velocity, v_c, is first chosen depending on the materials. Considering the analogy between MPW and explosion welding, this data can be derived from experiments carried out with EW. [3] [4] An example is given in Figure 2: values for the impact velocity and collision angle should be chosen from a point in the shaded area to obtain a successful weld. The required acceleration can then be calculated, under the assumption that the velocity increases linearly from zero to v_c when travelling a distance equal to the stand-off distance, the distance between the flyer tube and the inner work piece.

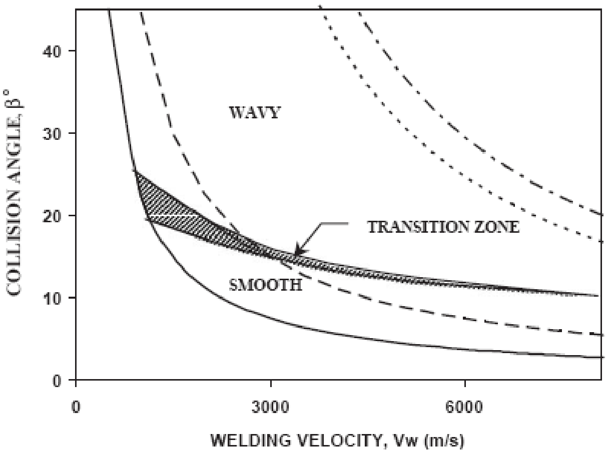

Figure 2: Example of a weldability window for EW (Al to Al joint) [3]

Next, the required pressure (exerted on the flyer tube) can be found as the sum of two components: the pressure to accelerate- and the pressure to deform the flyer tube. This pressure is exerted by the magnetic field, so a numerical value for this magnetic field can be obtained. Finally, through electrical circuit analysis, the required voltage stored by the capacitors is found.

Before further discussing the inaccuracies of the studied model, some analytical concepts are discussed.

2.1.2 RLC circuit

The electrical discharge circuit can be modelled as an RLC circuit. In this electrical circuit, *C* represents the total capacitance of the capacitor bank, *R* the equivalent resistance electrical circuit (circuit wires, coil and work piece) and *L* the equivalent inductance (circuit, coil, field shaper and work piece).
Circuit analysis shows that the discharge current is an exponentially damped sine wave (shown in Figure 3) represented by the following equation:

$$i(t) = \frac{V_0}{\omega_C L} \quad e^{-\xi . t} \quad \sin(\omega_C t) \tag{2}$$

In this equation, V_0 is the voltage to which the capacitor bank is charged, ω_c is the natural frequency of the circuit, *t* is the elapsed time and ξ is a damping factor. As ξ and ω_c are both functions of R, L and C, these three parameters *(R,L and C)* govern the entire circuit.
The value of *C* is a multitude of the capacitance of a single capacitor (the multitude equals the number of capacitors charged) [5] [6]. *R* and *L* are in reality *not* constant. Especially *L* shows a significant variation due to the field shaper and/or when the geometry of the work piece changes. For example an increase in the radial distance between the flyer tube and the field shaper will increase *L*, resulting in a lower amplitude of the discharge current. Consequently, the inductance is not constant during the welding process: compression of the flyer tube increases the radial distance and decreases *L*. These effects are neglected in order to keep the model simple enough to be applicable. [7] [8]

A current measurement as further described in **Error! Reference source not found.** can be used to determine the value of the resistance and the inductance. Given the measured current ω_c and ξ can be extracted. The equations defining ξ and ω_c then allow calculating *R* and *L*. When using a single MPW machine, an effective method would be to perform current measurements for a set of geometries and materials for each field shaper. Using curve fitting techniques, one or more functions could be extracted to model the influence of the above parameters on the value of the equivalent inductance *L*. Once such functions have been determined, a prediction of the current waveform can be made for each set of future experiments. [7]

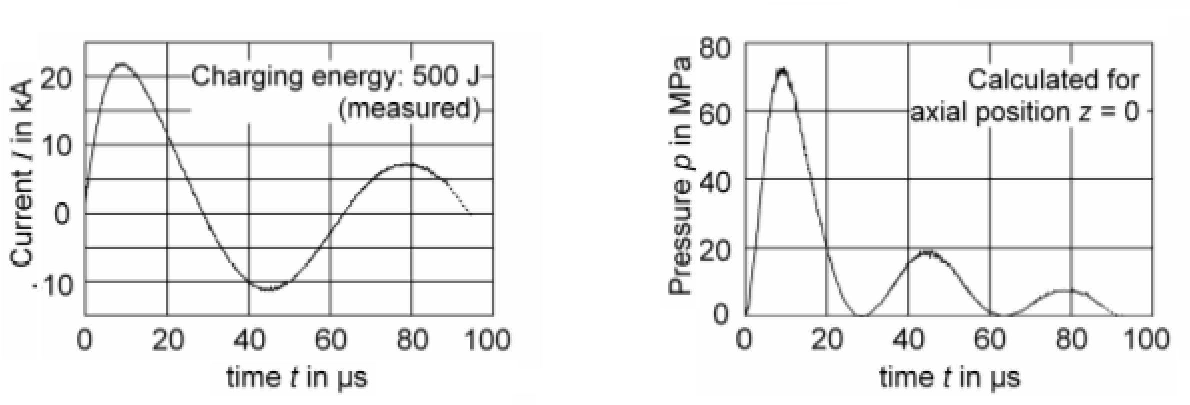

Figure 3: Discharge current and magnetic pressure [9]

2.1.3 Electromagnetic energy transfer

The damped oscillating current through the coil generates an axial transient magnetic field. According to Lenz's law, eddy currents in the work piece will be induced flowing in the opposite direction to its cause.
As a result, an electromagnetic force acts on the flyer tube, which is accelerated away from the coil and collides rapidly with the inner tube.

The magnetic pressure p exerted on the flyer tube is determined by the energy density of the magnetic field outside H_0 and inside H_i of the work piece and can be calculated on the basis of the (measured) coil current by equation 3 (where μ is the magnetic permeability) [9].

$$p = \frac{1}{2}\,\mu\,(H_0^2 - H_i^2) \tag{3}$$

The pressure waveform is also shown in Figure 3. It should be noted that in this equation H is dependent of time, axial and radial position. The magnetic field between the coil and the flyer tube differs from that between the flyer tube and the inner tube, due to the shielding effect. Quantification of the skin depth δ, simplifies the expression for the magnetic pressure to the form of equation 4 [10].

$$p = \frac{1}{2\mu} B_0 (1 - e^{2T/\delta}) \quad \text{with } \delta = \sqrt{2/\omega\kappa\mu} \tag{4}$$

These equations are valid for coils but do not take into account the effects of a field shaper, used to increase the amplitude of the magnetic field in a small region where welding will take place [11].

If it were not for the complex deformation behaviour, an analytical expression for the acceleration as a function of time could be established. Integration would then lead to a time function of velocity and radial displacement. As the stand-off distance is set in advance, a value for the time interval could be obtained and used to estimate the impact velocity consequently. [5]

2.1.4 Conclusions on the analytical modelling of the MPW process

The model proposed by Pulsar is (at this moment) the only analytical model available to describe the entire MPW process. However, after some research it is obvious that several simplifications and assumptions made in this model, limit the accuracy of its predictions.
First of all, the acceleration is assumed to be constant. This would require the magnetic pressure exerted on the flyer tube to be constant. However, this magnetic pressure originates from the damped sinusoidal current through the coil, and is consequently time-dependent.
Further the pressure required for deformation is determined in a simplified way. It is calculated as the pressure for which the yield strength is reached in a thin walled cylindrical tube subjected to radial compression. This formula can solely be used in case of linear elastic deformations and the simplification would suggest that the pressure compresses the entire tube with a radial displacement equal to the stand-off distance. In reality only one end of the tube is plastically compressed, and this at an extremely large deformation speed.

2.2 Numerical simulations

The discharge current and the magnetic field (and pressure) can be modeled analytically with acceptable accuracy. However, the effect of a field shaper (containing a radial slit where consequently B≈0) can only be quantified using finite element modeling techniques. In addition, the complex high speed deformation behavior of the flyer tube leads to complications when estimating the required deformation pressure. Consequently, the MPW process is increasingly being modeled using finite element (FE) methods.
[12] [13] [14]

3 EXPERIMENTAL STUDY

Theoretically it is obvious that the simplifications in the analytical model proposed by Pulsar lead to significant inaccuracy. However, due to the absence of more accurate analytical models, there is no clear insight regarding the severity of these inaccuracies. Many corrections are found in literature, but most of them are being used in FE models of the MPW process, so they are essentially not applicable to increase the accuracy of the proposed model. For instance, the acceleration is time dependent and can be estimated using the RLC circuit. Nevertheless, no applicable analytical model can be proposed using these complex time equations. For these reasons, the MPW machine will be instrumented and process parameters measured during experiments to obtain more insight in the process.

3.1 Measurement of process parameters

Measurement of the discharge current is executed by means of a Rogowski coil and a digital oscilloscope. The current waveforms are primarily used to determine a maximum value for the voltage over the capacitor bank (for safety reasons) [15]. In future experiments, the measurements could be used to determine the parameters of the RLC circuit, as explained in section 2.1.2.

Additionally an instrument for measuring the magnetic field has been designed. Narrow tolerances and the fact that the center of the MPW machine is inaccessible during the process prohibit the use of measuring probes which are commercially available. The custom probe shown in Figure 4, had to be designed for the purpose of the magnetic field measurement.

Figure 4: Magnetic field measurement

The probe consists of a cylindrical tube (PVC) and is to be placed around the flyer tube, thus filling the gap between the flyer and the field shaper. The probe tube supports a single turn of copper wire, through which the axial magnetic flux lines will flow. The measurement principle is based on Lenz's Law: the transient magnetic field induces a voltage over the wire of the probe. The voltage can be measured by means of a digital oscilloscope, and the waveform of the magnetic field can be derived.

$$\Phi = B\,.A \tag{5}$$

$$V = 2\pi f\,.\Phi \tag{6}$$

The probe was calibrated using a Helmholtz coil, which generates a uniform magnetic field. The coil is connected to a current source which sends varying amplitudes of excitation current through the coil. The probe is placed in the center of the coil, and for each amplitude the induced voltage in the probe is measured. The relationship between excitation current and induced voltage, leads to the area of the copper winding (A) in equation 5.

3.2 Welding Experiments

The complicated nature of the MPW process makes it difficult to obtain an accurate analytical or numerical model. One of the objectives of this thesis is consequently to determine relationships between several process parameters and weld quality on an experimental basis. By varying material combinations, stand-off distance, overlap distance, flyer tube thickness, etc. during a large number of welds, the goal is to obtain empirical formulas and/or intervals for the optimal settings of the process parameters.

Up to now, a preliminary series of twenty copper (flyer tube) - aluminum weld tests was executed. In the experiments the flyer tube thickness was kept constant. The overlap length, stand-off distance and the voltage over the capacitor bank were varied. Based on the limited number of tests performed, no general conclusions could be drawn so far.

The welded tubes were first subjected to a leak test (section 3.3) and the apparently most successful welds were selected. These selected joints were then examined in more detail using microscopic evaluation. This is in fact a destructive testing method, because the tubes have to be cut through in the axial direction.
After cleaning both parts, they are embedded in epoxy resin and polished in several steps, to attain a clean and smooth surface. On copper-aluminum welds the polishing has to be carried out very carefully, as both metals are relatively soft and scratch easily (which affects the image quality).
The polished surface is then placed under a microscope, enabling visual inspection of the weld in levels up to micrometers. The images obtained will show whether the two materials are connected and/or whether metallurgical/physical changes have taken place. Expected phenomena include the formation of an intermetallic layer and a wave pattern.

An example of a microscopic image is shown in Figure 5. This image shows a connection that was properly welded. The two materials are joined together and an intermetallic layer was formed.

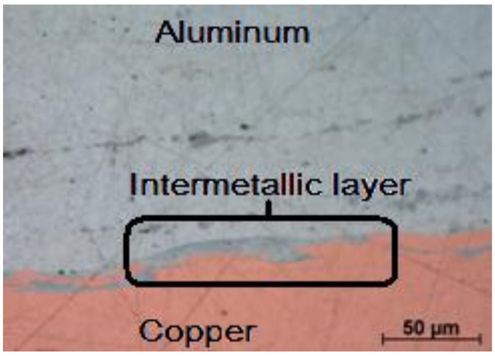

Figure 5: Microscopic image of a copper-aluminium MPW weld

3.3 Non Destructive Testing (NDT)

A simple leak test was developed in order to evaluate the welded tubes in a non-destructive manner. For several applications the most important requirement of the weld joining two tubes is that the connection does not leak. In this test the parts are connected to a source of pressurized air and are checked for leakage.
The welded tubes are connected to a pressurized air circuit, using a custom made connection, as shown in Figure 6, and the whole system is placed under water. A qualitative impression of the weld is obtained by inspecting the occurrence of air bubbles escaping from the joint. A more quantitative evaluation is possible by using a pressure gauge that measures the pressure in the circuit. If a pressure drop occurs, the welded connection is not leak free. The time necessary to obtain a certain pressure drop can be measured and used to describe the severity of the leak (and thus the quality of the weld).

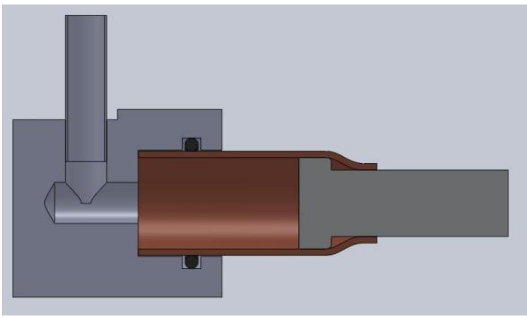

Figure 6: Leak test

4 FUTURE RESEARCH

The main objectives put forward at the start of our thesis are the evaluation of the analytical model and the development of welding windows based on extensive experimental research. Most attention thus far has gone to a general literature study and to the analytical modeling of the MPW process. In addition, a leak test setup and a magnetic field measurement probe were developed. The leak test setup will be further refined (accurate measurement of pressure changes) in the next stage of our research. The magnetic field measurement probe has been designed, constructed and calibrated, but has not yet been used in welding tests. Performing tests using the probe, will be the object of future experiments. Hopefully, the results will provide a more thorough understanding of the accuracy and applicability of the analytical model.
As mentioned before, we aim to determine relationships between welding parameters and weld quality on an experimental basis. By varying material combinations, stand-off distance, overlap distance, flyer tube thickness, etc. during a large number of welds, the goal is to obtain empirical formulas and/or intervals for the aforementioned parameters which result in a successful weld. In order for these relationships to be established, a large number of experimental weld tests will be performed. In addition to microscopic inspection, other non-destructive techniques such as ultrasonic testing [16] [17] and computer tomography [18] [19], will be applied to provide us with a better understanding of the MPW process. A last objective of our thesis is to develop a test method for the determination of weld strength.

5 CONCLUSIONS

Further research is imperative for the development of an accurate understanding and analytical description of the magnetic pulse welding process. The magnetic field measurement will hopefully lead to some valuable conclusions regarding the effect of the field shaper. Perhaps an analytical formula for a correction factor on the amplitude of the magnetic field (in the presence of a field shaper) could be obtained. On the other hand further experimental testing will provide deeper insight into relationships between different welding parameters. Multiple series of experiments will be performed and weld quality evaluated based on both destructive and non-destructive methods. The final objective of our thesis is to define *weldability windows*, which allow a simple determination of optimal process parameters.

6 NOMENCLATURE

EW Explosive Welding

FE Finite Elements

HAZ Heat affected zone

MPW Magnetic Pulse Welding

NDT Non-destructive testing

7 ACKNOWLEDGEMENTS

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