MAGNETIC PULSE WELDING
MPW

Bruno Manuel Coelho Tomás

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Orientadora: Professora Doutora Rosa Maria M. Miranda

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RESUMO:
Com o processo de Soldadura por Impulso Magnético (do inglês, Magnetic Pulse Welding - MPW) tem sido desenvolvida de forma a corresponder às exigências do mercado actual, relativamente à diminuição de peso dos componentes obtidos através de soldadura. Com esta diminuição, conseguem-se cortar alguns custos e ao mesmo tempo o processo MPW vai permitir soldar materiais dissimilares que até então não havia sido possível unir, pelo menos, não havia sido possível o desenvolvimento de uma técnica viável capaz de manter a estabilidade e capabilidade num processo normalizado.

A Soldadura por Impulso Magnético é designada por processo de “soldadura de alta velocidade”, a qual utiliza a força electromagnética para acelerar um metal contra outro, resultando numa soldadura em estado sólido. Apesar de ser designada por soldadura de alta velocidade, também tem a designação de ser uma “soldadura fria” devido à temperatura na altura da união não aumentar significativamente nos materiais, ao ponto de ser possível retirar a peça final sem ser necessário o uso de equipamento de protecção para o calor.

Uma fonte de alimentação de alta tensão, um conjunto de condensadores, um comutador de alta velocidade e uma bobina representa o equipamento mínimo necessário para soldar dois metais através do processo MPW. No entanto, ainda é possível inserir um computador para controlar os dados de entrada e saída do sistema, bem como um sistema Photon Doppler Velocimeter (PDV) cuja função é a medição de alguns parâmetros, tais como a velocidade e ângulo de impacto.

Na soldadura entre dois metais, estes devem ser inseridos no interior da bobina, e imediatamente após fechar o circuito através do comutador de alta velocidade, a energia armazenada no conjunto de condensadores será transferida na íntegra para a bobina gerando um intenso campo magnético. Este campo magnético irá penetrar na peça que se encontra mais próxima da bobina (designada por peça de trabalho), e a chamada corrente induzida será criada. Por sua vez, a corrente induzida irá dar origem a um campo magnético que se irá opor ao campo magnético da bobina (campo magnético que o originou). As forças electromagnéticas resultantes do campo magnético vão exercer pressão na peça de trabalho e forçá-la a chocar com a peça estática (peça que irá sofrer o choque). Este processo acontece em micro
segundos e devido à grande velocidade de impacto, combinada com um ângulo de colisão apropriado, dão origem à união entre os dois materiais.

Os parâmetros como a energia de descarga, distância entre a bobina e a peça de trabalho, pressão magnética, “efeito de pele”, velocidade e ângulo de impacto e a sua relação com o processo MPW serão descritos ao longo desta tese. Alguns investigadores, cujas investigações estão em parte descritas no capítulo oito, conseguem estabelecer a correlação entre os diversos parâmetros e a sua relação com o processo MPW. No entanto, este não é um processo perfeito e existem alguns inconvenientes que podem aparecer durante a soldadura. O capítulo cinco é dedicado à descrição das características existentes entre a peça de trabalho e a peça estática.

Devido ao processo MPW estar em constante desenvolvimento, a simulação do processo de soldadura é um factor muito importante, pois ajuda os investigadores a entenderem determinados comportamentos dos materiais. Desta forma, a simulação computorizada e as experiências realizadas complementam-se. Ao longo desta tese, vão ser descritas simulações entre o alumínio, o aço e o cobre, e os resultados obtidos serão descritos.

Finalmente, é importante ter conhecimento sobre as vantagens e desvantagens existentes no processo MPW, bem como está o processo implementado em indústrias como a automóvel, nuclear e a aeroespacial.

PALAVRAS-CHAVE:
Soldadura por Impulso Magnético; Soldadura; Parâmetros do Processo; Soldadura Electromagnética; Soldadura Fria
ABSTRACT

As an alternative welding technique, Magnetic Pulse Welding (MPW) process has been developed to meet market demands on decrease weight of welding components and maintain structure strength. With this decrease, also, costs are cut and at the same time MPW allow welding between dissimilar metals that have not been possible to join until now, at least with a feasible technique that could maintain process stability and capability.

Magnetic Pulse Welding is a high-speed joining process that uses electromagnetic force to accelerate one metal against another one, resulting in a solid state weld. Besides being considered a high-speed joining, it is also called as “cold weld” because temperature will not increase significantly in the bonding area, meaning that it is not necessary the use of protective equipment for heat when removing the final part from the working area.

A high power source, capacitor banks, discharge switch and coil are the minimum equipment necessary to weld two materials with MPW process. With the introduction of computer in the process, it becomes possible to control data, and with the Photon Doppler Velocimeter (PDV) in the system it is possible to measure some parameters like impact velocity and angle.

For welding two metals, they have to be inserted inside a coil, and after closing the high speed switch, discharge energy will go from the capacitor bank into the coil generating an intensive magnetic field. This magnetic field will penetrate the workpiece and Eddy Current is developed. Than, induced magnetic field is created in the opposite direction to the one from the coil. Electromagnetic forces, that results from magnetic field, will produce a magnetic pressure exerted on the workpiece and will force her to collapse into the parent metal. This happens in milliseconds and from the high velocity impact, combined with the appropriate contact angle will cause plastic deformation, giving place to bonding between both metals.

The parameters like discharge energy, standoff distance, magnetic pressure, skin effect, impact velocity and angle and their relation with MPW is described on this thesis. Some researchers, whose investigations are described in part at chapter nine, will give the correlation of the parameters with each other and with bonding
quality. Nevertheless, MPW is not a perfect process and there are some issues that can appear during the weld. Chapter five is dedicated to describing the characteristics of the interface flyer and parent metal.

Since MPW is a process in constant development, simulation is an important factor to take in account in giving support to researchers. Both, simulation and experiences complement themselves. On this thesis, simulation between aluminium, iron and copper are described and results given.

Finally, it is important to know the main advantages and disadvantages of MPW process, and how this process is being used on automobile, nuclear and aerospace industries.

KEY-WORDS:

Magnetic Pulse Welding; Welding; Process Parameters;
Electromagnetic Welding; Cold Welding
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<tr>
<td>$B$</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>$J$</td>
<td>Current density</td>
</tr>
<tr>
<td>$P$</td>
<td>Magnetic pressure</td>
</tr>
<tr>
<td>$k$</td>
<td>Step time increment</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Magnetic permeability</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Skin depth</td>
</tr>
<tr>
<td>$B_0$</td>
<td>Magnetic flux density - lower surface</td>
</tr>
<tr>
<td>$B_i$</td>
<td>Magnetic flux density - upper surface</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>Nabla operator</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Damping coefficient</td>
</tr>
<tr>
<td>$F$</td>
<td>Electromagnetic force</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of the midst</td>
</tr>
<tr>
<td>$I_1$, $I_2$</td>
<td>Current</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance</td>
</tr>
<tr>
<td>$A$</td>
<td>Cross-section area</td>
</tr>
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</table>
\( I \)  
Discharge current

\( V_0 \)  
Initial voltage

\( C \)  
Capacitor bank

\( L_{e1} \)  
Inductance – primary circuit

\( R_{e1} \)  
Resistance – primary circuit

\( M \)  
Mutual Inductance

\( L_{e2} \)  
Inductance – secondary circuit

\( R_{e2} \)  
Resistance – secondary circuit

\( L_c \)  
Coil self-inductance

\( L_e \)  
Equivalent inductance

\( a \)  
Diameter

\( L \)  
Length

\( r \)  
Radius

\( n \)  
Number of turns of the coil

\( h \)  
Standoff distance

\( R_0 \)  
Workpiece radius

\( R_c \)  
Coil radius

\( \theta \)  
Coil angle
$\delta_m$  
Skin depth of the coil

$\delta_w$  
Skin depth of the workpiece

$\delta_c$  
Skin depth of the concentrator

$P_c$  
Compaction pressure

$\sigma_f$  
Material flow stress

$h_0$  
Tube initial thickness

$r_0$  
Initial radius

$r(t)$  
Radial location of the tube

$F(t)$  
Sum of radial forces

$V_{\text{min}}$  
Minimum velocity

$R_c$  
Outer diameter

$R_i$  
Inner diameter

$\delta_i$  
Gap between outer and inner tube

$\rho$  
Density
1. Introduction

Magnetic pulse welding is a process that emerged at the beginning of the ‘70s due to the spawned spin off technology resulted from the nuclear energy programs. The process, at the beginning, was mainly developed for welding end closures onto nuclear fuel rod holders [1]. The technique used 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 (companies like Soulas United Nuclear Inc, in Richland, and General Atomic Technologies Corp., San Diego [1].

In the former Soviet Union several companies related to the Aerospace Industry exploited other applications of magnetic pulse welding technique. There were 36 specialized production sectors in this process [2]. In the Aerospace industry more than 4.200 parts were produced for airplanes engines and aircraft (models like Ty, XK, AH) and spacecraft [2].

With time, it has been verified the usefulness of the magnetic pulse welding at other industries, like the Automobile Industry. The need of the companies to reduce costs, times cycle and increase production, led companies to search for more efficient technologies in order to keep competitiveness and quality [3].

Magnetic Pulse Welding (MPW) is referred by some researchers as “Cold Process” [3-7] since the metallurgical bond is produced without fusion. Therefore, mechanical and chemical properties of the material do not undergo transformations. This technique can be defined as a solid state welding process that produces a weld by high velocity impact of the parts due to a controlled acceleration. During the process, materials are
accelerated to a high speed, at which, when impacted, a metallic bond forms between the two materials [3].

This type of weld belongs to the family of high-velocity material processes technologies. It is a technique known for its ability to produce complex components, in high strength or low ductility materials.

Welding between dissimilar materials is possible since joining occurs by plastic deformation. According to [4-6], limited fusion is observed because the metals acts, momentarily, like a liquid despite being in solid state.

Aerospace Industry have been looking for decreasing the weight of all components from any space shuttle, and, at the same time, strengthen the structure of the numerous joinings existing on board. One dissimilar joint where is possible to decrease weight and maintain strength consists on welding aluminium to titanium.

These two materials are very dissimilar, so that their mechanical and chemical properties are quite different.

With the development of MPW, aerospace manufacturers were able to improve significantly product design and production enabling dissimilar materials to be welded together and the use of lighter and stronger material combinations.

Through conventional welding, joining of these materials is very difficult if not impossible. Nevertheless, the electrical conductivity is important to create the electromagnetic forces that will push one material against the other.

Magnetic pulse welding has never achieved a clear place among mainstream manufacturing methods, because there is very little cooperation of researchers in different disciplines. Though this technique has been known for a long time, there are still opportunities of development and application.

With new developments and improvements, the application of one single material is no longer sufficient, and a sophisticated material mix will bring the desired technological characteristics required for the industries. For
example, it could be necessary to combine the corrosion resistance and strength of steel or titanium with the high electrical and thermal conductivity of aluminium or copper. By using conventional welding it will be difficult to do to their big difference on mechanical and thermal properties. Magnetic pulse welding can fill the gap on welding dissimilar metals. Depending on the geometry and tool coil, MPW can be used for compress or expand tubes and hollow profiles, even can form flat or preformed sheet metal parts.

Due to the quickness of the welding, the temperature does not rise up, so all mechanical and chemical properties of the materials can be maintained.

Theoretically, on MPW there are no size limitations for welding, what happens is that for larger pieces a larger amount of energy is required, and so, bigger machines are requested.

1.1. Objectives

Magnetic pulse welding has been studied by several research groups, due to its advantages of increase formability and possibility of joining dissimilar metals at low temperatures without filler material.

This study aims to present a review on Magnetic Pulse Welding (MPW), describe is physical principles and procedures, including equipment and parametric analysis.

Modelling of the process has been subjected to several studies and a revision is presented and discussed.

Finally, examples of industrial applications are provided, mainly those of high added value.
1.2. Thesis Structure

This document is structured into eleven chapters. The first introduces the subject and objectives of this study. Chapters two and three describe the welding process and the process parameters, respectively. Chapter four describes the analysis of the bonding characteristics. Chapter five and six are presenting modelling and simulation of the process, respectively. Chapter seven presents the equipment required for MPW process. The following, chapter eight, discusses materials and their behaviour under MPW process, for ferrous and non ferrous alloys in similar and dissimilar welds. Chapter nine describe the advantages and disadvantages and industrial applications are presented in chapter ten. Finally, in chapter eleven conclusions from this study are presented. On chapter twelve, are described all references to the articles consulted for the elaboration of these thesis.
2. **Process Description**

To achieve the goals of magnetic pulse welding the process needs to have (Fig.1) a high voltage power supply, a capacitor bank and a gap switch (capable of open and close very fast). Outside, there is a control system and a trigger system. Inside, the work area is composed by the coil and it is here where the weld takes place.

![Diagram of the magnetic pulse welding process](image)

*Fig.1 – Magnetic Pulse Welding process [8]*

Each welding operation begins with the charge of the capacitors bank until the precise energy level required for the process. This can take few seconds to several tens of seconds, depending on the power supply properties. Just after positioning the part to be treated in the coil, the trigger system (switch) close and current flows rapidly from the capacitor bank through the coil (again, in order to have good quality welding the discharge of the capacitor bank must happen very fast), causing magnetic flux to expand rapidly from the coil winding and outward.
The weld takes place in the interior of the coil or inductor (Fig.2). Here, a magnetic field is created when the energy passes through the inductor creating the first magnetic field (around the coil), and due to Eddy Currents at the surface of the outer material (or conductor material) the second induced magnetic field is created.

![Diagram of Magnetic Pulse Welding scheme](image)

**Fig.2**  – Magnetic Pulse Welding scheme [9]

This new magnetic field opposes the first one and the electromagnetic force (fem) is exerted on the outer material, making this to clamp at high velocity with the inner material. This impact will cause plastic deformation on the moving metal, and under precisely controlled conditions a solid-state weld is created between the two materials.

The impact velocity of the work piece is above 300 m/s, therefore, this process is also called as high-velocity forming process [6].

After the energy discharge, the trigger system opens the gap switch and the current is transformed from AC into DC. Meanwhile, the produced parts are taken out from the process and the capacitor banks are charged, until the desired energy is achieved, and the process is ready for run one more time.
The final result is similar to conventional welding, where it is possible to see the boundary that separate the two materials and the joining is more strong than the weaker material.

Fig.3 shows magnetic pulse welding between two tubes.

![Diagram of magnetic pulse welding](image)

**Fig.3** – MPW process for two tubes [3]

For this welding process, the tube with higher electrical conductivity should be the outer workpiece (aluminium) and the one with lower electrical conductivity, but stronger to the impact, must be the inner workpiece (titanium).

Welding tubes or plates is very much the same, where the current is discharged into the coil by opening of a trigger. A high-density magnetic flux is created around the coil and has a result an induced Eddy Current is created on the outer surface of a metal tube (Fig.4).
Fig. 4 – Schematic of MPW welding process of two tubes before and after welding [10]

The Eddy Currents oppose the magnetic field in the coil and a repulsive force is created, then, this electromagnetic force will drive the outer tube at an extremely high speed against the inner tube. From the impact, results the solid-state metallurgical bonding between both tubes, due to plastic deformation of the flyer tube.

In order have good welding seam, the work piece must provide a continuous electrical path.

It has been verified experimentally [11] that it is possible to weld tubes with perforated area (Fig. 5). But, when the tubes are like the ones from Fig. 5 a) and c) than the current flow will reduce and distort the forming forces [11].

Fig. 5 – Three different interferences a) part not closed b) perforated area c) slots [11]
Besides of joining metals, MPW can be used in calibration operations of tubes. The final result is going to be better than when using traditional technologies. Even so, this technique do not dispense the use of a mandrel on the calibration operation, in order to avoid formation of wrinkles [2,12].

Welding of dissimilar metals is one big advantage of magnetic pulse welding, and normally the flyer metal has better conductivity than the parental metal. Metals with high electrical conductivity and lower resistivity can be used has flyer metal without any issue. Nevertheless, sometimes, the flyer metal has low electrical conductivity, and one way found to circumvent this situation is to introduce a foil of high conductivity material between the flyer metal and coil [13]. This foil with better conductivity will make possible the increasing of the induced magnetic field, and so, increasing the magnetic pressure on the flyer metal. The main objective is the increase of impact velocity in order to obtain uniform bonding.
3. Processing Parameters

In order to ensure the welding quality as well as the efficiency of MPW process, it is necessary to understand the effects of the process parameters. The main process parameters are: Discharge energy, standoff distance, magnetic pressure, skin effect and impact velocity and impact angle.

In this chapter a brief description of the influence of each one on the process and their contribution for the weld quality will be presented.

3.1. Discharge Energy

As one of the most important parameter on MPW process, discharge energy depends on several other circuit parameters. For a given discharge energy, the current frequency is mainly determined by the total capacitance of the capacitor bank or by the total inductance.

Stored energy at the capacitor bank will be discharged into the coil, and it will be this energy the responsible for the movement of the flyer metal. Discharge energy must happen in few milliseconds in order to give high velocity to the flyer metal, and so, this would impact at high velocity into the parent metal. This is the condition to weld both metals, namely, when we are at the presence of two dissimilar metals and the parent metal have higher strength.
Fig. 6 illustrates how discharge happens through time.

![Discharge energy graphic](image)

**Fig. 6 - Discharge energy graphic [14]**

Increase on the charging voltage means increasing on discharge energy, and with this increase, the shearing strength of the welds will be enhanced [6] and the wavelength on the bonding will increase, as showed by Fig. 7 [9].

![Relationship between discharge energy and wavelength](image)

**Fig. 7 - Relationship between discharge energy and wavelength [9]**
High energy level is required, but tests should be done in order 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 introduce cracks to the welding process [7].

It has been observed [6,7] that with increasing of the gap between flyer metal and parent metal, discharge energy must increase, otherwise the flyer metal will collide with lower energy and will not bond with parent metal.

### 3.2. Standoff Distance

The standoff distance can be described as the distance by which the metals to be welded are separated from each other prior to discharge as shown by Fig.8

![Fig.8 – Standoff distance (Gap) [4]](image)

The 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 will be reduced, leading to reduction in the shearing strength and the width of the weld [6,7], as showed by Fig.9.

![Graph showing the effect of standoff distance on shear strength](image)

**Fig.9** - Effect of standoff distance on shear strength. B – sample cut from centre of welded zone; A and C – samples cut from edges of welded zone [7]

Whenever 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 higher should be the discharge energy in order to obtain a good quality welding [6,7].
Fig. 10 shows the behaviour of bonding interface when welding aluminium to titanium. The discharge energy and standoff distance increase from the left to the right.

![Image of bonding interface](image)

**Fig. 10 - Bonding interface as a function of Standoff Distance [15]**

Optimum value could be seen at section 3. Before that, standoff distance was low and there was not bonding between both metals. After section 3, standoff distance increase and it was observed intermetallic formation, and at the end crack happens.

### 3.3. 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, magnetic pressure will oppose the magnetic field from the coil and will force the flyer metal to gain velocity until collision. In order to have a successfully bonding, the magnetic pressure must be high. If not, the flyer metal will crash into the parent metal with lower velocity and no bonding will occur. So, high magnetic pressure can be obtained with high discharge energy or high frequency current.

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

It was observed [16] that at each collision between the flyer metal and parent metal have a maximum value at different collision angle.

### 3.4. Skin Effect

Theoretically, skin effect is the depth that magnetic field could reach at the flyer metal, from the top of is surface. Is tendency is to be highest at the surface of the conductor and then decay exponentially toward the other edge.

After discharge of energy from capacitor banks, the magnetic field created by the coil will reach the flyer metal and an induced current will be created on it. Eddy current will limit the penetration of the magnetic field from the coil and will create is own induced magnetic field, that will diffuse trough the thickness of the flyer metal. The depth trough which the interaction of both magnetic fields is limited within the flyer metal is called skin effect. With the skin effect, the repulsive magnetic field will produce forces that are the origin of magnetic pressure exerted on the flyer metal. Due to these magnetic forces, the flyer metal will gain velocity and impact the parent metal at very high velocity and pressure.

If skin effect is low, it can be increased by increasing frequency of the process. It is due to this parameter that the resistance of the conductor is considered to be a function of frequency. Moreover, the higher the electrical conductivity of the flyer metal, lower is skin effect depth. Meaning that, skin effect is inversely proportional to conductivity of flyer metal.
3.5. Impact Velocity

The impact velocity can be influenced by the energy inside the process and from the standoff distance or gap between both materials that are going to be welded. As showed at Fig.11 with the increasing discharge energy the velocity of the flyer metal will increase.

![Graph showing the relationship between Al sheet speed just before collision and Discharge Bank Energy](image)

**Fig.11 - Aluminium (flyer metal) velocity just before collision [8]**

On magnetic pulse welding the impact pressure is very high and consequently, the impact velocity is also very high, causing plastic deformation at interface of flyer metal and parent metal. The welding requires that both surfaces that are going to be joined should be free of contamination, and here, the high velocity of the flyer metal plays an important role, because it will create a “Jetting” that will remove any contaminants or oxidation particles from both contact surfaces [6].

Impact velocity is directly correlated with the energy and time of discharge from the capacitor, trough the coil into flyer metal. If the energy transferred
is done at low velocity the flyer workpiece will collapse and no bonding will happen.

Fig.12 shows the direct relationship between the discharge energy and the impact velocity acquired by the flyer metal. The material of this graphic is Cu110 with thickness of 3.175 mm.

![Graph showing the relationship between impact velocity and discharge energy](image)

**Fig.12 - Relationship between impact velocity and discharge energy [17]**

When the impact angle is fixed, impact velocity is the principal responsible for variations on the bonding. Meaning, if there is excessive velocity, it can cause some melting and so intermetallic formation, or, brittle damage can appear. On the other hand, if there is insufficient impact velocity the jet created could not be enough to remove all oxides from the surfaces, leading to intermetallic formations.

According to [16] it was observed that with the increasing of the impact angle the impact velocity will increase.
3.6. Collision Angle

At the impact point, the shock waves travel in both metals with a radial front, and an angle $\gamma$ depicted in Fig.13

![Solid State Cold Weld](image)

Fig.13 – 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, as graphically shown in Fig.14

![Pressure profile on MPW for different times](image)

Fig.14 – Pressure profile on MPW for different times [18]
On Fig.15 the shock waves travel from the collision point in the inner part and back to the surface, where the total path is the sum of X1 with X2.

![Shock wave propagation in MPW](image)

**Fig.15 – Shock wave propagation in MPW [18]**

The distance Z is the distance where the impact point would repeat, meaning that the collision point is ahead of the shock wave interferences. This explanation can be one reason why the first part of the welded interface is undulating [18].

Near the end of the weld, the collision point is severely reduced and the waviness will decrease.

The collision point is where the pressure reach is higher peak. Fig.16-b) shows the collision point and where the wavelength starts to take a form.

When the first wave is generated, regardless of the inner part diameter, a Kelvin-Helmholtz instability mechanism takes place and waves will be created periodically (Fig.16-d)). The instability and new collision points will generate new shock waves. The next wave is initiated by the interference continuity (Fig.16-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.16-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.16-g)).

![Fig.16 - The periodic wave formation [18]](image)

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. If true, the Kelvin-Helmholtz instability would have a multimode case. This could be the reason for the asymmetry of the interface waves (Fig.17).

![Fig.17 - Asymmetry on shockwaves [18]](image)
If the impact creates the right conditions of angle of impact and velocity, jetting is created and subsequently welding takes place [3].
4. Bonding Characteristics

Since MPW has been developed, one theory regarding bonding has been studied. It was the *film theory*, which says whenever “two absolutely clean surfaces are brought into intimate contact, bond formation will occur” [19].

After impact between the two materials, the shock wave moves through the metals producing distinct boundary between consolidate and unconsolidated regions. The welding region is not at equilibrium [20], it is moving towards stabilization of the joining of the two metals.

During impact of the flyer and parent metal, a jet is created between the two bonded surfaces by the impact force acting upon them. The jet strips the surfaces of unwanted surface contaminants and oxides, enabling magnetic pressure to plastically deform the metals for a short instant. It has been observed that the metals momentarily behave like liquids, despite being always in solid state. With this typical behaviour it is possible to permanently bond widely dissimilar metals [5,21].

Though it is a cold weld, the welding zone has homogeneous distribution of the grains and good strength. The strength of this zone is higher than the weakest material and if happens to crack, normally it is outside the welding zone and most probably, it will happen on the weakest material [4,6]. It has been studied [17] that local plastic deformation and impact shock harden local regions, when comparing with explosive and laser welding.

It is due to the jetting created between the two bonded surfaces, by the impact force acting upon on them, that the elimination of all traces of oxides and surface contaminants allowing the magnetic pressure to be responsible for the impact of two pure surfaces, stripped of their oxide layers to collide under high pressure, bringing the atoms of each metal workpiece into close enough contact allowing atomic level bonding. The most advantage of impact welding it that it can minimize the formation of continuous intermetallic phases during welding of dissimilar metals [17].
Magnetic pulse welding produces either a wavy or waveless morphology at the interface of both materials. The precise shape is a function of the properties of the metals and the parameters involved on the welding. On Fig.18 it is possible to visualize the wavy interface of Al 7075 [3], with evidence of plastic deformation.

![Macrograph of the bond area on a similar AA7075 join](image)

One most common welding consists on joining aluminium and stainless steel. The stainless steel (SS) has higher melting point and higher strength when compared with 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.19). In the other hand, for AA6111 the grains at the weld interface were flattened compared with the original grain morphology (Fig.20).
Such grain deformation from the aluminium indicates that large plastic deformation occurred in this area, due to the high-strain rate done 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 described at Fig.19 and Fig.20 is similar to that of the explosive welded joint [18,22]. Nevertheless, the amplitude and wavelength of the interfacial wave are much smaller in magnetic seam welding.
It is visible at Fig.21 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) [22].

Fig.21 – Intermediate layer between A6111/SPCC [22]

Despite the temperature does not rise significantly, it was seen that she increase [18] due to the jet and massive deformation of the surfaces, and in some cases, melting and solidification will occur (similarly to explosive welding). It is this temperature rising at the interface that encourages wave formation by softening of the interface and it is vicinity.

It was proven experimentally [18] that the wavelength of interface waves is proportional to the free path of shock wave propagation in the inner part of the welded couple. This shock wave theory claims that the waves, due to impact, propagates trough the metal parts creating periodic interference perturbation at the welding interface. Those interferences initiate a Kelvin-Helmholtz instability that creates the interface waves.
According to Fig. 22 the wavelength is proportional to the thickness of the inner part, since the radius of the pressure front of the reflected shock wave increases with the propagation distance, in cases where the inner work piece is a tube. Due to the thin wall (Fig. 22 c)) of the tube, the wave reaction is shorter because the distances that waves need to travel are shorter.

Fig. 22 – Wavelength, a) Short propagation, b) Long propagation, c) Work piece [18]

The wavy interface changes along the bonding zone, and at the start or ending zone of the weld, sometimes, the joining between both metals is not complete. If there is a section not completely connected, it will be here where the crack starts to be visible under cyclic load or corrosive environment [21]. Most of the times at the experiences, the investigators tend to rise the discharge energy in order to obtain good weld between both metals. But, the probability of obtaining intermetallic phases increase with the energy increasing. Fig. 23 shows the bonding of aluminium with copper, and at (b) the arrow is pointing into the direction of intermetallic zone formation. The difference between (a) and (b) is the current intensity. It has been studied [21] that for thickness below 5 microns of the intermetallic phase film, the bonded area rarely contain any cracks or pores. On the other hand, with thickness increasing the intermetallic phase begins to reveal some cracks perpendicular to the weld interface. Above 10 microns, the bonded area has numerous pores.
To avoid formation of intermetallic pores and cracks, low pulse discharge energy should be taken into account, but never forgetting the good quality welding.

Both, profile and amplitude of the waves after bonding, in the interface between flyer and parent metal are dependent from the shape of the flyer plate [23]. According to this research, it was tested three different kinds of flyer metals: Flat, U and V-shape. As result, the amplitude was higher for the Flat-shape metal and lower for the U-shape metal.

Standoff distance is one parameter that has high influence on the interface profile. As said before, there is an optimum value for standoff distance for each welding. When that value is away for optimum, it will have influence on wave formation from the interface flyer and parent metal, as showed at Fig.24 [15].
Fig. 24 - Bonding with Standoff Distance of: a) <1 mm; b) >2 mm [15]

On Fig. 24 it is possible to see the results between welding of aluminium and copper. On the left side (figure a)) standoff distance was less than 1 mm, the wavelength and range is small when compared to the one on the right side (figure b)), where standoff distance is higher than 2 mm.
5. Modelling

Modelling of this process is not a simple issue, and several researchers attempted to establish process models that are going to be described here.

When high current is applied to the coil, a high magnetic flux density $B$ is suddenly generated and penetrates the flyer metal. As a reaction, Eddy Currents (with current density $J$) is 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.

Depending on the geometry of the coil, the pathway would be slight different. At lower one-turn coil, only one metal is going to move (designated by flyer metal). On the other hand, with the lower and upper one-turn coil, both metals will move against each other. The concept is always the same, but it will be slightly different.

Accordingly to several researchers [20,24,25] MPW process can be replaced by an equivalent electrical circuit, that will help to understand and calculate all variables like magnetic field, electromagnetic force and so on.

One geometry that is being most used in the industries, it concerns welding between two tubes, from the outside and inside. This means, that the flyer metal is going to be the outer tube in one situation. On another situation, the flyer tube is going to be the inner tube.
5.1. Lower One-Turn Coil

For the next calculations it was used a flat one-turn coil, two plates and a fixture (Fig.25).

![Diagram of a flat one-turn coil scheme](image)

Fig.25 – Flat one-turn coil scheme [4,8]

The Eddy Current $J$ and the magnetic pressure $P$ were obtained as following [4,7,26]:

\[ \nabla \times J = -k \left( \frac{\partial B}{\partial t} \right) \]

(1)

\[ p = \frac{(B_o^2 - B_i^2)}{2\mu} = \left( \frac{B_o^2}{2\mu} \right) \left( 1 - e^{-2\pi i \delta} \right) \]

(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)

$B_s$, 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 [27], the skin depth give us the value of length towards the inside direction of the material at which the current is reduced to 36%.
5.2. Upper and Lower One-Turn Coil

This situation is composed by upper and lower one-turn coil and two plates, positioned in the middle [6,7].

Fig.26 and Fig.27 illustrates the scheme used for accomplished this experimentation [6].

![Diagram 1]

**Fig.26** – Magnetic flux and induced Eddy Current [6]

![Diagram 2]

**Fig.27** – Flat rectangular coil [6]
Electromagnetic impact welding is based on Ampere’s law, as following [6,7]:

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

(4)

Where:

I₁ and I₂, current (A)
F, electromagnetic force (Nm⁻¹)
d, distance between conductors (m)
\( \mu_0 \), permeability of the medium

The “I” shaped cross section design of the coil is placed at the centre for concentrating the current, thereby increasing the current \( i \), resulting on an increasing on the Lorentz force, generating higher impact between both sheets.

The Lorentz force is given by [6,7]:

\[ F = J \times B \]  

(5)

Where:

\( F \), is the Lorentz force (N)
\( B \), is the magnetic flux (T)
\( J \), is the current density (Am⁻²)

On such welding design, the calculation of the skin depth, according to equation (3), is important because if the value of the skin depth thickness is one-third of the sheet thickness or less, the magnetic field does not diffuse out of the work piece.
The required cross-section area of the coil conductor is calculated by:

\[ A = \frac{I_{\text{max}}}{J} \]  \hfill (6)

\( A \), is the cross-section area of the coil (m)

The magnetic flux density was determined has following \([6,7]\):

\[ B = \mu I \left[ \frac{\tan^{-1}(b/2d_1) + \tan^{-1}(b/2d_2)}{\pi b} \right] \]  \hfill (7)

Where:

\( d_1 \) and \( d_2 \), are the initial position of the sheets with respect to the coil

(\( d_1 \) and \( d_2 \) could be estimated using the final position of the sheets with respect to the coil)

\( I = i \), discharge current

\( b \), represent the width of the middle \( "I" \)-shaped coil

For the calculus of magnetic pressure the formula is the same as previous, that is, calculated according to equation (2).

### 5.3. Calculating Magnetic Pressure With Equivalent Circuit (LRC)

At this section it will be demonstrated how is it possible to use circuit theory to calculate pressure, current and depth effect along the workpieces, simulating magnetic pulse welding process. The current take the form of a damped sine and can be understood as a ringing Inductance-Resistance-Capacitance (LRC) circuit \([20,24,25]\).
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 on Fig. 28, which shows the RLC circuit (primary circuit) replacing the capacitor bank and the coil coupled with the concentrator. The concentrator coupling with the workpiece forms the RL circuit (induced circuit).

![Diagram of equivalent circuit](image)

**Fig.28 – Representation of the equivalent circuit [26]**

$V_0$ is the initial voltage of the capacitor bank

$C$ is 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
Trough ideal solenoid and considering a single turn cylindrical conductor with radius \( r \) and length \( L \), the self-inductance of conductor can be expressed as:

\[
L_c = \frac{\pi \mu_0 r^2}{l}
\]  

(8)

For a single-turn solenoid with diameter \( a \) and length \( L \), the self-inductance of the solenoid is expressed as:

\[
L_s = \pi \mu a^2 [(L^2 + a^2)^{1/2} - a]
\]  

(9)

In practical, the solenoid can be composed by several turns, so, multiplying equation (9) by \( n \), the following equation is obtained:

\[
L_s = \pi \mu a^2 [(L^2 + a^2)^{1/2} - a] * n^2
\]  

(10)

Where \( n \) is the number of turns per unit length.

The inductance of the concentrator with the workpiece is given by the following equation:

\[
L_{cw} = \frac{2\pi \mu R_0 h}{l \left[ 1 + \frac{2h}{\theta} \ln \left( \frac{1 + \frac{r_2 \theta \sin \theta}{\theta (1 - \cos \theta)}}{1 + \frac{r_2 - r_1}{1 - \cos \theta}} \right) \right]}
\]  

(11)

Considering that the magnetic field is constrained in the gap zone, the equivalent inductance of the coil is given by:
\[ L_c = L_c \left(1 - \frac{r_c^2}{r_m^2}\right) \]  
(12)

Where, \( L_c \) is the coil self-inductance.

The equivalent resistance of both circuits can be expressed as:

\[ R_{e1} = R_{\text{system}} + \frac{2\pi r_c}{\sigma_c l_c \delta_c} \]  
(13)

\[ R_{e2} = \frac{2\pi(r_l + h)}{\sigma_c l_c \delta_c} + \frac{2\pi r_o}{\sigma_w l_w \delta_w} \]  
(14)

The equivalent inductance of both circuits can be expressed as:

\[ L_{e1} = L_{\text{system}} + L_c (1 - \left(\frac{r_c}{r_m}\right)^2) \]  
(15)

\[ L_{e1} = \left[ \frac{2\pi r_c h}{l_c \left(1 + \frac{2h}{l_c} \ln \left(1 + \frac{r_c \sin \theta}{h(1 - \cos \theta)} \right) \frac{1}{1 + \frac{r_c}{r_m} \tan \theta} \right)} \right] \]  
(16)

Using equations (1) and (3), the inductance of the system is given by:

\[ L_c = \pi \mu \left( \frac{r_m}{l_c^2} \right)^2 \left[ (l_c^2 + r_m^2)^{1/2} - r_m \right] \]  
(17)

55
For electromagnetic field penetration into the coil, concentrator and tube materials, the geometrical values \( r_m, r_c, r_0 \) and \( h \) should be replaced by the following equivalents:

\[
\begin{align*}
\frac{r_m^*}{r_m} &= \frac{\delta_m}{2}, \quad \frac{r_c^*}{r_c} = \frac{\delta_c}{2}, \quad \frac{r_0^*}{r_0} = \frac{\delta_w}{2}, \quad \frac{h^*}{h} = 1 + \frac{\delta_c + \delta_w}{2},
\end{align*}
\]  

(18)

On (13) the \( \delta_m, \delta_w \) and \( \delta_c \) are the skin depths in the coil, workpiece, and concentrator, respectively.

The electric potential balance in the primary and secondary circuit yields to the following equations:

\[
\begin{align*}
\frac{d}{dt} \left( L_{c1} I_1 + M I_2 \right) + R_{c1} I_1 + V_0 + \frac{1}{C} \int_0^t I_1 dt &= 0 \\
\frac{d}{dt} \left( L_{c2} I_2 + M I_1 \right) + R_{c2} I_2 &= 0
\end{align*}
\]  

(19)

\( V_0 \) can be expressed as:

\[
V_0 = \frac{Q_1}{C}
\]  

(20)

Regarding energy balance, the resulting force between the magnetic field in the coil and the induced magnetic field in the workpiece, normally is referred as magnetic pressure. The induced magnetic force and pressure is given by equations (21) and (22) [24,28]:

\[
\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d}
\]  

(21)

\[
P = \frac{\mu_0 B^2}{2}
\]  

(22)
This numerical 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 [26].

The peak current generated by a capacitor bank discharge can be estimated from standard LRC equations. So, as long as the circuit resistance stays low, the \( I_{\text{max}} \) can be estimated by equation (23) [20]:

\[
I_{\text{max}} = V_o \sqrt{\frac{C}{L}}
\]  
(23)

5.4. Tube Compression

Bonding between two tubes from different materials, are being investigated due to market demanding.

Next chapters, will describe how is it possible to calculate the parameters involved on the joining of two tubes, where the flyer metal is the outside tube, and secondly, the flyer tube will be the inside one.
5.4.1. Tube compression from outside

External tube compression can be explained using section 5.3., where the MPW process is replaced by an equivalent RLC circuit. Fig.29 shows a schematic coupled circuit concept, already described at 6.3., where is illustrated a RLC circuit mutually coupled to an RL circuit.

Fig.29 – Equivalent MPW circuit [29]

At this section it is going to be used a tube full of granular material, in order to analyze the behaviour of the flyer tube under magnetic pressure [29].

The relation between the external circuit and the tube circuit is given by equations (19) and (20). From these equations is possible to obtain the sum of the voltages around the primary and induced circuit. Because the induced current is in opposite direction to the one that produced it, according to Lenz’s Law, $MI_1$ and $MI_2$ are positive in the equations.
To calculate the magnetic force, and knowing that an energy balance between the two circuits exists, the $F_m$ acting between the coil and the conductive tube is given by equation (24):

$$F = \frac{1}{2} \frac{dL_2}{dr} l_2^2 + \frac{dM}{dr} l_4 l_3$$  \hspace{1cm} (24)$$

Considering the tube as a thin walled structure with flow strength and magnetic pressure $P$ acting on the outside of the tube, the resistive compaction pressure from the granular material acting on the inside of the tube is given by $P_c$.

Fig.30 illustrates how the pressure acts on the tube wall.

![Fig.30 - Pressure distribution on the tube wall [29]](image)

Equation (25) describes the sum of radial forces acting on the differential element of the tube, giving the radial equation of motion:

$$F(t) = \frac{(P - P_c)r(t)^2}{\rho h_0 r_0^2} - \frac{\sigma_f}{\rho r(t)}$$  \hspace{1cm} (25)$$
$P$ and $P_c$ are the magnetic and compact pressures, respectively, acting on the tube.

$\sigma_f$ is the material flow stress of the tube

$h_0$ and $r_0$ are the tube initial wall thickness and initial radius, respectively

$r(t)$ is the radial location of the tube as a function of time

The radial motion of the tube is measured by the PDV (Photon Doppler Velocimeter) system, and it becomes possible to know the value of magnetic pressure with equation (26) and the value of compact pressure with equation (27):

$$P = \frac{1}{2} \frac{dL_2}{dr} I_2^2 + \frac{dM_{tt}}{dr} I_1 I_2$$

$$2\pi r(t) l$$

(26)

$$P_c = P - \frac{h_0 r_0^2}{r(t)^2} \left( \rho F(t) + \frac{\sigma}{r(t)} \right)$$

(27)

Flow stress is taken from the sheet properties of the material. Than, the magnetic pressure, radial location, radial acceleration and compact pressure can be computed through equation (27).
5.4.2. Tube Compression from Inside

Magnetic pulse welding can be used to weld tubes from the inside, not only from the outside (as described previously). Fig. 31 shows a schematic of magnetic pressure on the inside tube, where \( h \) is the gap between both tubes.

![Diagram showing tube compression from inside](image)

Fig.31 - Internal MPW welding [30]

Fig. 32 shows a coil inside of the internal tube. All parts are now in position to be welded. Number 1 is the external tube, number 2 is the internal tube and with number 3 is the coil.

![Diagram showing scheme of MPW process from inside of a tube](image)

Fig.32 - Scheme of MPW process from inside of a tube [31]
The value of $h$, according to [31], depends on the parts being welded. It was observed that with increasing gap value, the magnetic pressure required to give velocity to the internal tube, decrease. So, the equation (28) gives this variation:

$$h_{\text{min}} > \frac{V_{\text{min}}}{12f}$$

(28)

$V_{\text{min}}$ is the minimum velocity that is necessary to welding takes place, and $f$ is the frequency of the discharging current.

On the other hand, the maximum value for the gap must obey two conditions, where the first one is given by equation (29):

$$h_{\text{max}} < \delta_p R$$

(29)

$R$ is the internal radius and $\delta_p$ is the plastic deformation, both from the internal tube.

The second condition is given by equation (30):

$$h_{\text{max}} = \sqrt{R_C + R_i} - (R_C + \delta_i)$$

(30)

$R_C$ and $R_i$ are the outer and inner diameter of the internal tube. While, $\delta_i$ represents the gap between the coil and the internal tube.

The pressure at the wall of the internal tube is given by equation (31):

$$P = 4V_{\text{min}} f \cdot \rho t$$

(31)

$t$ is the thickness and $\rho$ is the density, both from the internal tube.
Moreover, this method of calculation of the variables was used on welding internal pipes to protect the external from corrosion, and the results were very good [31].
6. Simulation

Numerical calculation methods are very useful to get a deeper insight into the forming and joining process. Knowing all mechanical, thermal and chemical properties of the materials involved on the simulation and with specific software, it becomes possible to simulate how the forces are going to act on the materials, and if it is feasible welding between two materials.

The combination between simulation and measurements from real experience, have demonstrated to be helpful for investigators to achieve more realistic simulations, and a better understanding of parameters behaviour.

MPW simulations are very useful in the optimization of a process, because they can decrease time and cost in the industrialization of a process.

Has magnetic pulse welding is a process depending on several devices to get good results, these devices have losses, and most of the times on numerical simulations the losses are forgotten. Nevertheless, Fig.33 shows energy losses since the discharge from capacitors until the end of process. According to [32], only approximately 20% of the initial energy is used on forming or welding the metals. For the simulations described on this section, there will not be reference to energy losses during the process, and due to this reason, it is expected to have some differences between simulation and reality but not significant differences, mainly, due to the combination between simulation and experience.
For simulations the software used will be different from investigator to investigator. Sometimes, it belongs to company development, and the software can be: MSC Dytran or LS-DYNA 980. Other times, it was the investigator who has developed is own way of simulating, using Ansys software supported with calculations done with Maxwell formulas.

**6.1. Welding of AA 101 / Fe ASTM 897**

The objective is to simulate the mechanism of magnetic pressure seam welding, from a dynamic viewpoint and to reveal the appropriate joining conditions.

Computational of magnetic pressure seam welding was made using commercial Euler-Lagrange coupling software MSC Dytran [16].
The materials and their properties are summarized on Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus (GPA)</td>
<td>206</td>
<td>70.3</td>
</tr>
<tr>
<td>Yield Stress (MPA)</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>Density (Kg/m3)</td>
<td>$7.87 \times 10^3$</td>
<td>$2.70 \times 10^3$</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.3</td>
<td>0.345</td>
</tr>
<tr>
<td>Linear Expansion Coefficient (1/K)</td>
<td>$1.18 \times 10^{-5}$</td>
<td>$2.39 \times 10^{-5}$</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>79.2</td>
<td>26</td>
</tr>
<tr>
<td>Specific Heat (J/Kg.K)</td>
<td>440</td>
<td>900</td>
</tr>
<tr>
<td>Melting Point (K)</td>
<td>1808</td>
<td>933</td>
</tr>
</tbody>
</table>

Table 1 – Material properties [16]

On this simulation the materials have 200x1 mm, a standoff distance of 1mm and the pressure was done at 10mm length. The velocity varies from 100 to 500 m/s.

It was possible to verify in the simulation that the collision point moved along the surface of Fe plate [16], movement similar to the one described on the bonding mechanism chapter. Nevertheless, a wavy morphology was observed at the joint interface and more fine meshes were used for examination the joint mechanism with more accuracy. So, the number of nodes increases from 13.240 and 29.172 to 281.445 and 566.956.

Temperature increase was verified on the simulation, but according to the materials properties, melting is not possible because the temperature stays, always, below the melting point of aluminium (lowest melting point of the two materials).

Regarding velocity impact, the simulator have showed that with increase on velocity, higher will be the magnetic pressure and collision angle.
At the end, it is possible to say that the plastic strain distribution near the joint interface might be related to the success of magnetic pulse welding [16].

6.2. Welding of AA 6061-T6 / Cu 101

The main objective is to predict impact velocities and temperature distribution along the bounded interface [33].

Fig.34 shows a scheme of the metal involved on the magnetic welding.

![Fig.34 - Sketch of the experimental setup [33]](image)

For this simulation it was used the electromagnetism module available at DYNA. With this module it is possible to simulate mechanical, thermal and electromagnetic experiments.
At Fig.35 is represented the actuator, flyer and target involved. All components were meshed using solid hexahedral elements.

Fig.35 – Meshed three dimension [33]

Simulation (Fig.36) indicates rapid thermal cycling on the mating interface, the induced current change direction periodically and the maximum value for current density is on top and bottom edge of the welding area.
Apart from this simulation, it was realized experiments and the same parameters were analysed.

At all moments, the experiments reveal to have higher impact velocity, as showed by Fig.37.
One reason pointed for this difference it that the velocity from the simulation module was obtained from the average volume of peak velocity on different nodes along the interface. Another reason can be the target plate: in the simulation this metal is not fixed and so, will absorb some of the kinetic energy from the flyer metal, making the flyer velocity to decrease.

Fig.38 represents the temperature at five nodes from flyer AA6061-T6. It was observed an increase on the five nodes around 200 °C within 40 μs.

![Temperature profile on AA6061-T6 at 2,4 kJ](image)

Fig.38 – Temperature profile on AA6061-T6 at 2,4 kJ [33]

Based on the simulation the increased temperature stays below the melting temperature for each one of the metals involved. Nevertheless, near the interface, the metals experienced a fast heating and cooling cycle.

Local temperature increasing, favours the metal fluid flow at high strain rate, and at the same time favours the wavy interface formation that contributes positively to a good quality welding [33].
6.3. **Electromagnetic Forming (EMF)**

Utilizing the same fundamentals and principles as magnetic pulse welding, magnetic pulse forming (MPF) or electromagnetic forming (EMF) is another way of achieving specific geometries with different materials. It has been investigated [11] and concluded that electromagnetic forming is a more feasible technique when compared with other techniques that involve contact between tools and parts to be produced. Investigators have shown great interest in EMF of sheet metal, mainly, for automotive applications where it could be used to form aluminium and other low formability metals. Aluminium has been the main focus due to the aim of reducing weight on several components rapidly and with precision.

The aim of the present section is the description of the behaviour of metals under electromagnetic forming.

### 6.3.1. Conical formation

Aluminium AA5754 was the one used on the following investigation on EMF.

For numerical simulation it was used the version LS-DYNA 980 that works combining Finite Element Analysis (FEA) with Boundary Element Method (BEM), performing the electromagnetic analysis by solving Maxwell’s equations in the Eddy Current approximation [34]. The BEM is used to model the air, avoiding the mesh, while FEA simulates coil and workpiece.

To perform the simulation, it was assumed that the sheet metal behaves as a linear elastic-plastic, and the coil was modelled as an elastic material with Young’s Modulus of 97 GPa.
The simulation (Fig. 39) was used with a mesh of 28,800 elements. Higher the number of elements for the cone mesh, more precise the simulation as avoiding erroneous predictions due to element distortion.

![Fig. 39 – Mesh used for V-Channel model [34]](image)

The process was modelled as an RLC circuit, where $R=5.96 \times 10^{-3}$ Ohms, $L=48 \times 10^{-6}$ mH, $C=2.7 \times 10^{-7}$ F. For coil and sheet it was used a conductivity of $25 \times 10^6$ Ohm$^{-1}$m$^{-1}$. It was said [34] that these simplification results in some accuracy, however, the proposal was considered acceptable.

This simulation was carried out using a computer with two Opteron 270 dual core 64-bit 2 GHz processors with 2 Mbytes of L2 Cache and 16 Gigabytes of RAM.

The experimental and numerical results were obtained with voltage of 3.000 and 5.000 V.
From the graphic (Fig.40) the models below predict the peak current by approximately 4% during the rise of the current pulse, and under predict the current approximately by 20%.

![Graph showing current vs time for different voltages: Numerical 3000 V, Experimental 3000 V, Numerical 5000 V, Experimental 5000 V, Start of Deformation for the 3000 V case, Start of Deformation for the 5000 V case.](image)

**Fig.40 − Experimental and numerical profiles [34]**

The major difference between the workpiece from the simulation and the reality is the final geometry. Fig.41 shows the theoretical final shape.

![3D model of a V-channel predicted final shape with 3000 V.](image)

**Fig.41 − V-Channel Predicted final shape with 3.000 V [34]**
In reality, with 3.000 V some of the geometry was not made, as Fig.42 demonstrates.

Fig.42 – V-Channel produced final shape with 3.000 V [34]

The simulation captures the general trend, but not the difference in height in the experimental samples, which are more pronounced than in simulation. This discrepancy could happen due to the difference between the real coil and the model of it [35,36].

Similar behaviour was verified using 5.000 V, where the tests showed an uneven force distribution not seen during simulation. Nevertheless, the software is able to predict the major features observed experimentally on the samples, as the profile.

6.3.2. Rebound Effect and Discharge Energy

When the sheet metal impacts the die there could be some rebound effect from the die wall, mainly because some amount of kinetic energy is not transformed in plastic deformation of the metal [36,37]. Here, often high discharge energy is not synonymous of good geometry formation. Has shown by Fig.43 the first contact between the sheet metal and the die could result in rebound of the sheet metal. This area, and according to [37,38] will occur when the energy has not been completely dissipated, resulting on surface wear and friction caused by high contact forces combined with tangential movement of the workpiece.
At impact between the sheet metal and the die, there will be energy transfer in waves spreading through the die, as shown by Fig.44. Initially the wave spreads out through the die until it reaches one of the surface die. Then, the wave will reflect.

Rebound effect, tearing (due to local strain energy) or wrinkling (due to insufficient or inappropriate local strain energy) are the most common forming defects. If the strain energy or plastic work is well distributed during the forming process, it was verified [39] that tears and wrinkles will be eliminated, permanently. In order to obtain a good distribution of the strain energy the use of lubricants is recommended [38,39]. This method allows
the decrease on friction between the sheet metal and the die, and so, stress and strain distribution will be improved.

Regarding rebound effect, it can be eliminated or at least reduced by decreasing the discharge energy, decrease stiffness of the die or by inserting a coat cover plate between the die and the sheet metal. Two layers can be chosen: DLC-Layer and MoS2-Layer [37,38].

From the investigation [37] it was verified that all samples with coated cover plates have shown better wear and friction resistance when compared with the samples without coated cover plates.

At Fig.45 it is possible to see the effect of different discharge energy used on magnetic pulse forming. As the energy increase, more perfectly becomes the roundness of the parts [20].

Wrinkling can be suppressed with high energy discharge, because each point is going to travel radially inward touching the material almost at the same time.
7. Equipment

In order to have magnetic pulse welding process under production engineer conditions, a suitable layout must be developed. With all available technology on the market, this technique is growing up and becoming more precise, mainly due to improvements on the technologies used to build all equipment involved.

As required on all industries, MPW process must be capable of being safely controlled and operated. It is essential to measure, control and record all parameters, automatically.

The equipment used is the seventh generation of electromagnetic machines [11]. It is the result of 40 years of industrial experience and improvements. The equipment is considered compact, safe and could be built to stringent industrial safety codes and standards. They can be reliable, in such a way that if a breakdown occur, there are several detecting devices that will inform maintenance personnel of fault localization.

Most of the process variables can be controlled with specific software, and are capable of verifying the outputs, comparing them to the inputs in order to maintain a stable process. The main idea is to control as much variables as possible in order to decrease the energy lost, be capable to do a numerical analysis and understand the behaviour of materials during the welding.

With the developments using magnetic pulse welding and with series production, the equipment used is becoming more similar to the ones used on a typical welding process.
Like typical welding process, on Fig.46 it is possible to see the use of a remote station for operating the system by means of the PLC, controlling and monitoring the pulse involved on the process.

Fig.46 – Typical MPW equipment [3]

Has any electronic equipment, there are several safety cautions to have in mind in order to avoid accidents. Different risk points must be adequately insulated to prevent shorting and this insulating must be checked regularly for signs of wear. Because, failure could mean flying debris, a safety shield must be placed between the team member and the work coil.

The heavy equipment can be also called by magnetic pulse forming machines, and they were divided into three main categories [40]:

- Stationary machines for products made of highly electrically conductive materials
- Stationary machines for products made of low conductive materials
- Mobile machines
On Table 2 it is described several magnetic pulse welding machines according to their specification and availability on market.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MPF-5 (mobile)</td>
<td>5</td>
<td>10</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>MPF-10 (mobile)</td>
<td>10</td>
<td>10</td>
<td>78</td>
<td>200</td>
</tr>
<tr>
<td>MPF-12,5 (mobile)</td>
<td>12,5</td>
<td>25</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>MPF-20 (factory)</td>
<td>20</td>
<td>8,5</td>
<td>35</td>
<td>552</td>
</tr>
<tr>
<td>MPF-20Hf (factory)</td>
<td>20</td>
<td>25</td>
<td>38</td>
<td>64</td>
</tr>
<tr>
<td>MPF-40 (mobile)</td>
<td>40</td>
<td>8,5</td>
<td>45</td>
<td>1104</td>
</tr>
<tr>
<td>MPF-100 (factory)</td>
<td>100</td>
<td>25</td>
<td>30</td>
<td>320</td>
</tr>
</tbody>
</table>

Table 2 – Machine parameters [40]

Nowadays, economy governs the industry, so, choosing the proper system configuration is essential and depends from the following characteristics of the product: Cross-sectional dimension of the tube, workpiece material properties, magnetic pressure essential to accomplish the welding, cutting or forming operation and length of the pressure area.

The characteristic of magnetic pulse welding equipment depends of mostly of the parameters like discharge energy necessary to force the flyer metal to collide into the parent metal. Standoff distance and metal properties are other parameter that could influence equipment choice. Regarding these parameters, it is time to choose the coil (according to geometry to be welded), field shaper (if there will be tubes with different diameters) and capacitor bank (according to energy required to accomplished bonding).

In order to maximize the efficiency of the welding process, it is desirable that the resistance and inductance of the components stay low.
7.1. High Power Supply

The principal function of power supply is to convert AC power into DC for the welding, and send energy to charge the capacitors until the desirable quantity.

Through fibre optics coupler it is possible to convert AC signal and provide connection to a PLC control system.

7.2. Bank of Capacitors

The correct size unit for any particular application depends on how much energy is required to join the workpieces, the rate at which magnetic pulse is applied, and how fast the coil and other electronic components are able to dissipate heat [41].

In order to maintain consistent product geometry and to ensure high production rates, the electromagnetic pulses must be carefully controlled. The voltage charging is measured constantly and is turned off as soon as a preset level is reached.

The capacitor bank is the heart of the electromagnetic forming system. The main components are a number of capacitors that can store energy $E$ by storing electrical charge at voltages $V$.

One charging system is connected to the capacitors and could provide the necessary energy to weld. The voltage required is controlled by one transformer and this transformer will control the time required to charge the bank between discharge events. The time life of such capacitor depends on the cooling of the elements that dissipate the energy, during repeated use [20].
The charge of a bank of capacitors (Capacitors showed at Fig.47) until the desired energy is relatively slow, and once it is reached, a fast switch is used to let the current flow into the coil.

Fig.47 – Energy storage compartment [42]

The transferred energy from the capacitor bank into the coil will happen using a fast switching.

7.3. High Current Switch

Any switch used on magnetic pulse welding process needs to be efficient in the transmission of high currents, provide operational availability and most important needs to be resistant to the wear. Over the years, and with the increase on the specifications from industries, the switches fabricants developed new and more efficient high current switches. Nowadays, the main advantages are the reliability, lifetime and almost no maintenance of them, when the choice is done correctly according to the necessary energy and repeatability. Due to technology evolution, today’s production capabilities make it possible to produce switches with high blocking voltage combined with high current handling.
Mercury-filled igniton-type or solid state silicon controlled rectifier switches are two different and common types of switches used on MPW process. The first one can have limited life and be “temperamental”, while the second one, has to be well designed in order to avoid inefficiency and because it is an expensive part of the equipment [20].

The development of a high system ringing frequency is quite important, because if the electrical oscillation frequency is too low, than, intense Eddy Currents are not induced in the workpiece and the force developed is not very high. It is known [20] that materials of lower conductivity demand higher ringing frequency for effective forming or welding.

Solid state switches are optimized for pulsed applications and are considered state of the art by ABB Switzerland Ltd [43,44]. This company produces switches in different versions with silicon wafer diameters up to 120 mm and blocking voltages of over 6500 V. Table 3 shows several devices used as switch depending on the energy quantity required for the application.

<table>
<thead>
<tr>
<th>Device type</th>
<th>Max. forward blocking voltage</th>
<th>Max. peak pulse current capability</th>
<th>di/dt</th>
<th>Switch-on</th>
<th>Switch-on/off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thyristor</td>
<td>(\leq 8500) V</td>
<td>120 kA</td>
<td>1.5 kA/\mu s</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>GTO-like thyristor</td>
<td>4500 V</td>
<td>150 kA</td>
<td>50 kA/\mu s</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Integrated GTO-like thyristor</td>
<td>4500 V</td>
<td>150 kA</td>
<td>50 kA/\mu s</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>GTO</td>
<td>4500 V</td>
<td>4 kA</td>
<td>3 kA/\mu s</td>
<td>4 kA</td>
<td>4 kA</td>
</tr>
<tr>
<td>IGCT</td>
<td>(\leq 6000) V</td>
<td>4 kA</td>
<td>2 kA/\mu s</td>
<td>4 kA</td>
<td>4 kA</td>
</tr>
<tr>
<td>IGBT (Wire bonded module)</td>
<td>(\leq 6500) V</td>
<td>1 kA</td>
<td>5 kA/\mu s</td>
<td>1 kA</td>
<td>1 kA</td>
</tr>
</tbody>
</table>

Table 3 – Semiconductors [43,44]

When the capacitor is completely discharged the first device to select is the switch-on, because the switch-off is not needed.

According to [28] the discharge must not happen with contact of the terminals, and to avoid that situation two switches are recommended: one is the spark-gap and the other is the Thyatron valve. Both of them are
electronic controlled high voltage switches and can support high peak currents.

Switches life-time has increased over the years, but it is not enough for industries demanding more than 1 million shots until it becomes necessary change it. In order to reach this number, the switches can be joined into a device (see Fig.48), and that device can be connected in series. This way, the switches are going to share current and voltage, as shown on Fig.49. Here is represented one stack, and according to [44] the amount of energy that one stack can handle is limited (depending on the switches capacity). Nevertheless, it is possible to increase capacity introducing more stacks in parallel, where each stack has its own power supply and one distribution box, that will fire each stack independently or all parallel stacks simultaneously.

Fig.48 - Assembly of switches device [44]
Despite of the higher price of these switches, it will be compensated by the higher reliability, practically no maintenance and lower operation costs.

7.4. Coil

The coil design and material is one of the major item that influences the work parameters, where is possible to obtain different results with the same inputs. The shape of the coil is a factor that contributes to the determination of the pressure and velocity distribution on the flyer metal.

The biggest concern in the working coils is the high pressure, fast current rise and high repetition rate made during the welding process. The demands for this working coil are severe, because, not only must conduct extreme currents at high voltage without fail, has, it must do it under explosive pressure forces. Nevertheless, it have to last for several thousands cycles or it can not be used as an industrial process [40].

Thinking on the requirements from different industries, there is several types of coil designs [40] as wound, housed, flat, bitter-type, mono-wind and
special purpose coils (SPACE). For each application a different coil design can be chosen.

Regarding the coil design, magnetic pulse welding can be separated into three categories [41]: Compression, Expansion and Sheet contouring.

Compression coils (Fig.50-(a)) will deform the tubular workpiece radially inward. They are generally used for attaching tubes to fittings and for clamping components to produce tight seals (as rubber boots into automobile ball joints). Generally, these coils are designed for 1,000,000 shots.

![Diagram of coil designs for different MPW operations](image.png)

Fig.50 – Coil design for different MPW operation: (a) compression (b) expansion (c) sheet contouring [41]

Expansion coils (Fig.50-(b)) will deform the tubular workpiece radially outward, mainly because they are placed inside the workpiece. This process is mostly used for produce contouring ducting intersection parts, and to punch holes in tubing if necessary. Generally these coils are designed for 100,000 shots.
Sheet contouring coils (Fig.50-(c)) are flat and can be placed above, below or both regarding the flat workpiece. These coils are used has a magnetic hammer for correcting deformations of large surfaces, such as aircraft wings, and for electromagnetic riveting.

The highest electromagnetic pressures can be generated when the working surface of the coil is made from a monolithic of a high strength and high conductivity material.

Fig.51 illustrates other coil geometry. These one is separated into two halves, meaning that the both multi turn coils will be connected in series to weld. The coils acts independently, but together they act has a single cylindrical coil.

![Assembled halves of the coil](image)

**Fig.51** - Two independently multi turn coil [45]

Life coil depends on the energy used for magnetic welding. Her life his significantly shortened with high level of energy used for welding the workpiece, where the opposing force (Eddy Current) will increase with the increasing energy used.
7.5. Control System

It is important on MPW to have a good control of all parameters, in order to have a good strength on the joining of the workpiece and to ensure excellent process repeatability [41].

It is essential to keep the magnetic pressure constant, so, a constant charging voltage of the capacitors will be helpful. If there are several high current switches on the system, they all should firing within nanoseconds in order to prevent deviations of the first current amplitude [46].

Monitoring of the current amplitude and frequency is mandatory, because it’s the integrity of the machine that is being controlled and maintained. More, this control will provide useful data for the quality insurance system at all time [46].

With the introduction of a pulse generator control algorithm, the stability of the process can be maintained: if one capacitor fails, the discharge frequency will also be changed [46].

7.6. Field Shaper

For magnetic pulse welding the field shaper is not mandatory, it is more a plus and for several reasons could be helpful.

Normally, the coil is designed for a specific diameter (when welding tubes), but with the field shaper, it becomes possible to change the workpiece diameter by changing only the field shaper. The length of the welding could differ from work piece to work piece, as it can be seen on Fig.52 and Fig.53, where the field shaper can concentrate the magnetic pressure in specific areas [11,46]. Another advantage on using the field shaper, relay on longer coils life time. Nevertheless, when comparing this setup with another without the field shaper, the efficiency coefficient of the process will decrease due to the extra volume between the coil and work piece [47].
At the bore (Fig.52), the length is normally smaller than the field shaper length and the magnetic pressure can be concentrated in specific area [46]. Fig.53 shows a field shaper that is concentrating the pressure in two different areas indicated by letter A.

Fig.52  – Schematic of a field shaper inside a compression coil [46]

Fig.53  – Magnetic field on a field shaper [11]
7.7. Peripheral Components

With the improvements on technologies there was some need in making specific instruments that could be coupled to MPW process, namely, instruments that could give to the investigator the value of some parameters in order to control the process and be able to go on in the right direction.

The Photon Doppler Velocimeter (PDV) is one instrument that Stand and co-workers from LLNL introduced at MPW process [48]. These PDV is able to provide sub-micron resolution, temporal resolution the in nanosecond range and it was designed to collect data at multiple locations using several channels. It is easily handled, because it only needs a thin fibber optic line between the instrumentation and the target. A schematic of the PDV system is shown in Fig.54.

![Schematic of PDV system](image)

**Fig.54** - Schematic of PDV system [48]

These system consists on a Fibber Laser, Splitters for when it is needed several measure channels, Circulators that will guide the light from the laser out to the probe and reflect light from the probe to the detector, Probes and
an Oscilloscope with several channels and capable of storage large amount of data on each channel in a short period of time.

Once installed on the process, immediately after the first impact of the welding between the two metals, the PDV system that already has produced a Doppler shifted light, is going to combine this shifted light with the incident light signal producing a beat frequency that is proportional to the velocity of the moving surface. The results will be measured and analyzed at the oscilloscope and with modern equipment in order to yield velocity Vs time profile with good accuracy (see Fig.55).

![Fig.55 - Schematic of MPW process with PDV system [48]](image-url)
With the PDV it is possible to measure impact velocity and angle on magnetic pulse welding [48], as shown on Fig.56.

**Fig.56 - PDV probes installed on MPW process [48]**

PDV probes are placed in the area where measure should take place. The communication with the PLC or oscilloscope is done in seconds, giving an opportunity of response time or adjusting when implemented on standard process. For investigators it is advantage his use for collecting data and verifies the behaviour of different materials on the same process, with the same variables.

When installed on standard process and connected with a computer, he is able to assume control of process parameters by monitoring them at all instance, and stop when deviation occurs.
8. Materials and Their Behaviour Under MPW

Similar and dissimilar materials, coupled with the development of technologies required for MPW process, present huge possibilities in terms of overcoming the complex obstacles posted on traditional welding. Depending on the materials used, the energy necessary for welding can be higher or lower, accordingly to the electrical conductivity properties of each one. This means, that the material where the Eddy Current is going to act directly, must be a good conductor. Otherwise, the energy has to be higher to overcome the material resistivity.

Almost any material presents the possibility of welding trough MPW [4,49], namely, similar joints of aluminium, copper, nickel and steel and dissimilar welds of aluminium to copper, magnesium and titanium, copper to bronze and nickel to titanium.

Magnetic pulse welding is characterized for being capable of welding similar and dissimilar metals. When welding dissimilar metals the flyer metal should have good conductivity and the target should have higher yield strength to avoid plastic deformation [17].

It has already been said that on MPW, the flyer metal should have high electrical conductivity, mainly, because the material resistivity is one parameter with major influence on the determination of skin depth of the electromagnetic field, and therefore, electromagnetic pressure [11].
On Fig.57 there are several examples of the relationship between material resistivity and skin depth. Copper and aluminium, due to their low resistivity, are the better material to be nominated as flyer metal. On the other hand, steel and stainless steel are better materials to be nominated as parent metal of the welding process. If not, discharge energy or frequency has to be increased.

![Diagram](image)

**Fig.57 – Skin depth Vs Electrical resistivity [11]**

In order to obtain good results, the metal resistivity should not be higher than $15 \times 10^{-6}$ Ohm-cm [11].
On Table 4 it is possible to find the mechanical and thermal properties of some materials used on MPW process.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Steel</th>
<th>Stainless Steel</th>
<th>Aluminium</th>
<th>Titanium</th>
<th>Copper</th>
<th>Magnesium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</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 [ºC]</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 [10⁻⁹Ω-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>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>

Table 4 - Mechanical and thermal properties of MPW materials

One major challenge using MPW process is the joining of two very different metals like titanium and aluminium, as demonstrated by their properties. Trough conventional welding it is not achievable, due to the gap of their melting point: 660 ºC for aluminium and 1.668 ºC for titanium.

8.1. Ferrous

8.1.1. Steel

Steel is used in almost every industry, mostly due to his strength and durability. Nevertheless, decrease on weight is being requested and the use of steel is being less. Accordingly to Table 4 steel is the heavier metal compared to all others.

Because it as the highest elastic modulus, it can be used as parent metal due to his good impact resistance.
The high melting point makes it difficult to weld with another metal that is lighter. Magnetic pulse welding has arrived to full fill the emptiness when welding steel with other metals with lower melting point.

8.1.2. Stainless Steel (SS)

High oxidation resistance at air ambient is one of the most notorious properties of stainless steel. They can be divided into three main categories: austenitic, ferritic and martensitic [46]:

Austenitic stainless steel is the most normal steel (over than 70% of stainless steel production), and due to the quantity of nickel the structure of such steel will be non-magnetic.

Ferritic stainless steel normally has better engineering properties than austenitic, but corrosion resistance is lower due to lower nickel percentage. Normally is less expensive.

Martensitic stainless steel is the worst in corrosion resistant but it has very good strength, and his highly machineable.

Stainless steel is very similar to steel: heavy and with a high melting point. It is difficult to join using conventional welding methods (TIG, MIG...). Trough MPW it becomes possible to join SS with dissimilar materials (like aluminium or magnesium), because welding temperature will not rise enough to achieve the lowest melting point.

When welding SS with steel or SS (similar materials), and because they have high resistivity, the discharge energy must be higher then welding with dissimilar metals like aluminium or magnesium.
8.2. Non-Ferrous

8.2.1. Aluminium

Aluminium, being a light material has been high requested for applications at automobile and aerospace industries. With MPW it is possible to join aluminium with metals such as steel and titanium, because the temperature at impact between both metals will not rise near the melting point of the aluminium. Due to the lower resistivity and high electrical conductivity, makes this metal good for being the flyer one. Meaning, lower discharge energy, when compared with welding of SS to SS.

Regarding formability, MPW is able to handle without any problem, increasing significantly the ability of giving form to aluminium sheets [6].

It was observed [50] that under high strain rates, aluminium ductile behaviour increases, which facilitates magnetic welding.

There are many types of aluminium series, one good that is being requested more and more for aerospace industry is the one that belongs to the 7xxx series. When joining to other material by fusion welding it is normal to have inter-granular corrosion. Nevertheless, by magnetic pulse welding it is difficult to happen because the impact velocity creates a jet that will sweeps all impurities from the surfaces of contact. On the other side, these grains are correlated to the ratio Zn:Mg and from the contribution of the copper [51].

According to [52] the T73 aluminium eliminates the corrosion problem due to his finished toughened, and because with MPW all mechanical and chemical properties of the aluminium are maintained after welding.
8.2.2. Titanium

Changing material from steel to titanium weight is gained on production of a component. For welding, the joining between titanium and other metal is difficult, mainly due to his high melting point (highest from Table 4).

With MPW the welding between titanium and any other metal is possible, because melting points are not important parameter for a process where temperature will not rise significantly.

After welding all mechanical, thermal and chemical properties of both materials are maintained, even at the welding zone. This means that on structures like space frames, it can be used titanium with aluminium or magnesium, and, on one hand the area where there will be high tension will be made of titanium which as high tensile strength, and on the other hand, on areas where there will not suffer from high tensions, aluminium or magnesium could be used to decrease weight on final assembly.

It is a material with excellent corrosion resistance, and it has been observed [50] that under high strain rates, titanium ductility behaviour decrease.

8.2.3. Copper

Copper is a ductile metal with high thermal expansion so, when using conventional welding their properties could be changed. Because MPW is a cold weld no changes on copper properties will be verified.

It is the metal with the lowest electrical conductivity from Table 4, so, as the flyer metal it is a material that does not need very high discharge energy to gain velocity and be able to bond with other material.

Copper is a good material for electromagnetic forming, because it is a ductile and malleable metal, being easily worked. It has good corrosion resistance. One disadvantage on copper is related to the joining with dissimilar metals. At the welded zone, some electrochemical reaction can happen, and eventually, will destroy the functionality of the union.
8.2.4. Magnesium

Magnesium alloys is gaining interest in the automotive and aeronautic industries, mainly, because both industries are looking for reducing the weight of their components. When compared with aluminium and steel, magnesium has lower density, approximated 30% lighter than aluminium and 75% than steel, meaning that magnesium is the lightest structural metal [53,54,55]. Combining it with titanium or steel is not difficult due to his lower electrical resistivity. So, is a good material as flyer metal where the discharge energy necessary will not be as high as for steel. It is possible to say that magnesium is very good mouldable metal, capable of producing quality welding within MPW process.

The most disadvantage of magnesium it is corrosion formation. With MPW process (cold process) it becomes possible to produce magnesium alloys with small percentages of iron, copper, and nickel, increasing considerable corrosion resistance [55].

It has been tested under high velocity welding technologies, and the results were favourable to the feasibility of this metal on MPW process [54]. Is ductility and formability increase at high strain rates.

It was observed [50] that under high strain rates, magnesium ductility behaviour increases.
8.3. Welding of Similar Materials

Bonding of similar materials will be described on several investigations made by researchers. Several parameters like discharge energy, standoff distance and skin effect were studied experimentally and compared with theoretical models.

8.3.1. Welding of AA1050 / AA1050

The proposition for this investigation is to understand how standoff distance will influence the welding between aluminium 1050.

Two flat rectangular one-turn copper coils were designed for electromagnetic impact of 1mm thick flat aluminium sheets [6].

The properties of the aluminium used in these investigations are described in Table 5.

<table>
<thead>
<tr>
<th>Alloy designation and temper</th>
<th>Density (kg/mm³)</th>
<th>Electrical resistivity (ohm·cm)</th>
<th>Yield strength (YS) (MPa)</th>
<th>UTS (ultimate tensile strength) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 1050-O</td>
<td>2700</td>
<td>$2.81 \times 10^{-6}$</td>
<td>28</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 5 – Properties of aluminium alloy [6]

For standoff distance, six different values were tried while the discharge energy was kept constant during the welding [6].

The capacitor bank was charged with 10 kJ at 10 kV, the coil was made of copper and has an inductance of 0.74 nH.
In the middle, and in order to increase the current density, was placed a web of 5 mm wide and 70 mm long with "I"-shaped cross-section, as represented by Fig.58.

![Fig.58 – Flat rectangular coil [6]](image)

The total inductance of the circuit was 0.7 µH.

At initial position of the sheet, \( d_1 = d_2 = 0.07 \times 10^{-3} \) m

At final position of the sheet, \( d_1 = d_2 = 1.5 \times 10^{-3} \) m

From equation (7) it was observed that the magnetic flux diminished from it is initial value of 50 T to average of 33 T, at the time of collision. This means, initial the magnetic pressure was 950 MPa and at impact was 425 MPa, according to equation (2).
Trough this method, the samples have two welded zones and one zone without welding, at the centre of the weld (Fig.59).

![Sample of AA/AA with no welding zone](image)

Fig.59 – Sample of AA/AA with no welding zone [6]

It were pointed several reasons for the non welding zone, and it could be from the possible entrapment of the oxides, the rebound effect due to normally acting Lorentz force at the centre and the complex deformation state at the interface.

To verify the weld quality it was done an axial tensile test to all samples and the result obtained is shown at Fig.60, where the points without color represent samples where the parent metal fail, and the color points represent samples where the zone weld fail.

![Shear strength Vs. Standoff Distance](image)

Fig.60 – Welding results of Al/Al [6]
The results for the variation in the standoff distance demonstrate that the B samples (taken from the central part of the welds) have higher shearing strength (Fig.61), when compared to samples A and C (taken from the weld edges).

![Sample taken for axial test](image)

**Fig.61** – Sample taken for axial test [6]

For a certain set of process parameters the standoff distance has one optimum value where the shearing strength and width of the weld reach their maximum value. If the standoff distances decrease or increase from his optimum value, a decrease on the shearing strength will be verified. This can be explained due to the maximum velocity and kinetic energy at some value of standoff distance, where below or above the sheets cannot fly with maximum velocity. For lower values of standoff distance, collision takes place before sheets attain the maximum velocity, and for higher values the velocity attained drops to a lower value at the time of collision.
8.3.2. Welding of AA6063 / AA6063

The main objective for this experiment is to compare real welding situation with empirical one. For the simulation it was used electromagnetic and mechanical software ANSYS. The material used was only aluminium EN AW 6063.

The experience consists on welding of aluminium tube with aluminium bolt (Fig.62).

![Diagram of welding setup]

Fig.62 – Setup [56]

The tube as an outside diameter of 18 mm and an thickness of 1 mm. The bolt has a conical joint region with an inclination of 4 °. The standoff distance has a value of 2 mm, between the tube and the bolt.

The properties of the aluminium used are showed on Table 6.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific resistance $\rho$</td>
<td>$3.3 \times 10^{-3} , \Omega \cdot m$</td>
</tr>
<tr>
<td>thermal conductivity $\lambda$</td>
<td>$201 , \text{W m}^{-1} \text{K}^{-1}$</td>
</tr>
<tr>
<td>specific heat capacity $C_W$</td>
<td>$898 , \text{J kg}^{-1} \text{K}^{-1}$</td>
</tr>
<tr>
<td>thermal expansion coefficient $\alpha_W$</td>
<td>$23.5 \times 10^{-6} , \text{K}^{-1}$</td>
</tr>
<tr>
<td>permeability $\mu$</td>
<td>$1 , \mu_0 = 1.2566 \times 10^{-6} , \text{H m}^{-1}$</td>
</tr>
</tbody>
</table>

Table 6 – Material properties of aluminium EN AW 6063 [27]
The welding equipment used for the experimentation was a ELMAG, with a capacity of C=240 μF and a loading voltage of U=7.6 kV to 9.1 kV, meaning an discharge energy of 7 kJ to 9 kJ. The inductance of the welding equipment has a value of L<sub>i</sub>=0.36 μH, and the inductance of the coil id L<sub>coil</sub>=1.930 μH. The frequency of the circuit is f=7.3 kHz and the coil have 10 windings, which are used together with a field former. The skin depth was calculated for 1.07 mm.

The sequential phases are represented schematically on Fig.63.

The tube is the flyer metal and the bolt is the target.

It was observed that at collision point there is a turn of the state of material into a quasi-viscous state. It is due to this state that it becomes possible to form a thin interface layer between both metals.

Temperature at the time of collision will rise up, but will not reach significant values. It will never go up 350 K, which is approximately 38% of the melting temperature. And, accordingly to simulations, the heat generated will have low influence on the welding process, so, it was concluded that the heat generation could be neglected in further simulations or experiments.
The simulation can be represented has showed at Fig.64.

![Simulation representation](image)

For these experimentations and simulations, it was verified accordance when using discharge energy of 8 kJ. Nevertheless, is important to have in our minds that the results obtained are only valid for the welding of this two materials and with the conditions described above.

### 8.3.3. Welding of AA 6061 / AA 6061

This experiment is going to identify the influence of parameters such as impact angle and thickness of the flyer metal on the joining interface, and at the same time boundary analysis will be done.

The aluminium used was EN AW 6061-T6, and his properties are described on Table 7.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$R_{0.2}$ [N/mm²]</th>
<th>$R_m$ [N/mm²]</th>
<th>A [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AW-6061 T6</td>
<td>240</td>
<td>260</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 7 – Mechanical properties of aluminium 60601-T6 [57]
The energy discharged from the capacitor bank has a current of 930 kA and a frequency of 14 kHz through a coil. The resulting magnetic pressure has a value of 400 MPa on the surface of the flyer.

It was used a coil, a field shaper and a holder to make possible the alignment inside the coils of the parts to be joined (Fig.65).

![Fig.65 – Scheme of the welding process [57]](image)

Inside the coil the positioning of the metals to be joined are described on Fig.66.

The aluminum tubes have an outside diameter of 50 mm and a thickness of 1.5 mm, 2 mm and 3 mm. The welding zone has a length of 25 mm, an initial length of 5 mm and than an angle of 30 °.
The angle $\alpha$ varies from 5° and 7.5° and 10° (see Fig.66).

Fig.66 – Schematic setup of welding metals [57]

As shown at Fig.67 there is a direct relationship between weld length and the thickness of the flyer tube. The standoff distance was always 1 mm.

Fig.67 – Weld length according to tube thickness for 1 mm gap [57]

The magnetic discharge energy was constant during the experience, so, the conclusion is that the increasing wall thickness results in a lower contact
pressure between both parts, meaning that it is required more energy to have the same weld length with higher thickness.

Applying the angles of 5° and 7,5° and 10° for \( \alpha \) it was verified that with an standoff distance of 3mm and a contact angle of 5°, the welding was not accomplished (see Fig.68). The contact pressure was enough, but the contact angle did not result in a continuous contact and so, in a weld joint.

![Fig.68 - Weld length according to tube thickness for 3mm gap [57](image)](image)

Despite of not being described on this paper, it was experimentally verified that with samples of 7,5° and 10° and wall thickness of 1,5 mm and 2 mm the welding between both metals occur.
When welding occurs, the grains in the bonding zone will be deformed in direction of the line contact (see Fig.69). This is caused by the different velocities of both metals, where the material close to the interface has to move faster across the wave than the material that is more distant.

![Fig.69 – Weld interface [57]](image)

### 8.4. Welding of Dissimilar Materials

Bonding of dissimilar materials is the most important characteristic from MPW process. It allows the bonding between two very different materials as aluminium and titanium, that with standard welding (MIG or TIG) it will no be possible.

On this chapter it will be described several investigations made by researchers using dissimilar metals. Several parameters like discharge energy, standoff distance, skin effect and impact velocity were studied experimentally and compared with theoretical models.
8.4.1. **Welding of AA1050 / Fe, Ti and Mg (AZ91D) Sheets**

For this investigation a new geometry coil will be used on the welding of different materials: aluminium 1050/ Fe, aluminium 1050/ Ti and aluminium 1050/ Mg (AZ91D).

On this research it were used two capacitors banks in parallel of 100 μF/10 kV, with an inductance of 0,02 μH [4], as showed by Fig.70.

![Schematic illustration of MPW with a flat one-turn coil](image)

**Fig.70** – Schematic illustration of MPW with a flat one-turn coil [22]

Flat one-turn coil made of Cr-Cu alloy, with a upper and lower plate with thickness of 2 mm and an inductance value of 0,04 μH [4].

Sheets from 0,5 – 1mm
With a energy discharge of 1,2 kJ, the current flows through the one-turn coil about 50 μs and the oscillating period was about 22 μs (Fig.71).

![Graphs showing current and energy vs. time](image)

(a) (b)

Fig.71 – (a) Current signal (b) Energy [8]

The maximum current measured was 150 kA.

Supposing that the discharges current flows uniformly on the surfaces, than, the depth of the skin effect calculated is 0,38 mm for Al sheet.

The magnetic flux density was estimated to be 20 T, while the magnetic pressure, according to (2), was estimated around 150 Mpa.

Existence of a wavy morphology meaning quality weld between Al / Fe, Ti and Mg is achievable (see Fig.72).

![Images of Al, Fe, Ti, Mg bonding area](image)

Fig.72 – Bonding area [4]
It can be concluded that the coil geometry used produces a good bond on the interface through MPW process.

It was observed a decrease on thickness of the aluminium sheet, mainly due to a good weld between the materials. It can be said that the bonded is formed by solid-state welding [4].

8.4.2. Welding of Al / SS

It will be investigated the behavior of aluminium as flyer metal. Also, several parameters such as standoff distance and tensile shear strength will be analyzed and commented at the end.

The methodology used is similar to the one from section 8.3.1 and so it will not be described here.

For this investigation it was used a three dimensional, “I” shaped, flat one turn copper coil as shown on Fig.73 [7].

![Image of Copper Coil]

**Fig.73 – Three dimensional flat copper coil [7]**

The aluminium sheet has 1 mm thickness and is the conductor. The stainless sheet has 0,25 mm thickness and 50x50 mm long and wide.
The capacitor bank was charged with 10 Kj at 10 kV. The coil is made of copper and has 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 as 18.5 kHz, in order to ensure that skin depth on the flyer material (aluminium) was less than its thickness.

From several parameters studied, Fig.74 shows how tensile shear strength behaves with the increase of standoff distance.

Letter “A” and “C” belong to samples cut from the edge of the bonded area. Letter “B” belongs to samples cut from the middle of the bonded area.

![Graph showing tensile shear strength vs standoff distance](image)

**Fig.74 - Welding results of Al/SS [7]**

It was observed [7], as expected, that the samples from the middle, “B”, were the ones with higher shearing strength. The samples from the edges have behaviour very similar and strength lower than the ones with letter “B”.

One reason pointed for the higher shear strength on samples “B”, relies on higher penetration of the magnetic field at the centre of the samples, than at
the edges. Another reason is that the current that flows through the sheets, will change direction at the edge. This weakness of the magnetic field will decrease the magnetic pressure on the flyer material, so, as a result, the bonded area it will have lower shear strength.

The optimal standoff distance is 1,5 mm and from Fig.74, when this value deviates from is optimum, the strength of the welded area will decrease and more energy is required to achieve good quality welding.

For a optimum value of standoff distance the strength is maximum, when above or below the kinetic energy of the flyer metal is reduced, meaning that the his velocity is decreased and the magnetic pressure will be less. In order to compensate the deviation, more energy is required to obtain the same result.

The microstructure of the bonded area shows that welding occurs between aluminium and stainless steel. Fig.75 shows a linear bonding interface.

![Fig.75 – Aluminium and Stainless Steel interface [7]](image)

Increasing the discharge energy will increase the magnetic pressure, and thus, increasing the strength for a specific standoff distance.
8.4.3.  **Welding of AA6061-T6 / Cu101**

The main objective was to study the discharge energy, the impact velocity and angle [33] during the welding of two dissimilar metals. It were used sheets of AA6061-T6 and Cu101 (see Table 8 for material properties) for this experiment.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Flyer Workpiece (AA6061-T6)</th>
<th>Target Workpiece (Cu101)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity ($\Omega \text{ mm}^{-1}$)</td>
<td>(0.250627 \times 10^5)</td>
<td>(0.584795 \times 10^2)</td>
</tr>
<tr>
<td>Mass Density (g/mm$^3$)</td>
<td>(2.7 \times 10^2)</td>
<td>(8.94 \times 10^2)</td>
</tr>
<tr>
<td>Young's Modulus (GPa)</td>
<td>68.9</td>
<td>115</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td>Yield Stress* (MPa)</td>
<td>276</td>
<td>195</td>
</tr>
<tr>
<td>Heat Capacity (J/g °C)</td>
<td>0.896</td>
<td>0.385</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>167</td>
<td>391</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>582–651.7</td>
<td>1083</td>
</tr>
</tbody>
</table>

Table 8 – Properties of AA6061-T6 and Cu101 [33]
Impact angle and velocity are two important parameters involved on this process to make a successful welding. Both materials were placed on the welding zone according to Fig.76, and the flyer material was pre-flanged with an angle of 45 ° (see Fig.34).

![Magnetic pulse welding process](image)

Fig.76 – Magnetic pulse welding process [33]

![Sketch of the experimental setup](image)

Fig. 34 – Sketch of the experimental setup [33]

The flyer material is a flat sheet with a width of 152.4 mm and 304.8 length and thickness of 0.5 mm. One of the edges was flanged at 45 ° with a length of 12.7 mm.

The applied discharge energy was 2.4 kJ, 4.8 kJ and 7.2 kJ.

To measure the experimental impact velocity it were used Photon Doppler Velocimeter (PDV) probes. On [33] is described how PDV probe works.
It was used a Rogowsky coil coupled to the oscilloscope in order to capture the primary current signal.

From Fig.77 it is possible to verify that the primary currents for different discharge energy have similar period but different magnitude, and that with high energy discharges, higher will be the induced current.

![Graph](image)

**a) AA6061-T6**

![Graph](image)

**b) Cu101**

Fig.77 – Primary current with different discharge energy [33]

Both graphics show that the primary current is mostly dependent on the actuator and capacitor bank instead of the metals involved on the welding.
The graphic from Fig.78 was obtained using the PDV system. The PDV is very accurately for measuring impact velocities.

Fig.78 – Impact velocity at 4,8kJ discharge energy [33]

The conclusion from Fig.78 is that the flyer plate reaches the peak velocity of 91 m/s within 60 µs [33]. This peak velocity last for 20 µs and then start to decrease rapidly. The flyer plate first will contact the target plate and than will join, giving origin to a wavy interface.

8.4.4. Welding of Copper (DHP R290) / Brass (CuZn39Pb3)

The main objective for this experimentation [58] is to see the weldability between copper and brass. Table 9 gives some characteristics about the two metals.

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Brass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
<td>EN 12449 Cu-DHP R290 (Mat. No.: CW024A)</td>
<td>EN 12164 CuZn39Pb3 (Mat. No.: CW614N)</td>
</tr>
<tr>
<td>Chemical composition (wt%)</td>
<td>Cu: 99.9 %</td>
<td>Cu: 57 - 59 % Pb: 2.5 - 3.5 % Zn: rest</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>min. 250</td>
<td>min. 250</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>min. 290</td>
<td>min. 430</td>
</tr>
</tbody>
</table>

Table 9 – Copper and brass properties [58]
The geometry of the coil is according to Fig.79, and it was welded tubes inside of it.

![Coil geometry](image)

Fig.79 – Coil geometry [58]

For this investigation it was used a capacitor with a maximum charging voltage of 25 kV and a discharge circuit of 15 kHz. To obtain this energy it was selected a Pulsar model 50/25 system [58]. The capacitance of the capacitor banks is equal to 160 µF.

With the field shaper is possible to concentrate the pressure from the magnetic flux induced by the multi-turn coil.

It was used tubes with an outer diameter of 25 mm and 1,5 mm thickness.

The discharge current frequency and the overlap distance of the tube and workpiece were kept constant. The width of the air gap between the flyer tube and the workpiece, the position of the field shaper were changed during the experiments and the charging voltage of the capacitors.
On Table 10 are summarized the parameters range used during the experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube end position in the field shaper</td>
<td>Centre of field shaper + 0,5 up to + 5,5 mm</td>
</tr>
<tr>
<td>Air gap width</td>
<td>0,8 - 2,5 mm</td>
</tr>
<tr>
<td>Capacitor charging voltage Energy</td>
<td>12 - 20 kV</td>
</tr>
<tr>
<td></td>
<td>11,5 - 32 kJ</td>
</tr>
</tbody>
</table>

Table 10 – Parameters variations [58]

From the experiments done, it was observed that with an air gap smaller then 1 mm or higher than 2 mm there was no bonding between both materials. But, in the range of 1 to 1,5 mm the welding has gone well and it is possible to verify the joining (see Fig.80).

Fig.80 – Copper/Brass Boundary [58]
After macroscopic observations, it was verified that the welding zone can be divided into three zones (see Fig.81).

Fig.81 – Metallographic zone [58]

Only at the middle zone occur welding. After discharge of energy, the impact happens from left (run-in zone) to right (run-out zone), but no welding occurs in these zones. Nevertheless, no correlation was found between the lengths of the run-in, run-out zones and the settings of the process parameters.

In the run-in zone is where the inner workpiece has suffered more deformation during the impact. This deformation declines gradually towards the run-out zone (end of the weld). So, the welding always happen from left to right and if the inner workpiece has not the strength to held the impact, than a mandrel should be applied to prevent such deformation.

Fig.82 shows that the size and orientation of the grains in the interface area have changed due to impact, due to plastic deformation (dark zone).
After welding, sometimes, it can be observed cracks in the intermetallic layers, mainly due to rapid solidification and some local melting point (Fig.82).

![Crack along the welded zone][1]

**Fig.82 – Crack along the welded zone [58]**

In explosive welding it is normal to have some melt pockets or porous inside the welding area. At magnetic pulse welding the temperature do not increase very much, but sometimes it is enough to generate some welding zones where brittle interlayer will be formed.

It has been verified [58] 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.
8.4.5. Welding of Al99.5 / TiAl6V4

The objective for welding aluminium Al99.5 with titanium TiAl6V4 is to investigate the influence of impact velocity on bonding these two dissimilar metals [59].

It was used samples with a size of 30x8 mm and a thickness of 0,1 mm. It was prepared by milling a rib profile.

All contact surfaces were cleaned with acetone.

The angle of impact was 5° at all trials, and the impact velocity was in the range from 10 to 130 m/s.

From the investigations [59] it was concluded that in the range of 10 m/s to 25 m/s, there was not any bonding on atomic scale. When the impact velocity was higher than 25 m/s, then at least some sections of the samples were welded.

From Fig.83 is clear showing that an increase of the impact velocity leads to a higher ratio of the welded area and contact surface.

![Graph](image)

Fig.83 – Impact velocity Vs Welded surface [59]
When analysing the graphic on a statistic way, the interpretation of the microstructural data suggest a linear correlation between this ratio and the impact velocity.

Micrograph analysis demonstrate that 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 bonding (see Fig.84).

![Microfracture](image)

**Fig.84 – Bonding interface [59]**

When a certain value of impact velocity is exceeded, there will be deterioration of the joining. For these combinations of metals, the optimum value stays between 100 m/s and 130 m/s (being carefully at values close to 130 m/s).

Analogous, it was made experiments with tubes. For aluminium a tube of 20 mm diameter and 1 mm thickness and for titanium a tube of 15 mm diameter and 2,5 mm thickness. Both workpieces were positioned coaxially in the compression coil. The initial gap between them is 1,5 mm.

After some experiments, the desirable impact velocity is around 100 m/s with energy of 500 J.
With a discharging energy of 1.000 J there was wavy interface between 4 and 6 mm in Z positive and negative (Fig.85).

![Image](image.png)

**Fig.85** – Welding seam from Z=0mm to Z=12mm [59]

At the centre and edges the bonding was not accomplished. With the increasing of discharge energy up to 1.500 J the bonding interface is more linear. At the centre between 0 - 3 mm there was not any wavy interface, but above 3 mm the weld was successful.

![Image](image.png)

**Fig.86** – Impact velocity and impact angle along both metals [59]
When the first impact happens (Z = 0 mm) the impact angle is 90° and the parallel velocity \( (V_{\text{par}}) \) is very low. The relative movement between both metals depends on the parallel velocity, and not of the perpendicular velocity, that is high at this first moment. Meaning, the weld has poor quality.

Joining Fig.85 and Fig.86, with higher energy discharge and parallel velocities means better welding zone.

In conclusion, it is suggested the use of high impact velocities at some angle value in order to have bonding zones with high quality level.

8.4.6. Welding of Al6060 / Mandrel from different material

Space frame structures are being very appreciated by several industries, namely the automobile and motorcycle. In these structures the main objective is to decrease weight and at the same time maintain good strength capable of support all tensions during structure life-time.

The objective of this investigation is to study the influence of the mandrels stiffness and strength on the mechanical properties of the joint. Mandrels from aluminium alloys, copper alloys and steel were chosen to do the comparison between the welding of AA6060 tube with them.
Table 11 describes the material used for all nine mandrels, and Fig.87 shows the welding assembling process and the properties of the equipment used. The tube used is a aluminium AA6060 with 20 mm of diameter and 1 mm of thickness.

<table>
<thead>
<tr>
<th>ID</th>
<th>Material</th>
<th>Alloy composition</th>
<th>Yield strength [MPa]</th>
<th>Young’s modulus [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>AA5754</td>
<td>AlMg3</td>
<td>100</td>
<td>70,000</td>
</tr>
<tr>
<td>B</td>
<td>AA6060</td>
<td>AlMgSi0.5</td>
<td>160</td>
<td>70,000</td>
</tr>
<tr>
<td>C</td>
<td>AA7075</td>
<td>AlZn5.5MgCu</td>
<td>460</td>
<td>70,000</td>
</tr>
<tr>
<td>D</td>
<td>G1100P</td>
<td>Cu-ETP</td>
<td>180</td>
<td>116,000</td>
</tr>
<tr>
<td>E</td>
<td>Cu10Zr</td>
<td>CuZr</td>
<td>470</td>
<td>116,000</td>
</tr>
<tr>
<td>F</td>
<td>NSB1</td>
<td>CuNi3Sn1</td>
<td>590</td>
<td>116,000</td>
</tr>
<tr>
<td>G</td>
<td>S235</td>
<td></td>
<td>235</td>
<td>210,000</td>
</tr>
<tr>
<td>H</td>
<td>1.0715</td>
<td>9SMn28k</td>
<td>440</td>
<td>210,000</td>
</tr>
<tr>
<td>I</td>
<td>1.0601</td>
<td>C50</td>
<td>580</td>
<td>210,000</td>
</tr>
</tbody>
</table>

Table 11 - Mandrel material [60]
During these tests, the tube is going to be deformed plastically and the mandrels elastically. Afterwards, a tensile test is going to be done in a 200 kN Zwick machine with a crosshead velocity of 2 mm/min. The tensile test will give the strength value necessary to separate tube from mandrel.

The results obtained from tensile tests are described on Fig.88.

![Fig.88 - Tensile tests results [60]](image)

It was verified that with increase on the gap between the tube and mandrel, leads to an acceleration distance causing a reduction of the discharging energy, meaning, less impact velocity and pressure. On the other hand, when the gap is maintained at 1,2 mm, an increase on the discharge energy leads to higher value of axial or pull-out forces. Additionally, it was verified that when using a mandrel with high strength and stiffness it results in higher axial force to separate both parts.

Looking to Fig.88 it seams reasonable to choose a mandrel material of higher strength and higher stiffness than the tube material.

Trough magnetic pulse welding it becomes possible to join dissimilar or similar metals, which can resist axial forces as high as the yield strength of the tube.
9. Advantages and Disadvantages

Magnetic pulse welding is a technique with advantages and some disadvantages. Nevertheless, it has been verified to be an efficient process through time. The disadvantages, have being minimized or even eliminated as researches develop new tools and the process becomes more precise and clean.

The principal advantage of MPW is the controllability and repeatability, but there are many other advantages. Below, some of them were listed:

- Possibility of joining dissimilar materials, while their mechanical and chemical properties will be maintained [1,3-5];
- It is a Cold Process because the temperature will not raise up, significantly, during the weld process, mainly due to the short time of energy discharge (in the order of milliseconds) [1,3-5];
- It is a clean process, due to jetting derived from the high velocity impact. This means, at the time of the impact between both materials the magnetic pressure will remove any oxidation and dirty from the contact surface (Fig.89) [1,3,41], and metallurgical bonding is achieved between clean surfaces. For this reason, it is not necessary to do any surface cleaning before and after welding [11];

![Diagram](image)

**Fig.89** – Scheme of impurity removal, Jetting [10]
• Better corrosion resistance at the welding zone. Sooner, appear corrosion on one of the two materials, than on the welding zone [3,5];

• MPW provides the advantage of higher strength-to-weight ratio without any heat affected zone [5,26];

• The welding zone is stronger than the weaker of the base metals, so failure, always occur outside of the welded zone (Fig.90) [8,20];

Fig.90 – Mechanical tests shows failure outside the welding zone [57]

• Ambient friend, because when compared with other welding processes do not emit harmful gases into the atmosphere, radiation and it is not necessary to add material into the welding. Due to the absence of friction on the process, no lubricants are required. It some times called as “Green Process”. [1,3,11];

• For any industry, to be an ecological process has its advantages. From the economical view, any rework cost will be eliminated from the process, diminishing cycle time and raising process capability [1-3,40];

• No postweld finishing or cleaning is required after welding [5,40];
• Magnetic pulse welding technology brought improvement in the quality and productivity while reducing costs per part, by introducing revolutionary production designs there were not possible until today [3,5,41];

• Magnetic pulse welding is particularly suitable for large series production and for automated feeding system. Mainly, due to his lowest maintenance and quick changeover [3,40,41];

• The equipment can be operated by unskilled workers [11,41];

• On MPW the material that is going to suffer the electromagnetic force, must be good electrical conductor. Nevertheless, if not, it is possible to insert an aluminium or brass part (metal with lower resistivity) between the inductor and the moving material, helping the conductivity. At the end, the extra part is simply throw way [1,6,41];

• Magnetic pulse welding is mostly used on joining metals, but is applicability has been positively verified at powder compaction [61]. It becomes a different way of producing parts with some level of complexity.
Despite having numerous advantages, there are some limitations or disadvantages on MPW process.

Listed below, are some of the disadvantages that can be found on MPW process:

- There are some few cases where oxidation appears on the welding zone. It was verified [6] that the origin was on some lengths where the fusion between both materials has not happen. This small gaps are only visible at microscope, so, from time to time it is necessary to verify the penetration of the welding to avoid gap that will induce corrosion;

- The part that is going to suffer plastic deformation, must have good electrical conductivity, otherwise, higher energy will be required and the cost of the process may be comparatively higher [3,4,41];

- Nowadays, the coil inductor is still a very expensive material, and needs to be replaced periodically [41];

- Due to impact velocity and pressure, the inner material must have sufficient structural strength to withstand the impact, and do not deform together with the outer material [1].

- Due to the high intensity of current and voltage, the security level must be kept high, and special safety precautions need to be implemented before industrialization of the MPW process [62].
10. Industrial Applications

Nowadays, companies are attempting themselves to acquire new market shares by increasing their product range. It is an international competition and is emerging trend towards individualization of customer requirements. The result, is a pressure to decrease costs, increase efficiency of the existing processes and to harness technologies that are new or have been some how neglected.

Magnetic pulse welding is one of the processes that have been neglected, and since the 70’s has been studied and developed. What begin to be expensive and was only used at nuclear energy applications, today, it is possible to see the usefulness of MPW at different industries like automotive or electrical. It is becoming a feasibility process where industries can use this technique in large series production, and where quality is maintained.

MPW process is synonymous of quick changeover and no additional rework of the parts after or before welding. During welding, there will not be emitted harmful gases into the atmosphere, contributing to cut losses buying smoke equipment for their workers, neither, extraction equipment to control ambient around the working area.

At the end, the main objective that all industries are looking and can be achievable is decreasing the weight of their components.
Table 12 shows some examples of components produced by MPW on different industries [1,40,41].

<table>
<thead>
<tr>
<th>Nuclear Industry</th>
<th>Aerospace Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Welding of closing caps</td>
<td>• Lining of ammunition control rods</td>
</tr>
<tr>
<td>• Welding of end closers of nuclear</td>
<td>• Components of fuel pumps</td>
</tr>
<tr>
<td>fuel rods</td>
<td>• Welding of tubular space frames</td>
</tr>
<tr>
<td>• Welding of metal canisters</td>
<td>• Composite Over wrapped Pressure Vessels (COPV)</td>
</tr>
<tr>
<td>• Welding of nuclear fuel pins</td>
<td>• Correcting surface deformations on aircraft skins</td>
</tr>
<tr>
<td></td>
<td>• Riveting aircraft wing spars</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Automotive Industry</th>
<th>Electrical Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Drive shafts</td>
<td>• Electrical fuses</td>
</tr>
<tr>
<td>• Components of air conditioning</td>
<td>• Components of electrical motors</td>
</tr>
<tr>
<td>• Fuel filters</td>
<td>• Cable ducts</td>
</tr>
<tr>
<td>• Tubular seat components</td>
<td>• Welding of connectors to cooper cables</td>
</tr>
<tr>
<td>• Fastening clamping rings over</td>
<td>• Assembling coaxial cable termination joints</td>
</tr>
<tr>
<td>rubber sleeves on shock absorbers</td>
<td></td>
</tr>
<tr>
<td>• Attaching reinforcing bands on</td>
<td></td>
</tr>
<tr>
<td>oil filters</td>
<td></td>
</tr>
<tr>
<td>• Space frames</td>
<td></td>
</tr>
</tbody>
</table>

Table 12 – Magnetic Pulse Welding applications
10.1. Nuclear Industry

Nuclear Industry was the responsible for the discovery and the initial development of magnetic pulse welding on the production of end closures and nuclear fuel rods (see Fig.91). These parts are reported as the first components produced using MPW technique.

![Fuel rods](image)

Fig.91 – Fuel rods

10.2. Automotive Industry

Automotive Industry is demanding a higher efficiency at lower costs, size and weight in their parts and processes. The car makers are considering the quality to be as important as price in their specifications. So, magnetic pulse welding is starting to be considered by manufacturers a good and practicable alternative technology [3]. One of the most common strategies is to use components of reduced cross-section but with higher strength.

There are two principal companies developing this technique and process, and they are Pulsar and Dana [63].

Pulsar is a small Israelite company that belong to the Cleal Industries Group. Pulsar have the patent for their own form of magnetic pulse welding
technology, where is incorporated a switch with the capacity of transferring 2 million amperes in less than 100 microseconds.

The simulation software used was developed in-house and was programmed to give, has an output, the peak of magnetic pressure, frequency, impact velocity, splash energy, contact time, weld length and the specific parameters to produce [3]. Using this software, at Pulsar, the team member will be warned if the welding was successful or not (welding is monitored and controlled by the PLC).

Magnetic pulse welding has been developed in such a way that can compete with classic production methods, and this technique is being used not only to weld but to crimping, cutting and perforating [40].

Dana is a big USA company that have won the Automotive Manufacturing Award in 1999, and for the people working here the key to the process lies in the electrophysics and in the optimization of the equipment.

In resume, magnetic pulse welding allows manufacturers to significantly improve their product designs and production results, by enabling both dissimilar and similar materials to be welded together, thus providing the opportunity to use lighter and stronger material combinations, obtaining minimum weight from the joining.

Some companies [63] are beginning to see the advantage on magnetic pulse welding to produce space frame structures in their new models. A space frame is a skeletal like structure composed of struts and joints which are designed to bear the majority of the load that a vehicle might have to support during is life, leaving the body panels free of stress [63]. These space frame are made of aluminium or steel and with magnetic pulse welding, it is possible to have a combination of both materials, contributing for the lightweight of final assembly, maintaining the strength of the steel at the joints. At the end, the important is to obtain a light weight structure where the mechanical and thermal properties of the metals are maintained.
Fig. 92 and Fig. 93 show the Audi A8 and Jaguar XJ space frame, respectively. For Audi A8 the aluminium involved has suffered special treatment, what made possible to obtain a very strong hardness and high melting point [64].

![Audi A8 Space Frame ASF](image)

**Fig. 92** – Audi space frame structure [64]

![Jaguar XJ aluminium space frame](image)

**Fig. 93** – Jaguar XJ aluminium space frame [55]
Another example of MPW on space frame structures relays on the BMW-C1E bike (Fig.94).

![Fig.94 - Structure of BMW-C1E [65]](image)

Aluminium is a metal that is being tested in these structures, due to its weight, mechanical and thermal properties. It has been considered feasible is use on magnetic welding [47,65].

Due to the low maintenance and durability, MPW is being tested in different areas on the Automotive Industry. On exhaust systems, MPW process is being used for flanging mufflers, as shown on Fig.95 [66].

![Fig.95 - Flange by MPW [66]](image)
The main objective is to obtain a good hemmed union on different areas of a complex parts, such has muffler flanges, especially when using aluminium alloys.

10.3. Aerospace Industry

Magnetic Pulse Welding has gain his space on this industry, by the fact that when using traditional technologies for joining hollow parts their quality does match the increased requirements of production.

Due to this technique it was possible to join copper with steel and in order to reduce weight, the joining of carbon-plastic with steel [2]. It is obvious the benefit on joining dissimilar materials for these industry, mainly because the bounded zone have no intermetallic formation contributing for the deleterious effects of the involved parts.

Crimping is one way to use magnetic pulse welding on parts that need to support high force or torque [20]. Structural crimping does not require high velocity impact that is necessary to welding two materials. One good example remains on Boeing 777, 737 and 747 where this technique is used for crimping high lift torque tubes of 0,128 inch onto steel yoke fittings. Has already discussed above, and after torque test, it was verified that the tube does not fail on the joint but fails in the parent metal [20]. This electromagnetic crimp can effectively replace a design that was troublesome with respect to fatigue.
Fig. 96 a) shows some aircraft flight control tubes used and b) is possible to see the tubes installed on a commercial airplane.

Fig. 96 – a) Aircraft flight control tubes b) Aircraft flight control tubes in use [42]
11. Conclusions

Magnetic Pulse Welding has been growing since the 70’s and most probably on the next years, the development on this technique will permit a standard implementation on different industries.

With demands from customer, the equipment is being more reliable, cheaper and with more durability. Parameters are being precisely controlled with introduction of PLC, PDV system, and others, which can verify all variables at any time with accuracy. Whenever a breakdown happens, there are systems capable of informing the controller the root cause of failure process.

It has been verified [3-5] that MPW is a Cold welding process. During welding, the increasing of temperature at the bonding will not have significant impact on the process, and it always stays below melting point from the lowest of the materials.

It was verified that welding between dissimilar metals is no issue for MPW technique. It depends, mostly on the parameters setup. On the several experiences described, when the metals involved have higher tensile or yield strength the discharge energy must be higher, and the opposite is valid. Nevertheless, the success of getting good welding between two metal sheets, two tubes or other geometry configuration 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.

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 the flyer metal must have a larger wall thickness, resulting on high magnetic pressure. Thus, the higher is the
value of the electrical conductivity, less energy is required to have high impact velocity and the bonding between both materials will happen in good conditions. For example: for welding aluminium with copper, lower electrical and thermal resistance is needed to achieve strong joints. When comparing with welding of aluminium with titanium or steel, it is needed more energy in order to achieve joints with high strength [15].

Standoff distance as an optimum value for achieving good welding, and it was verified that when standoff distance deviates from optimum, than, discharge energy must increase in order to compensate the deviation and maintaining the same impact velocity. When the deviation decrease the distance between both materials, more energy is required by the process to increase magnetic pressure and impact velocity to the flyer metal. On the other hand, if standoff distance increases, than, more energy is required by the flyer metal due to the distance that he must travel before the impact into parent metal.

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 [16].

After bonding, if there is a rupture, most probably, it will happen outside the welding area, and furthermore, it will be on the weakest material and never on the bonding zone [8].

With simulation software it is possible to predict and understand behaviour of the welding. But, it is a support that needs inputs from tests in order to have a simulation with more accuracy.

MPW process is being developed for welding between two tubes and two sheets but for other kind of geometry it needs to be more investigated.

For welding materials with low electrical conductivity, the system must have higher energy in order be able to increase magnetic pressure on the flyer metal. One way found to overcome this material resistivity, relays on the introduction of one sheet metal with high conductivity between the inductor
and the flyer metal. On Fig.57 it is possible to see that silver or copper are the best material to use regarding high electrical conductivity. Next is aluminium alloy, brass and at the end steel is the metal with lower electrical conductivity. After the bonding, the “extra” part is removed and through it way. Nevertheless, higher energy is always required to have good quality bonding.
12. References


Presented at the 3th International Conference on High Speed Forming, Dortmund, Germany (2008), pp. 51-60.


