Magnetic pulse welding on the cutting edge of industrial applications

(Soldadura pormpulso magnético na vanguarda das aplicações industriais)

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Abstract

Magnetic Pulse Welding (MPW) applies the electromagnetic principles postulated in the XIXth century and later demonstrated. In recent years the process has been developed to meet highly demanding market needs involving dissimilar material joining, specially involving difficult-to-weld materials. It is a very high speed joining process that uses an electromagnetic force to accelerate one material against the other, resulting in a solid state weld with no external heat source and no thermal distortions. A high power source, the capacitor, a discharge switch and a coil constitute the minimum equipment necessary for this process. A high intensity current flowing through a coil near an electrically conductive material, locally produces an intense magnetic field that generates eddy currents in the flyer according to Lenz law. The induced electromotive force gives rise to a current whose magnetic field opposes the original change in magnetic flux. The effect of this secondary current moving in the primary magnetic field is the generation of a Lorentz force, which accelerates the flyer at a very high speed. If a piece of material is placed in the trajectory of the flyer, the impact will produce an atomic bond in a solid state weld. This paper discusses the fundamentals of the process in terms of phenomenology and analytical modeling and numerical simulation. Recent industrial applications are presented in terms of materials, joint configurations and real examples as well as advantages and disadvantages of the process.

Key-words: Magnetic Pulse; Welding; Electromagnetic Welding; Cold Welding

1. Introduction

Magnetic pulse welding is a process that emerged at the beginning of the '70s as a spin off technology of nuclear energy programs. The process was mainly developed for welding end closures onto nuclear fuel rod holders [1]. The technique was invented by Russian scientists from the Kurchatov Institute of Nuclear Physics. In USA, the Maxwell Laboratories Inc. (San Diego) have licensed this technology and built welding equipment for Westinghouse Hanford Co., which fabricated a nuclear reactor for the Energy Department. Other USA companies followed Maxwell Laboratories and further developed the magnetic pulse welding process [1,2]. In the Aerospace industry more than 4.200 parts were produced for airplanes engines and...
Magnetic Pulse Welding (MPW) is a cold process [3-6] since the metallurgical bond is produced without fusion and therefore, mechanical and chemical properties of the material do not undergo liquid-solid transformations. This process can be defined as a solid state welding one that produces a weld by a high velocity impact of the parts under controlled conditions. During the process, materials are accelerated to a high speed, at which, when impacted, a metallic bond forms between the two materials [3]. Welding between dissimilar materials is possible since joining occurs by plastic deformation without melting. According to [5,6] insipient local fusion is observed because the metals briefly act like a liquid.

Magnetic pulse welding has never achieved a clear place amongst mainstream manufacturing processes. Though this technique is known for a long time, there are still opportunities of development and application, specially for joining multi materials. For example, in applications requiring to combine the strength of steel or titanium with the high electrical and thermal conductivities of aluminium or copper, fusion welding is possible though the very distinct mechanical and thermal properties of these materials places several difficulties. Laser and tungsten arc welding can be used but the productivity is limited, as well as, the joint quality. Solid state processes are more and more applicable and amongst these, MPW, is seeing an increasing interest.

One of the main advantages of MPW are related to the solid state welding processes and the possibility of joining dissimilar materials while their mechanical and chemical properties will be almost maintained. These advantages rely in the fact that there is no heat introduced and no thermal distortions and it is a clean process where the jet formed in the high velocity impact between both materials remove any oxidation and dirty from the surfaces (Fig.51) [1,3,7,8] that do not emit harmful fumes or gases or radiation. It is a repeatable process that does not require additional reworks [1,3,4] dedicated to high mass production easy to robotize. The process brought up improvements in the quality and productivity while reducing costs per part, by introducing revolutionary production designs there were not possible until today [3,4], being suitable for large series production and for automated feeding system with low maintenance and quick changeover [3,9].

### Table 1. Industrial applications of MPW

<table>
<thead>
<tr>
<th>Nuclear Industry</th>
<th>Aerospace Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closing caps</td>
<td>Lining of ammunition control rods</td>
</tr>
<tr>
<td>End closers of nuclear fuel rods</td>
<td>Components of fuel pumps</td>
</tr>
<tr>
<td>Metal canisters</td>
<td>Tubular space frames</td>
</tr>
<tr>
<td>Nuclear fuel pins</td>
<td>Composites over wrapped Pressure Vessels</td>
</tr>
<tr>
<td>Space frames Drive shafts</td>
<td>Electrical fuses</td>
</tr>
<tr>
<td>Reinforcing bands on oil filters</td>
<td>Components of electrical motors</td>
</tr>
<tr>
<td>Components of air conditioning</td>
<td>Cable ducts</td>
</tr>
<tr>
<td>Fuel filters</td>
<td>Connectors to cooper cables</td>
</tr>
<tr>
<td>Tubular seat components</td>
<td>Coaxial cable termination joints</td>
</tr>
</tbody>
</table>

Some companies [11] use MPW to produce space frame structures made of aluminium or steel contributing for the lightweight of final assembly, maintaining the strength of the steel at the joints (Fig. 2).
Magnetic pulse welding on the cutting edge of industrial applications

2 - Fundamentals and Process Description

Magnetic pulse welding is a solid state process for joining metallic materials specially highly electrical conductive ones, that uses a high intensity AC current to produce an electromagnetic field to create an impact force to bond two metallic parts at an atomic level.

Figs. 3 and 4 present a schema of the process, for plate and tube, respectively. A high power source, the capacitor bank is charged up to the energy required. This pulse generator provides AC electric current of high intensity in short pulses. The parts are placed in the electromagnetic coil. The high intensity current flowing through a coil near the electrical conductive material, locally produce an intense magnetic field that generates eddy currents in the flyer part according to Lenz law. The induced electromotive force gives rise to a current whose magnetic field opposes the original change in the magnetic flux. The effect of this secondary current moving in the primary magnetic field is the generation of a Lorentz force, which accelerates the flyer at a very high speed. This impact causes plastic deformation on the moving part, and under precisely controlled conditions an atomic bond in a solid state weld is created between the two materials. The impact velocity is above 300 m/s, therefore, this process is also called as high-velocity forming process [5].
For the tubular joint configuration the same principle is applied. The high-density magnetic flux created around the coil induces Eddy Current on the outer surface of a metal tube as shown in Fig. 5.

The main process parameters are: the discharge energy, the standoff distance, the magnetic pressure, the impact velocity and the collision angle.

**Discharge energy**

Stored energy in the capacitor bank is discharged into the coil and this energy is responsible for the movement of the flyer metal. Discharge energy takes place in a very short time in the range of a few microseconds in order to accelerate the flyer metal so that it impacts the other part at a high velocity.

Increasing the charging voltage or the capacitance of condensers, increases the discharge energy and, thus, the shearing strength of the welds will be enhanced [5]. In fact, there is a threshold value of the discharge energy to produce the weld. However, the correct energy must be used to avoid exceeding critical strain rate of the material that can tear them. It means that for each material combination there is a minimum of energy necessary to join both materials, and there is a maximum of energy before tearing or cracks to the welding process [6].

**Standoff Distance**

The standoff distance is the distance between parts prior to the discharge. This gap must exist at each welding, because, when magnetic pressure is done on the flyer metal, it must have space to gain velocity and acquire kinetic energy that is going to be transformed into impact energy. In order to have good welding between both metals, there is an optimum value of standoff distance, which varies according to the welding materials. When standoff distance deviates from that value, the velocity and the kinetic energy reduces, leading to a reduction in the shearing strength and the width of the weld [5,6], as shown in Fig. 6 for Al/steel joints.

If the standoff distance is low, collision takes place before the flyer metal could reach the maximum velocity. On the other hand, for higher standoff distance, the velocity drops to a lower value at the time of collision. In terms of discharge energy, the higher the gap, the higher should be the discharge energy in order to obtain a good quality weld [5,6].
**Magnetic Pressure**

Magnetic pressure is one of the parameters responsible for driving the flyer metal into the parent metal. Due to the induced Eddy Current, the magnetic pressure will oppose the magnetic field from the coil and force the flyer metal to gain velocity until collision. In order to have a successful bond, the magnetic pressure must be high, otherwise the flyer metal will crash into the parent metal with lower velocity and no bonding will occur. High magnetic pressure can be obtained with high discharge energy or high frequency current.

When the standoff distance increases, the discharge energy must increase to improve the magnetic pressure, maintaining bonding quality. On the other hand, for a given standoff distance, increasing the magnetic pressure will increase the tensile shear strength of the joint.

It was observed [13] that at each collision between the flyer metal and the parent metal have a maximum value at different collision angles.

**Impact Velocity**

The impact velocity is influenced by the energy and the standoff distance. As shown in Fig. 7, the discharge energy and the velocity vary accordingly.

![Graph showing Aluminium (flyer metal) velocity just before collision](image)

**Fig. 7. Aluminium (flyer metal) velocity just before collision [5].**

On magnetic pulse welding the impact pressure is very high and consequently, the impact velocity is also very high, causing plastic deformation at the interface between parts to weld. The welding requires that both surfaces that are going to be joined should be free of contamination, and thus, the high velocity of the flyer metal plays an important role, because it will create a jet that will remove any contaminants or oxidation particles from both contact surfaces [5].

The impact velocity is directly correlated with the energy and discharge time from the capacitor, through the coil into the flyer metal. If the energy is transferred at low velocity, the flyer workpiece will collapse and no bonding is produced.

**Collision Angle**

At the impact point, the shock waves travel in both metals with a radial front, and an angle depicted in Fig. 8.

![Diagram showing Shock wave propagation in MPW](image)

**Fig. 8. Collision point [3]**

The pressure peak is always at the collision point, because the shock wave travel speed is higher at the start point and decreases with time. Fig. 9 depicts the travel path of the shock waves from the collision point in the inner part and back to the surface, where the total path is the sum of X1 and X2. Z is the distance of the period, that is, the collision point is ahead of the shock wave interferences, and thus, in the collision starting point, the interface shows a wavy morphology while its amplitude decreases till the end of the weld due to shockwave damping.

![Diagram showing Shock wave propagation in MPW](image)

**Fig. 9. Shock wave propagation in MPW [14]**

The collision point is where the pressure reach is higher peak. Fig. 10-b) shows the shock wavelength formation. When the first wave is generated, regardless of the inner part diameter, a Kelvin-Helmholtz instability mechanism is observed and waves are created periodically (Fig. 10-d)). Instability and new collision points generate new shock waves. Thus, the following wave is initiated by the interference continuity (Fig. 10-e)). New interference can not be created while waves are formed by metals movements across the interface. Due to decrease of the propagation velocity with the weld progression, the shock wave interference meets the collision point further along and for this reason, the wavelength increases (Fig. 10-f)). After some point, \( V_c \) is so small that the interferences are ahead of the collision point and new waves cannot be generated (Fig. 10-g)).
If the part to be welded has different thicknesses and since stress waves travel both in the inner and outer parts, there might be more than one mode of interference. In this case, the Kelvin-Helmholtz instability would be a multimode. If the impact creates the right conditions of impact angle and velocity, jetting is created and, consequently, welding takes place [3].

3 - Bonding Characteristics

Magnetic pulse welding produces either a wavy or waveless morphology at the interface of both materials. The precise shape is a function of the materials properties and the process parameters. Fig. 11 shows the wavy interface of Al 7075 [3], evidencing plastic deformation.

One most common welding consists on joining aluminium and stainless steel. The stainless steel (SS) has higher melting point and higher strength when compared to aluminium like AA6111. Due to their differences, when the welding takes place, the interface zone differs from one metal to the other. For the SS there is no change in grain morphology at the vicinity of the wavy weld interface (Fig. 12). In AA6111 extensive plastic deformation was seen at the interface [15] due to the high-strain rate exerted by the electromagnetic force. For this reason, it is suggested that aluminium behave as a fluid at a high strain-rate deformation. The morphology of the interface is similar to that of explosive welded joints [14,15]. Nevertheless, the amplitude and wavelength of the interfacial wave are much smaller in magnetic seam welding.

It is visible at Fig. 13 the intermediate layer that is formed between welding of A6111 and SPCC, where it is revealed that this layer is a mixture of fine crystal grains (indicated by arrows) and finer equiaxed crystal grains assumed as Fe-Al intermetallic compound (indicated by dual arrows).
Despite the temperature does not rise significantly, it was seen that increase due to the jet and massive deformation of the surfaces, and in some cases, melting and solidification occur (as in explosive welding). It was proven experimentally that the wavelength of interface waves is proportional to the free path of shock wave propagation in the inner part of the welded joint. This shock wave theory claims that the waves, due to impact, propagate through the metal parts creating periodic interference perturbation at the welding interface. Those interferences initiate a Kelvin-Helmholtz instability that creates the interface waves. To avoid formation of intermetallic pores and cracks, low pulse discharge energy should be limited.

Both, profile and amplitude of the waves after bonding, in the interface between flyer and parent metal are dependent on the shape of the flyer plate. According to these researchers, three different kinds of flyer metals were tested: Flat, U and V-shape. As result, the amplitude was higher for the Flat-shape metal and lower for the U-shape one.

4 – Analytical modelling and numerical simulation

Modelling of the process is not a simple issue, and several researchers attempted to establish process models. Basically, when the high current intensity is applied to the coil, a high magnetic flux density $B$ is suddenly generated and penetrates the flyer metal. Eddy Currents (with a current density $J$) are created at the surface of the flyer metal. As a result, an electromagnetic force of $J \times B$ will force the flyer metal until it collides into the parent metal. Accordingly to several researchers MPW process can be replaced by an equivalent electrical circuit that will help to understand and calculate variables like magnetic field or electromagnetic force. These calculations depend on the weld geometry. Most common ones are tube to tube and plate to plate, and these have been the most extensively studied. The Eddy Current $J$ and the magnetic pressure $P$ were obtained as follows:

\[ \nabla \times J = -\sigma \frac{\partial B}{\partial t} \]  
(1)

\[ p = \frac{(B_0^2 - B_i^2)}{2\mu} = \frac{B_0^2}{2\mu}(1 - e^{-2t/\delta}) \]  
(2)

\[ \delta = \frac{1}{\sqrt{\pi \sigma \mu f}} \]  
(3)

Where:
- $\sigma$, is the electrical conductivity of the work piece (mΩ$^{-1}$)
- $\mu$, is the magnetic permeability of the work piece (Hm$^{-1}$)
- $\delta$, is the skin depth (m)
- $B_0$, is the magnetic flux density at the lower surface (T)
- $B_i$, is the magnetic flux density at the upper surface (T)
- $f$, is the frequency of transient current (Hz)
- $t$, is the thickness of the conductor metal (m)
- $P$, is the magnetic pressure (Pa)
- $J$, is the current density (A/m$^2$)

From equation (1) it is possible to see that when using materials with higher electrical conductivity, means higher Eddy Currents, and as result, stronger magnetic pressure. According to (2), the value of magnetic pressure increases and the depth of the skin effect (3) decreases with the increasing the electrical conductivity. According to [21], the skin depth give us the value of length towards the inside direction of the material at which the current is reduced to 36%. Equation 2 can be used to calculate the magnetic pressure.

The circuit theory allows calculating the pressure, the current and the depth effect along the workpieces, simulating MPW process. The current takes the form of a damped sine and can be understood as a closed circuit: Inductance-Resistance-Capacitance (LRC) [17-19]. A magnetic pulse welding process...
is equivalent to a primary RLC circuit coupled with a secondary RL circuit. A schematic model of the system analyzed is shown in Fig. 14, where the RLC circuit (primary circuit) replaces the capacitor bank and the coil.

Fig. 14. Representation of the equivalent circuit [20]

\[ V_0 \] is the initial voltage of the capacitor bank  
\[ C \] is the capacitance of the capacitor bank  
\[ L_{e1} \] is the total inductance of the primary circuit  
\[ R_{e1} \] is the total resistance of primary circuit  
\[ M \] is the mutual inductance between the coil and workpiece  
\[ I_1 \] is the coil current  
\[ I_2 \] is the equivalent induced current in the workpiece  
\[ L_{e2} \] is the workpiece equivalent inductance  
\[ R_{e2} \] is the workpiece equivalent resistance

Regarding the energy balance, the resulting force between the magnetic field in the coil and the induced magnetic field in the workpiece, normally is referred as the magnetic pressure. The induced magnetic force and pressure is given by equations (4) and (5) [18,22]:

\[ F = \frac{\mu_0 I_1 I_2}{2\pi d} \]  
\[ P = \frac{\mu_0 B^2}{2} \]

This analytical method was developed for calculating system inductance and electromagnetic pressure on the workpiece. The analytical results were verified experimentally for the primary and induced current [20].

The peak current generated by a capacitor bank discharge can be estimated for a standard LRC equations. So, \( I_{\text{max}} \) can be estimated by equation (6) [17]:

\[ I_{\text{max}} = V_0 \sqrt{\frac{C}{L}} \]  

Numerical calculation methods are very useful to optimize the process because they can decrease time and cost to run the process as well as to get a deeper insight into it. From the mechanical, thermal and chemical properties of the materials involved, simulations with dedicated softwares, either commercial as MSC Dytran or LS-DYNA 980 or developed, allow assessing welding parameters.

As an example Zhang et al. [23] tried to predict impact velocities and temperature distribution along the bounded interface in AA6061-T6 to Cu101 using the electromagnetism module available at DYNA. With this module it is possible to simulate mechanical, thermal and electromagnetic experiments.

Fig. 15 presents the actuator, flyer and target involved. All components were meshed using solid hexahedral elements.

Fig. 15. Meshed three dimension [23]

Fig. 16. Current density of the flyer plate at 2.4 kJ [23]
The simulation (Fig. 15) shows a rapid thermal cycle on the bonded interface, the induced current change direction periodically and the maximum value for current density is on top and bottom edge of the welding area. Fig. 17 presents the temperature at five nodes of flyer AA6061-T6 alloy. It was observed an increase on the five nodes around 200ºC within 40µs.

Fig. 17. Temperature profile on AA6061-T6 at 2.4 kJ [23]

Based on the simulation, the temperature was seen to be below the melting temperature for each material involved, though, near the interface, the metals experienced a fast heating and cooling cycle. Local temperature increasing, favours the metal fluid flow at a high strain rate, and at the same time favours the wavy interface formation that contributes positively to a good quality welding [23].

5 - Materials

Almost any material can be welded by MPW [4,24], namely, similar joints of aluminium, copper, nickel and steel and dissimilar welds of aluminium to copper, magnesium and titanium, copper to bronze or nickel to titanium. When welding dissimilar metals the flyer metal should have high electrical conductivity and the target should have higher yield strength to avoid plastic deformation [8,25].

Fig. 18 depicts several examples of the relationship between material resistivity and skin depth. Copper and aluminium, due to their low resistivity, are the best ones to act as flyer material, while steel and stainless steel are predominantly used as parent metals, otherwise the discharge energy or frequency has to be increased.

Table 2 resumes mechanical and thermal properties of most common materials used in MPW.

Table 2. Mechanical and thermal properties of MPW materials

<table>
<thead>
<tr>
<th>Properties</th>
<th>Steel [g/cm³]</th>
<th>Stainless Steel [g/cm³]</th>
<th>Aluminium [g/cm³]</th>
<th>Titanium [g/cm³]</th>
<th>Copper [g/cm³]</th>
<th>Magnesium [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.75 - 8.05</td>
<td>7.75 - 8.05</td>
<td>2.7</td>
<td>4.5</td>
<td>8.9</td>
<td>1.74</td>
</tr>
<tr>
<td>Elastic Modulus [GPa]</td>
<td>190 - 210</td>
<td>190 - 210</td>
<td>69</td>
<td>100 - 120</td>
<td>117</td>
<td>46</td>
</tr>
<tr>
<td>Thermal Expansion [10⁻⁶/K]</td>
<td>9 - 15</td>
<td>9 - 20.7</td>
<td>23.1</td>
<td>8.4</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Melting Point [°C]</td>
<td>1370</td>
<td>1454</td>
<td>660</td>
<td>1668</td>
<td>1083</td>
<td>650</td>
</tr>
<tr>
<td>Thermal Conductivity [W/m-K]</td>
<td>26 - 48.6</td>
<td>11.2 - 36.7</td>
<td>237</td>
<td>17</td>
<td>381</td>
<td>156</td>
</tr>
<tr>
<td>Electrical Resistivity [10⁹Ω - M]</td>
<td>210 - 1251</td>
<td>75.7 - 1020</td>
<td>27.5</td>
<td>55</td>
<td>1.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Tensile Strength [MPa]</td>
<td>758 - 1882</td>
<td>515 - 827</td>
<td>110</td>
<td>1060</td>
<td>200 - 400</td>
<td>135 - 285</td>
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<tr>
<td>Yield Strength [MPa]</td>
<td>366 - 1793</td>
<td>207 - 552</td>
<td>95</td>
<td>1480</td>
<td>70</td>
<td>80 - 280</td>
</tr>
<tr>
<td>Hardness [Brinell]</td>
<td>149 - 627</td>
<td>137 - 595</td>
<td>245</td>
<td>716</td>
<td>874</td>
<td>260</td>
</tr>
</tbody>
</table>
Welding of Similar Materials

Ferrous

Dissimilar joining of steels to non-ferrous alloys as Al, Cu or Ti is quite difficult by fusion welding and MPW is used instead with major advantages [26,27].

Non-Ferrous

As a light material, aluminium finds numerous applications in transport and aerospace industries. Together with copper, since both alloys have a high electrical conductivity, they are used in MPW as the flyer part. It was observed [28] that under high strain rates, aluminium ductile behaviour increases, which facilitates magnetic welding similarly to Ti alloys that exhibit excellent corrosion resistance associated to high mechanical resistance. Magnesium alloys is gaining interest in the automotive and aeronautical industries, mainly, because of their high weight to resistance ratio since Mg is the lightest structural material [28,29,30]. It has been tested under high velocity welding technologies, and MPW is feasibility in Mg alloys [30] where ductility and formability increase at high strain rates. Similar welding of aluminium alloys AA1050 [5], AA6063 [21] and AA6061 [28] in plates or tubes have been studied by several research groups in order to assess the effect of welding parameters on the bonded length, the interface morphology and the overall mechanical strength. In solid state welding these alloys do not exhibit major weldability problems.

Welding of Dissimilar Materials

Dissimilar welding of AA1050 to Ti and AZ91 alloys in sheets of 0.5 to 1 mm thick was studied using two capacitor banks in parallel of 100 µF/10kV, with an inductance of 0.02 µH [4, 30], with an energy discharge of 1.2 kJ and the maximum current measured was of 150 kA. A wavy-like morphology of the interface was observed between Al/Fe, Ti and Mg as shown in Fig. 19) with a good bonded interface free of intermetallics or defects, which is a remarkable result.

When welding 1 mm thick aluminium to 0.25 mm thick stainless steel, the capacitor bank was charged with 10 kJ at 10 kV. A copper coil was used with an inductance of 0.74 nH. The total inductance of the circuit was 0.7 µH. The parameters were adjusted to get a frequency of oscillating current of 18.5 kHz, in order to ensure that skin depth on the flyer material (aluminium) was less than its thickness. Fig. 20 shows the tensile shear strength variation with the standoff distance.

As expected, it was observed [6] that the samples from the middle of the weld had a higher shearing strength due to a higher penetration of the magnetic field in the centre of the welded length than near the edges, but also because the current flowing through the sheets change direction at the edges. This weakness of the magnetic field will decrease the magnetic pressure on the flyer material, so, as a result, the bonded area has lower shear strength. For an optimum value of standoff distance the strength is maximum, when above or below the kinetic energy of the flyer metal is reduced, since the velocity decreases and so does the magnetic pressure. In order to compensate the deviation, more energy is required to obtain the same result. The microstructure of the bonded interface shows a good continuous weld between aluminium and stainless steel free of defects (Fig. 21).

Welding Copper (DHP R290) to Brass (CuZn39Pb3) [31] a bonded interface similar to explosive welding was seen with a brittle interlayer despite the fact that the temperature do not increase significantly (Fig. 23). However, it has been verified [32] that the jet will increase the temperature between metals, so, in order to avoid melting, the discharge energy or the impact...
angle should be decreased. In fact, the jet is dependent on the impact angle, the discharge energy and the impact velocity.

An interesting study was conducted on welding pure Al (99.5) to TiAl6V4 aiming to investigate the influence of impact velocity on bonding these two dissimilar metals [30]. It was concluded that in the range of 10 m/s to 25 m/s, there was no bonding on the atomic scale, and above this value some sections of the samples were welded. Fig. 23 shows that an increase of the impact velocity leads to a higher ratio of the welded area and contact surface.

Micrograph analysis at the interface between both metals, with an impact velocity of 130 m/s show micro fractures in the aluminium, running parallel to the contact surface of the weld (Fig. 24).

When a threshold value of impact velocity is exceeded, there is a deterioration of the joint. For this combination of metals, the optimum value relies between 100 m/s and 130 m/s. A similar study was performed on tubes of aluminium with 20 mm diameter and 1 mm thick and titanium with 15 mm diameter and 2.5 mm thick. Both workpieces were positioned coaxially in the compression coil with an initial gap of is 1.5 mm. After some experiments, the desirable impact velocity was established to be around 100 m/s with a energy of 500 J. For a discharging energy of 1.000 J there was a wavy interface of 4 and 6 mm in amplitude. Increasing this parameter the bonded interface was more flat and he weld was successful.

Conclusions

Magnetic Pulse Welding has been growing since the 70’s and there is an increasing interest in the welding process in several industrial sectors.

It is a cold welding process in which two metal surfaces in placed in close contact by the effect of a high speed electromagnetic force produced in a short pulse capacitor.

There is no heat developed in the interfaces due to the very short duration of the process in the range of few tens of millisecond.

The impact velocity is proportional to the current intensity, the distance between the plates and the voltage. When impact occurs, its higher value is achieved with higher collision angle. The development of a uniform plastic strain distribution along
the bonding is the result of good angle impact [13].

When current frequency increases, magnetic pressure will increase. Higher frequencies have larger magnitude with short peak time period, but, for lower frequency the pulse will decrease during more time. Thus, deformation of the flyer metal will be quicker for high frequencies, due to higher discharge current frequency results in quick damping of the current. It is possible to conclude that when a flyer metal has lower conductivity, the process must have higher frequency and large wall thickness (for flyer metal) resulting on high magnetic pressure. Thus, the higher is the electrical conductivity, less energy is required to have collision and create bonding. For example: welding between aluminium and copper it was necessary lower electrical and thermal resistance to achieve strong joints. Comparing with welding of aluminium to titanium and steel, it was needed more energy to achieve high joints [34].

Standoff distance as optimum value for welding, and when it deviates discharge energy must increase. If the gap diminished more energy is needed to give more velocity to the flyer metal. On the other hand, if the gap increases, more energy is needed because the flyer metal has a bigger distance to go trough before impact into parent metal.

Welding between dissimilar metals is not an issue for MPW technique providing both metals are electrical conductors. When the metals involved have higher tensile or yield strength the discharge energy must be higher, and the opposite is also valid. Nevertheless, the success of getting good welding between metal sheets, tubes or other configurations depends mainly on the discharge energy, standoff distance, thickness of the flyer metal and parent metal, material of the metal and coil geometry and strength.

Increasing applications exist especially in automotive industry in dissimilar joining of structural resistant light alloys [34,35].

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Magnetic pulse welding on the cutting edge of industrial applications

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