Tube Welding

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1 Working principle

In magnetic pulse welding, electromagnetic forces are used to impact two materials against each other at high speed. A power supply is used to charge a capacitor bank; when the required amount of energy is stored in the capacitors, it is instantaneously released into a coil. The discharge current induces a strong transient magnetic field inside the coil, which in turn induces eddy currents in the outer workpiece (here in this case a tube).

These eddy currents prevent the magnetic field to diffuse through the outer workpiece, and cause a difference in magnitude of the magnetic field on both sides of this workpiece. The difference generates a magnetic pressure, which causes the outer workpiece to impact with the internal workpiece.

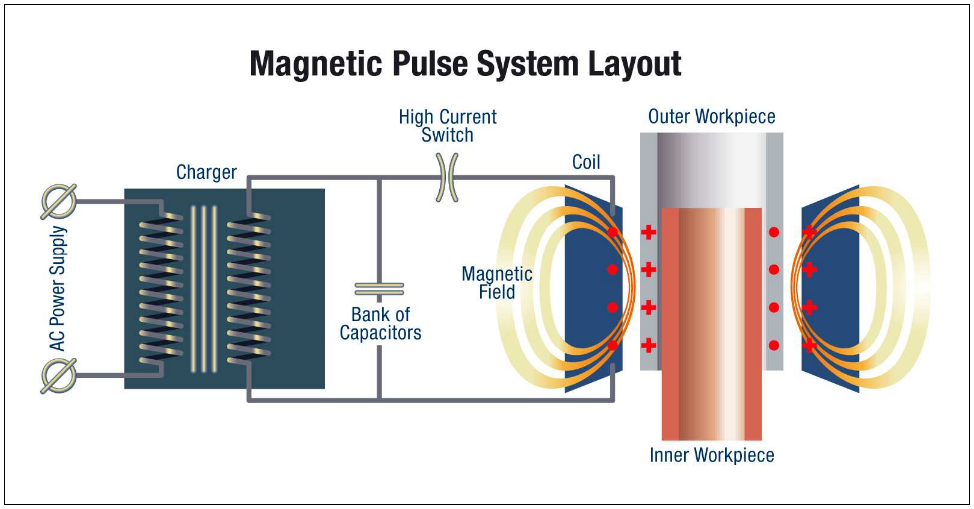

Figure 1 : *Principle of magnetic pulse welding [1]*

The collision between the workpieces causes bonding through several bonding mechanisms. Bonding between materials is created when the distance between their atoms becomes smaller than the range of their mutual attractive forces. In that case, electrons are shared between the two materials and an intermetallic phase (possibly with a high hardness) can be formed.

Microscopic roughness of the materials and surface contaminants can prevent the materials from being brought close enough together. Cleaning of the surfaces before the start of the bonding process is therefore required.

However, the workpieces are impacted with high velocity and under a certain angle, which generates a jet along the materials’ surface before they contact. This jet is able to remove surface contaminants such as oxide films, which reduces the need for pre-process cleaning. Also, due to the intense plastic deformation, mostly in the more ductile material, microscopic roughness isn't necessarily an obstacle when bringing the workpieces together. In general it is assumed that no pre-weld cleaning is required at all [2].

Previous experiments showed that a wavy or a flat bond interface is formed. If an intermetallic layer is formed, this is caused by mechanical mixing, intensive plastic deformation and/or melting. The temperature increase to cause these melting phenomena is believed to occur due to Joule effects and the collision itself. Because the process takes place in a very short lapse of time, heating is not enough to generate a temperature increase in a wide area, so there is no significant heat affected zone, as can be concluded from previous experiments [3].

Cross-sections of an aluminium-steel and an aluminium-copper weld are shown in Figure 2 and Figure 3 [4].

The exact microstructure in the weld zone depends on the process parameters and the materials used. The formation of the wavy interface is similar as in explosion welding. Typical examples of weld interfaces are shown in Figure 4 to Figure 11. This illustrates the material dependence of the interface morphology. The aluminium-aluminium (Figure 4) and the copper-brass welds (Figure 6) have a wavy pattern. The aluminium-mild steel weld interface in Figure 8 shows a flat interlayer.

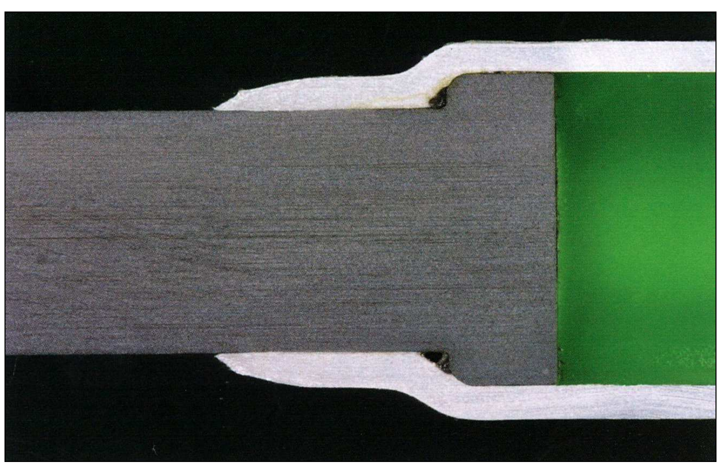

Figure 2 : *Aluminium - steel weld [4]*

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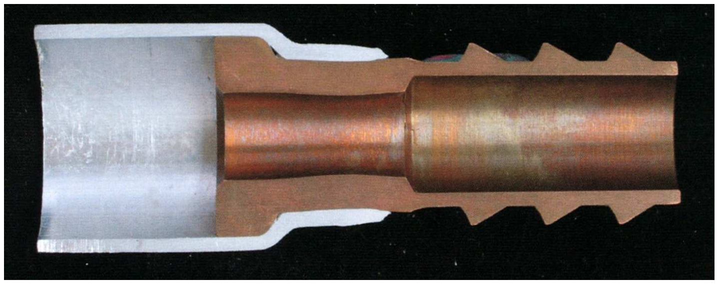

Figure 3 : *Aluminium - copper weld [4]*

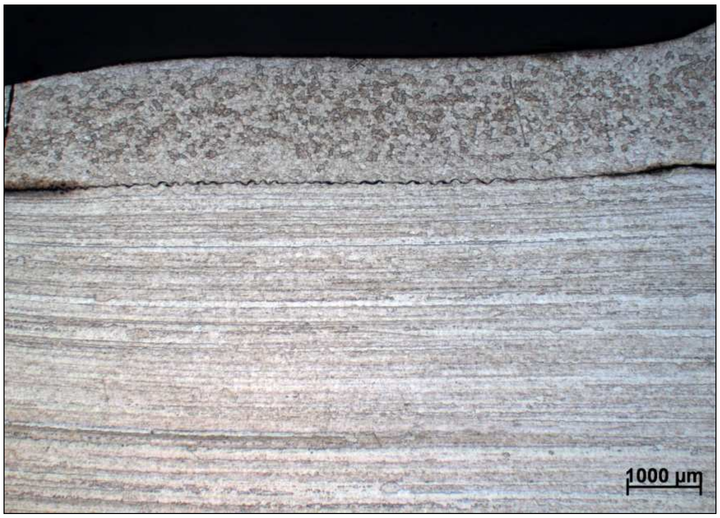

Figure 4 : *Aluminium - aluminium weld interface [9]*

Figure 5 : *Detail of Figure 4 [9]*

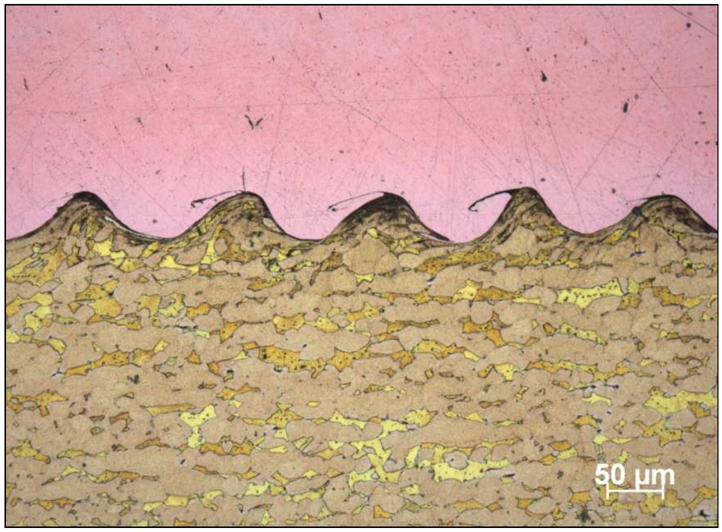

Figure 6 : *Copper-brass weld interface [9]*

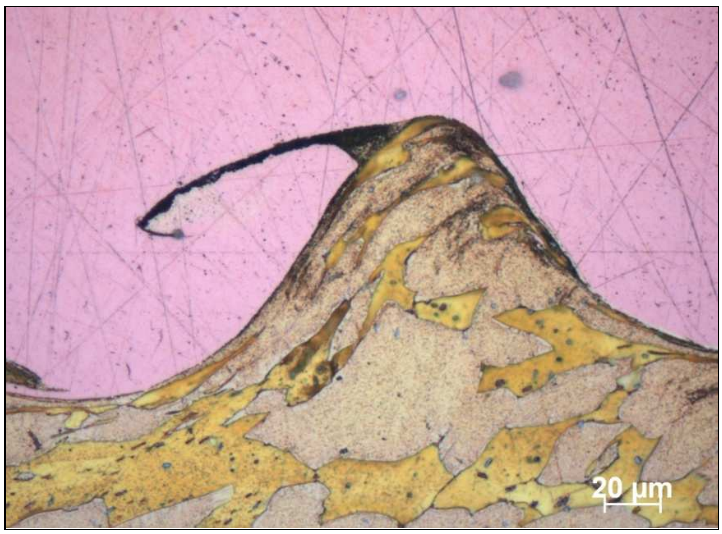

Figure 7 : *Detail of Figure 6 [9]*

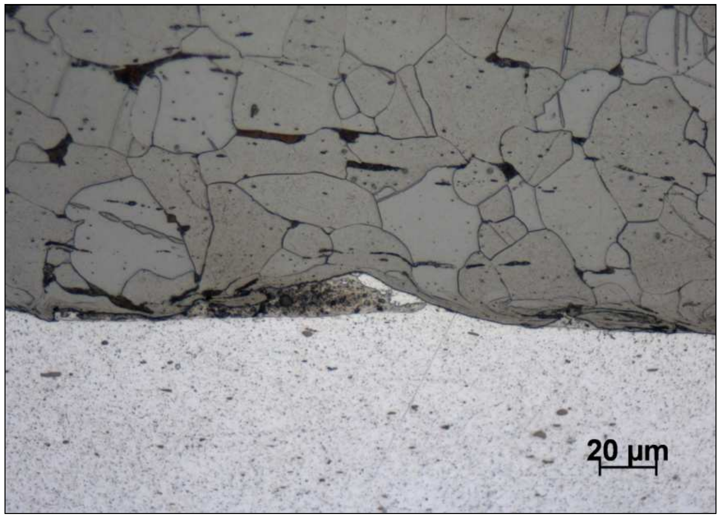

Figure 8 : *Aluminium - steel weld interface [9]*

Figure 9 : *Aluminium - copper weld interface [9]*

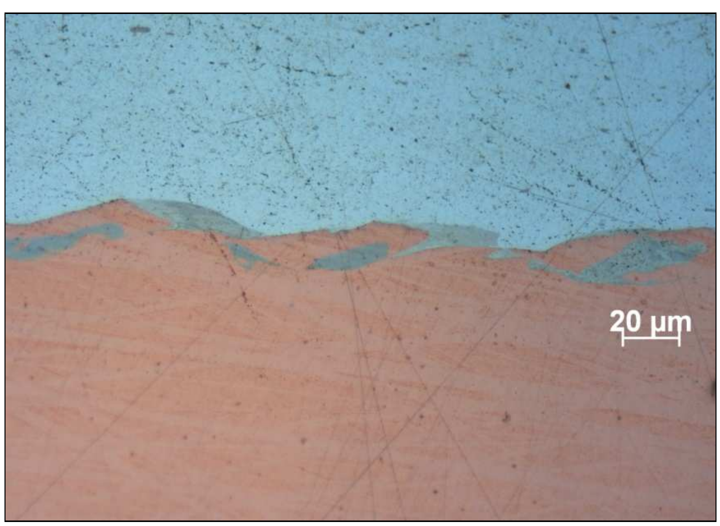

Figure 10 : *Detail of Figure 9 [9]*

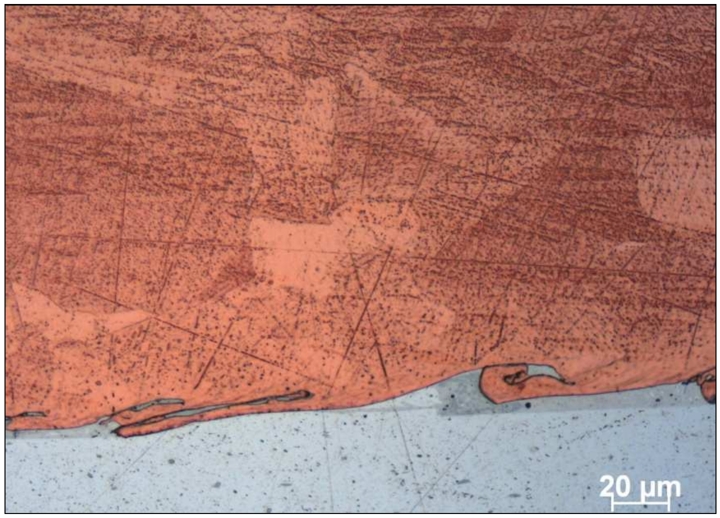

Figure 11 : *Copper - aluminium weld interface [9]*

The interface layer shows an increase in hardness relative to the base material (see Figure 12). This can be attributed to severe plastic deformation or to a new fine-grained microstructure produced by melting and rapid solidification of the weld interface. This interface layer may support two possible mechanisms of bond formation: bonding as a result of solid-state processes based on accelerated mass transfer due to intensive plastic deformation at very high rates, and bonding as a result of solid-liquid interaction and based on the formation of a thin layer of molten metal between the components [3].

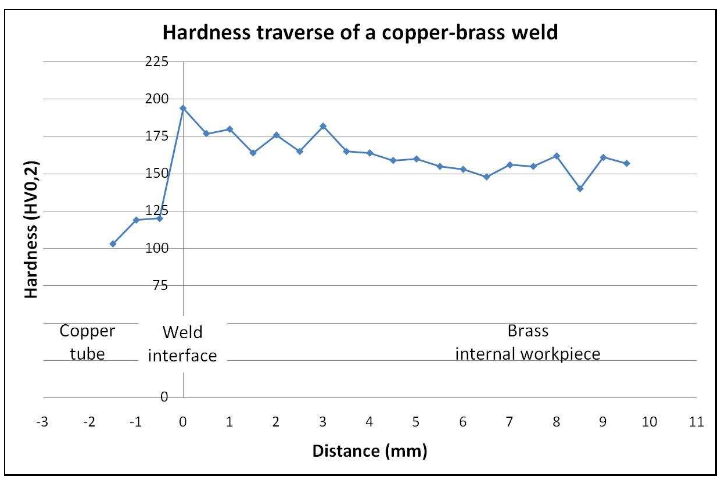

Figure 12 : *Hardness traverse of a copper-brass weld [9]*

2 Advantages of magnetic pulse welding

The electromagnetic joining process has interesting opportunities for :

- joining of conventionally non-weldable materials, in a quick and cost-effective manner, such as dissimilar material joints,
- development of complex workpieces or new products, which were previously not possible with the conventional joining processes.

- The magnetic pulse welding process is a "cold" joining process. Temperature increase is very local (in the order of 50 µm), so the workpieces reach no more than 30-50°C at the outer surfaces. This means that after welding, parts can immediately be unloaded and further processed with standard equipment.

The technology has a much lower negative environmental impact and is much more environmentally friendly compared to conventional welding technologies :

- There is no heat, radiation, gas or smoke, shielding gas, which is less harmful for the operator.
- The magnetic pulse welding process consumes less energy.
- In hostile environments machines can perform the joining operation, avoiding supplementary investments in operator safety.
- It is possible to improve the work conditions of the welder or operator, since the technology is environmentally clean.

3 Limitations

Magnetic pulse welding imposes some limitations considering the workpieces to be joined. The geometry and size of the parts to be welded are defined by the shape and size of the coil or field shaper. Some shapes, such as rectangle workpieces, are difficult or even impossible to weld as the sides are much easier to deform than the corners.
Lap joints are required, since the outer workpiece must impact the inner part to create the weld.

Also, the size of the parts to be welded is limited. Possible diameters probably range from 5 to 254 mm [5]. The largest tube diameter that is welded until now is 121 mm, larger sizes have not been tried due to a lack of demand [6]. The maximum size is limited by the cost of the machine, which increases significantly for larger diameter workpieces.

The outer tube needs to be a good electrical conductor, otherwise a conductive driver material should be used to increase the impact velocity. When the thickness of the inner workpiece is insufficient to withstand the impact of the outer tube, a mandrel is required to prevent deformation.

The process can only be used in a workshop due to the size of the welding machines. From the point of view of the potential applications, which are mostly factory-made parts, this is not necessarily a disadvantage. Also, one should be precautious because of the influence of the magnetic fields on electronic components and other plant equipment.

The process parameters are very part-specific, as was observed in previous experiments. The weld quality is sensitive to fluctuations in the collision conditions, such as the coaxial positioning of the parts or the angle of impact. The sensitivity to these fluctuations is smaller when the interface is more wavy [24].

Summary of the limitations:

- Only lap joints can be formed.
- Only tubes and sheets are possible to weld until now.
- The size of the tubes is limited.
- The process only works with a high conductive tube materials.

- The process is not suitable for in-field applications.
- The process is very sensitive to changes in process parameters.

When comparing magnetic pulse welding with magnetic pulse crimping, the following differences can be determined :

- Magnetic pulse welding requires (outer) materials with a high electrical conductivity and good cold formability. In contrast, magnetic pulse crimping can also be used for materials which are more difficult to cold-form (higher strength steels) and which have a low electrical conductivity (for example stainless steels).
- The quality of magnetic pulse welds is very dependent on the process parameters and the parameter window for reliable welds is narrower than for crimp joints.
- Magnetic pulse welding is always carried out with a radial air gap between the outer tube and the internal part (distance required for deformation and acceleration of the outer tube). In contrast, magnetic pulse crimping can be carried out with components which fit gap-free into each other. Therefore magnetic pulse crimping requires less or no design changes to be implemented.
- Magnetic pulse crimping can join materials which are impossible to join using magnetic pulse welding.
- Magnetic pulse welding needs a higher energy level, and thus larger and more expensive pulse generators.
- The quality of magnetic pulse welds is much more dependent on the surface preparation and cleanliness of the surfaces to be joined.

4 Electromagnetic pulse equipment

The electromagnetic welding set-up consists of an energy-storage capacitor bank, a high-voltage charging power supply, a discharge circuit, a work coil and, if appropriate, a field shaper.

4.1 Pulse generator

To generate the required magnetic pressure, it is necessary to apply pulsed currents in the range from 100 kA to more than 2000 kA. The energy has to be stored in a pulse generator, consisting of a capacitor bank, a charging unit and a high current switch.

The high-voltage charging power supply receives its power from the power grid and supplies it to the energy storage capacitor bank. The capacitor bank stores the energy until it reaches the predefined target level. The amount of stored energy is measured through the charging voltage level, which is the parameter that needs to be set before starting the process.

When the required energy level is reached, the capacitor bank discharges a current pulse through a secondary circuit containing the coil. The capacitor bank needs to possess a sufficiently high capacitance in order to store enough energy, while the inductance of the discharge circuit should be low enough, in order to ensure a fast energy release and thus a larger current pulse when discharging the current through the coil [7]. The damped sinusoidal current induced in the work coil (see Figure 13) produces a transient magnetic field [8].

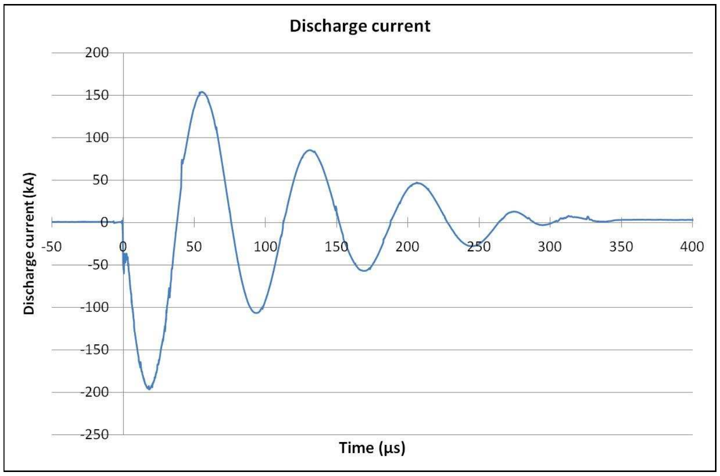

Figure 13 : *Discharge current during a magnetic pulse welding experiment [9]*

4.2 Coils and field shapers

Coils and field shapers are used to focus the magnetic pressure onto a certain area of the outer workpieces. A coil consists of one or more electrical windings and is made from a highly conductive material, usually a special copper or aluminium alloy.

Either single-turn coils or multi-turn coils can be used. A single-turn coil is shown in Figure 19. Multi-turn coils (see for example Figure 18) are mostly used in combination with a field shaper [6].

A multi-turn coil can be used in combination with several field shapers suitable for different geometries. The whole setup must be electrically isolated, otherwise the fields generated by the conductors and coil can interact with adjacent tooling. Also, the coil and field shaper need to be of sufficient strength, as they undergo a very high pressure opposite to the magnetic pressure on the tube.

The primary current running through the coil induces a strong magnetic field in the area within the solenoid (see Figure 14), with the field lines parallel to the coil axis. When inserting a conductive material into the coil, the field lines will be blocked by the workpiece. When the electromagnetic field penetrates the conductive workpiece, mobile charges will start to oscillate with the same frequency of the field, which causes an alternating current; the so-called eddy currents.

The magnitude of the eddy currents will be maximal at the surface, and decline exponentially further inwards the material. The eddy currents hinder the further penetration of the magnetic field through the workpiece as can be explained physically [10, 11].

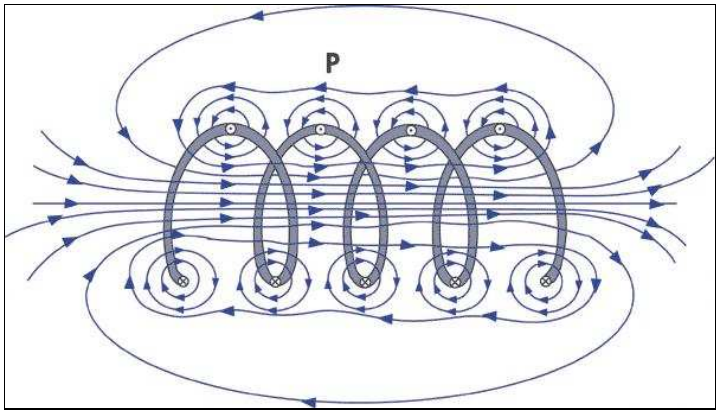

Figure 14: *Magnetic field caused by an electrical current in a solenoid coil*

A multi-turn coil is often inductively coupled to a field shaper. If properly designed, the entire current flux that is created in the primary current can be transferred to the bore of the field shaper. Field shaper-based coils are used to develop a high electromagnetic pressure, while being able to increase the inductance of the coil. This is less efficient than a well-designed single-turn coil would be, as more energy is dissipated in the field shaper [12]. But nevertheless, a field shaper homogenises the magnetic pressure acting on the tube, increases the pressure value and decreases the distributional gradient of pressure at the end of the tube [13].

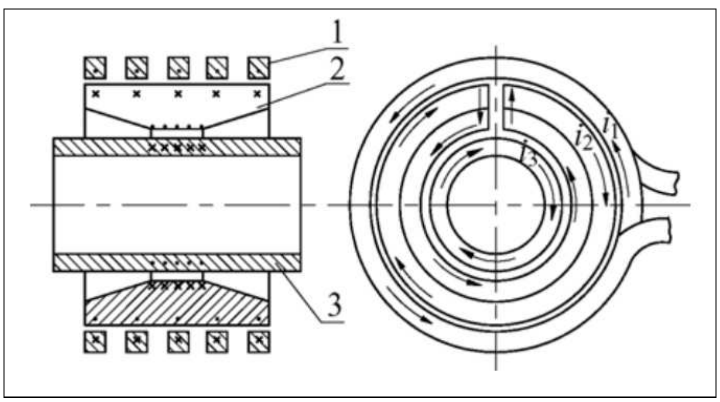

Figure 15 : *Current in the field shaper induced by the primary coil [13]*

A field shaper is sectioned with at least one radial slot (see Figure 16), and is electrically insulated from the workpiece and the coil. The axial coil length and the field shaper length at its outer diameter are usually the same, with the gap between coil and field shaper being kept as small as possible.

As the electrical pulse is transferred, the coil induces an eddy current in the skin of the field shaper, which flows to the inner surface of the field shaper bore by means of the radial slot (see Figure 16). The inner diameter of the field shaper is similar to the outer diameter of the work piece. The axial length of the inner bore is usually shorter than that of the coil and thus provides a current concentration. This has two effects : on the one hand, the magnetic field lines are concentrated onto the ridge and, on the other hand, the non-uniform magnetic field of coils with multiple windings is homogenised [14].

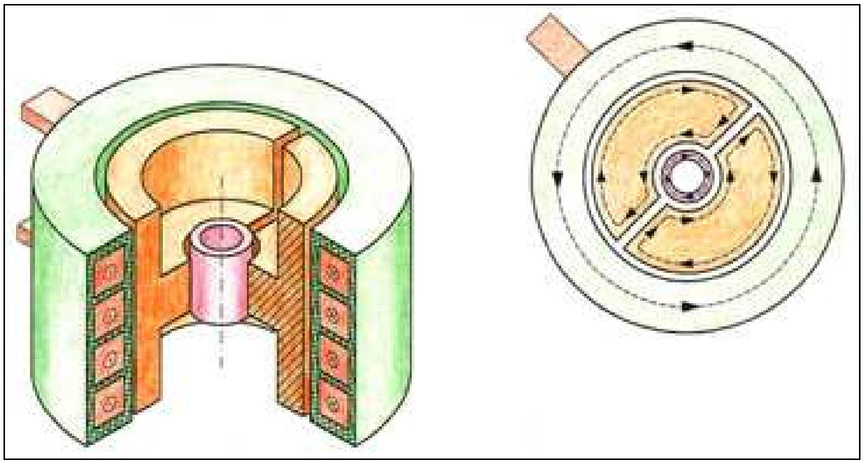

Figure 16 : *Current flow in the field shaper and coil [15]*

If a field shaper is used, the magnetic pressure that has to be created by the coil is smaller than the pressure that acts onto the workpiece, thereby significantly increasing the service life of the coil compared to a direct-acting single-turn coil, leading to a higher efficiency and more favourable costs. A variety of workpiece diameters and geometries can be processed with a standard multi-turn coil and the addition of suitable field shapers, with minimal time and effort. A field shaper can be changed within two minutes. A field shaper is not necessary for many part-specific systems using single purpose coils in service, but can contribute to part flexibility on the shop floor.

Figure 17 : *Magnetic pulse equipment at BWI [9]*

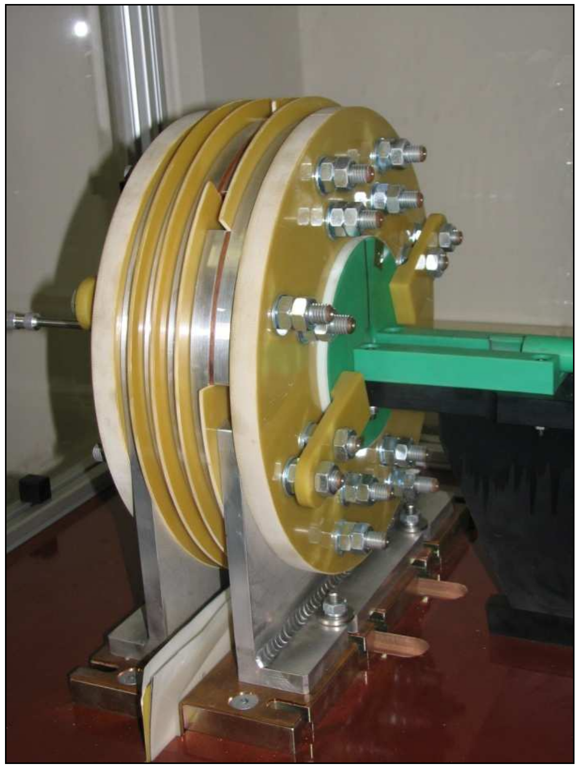

Figure 18 : *Multi-turn coil with a field shaper [9]*

Figure 19 : *Single-turn coil [9]*

Figure 20 : *Work table with the coil of a magnetic pulse equipment (laboratory set-up) [9]*

5 Process parameters

Just as in explosive welding, the quality of magnetic pulse welds is dependent on the impact angle and the impact velocity during coalescence. Numerous process parameters influence these 2 parameters in some way. These include the material properties, the electrical properties of the magnetic pulse welding machine and the geometry of workpieces and field shaper. The majority of these parameters will be invariable throughout the experiments, either because they are inherent to the magnetic pulse welding equipment, or because they are chosen to be kept constant.

The parameters which influence the process are :

- Material properties :
  - magnetic permeability
  - electrical conductivity
  - mechanical properties
  - density
  - thermal conductivity

- The impact welding parameters :
  - impact velocity
  - impact angle
- Geometrical properties :
  - width of the air gap
  - shape of workpieces
  - concentricity
  - thickness of the outer workpiece
  - diameter of the outer tube
  - relative position of the field shaper
  - axial length of the field shaper
- Electrical parameters
  - voltage level
  - frequency

5.1 Material properties

5.1.1 Magnetic permeability

The permeability of a material defines the degree of magnetisation. For all diamagnetic or paramagnetic metals, the value equals the permeability of air; $\mu_0 = 4\pi.10^{-7}$H/m. For ferromagnetic metals, the value will be a factor 10 to 10.000 higher, depending on the magnetic state. Most commonly used materials (e.g. aluminium, copper, magnesium, titanium) are dia- or paramagnetic, the only ferromagnetic material that is of any importance is iron. Therefore steel and stainless steel have a much larger permeability and thus a smaller skin depth. In this case, the material will conduct the magnetic field better, which prevents it from diffusing through it.

To understand the influence of the material magnetic permeability, it is necessary to take a closer look at the skin depth, which is given by:

$$\delta = \frac{1}{\sqrt{\pi.\sigma.\mu.f}}$$

With : σ : the electrical conductivity [m/Ω]
μ : magnetic permeability of the workpiece [H/m]
f = the frequency of the discharge current [Hz]

The magnitude of the alternating eddy currents in the workpiece will be maximal at the surface, and will decline exponentially further inwards the material. The skin depth is the depth at which the amplitude of the eddy currents falls to 1/e of its original value at the surface. In order to maximise the influence of the eddy currents, the skin depth should be small enough, in order to concentrate the current at the interface, so that the magnetic field doesn't diffuse through the workpiece.

In order to maximise the magnetic pressure, the skin depth should be small relative to the workpiece wall thickness. When the thickness of the tube is the same as the skin depth, the magnetic pressure equals 86% of its maximum value. When the thickness of the tube is twice the skin depth, the pressure reaches 98% of its maximum value.

When using very thin tubes, it is likely that a great share of the magnetic field is diffused through the wall thickness. In that case, the only way to reach a skin depth which is smaller than the thickness of the material is by adjusting the frequency of the current [10]. Another possibility is to wrap a thin conductive driver around the less conductive workpiece.

5.1.2 Electrical conductivity

The electrical conductivity of the outer tube is expressed in $m\Omega^{-1}$. Its only effect on the process which is known, is its influence on the magnitude of the eddy currents in the workpiece. This influence is expressed in the formula of the skin depth. A higher electric conductivity means that the induced electrical currents will be larger in value, and thus cause a larger opposing magnetic field. Consequently the magnetic pressure will be larger, which is important to cause bonding.

5.1.3 Mechanical properties

The workpiece mechanical properties are mainly of importance for the deformation of the material. The yield strength σ_y is directly related to the pressure required on the workpiece.

Strain hardening and strain rate hardening are two other important material characteristics which influence the formability of the workpiece. It is well known that the fundamental constitutive behaviour (stress, strain, strain-rate relations) for most metals change qualitatively at strain rates above about 10^{-4} s^{-1}. Above these strain rates, the apparent strain rate sensitivity of the material increases markedly [12]. The strain and strain rate hardening can be included into the material constitutive law. The Johnson-Cook model for yield stress expresses these influences :

$$\sigma_{pl} = \left[A + B.\varepsilon_{pl}^{n}\right].\left[1 + C.\ln\left(\dot{\varepsilon_p}\right)\right].\left[1 - \frac{\theta-\theta_{trans}}{\theta_{melt}-\theta_{trans}}\right]$$

With :

- σ_{pl} : von Mises yield stress [MPa]
- ε_{pl} : the equivalent plastic strain [-]
- $\dot{\varepsilon_p}$: the plastic strain rate for $\dot{\varepsilon_p}$ = 1,0 s^{-1} [s^{-1}]
- A, B, n : yield and strain hardening constants [-]
- C : strain rate constant [-]
- m : thermal softening constant [-]
- θ : absolute temperature when the stress is applied [K]
- θ_{trans} : transition temperature defined as the one at or below which there is no temperature dependence on the expression of the yield [K]
- θ_{melt} : temperature when the stress is applied [K]

The first 2 factors comprised in this equation express the influence of strain and strain rate hardening on the yield stress, while the third factor expresses the effect of the temperature. The material dependent parameters A, B, C, n, m have to be determined from straining tests. At the melting temperature, the stress approaches zero for all strains and strain rates [16].

Also the elastic modulus will be of importance in the deformation of the outer tube. The tube will be compressed to a smaller diameter, which includes a big deformation along its circumference.

Another important mechanical property is the elongation at break. This parameter defines the ductility of the material. Brittle materials or materials with low ductility can crack or fracture during the process.

5.1.4 Density

The density ρ [kg/m^3] of the tubular workpiece is of importance, since heavier materials require a higher pressure to accelerate to reach the required impact velocity.

However, the effect of the density is less significant as expected. Due to the higher mass of thicker workpieces, their kinetic energy at impact will also be higher. It is the kinetic energy which is responsible for the deformation of the workpieces and the jet formation. As the kinetic energy is also dependent on the impact velocity of the workpiece, the required velocity can be smaller and still result in a good bond. Hence, heavier workpieces require a lower impact velocity, as their kinetic energy is higher due to this higher mass. These both effects (higher required pressure and lower required impact velocity) oppose each other, so the influence of the density on the process is expected to be insignificant.

5.1.5 Thermal conductivity

The material thermal conductivity has no influence on the welding process itself, but it can influence the formed interlayer between the two materials. During the welding process, the eddy currents will generate Joule heat in the flyer workpiece, proportional to i^2/σ, with σ being the thermal conductivity. More important, heat is also generated by the severe plastic deformation due to the impact and interface wave creation and by the jet action. Also, the exothermal creation reaction of the intermetallic layer is a source of heat. This last effect however is additional after the material has already molten [17].

The generated heat needs to dissipate through the material [18]. When the material thermal conductivity is low, this heat will cause a temperature increase at the interface, as the density of the currents is maximal here, which can result into local melting of the least conductive material, especially when using high energy levels. Melting has been found as one of the bonding mechanisms [19]. The heat resulting from the plastic deformation of the area adjacent to the interface and the deformation caused by the jet increase the interface temperature much above the melting temperature [17]. The lower the thermal conductivity, the narrower the molten interface [20]. Melting and subsequent solidification can result in intermetallic layers, which have a higher hardness, but increase the cracking susceptibility. In general, they decrease the quality of the weld [21].

Because the process only lasts for about 100 µs, heating occurs only during this short time. Therefore, if melting takes place, it is limited to the interlayer and was found mainly in the middle part of the welding zone [22]. Previous magnetic pulse welding experiments were successfully conducted with stainless steels [23] and titanium [24], materials with thermal conductivities as low as 12 W/mK. Melting is most likely a negative effect for the bond formation, but can be avoided when the energy of the system is not chosen too high [17].

With very thin materials, which might be the case when using a conductive driver sheet, the heat can't spread over a large enough volume and consequently the temperature may increase too much and the driver could vaporise. This effect was experienced during experiments with tube forming [25].

5.2 The impact welding parameters

5.2.1 Impact velocity

The impact velocity is of crucial importance for the coalescence of the 2 workpieces, as it is this kinetic energy which is transformed into energy to be used for bonding. The impact velocity is directly related to the contact pressure which is required to move the outer tube, and hence to the energy level used when conducting the weld.

The workpiece geometry also has its influence on the impact velocity, just like the material characteristics. The impact velocity is important in that way that it needs to ensure a high enough pressure between the two materials, in order to allow joining. The conclusions regarding the bonding process in explosive welding learn that, if the velocity is too low, the impact energy is insufficient to initiate bonding. On the other hand, when the velocity is too high and reaches supersonic values, no jet force will occur and the materials will not bond.

5.2.2 Impact angle

The angle between the two impacting surfaces is the second crucial parameter. This parameter depends on the geometry of the workpieces. This angle needs to be in a certain range in order to induce the jet along the surfaces. A backflow of material will then move along the surface ahead of the collision point (see Figure 21), will deform the micro-roughness and damage the inert surface layers, so that they are prepared for interaction. If the workpieces would impact with an angle out of this range, the surface wouldn't be prepared by the backflow and consequently there would be no bonding action.

The angle of incidence varies during the welding process [26]. In explosive welding, these variations are within a small range and the angle is therefore in calculations usually assumed constant.

It is so far not known how the impact angle varies in magnetic pulse welding. The angle is impossible to measure as this would require images of the two surfaces during the welding process. Due to the high speed and inaccessibility of the weld zone, these are simply impossible to capture. An indirect way is to calculate the angle through the horizontal and vertical component of the velocity, but these are also nearly impossible to measure.

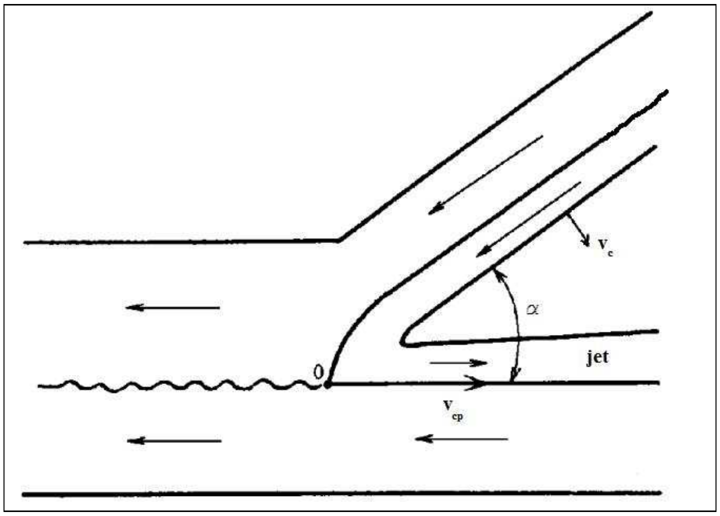

Figure 21: *The backflow of material during impact welding when viewing the process with the impact point as a fixed point. [27]*

5.3 Geometrical properties

5.3.1 Width of the air gap

The width of the air gap is the distance between the outer tubular workpiece and the internal workpiece. The gap or stand-off distance should be large enough so that the outer workpiece will have the time to accelerate up to the desired velocity.

If the width of the air gap is too large, the velocity might start decreasing again. This effect was noticed in [10], where the air gap width had one optimum value, which gives the maximum tensile shear strength of the weld.

It is clear that at a given energy level, the width of the air gap is a crucial parameter influencing the value of the impact velocity and thus the quality of the weld. A larger air gap width enables the workpiece to accelerate during a longer time before impact, and thus reach higher impact velocities at the same energy level. However, because it will take longer until impact, the pressure peak might have passed before the impact occurs and the velocity might start decreasing again.

Apart from its influence on the velocity, it will also require more energy to deform the workpiece. The material needs to be compressed from an inner diameter d_i to an inner diameter d_i – 2.s, with s the air gap width. With a larger width s, the material has to be compressed more and the energy required to do this will also increase. Clearly, this effect is a disadvantage due to the tubular shape of the workpieces.

5.3.2 Workpiece shape

A possible weld configuration is shown in Figure 22. The zone between the collar and the workpiece holder is where the workpieces will impact. This zone can be designed straight (see Figure 23b and Figure 24), or tapered. With a straight interface, the impact velocity is expected to be practically constant along the weld. The impact angle will increase towards the end of the weld. Putting the workpiece under a certain initial angle both influences the impact angle as the impact velocity. The configuration as shown in Figure 23a) decreases the impact angle in comparison with the straight surface. The opposite configuration is also possible in order to increase the process' impact angle. The impact velocity will vary along the weld length, as the width of the air gap is variable as well.

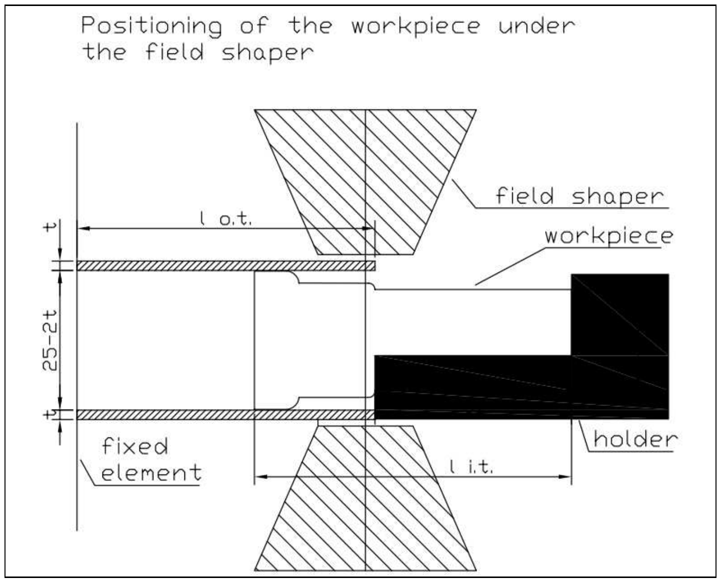

Figure 22: *Positioning of the workpieces inside the field shaper [9]*

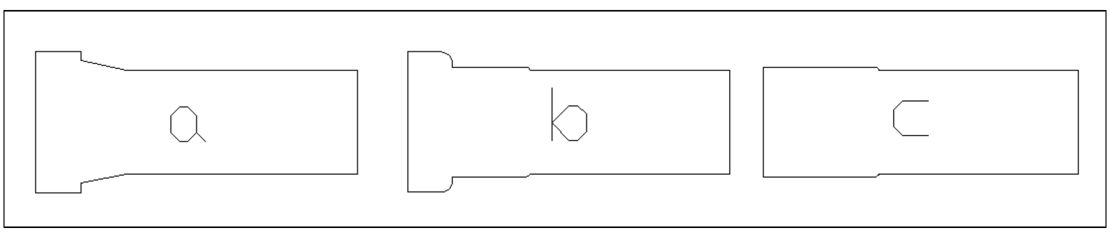

Figure 23: *Different possible geometries of the inner workpieces : [9]*

a) slant configuration
b) straight configuration
c) configuration without collar

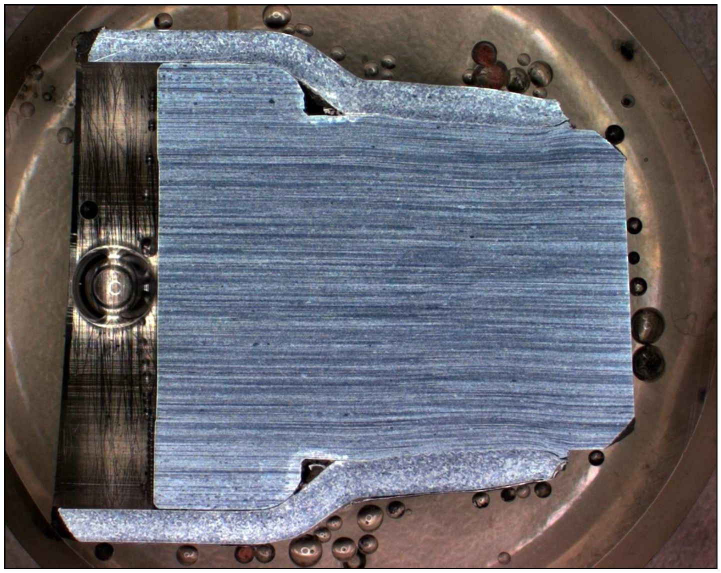

Figure 24 : *Cross section of a aluminium - aluminium weld [9]*

Due to the high force of the impact, there is a risk that the internal workpiece deforms. Therefore, when using tubular internal workpieces, a mandrel can be used to prevent this deformation.

5.3.3 Concentricity

If the workpieces are not concentric, part of the circumference of the outer tube would have to cover a bigger distance towards the inner workpiece. Consequently, this part would also need a larger deformation. The impact velocity would then differ over the circumference of the workpieces, and the quality of the weld would not be the same everywhere. Clearly, this has to be avoided.

The outer workpiece has to be aligned with the internal workpiece. To ensure the concentricity of the inner workpiece with the outer, the inner workpiece can be designed with a collar, as can be seen in Figure 23a and b. If there is no easier way to ensure the geometrical positioning of the tubes, it is possible to use a positioning and insulating plug. This plug maintains the tubes' mutual concentricity, the width of the air gap and isolates the tubes from the coil. High density and high molecular weight polymers are best used as material for these plugs [28].

5.3.4 Thickness of the outer workpiece

A larger wall thickness of the outer tube means that the formability of this part decreases. It will have a bigger mass which needs to be accelerated towards the internal workpiece. Both the pressure required for deformation of the outer tube and the pressure required for acceleration will increase, since both pressures are directly related to the wall thickness. When the energy level and hence the magnetic pressure is chosen constant, the impact velocity will decrease for a larger wall thicknesses of the outer tube.

5.3.5 Diameter of the outer tube

The diameter of the outer tube will mainly have an influence on the formability of the tube. The use of larger diameter tubes implies that there is more material which needs to be deformed and accelerated. As a result, for a larger diameter, a higher energy level is required.

The diameter of the tubes to be welded is limited by the size of the field shaper. To ensure a good radial alignment, the outer diameter is chosen to fit the insulation surrounding the field shaper.

5.3.6 Relative position of the field shaper

The position of the field shaper relative to the workpieces plays an important role for the deformation of the outer tube and thus for the impact behaviour. The two possible ways of the field shaper placement are shown in Figure 25. In the configuration with the field shaper entirely over the workpiece (Figure 25a), the central part of the tube will impact to the inner workpiece. From here the weld will propagate to both sides. Also the jet will occur on both sides of the initial impact. In the configuration with the field shaper placed over the end of the outer tube (Figure 25b), the end of the tube will impact first, and the weld will propagate in one direction.

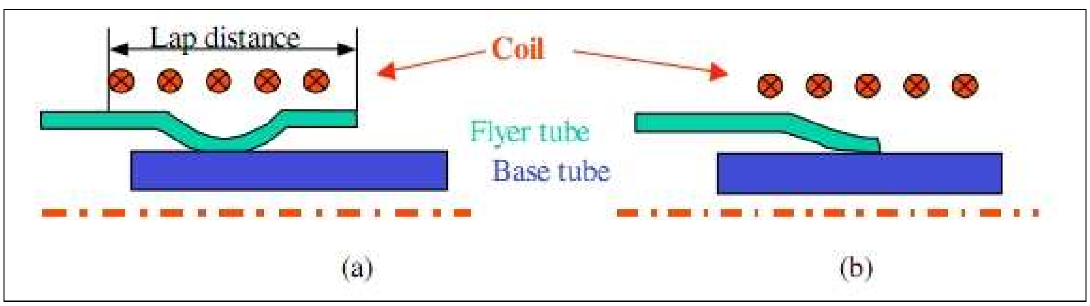

Figure 25 : *Different possible positions of the field shaper [24]*
a) middle joint
b) end joint

The deformation will be smaller when the field shaper is positioned over the end of the workpiece, as there is less material which has to be deformed. Hence, the end joint requires less energy than the middle joint.

In the configuration of Figure 25b, the field shaper will overlap with the outer workpiece over a certain working zone l_{FS} (see Figure 26). l_{FS} is defined as the distance between the tube end and the edge of the field shaper which is placed over the flyer tube. The further the field shaper overlaps, the longer the magnetic pressure zone of the outer workpiece, and the more material that will be deformed. Also, a longer working zone allows longer welds to be formed. This parameter will have an important effect on the impact angle and possibly as well on the impact velocity during the process, as the deformed zone will be larger and the deformation will happen faster with a bigger overlap.

5.3.7 Axial length of the field shaper

The axial length of the field shaper is the length over which the magnetic field will be concentrated. When keeping the energy level constant, the magnetic field and hence the magnetic pressure will be higher when the length of the field shaper is decreased. The energy will be concentrated in a smaller zone. In order to keep the same magnetic pressure with a longer field shaper, the energy level needs to be increased.

The required length of the field shaper is dependent on the overlap of the field shaper with the outer workpiece (l_{FS} in Figure 26). As the magnetic field might show discontinuities towards the edge of the field shaper, the field shaper should be longer than the overlap.

If the length of the field shaper is too large in comparison with the required overlap, energy is saved by using a smaller field shaper. Working with a smaller field shaper length can also be of use to generate a higher local magnetic pressure with the same energy level. In this case the working zone and hence the potential welding zone will be smaller.
Opposite to this, if the magnetic pressure is large enough, it will be possible to obtain a longer welding zone.

It should be noted that the length of the working zone also influences the impact angle. Welding with a shorter working zone in order to increase the magnetic pressure is therefore not a guarantee for successful welds.

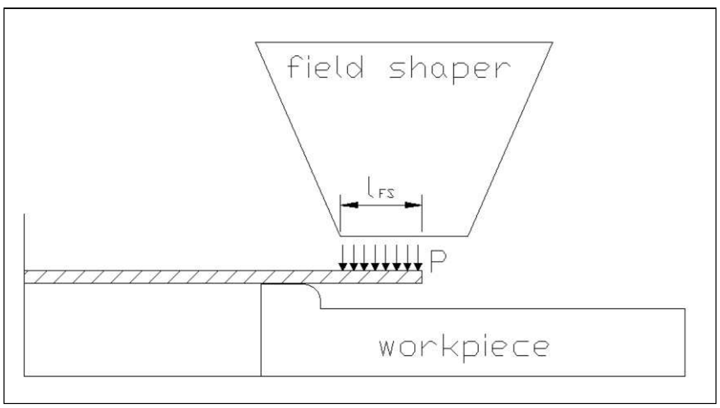

Figure 26: *Magnetic pressure on the outer tube caused by the overlap of the field shaper [9]*

5.4 Electrical parameters

5.4.1 Voltage level

The capacitor charging voltage is directly related to the energy level. The voltage level is a crucial parameter in the formation of the weld, as this parameter determines the impact velocity for a given geometry and given materials of the workpieces. If in a chosen experimental setup a defect-free weld is not obtained and the cause is believed to be an insufficient impact velocity, then bonding can sometimes be achieved by simply increasing the chosen voltage level. On the other hand, choosing a voltage level and hence an impact velocity which is too high, could lead to failure of the weld as well.

As an increase in the voltage level results in an increase of the magnetic pressure on the outer workpiece, also the deformation behaviour will be different, so it is not unlikely that the impact angle will also change at higher energy levels. The voltage level is the parameter which is easiest to change in experiments, and will come up as one of the most important parameters for a successful design.

5.4.2 Frequency

The discharge frequency determines the skin depth of the material. Increasing the frequency reduces the induced current layer thickness. This can be a reason to adjust the frequency of the current when using thin outer tubes. For example, when dealing with conductive drivers, the skin depth will become too large and therefore it will be necessary to increase the frequency.

Apart from its effect on the skin depth, the frequency also influences the space distribution of the magnetic field, the peak value of the magnetic pressure and the pulse width of the magnetic pressure. The pulse width of the magnetic pressure influences the acceleration duration of the outer tubular workpiece. The longer it accelerates, the more the tube will increase its velocity. Lower frequencies lead to larger pulse widths [29].

Adjusting the frequency is only possible by making adjustments to the capacitor banks, but in most cases can't be adjusted in the magnetic pulse welding equipment.

6 Applications

Figure 27 shows a high pressure capsule manufactured from aluminium EN AW-7075-T6. This is a material which cannot be welded conventionally. Figure 28 compares an automotive air conditioner accumulator realised by magnetic pulse welding and MIG welding. Magnetic pulse welds have a better esthetical aspect.

Figure 27 : *EN AW-7075 high pressure capsule [30]*

Figure 28 : *Automotive A/C accumulator - Comparing magnetic pulse welding and MIG [30]*

Figure 29 : *Magnetic pulse welded driveshaft (aluminium – steel joint) [31]*

Magnetic pulse welding is particularly suitable for large series production and for automated systems. For example, the application shown in Figure 30, an automotive air conditioner receiver-dryer made from EN AW-6061, is produced in production lots of 2-3000 units per shift.

Figure 31 shows an aluminium EN AW-6061-T6 automotive driveshaft application. In Figure 32, an automotive fuel filter is shown, manufactured from aluminium EN AW-1060. This product must survive 150.000 cycles at 7 bars pressure to meet the specification requirements.

Figure 30 : *Automotive aluminium A/C receiver-dryer [30]*

Figure 31 : *Automotive aluminium- aluminium driveshaft [30]*

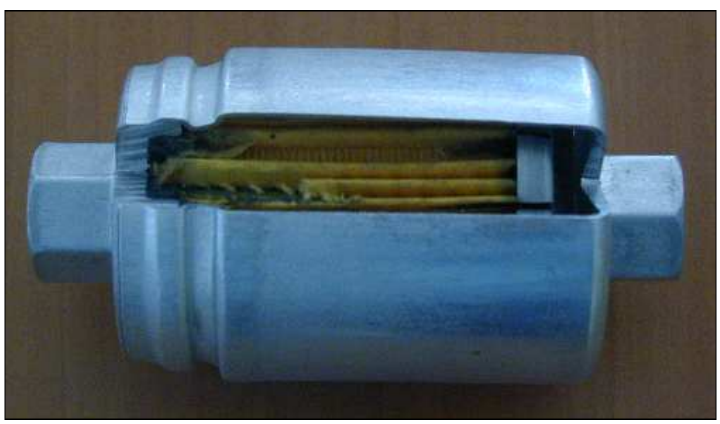

Figure 32 : *Automotive aluminium fuel filter [30]*

Figure 33 shows the versatility of the process, in the possibility of creating good welded joints between aluminium EN AW-6060-T7 and stainless steel AISI 304, or aluminium EN AW-3003-H14 to stainless steel AISI 304 for an automotive earth connector. This part is subsequently friction welded to the aluminium car chassis.

Figure 33 : *Automotive earth connector (aluminium-stainless steel) [30]*

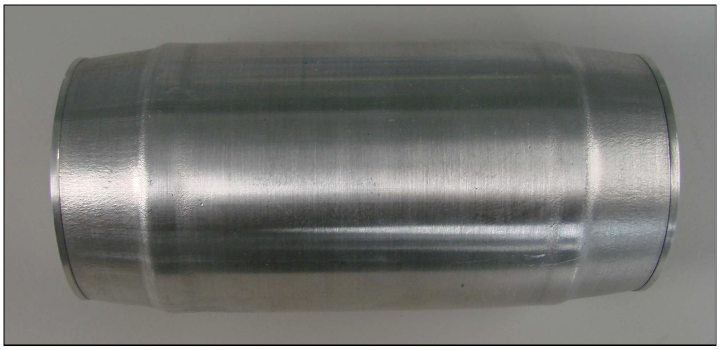

Figure 34 : *Aluminium pressure capsule welded to aluminium end caps [31]*

Figure 35 : *Aluminium - steel weld (drive shaft) [30]*

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