3D Impacts Modeling of the Magnetic Pulse Welding Process and Comparison to Experimental Data

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Abstract

Magnetic Pulse Welding (MPW) is a solid state (cold) welding process known to present several advantages. When properly designed, such an assembly is stronger than the weakest base material even for multi-material joining. These high quality welds are due to an almost inexistent Heat Affected Zone which is not the case with fusion welding solutions. Another advantage is a welding time that is under a millisecond. In order to define the MPW parameters (mainly geometry, current and frequency), recent developments have made it possible to adapt welding windows from the Explosive Welding (EXW) for use in MPW. Until now, these welding windows have been simulated only in 2D geometries showing how the impact angle and the radial velocities progress in a welding window. The aim of this paper is to present our most recent development, which builds on this analysis to develop a 3D model in order to deal for example with local planar MPW. Simulation results will be presented and then compared to experimental data for a multi-material join case.

Keywords

Magnetic pulse welding (MPW), Dynamic simulations, Welding windows

1 Introduction

High Pulse Power (HPP) processes are drawing ever more attention from industry, in particular in the case of Magnetic Pulse Welding of two different materials or in complex geometries. Conventional processes that rely on melting of the materials, is only rarely able to successfully assemble such different materials. The reasons for this are related to strong differences in the respective material properties, such as their melting points or thermic expansion rates. This in turn leads to strong residual stresses and therefore potential cracks. Moreover, thick layers of intermetallic materials are created in proximity to the interface during the re-solidification step. This results in a brittle and mechanically weak heat affected zone and thus a limited quality assembly between the two materials (Kapil 2015).

Solid state welding solutions, such as Explosive Welding (EXW) and Magnetic Pulse Welding (MPW), are known to bond material without or with a very limited solid to liquid phase change during the process. Both processes are based on a high velocity oblique impact. This way, the heat affected zone is negligible and leads to high quality welds when the welding parameters are properly chosen.

The MPW process consists in a fast discharge (several microseconds) of a high current in a coil, inducing strong Lorentz forces in the part to be accelerated. This process is currently available at Bmax alongside a number of other industrial HPP technologies, such as Magnetic Pulse Forming/Crimping or Electro-Hydraulic Forming.

When compared to EXW, and when thicknesses are not too large, the MPW solution is more suitable for mass production for obvious production rate, cost and safety reasons. MPW can also be adapted to a wide range of geometries (tubular or planar) and to various weld sizes (up to more than a meter in length). One of the necessary preconditions for MPW is to control the evolution of impact parameters as these are essential to achieving a high quality weld in geometries other than 2D. This requirement motivated the recent development presented in this paper, based on 3D impact modeling. These simulations make it possible to apply the technology on 3D geometries and to analyze the welding process, in a strong multi-physics model, with a reduced calculation time. This allows us to greatly shorten the fine-tuning phase of the process to obtain the proper welding parameters that are necessary to optimize the joining strength.

To begin with, a short explanation of the MPW theory is presented. This includes how a welding window is built and gives the appropriated ballistic conditions to bond two given materials. This in turn provides the basis for a simulated prediction of the potential welded zones.

For this purpose, 2D and 3D multi-physical simulations are performed with dynamic explicit LS-DYNA code. A post-processing program developed by Bmax is used to define the ballistic history of the collision model and to plot it in the welding window graph. The method is first demonstrated in a 2D geometry showing a comparison between multi-physical simulations and experimental results (Cuq-Lelandais and al., 2014).

The method is then extended to a 3D geometry case with the same welded materials. In this case, a planar welding example is used. The ballistic results are shown in the

Welding Window and compared to the experimental equivalent test. Moreover, this latter is projected on the geometry to directly identify the potential welded area.

2 Welding Window Theory and Numerical Methodology

2.1 Theoretical Background

Cold welding between two parts is achieved using an oblique impact at high speed. In the case of MPW, a high current discharge (hundreds of kA) flows through a coil, inducing Lorentz forces on the part to move. This strong and short loading causes the part acceleration within few microseconds on about a millimeter standoff distance. It can reach several hundreds of m/s at impact with the parent part. Extensive studies on the EXW method showed welding is achieved for a given range of impact angles and velocities, referred to as the Welding Window (Grignon, 2003 and Kapil, 2015). The impact welding process implies multi-physical and dynamic phenomena, including mechanical, thermal and thermodynamics fields. To obtain a strong welding, several necessary conditions must be achieved. Whereas the welding windows for the EXW plot collision angle versus collision point velocity (V_c), Cuq-Lelandais and al. (2014) have proposed to plot the more practical collision angle (α) versus normal impact velocity (V_n) for MPW (see Fig. 1).

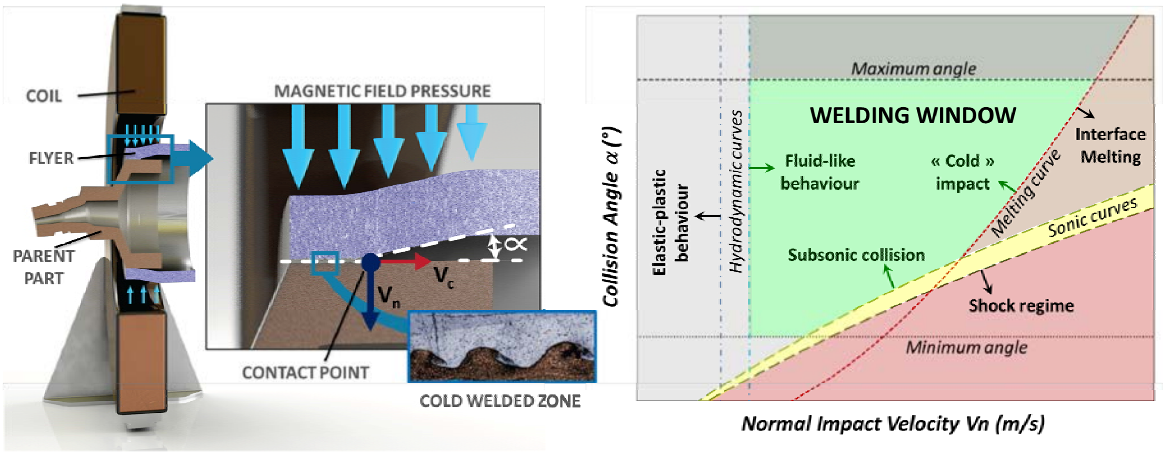

***Figure 1**: MPW oblique impact process and a typical theoretical Magnetic Pulse Welding Window*

- **Jetting conditions:** The collision point has to be subsonic compared to the local materials speed of sound to generate a jet. A supersonic case leads to an oblique shock wave behind the collision point.
- **High Pressure/hydrodynamic regime:** If the velocity is not high enough to provide a fluid-like behavior, the parts are only bent following an elastic-plastic regime.
- **No fusion during the collision:** The process has to remain "cold". If the pressure is too high, the materials can locally melt and then re-solidify, implying issues to those in the traditional welding processes.

Contrary to the EXW method, the impact collision history in MPW is transient due to the non-constant magnetic pressure. For this reason it is necessary to develop a numerical method to predict the evolution of these parameters and thus determine the potential welded/unwelded zones to optimize the joining parameters, in particular when the geometry becomes complex. Such analysis is demonstrated in the following example in a 2D axisymmetric geometry.

2.2 Numerical Ballistic Analysis – 2D Axisymmetric Example

This case study examines the MPW of an aluminum alloy outer tube on a steel anvil. The coil surrounds the outer tube and is loaded with an imposed current pulse, inducing the outer tube acceleration. The calculation is run with the LS-DYNA® code (Hallquist, 2015). This latter is the only commercial code available to perform parallel 3D Magneto-Hydro-Dynamic (MHD) with a strong coupling with high speed mechanics, electromagnetics (Eddy currents) and thermal effects (including Joule effects and electrical conductivity equation of state) (L'Eplattenier, 2009). This model provides a complete analysis of the collision history, which can be reported on the Welding Window graph (see Figures 2 & 3). For comparison purposes, experimental welded zones can be identified by using a cross section micrography. Welding starts only 0.5 mm after the first impact point (entry zone). It can be seen that two zones have been bonded with a smooth interface, leaving a central region unwelded. The welded lengths measured are in good agreement with the simulation which exhibit a similar behavior.

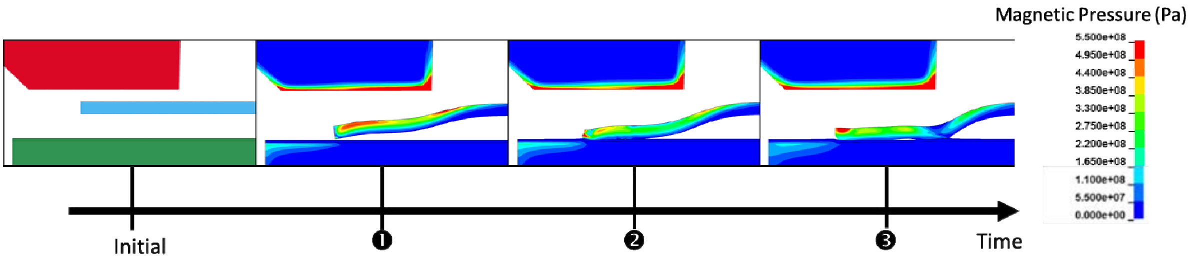

***Figure 2**: 2D cylindrical MPW impact Simulation – Magnetic pressure contours at different times*

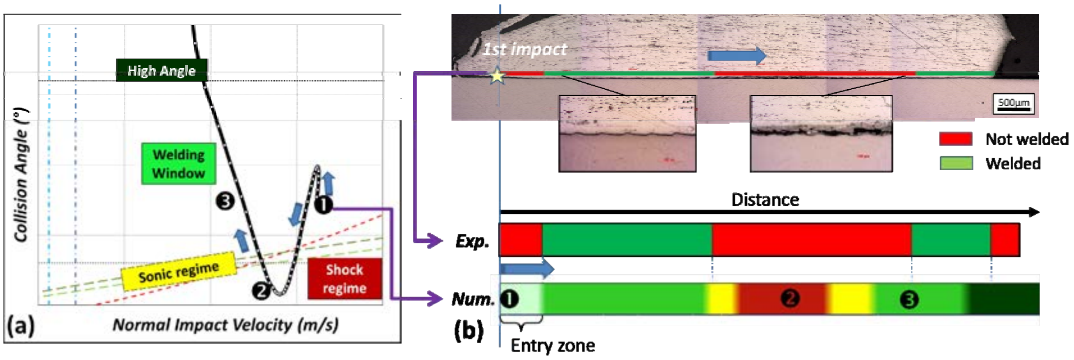

***Figure 3**: Simulation ballistic results on the Aluminum/Steel Welding Window graph (a) - Experimental/Numerical comparison of the welded zones (b)*

2.3 Results Interpretation – Eulerian Calculations

In this case, the deformed shape of the tube is not optimized and presents large variations of the collision angle. The ballistic path goes out of the Welding Window when the collision angle becomes too weak (flat impact), and comes back later on, in the last third of the impacted zone.

The local impact behavior in both welded and unwelded zones can be compared to impact simulations as shown in Figure 3 where the collision point is followed at different times.

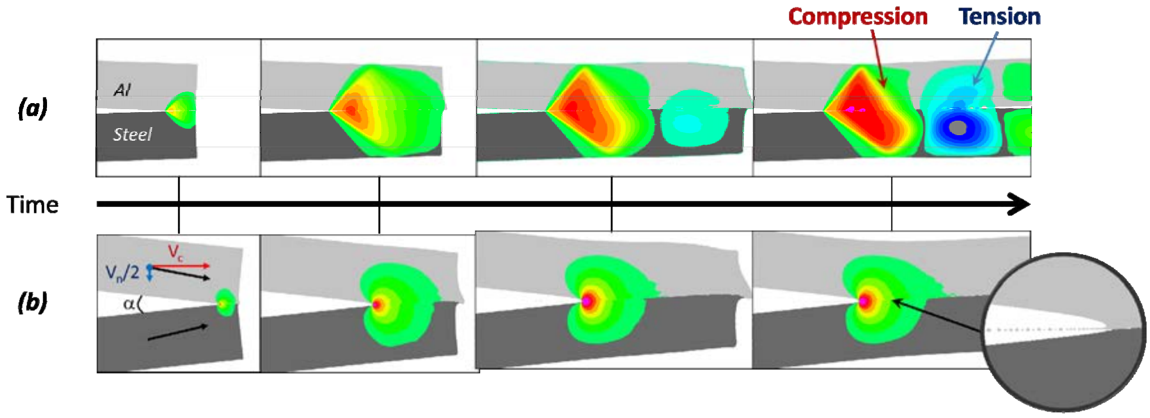

Figure 4*: Simulations of the impact local behavior for different collision angles α at the same impact velocity: (a) = 4° angle; (b) = 12° angle – Fringes = Pressure*

When the angle is low (Fig.4-a), the collision point velocity is higher than the materials speed of sound. It results in a shock behavior, similar to a Mach cone, and no jet is generated. In addition, the reflected waves create a tensile state just behind the collision point, tending to peel off the parts. This can be considered as a bounce back in the central zone, which can affect the weld quality since it may propagate the tensile waves to the already bonded zones (Cuq-Lelandais and al., 2014). In the areas suitable for welding, the collision angle is higher and the corresponding simulation presents a cardioid pressure field, maximum at the collision point, with jetting. As it can be seen on the Fig. 4-b, the jet does not appear at the first impact, but only after a certain rise time in impact pressure. This inertia can explain why welding does not occur immediately in the entry zone, even if the ballistic conditions are good in the welding window.

This 2D example shows a good agreement between the welding windows theory, the simulations and the corresponding experimental test. The numerical results make it possible to explain the welded zones distribution and lengths, thanks to the ballistic analysis on the welding window graph.

3 3D Case Analysis – Planar Welding

The ballistic interpretation of a MPW impact validated in 2D geometries can be applied on a 3D case. In this work, a planar welding setup is presented, which is used to bond two metallic plates along a double weld straight line, as it can be seen in Figure 5.

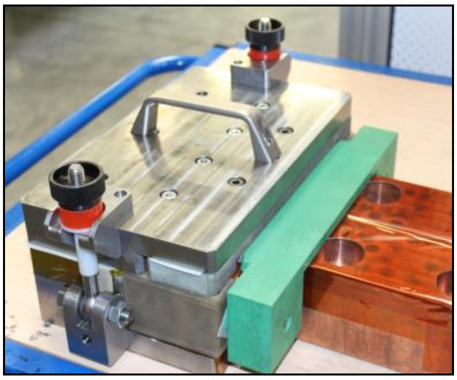

***Figure 5**: Planar MPW setup*

3.1 Planar Welding – Numerical Model

The model of the geometry and a cross section of the line to be welded are shown in Figure 6. The electrical pulsed loading delivered into the coil (IN/OUT on the figure 6-a) is calculated by an RLC circuit solver. The mesh is fine enough to accurately estimate the magnetic field diffusion (5 cells in the skin depth). This model contains about 700,000 elements to represent all the components. The model is run by coupling the electromagnetic solver with an explicit mechanical analysis using massive parallel computing, which reduces the calculation time. This case takes about one day to complete on 32 CPUs (Intel® Xeon® x7560).

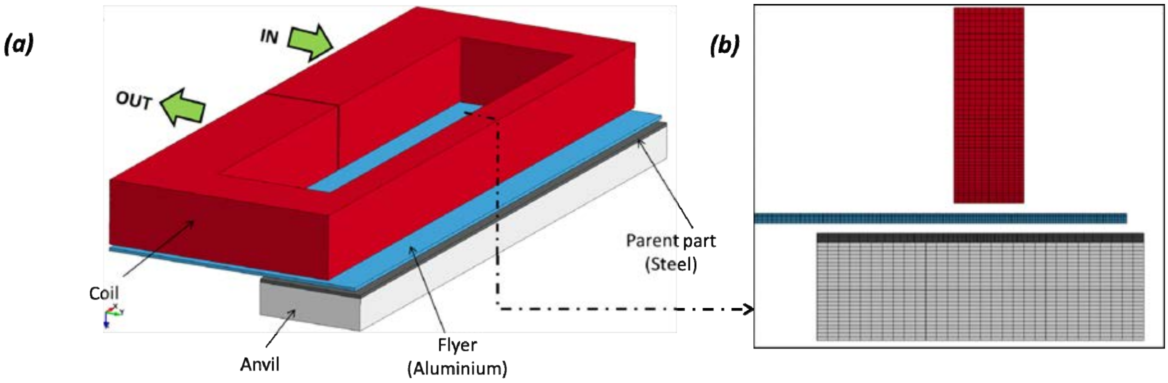

***Figure 6**: Planar MPW simulation model. (a) = 3D overview – (b) = Active zone cross section*

3.2 3D Multi-Physical Dynamic Behavior

The model presented in 3.1 provides a full 3D analysis, including electromagnetic effects, induced current in the flyer or the magnetic pressure distribution. Figure 7 exhibits for the model current densities (a) and Lorentz forces (b) at current peak. The current density in the coil is at its highest at the edges, whereas for the flyer it is located at the center of the coil (Fig. 7-a). The resulting Lorentz forces on the flyer show (Fig 7-b) a maximum at the center of the coil. However, significant forces on the flyer are applied next to the sides of the coil leading to substantial deformations in these regions.

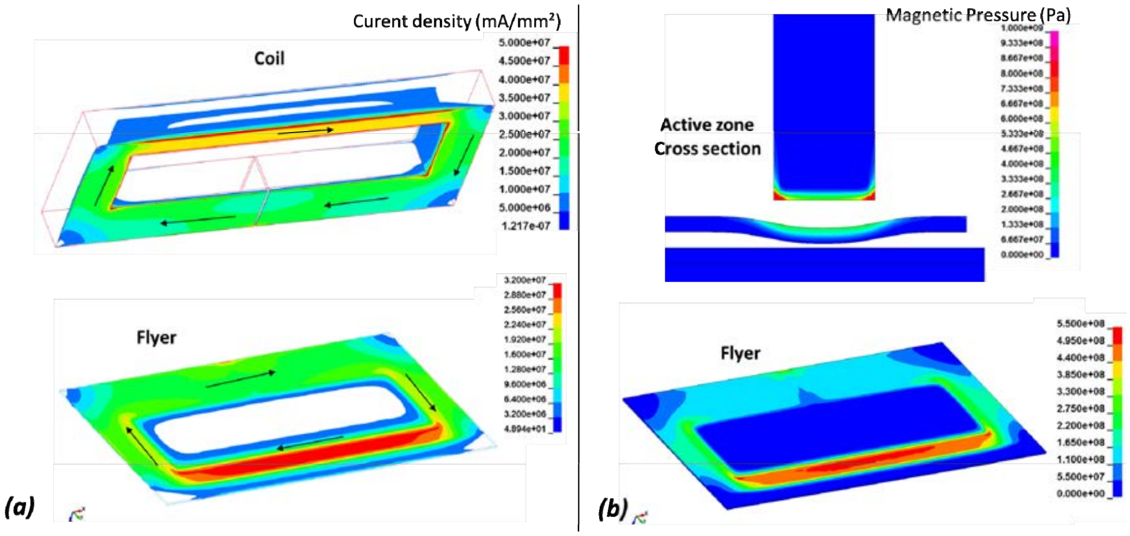

***Figure** 7: Planar MPW simulation at the quarter of period. (a) = Current densities (coil & flyer view) – (b) = Magnetic Pressure (model median cross section and 3D flyer view)*

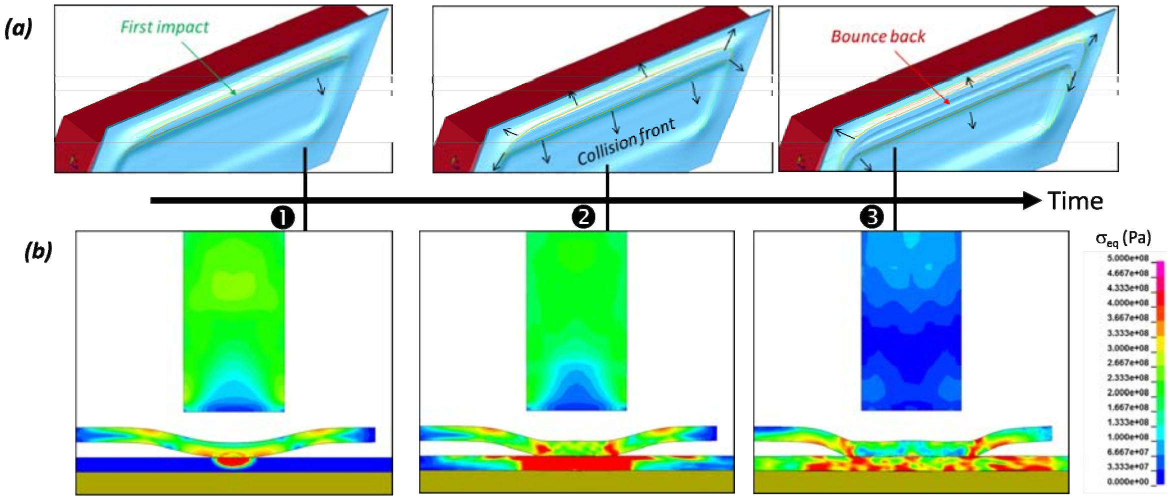

***Figure 8**: Planar MPW impact evolution at different times: upper = Flyer deformation and impact – lower = Equivalent stresses on the 2D active zone cross section*

Also, 3D modelling makes it possible to analyze mechanical stresses on the parent part and the coil. The 2D median cross section equivalent stresses are presented in Figure 8, showing two distinct behaviors. First, when the impact velocity is high (2), the stresses concentrate only around the collision point. On the other hand, when the impact velocity is reduced, the stress field shows a bending, with two tension/compression zones across the thickness. The stresses in the coil are checked in order to always keep them below the material yield stress, ensuring adequate life time for industrial uses.

3.3 3D Ballistic Results

Furthermore, a global ballistic post-processing can be performed similarly to the 2D case. Such analysis appears to be helpful in revealing the favorable zones where welding between the two plates can be achieved. Consequently it can be used to adapt the coil shape and the gaps in order to increase the welding area and thus the strength of the assembly.

The analysis can be run on the whole impacted area, as can be seen in Figure 9 where only half of the model is shown. This provides a characterization of the main ballistic data. For a 3D analysis, the impact time contours on the geometry make it possible to draw the collision front evolution. In this case, 2 symmetric linear fronts start at the center of the coil location, where the impact velocity is the highest but normal to the parent part (no angle). They expand then on both sides and the impact velocity reduces progressively, while the angles increase.

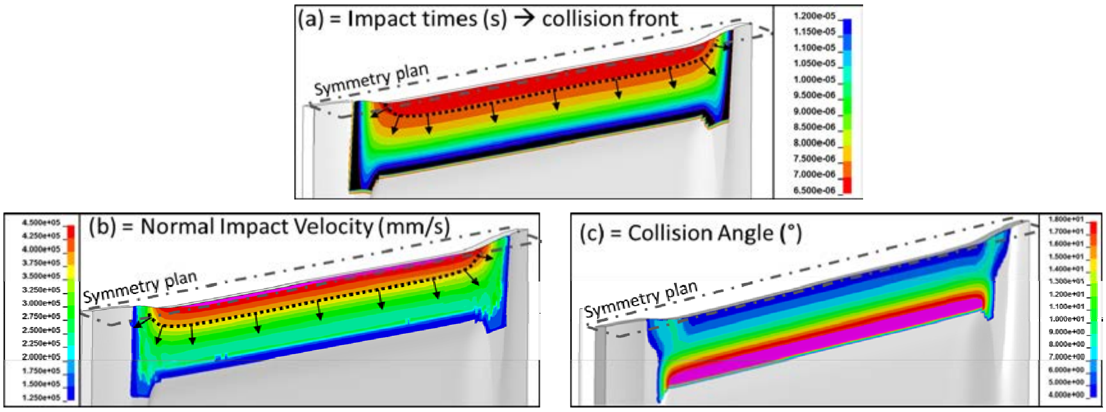

Figure 9*: 3D ballistic analysis on the impacted zone for half of the model: (a) = Impact time contours – (b) = Normal impact velocity contours – (c) = Collision angle contours*

Concerning the Welding Window ballistic curve, if a 2D analysis is suitable as the collision is curvilinear; it becomes harder to draw it for a 3D problem where the collision follows a surface. As one can plot the main ballistic parameters on the geometry, it is possible to directly project the Welding Window and interpret the weldability in terms of zones. Figure 10 gives the Welding Window projection applied to the planar MPW case. The zones where appropriate conditions for welding are reached appear as green. This latter can be compared to the experimental test (upper picture). In this picture, all the unwelded flyer zones have been removed. The simulation gives a good evaluation of the experimental welded lateral half-length: 7.9 vs. 7.7 cm measured on the sample.

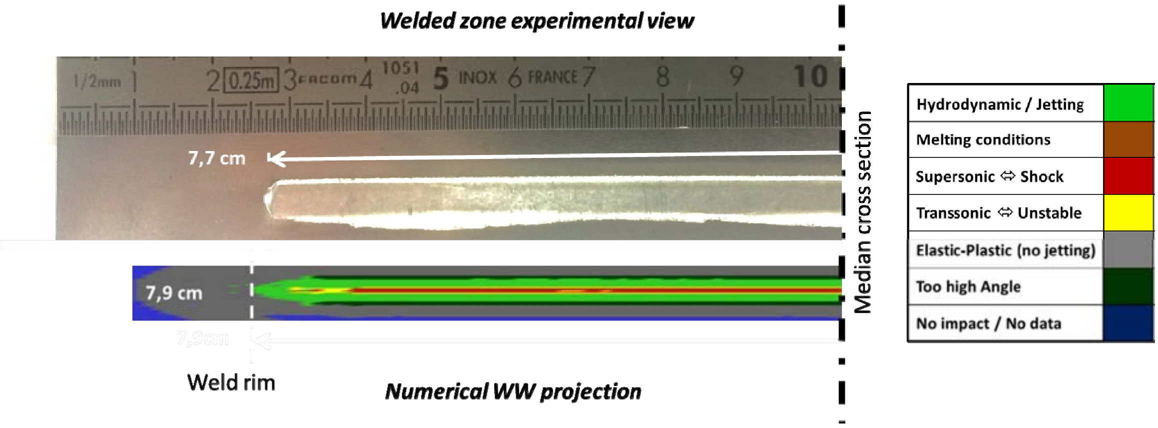

Figure 10: Experimental/Numerical comparison of the welded lengths in the impacted zone – Welding Window projection on the geometry

In addition, 2D cross section analysis can be done, leading to a more classical interpretation as for the 2D cylindrical case. Experimental axial welded length is compared to the ballistic curve results taken in the median cross section as performed in paragraph 2.2 (see Figure 11 - right). They are also quite closely correlated with the theoretical Welding Window.

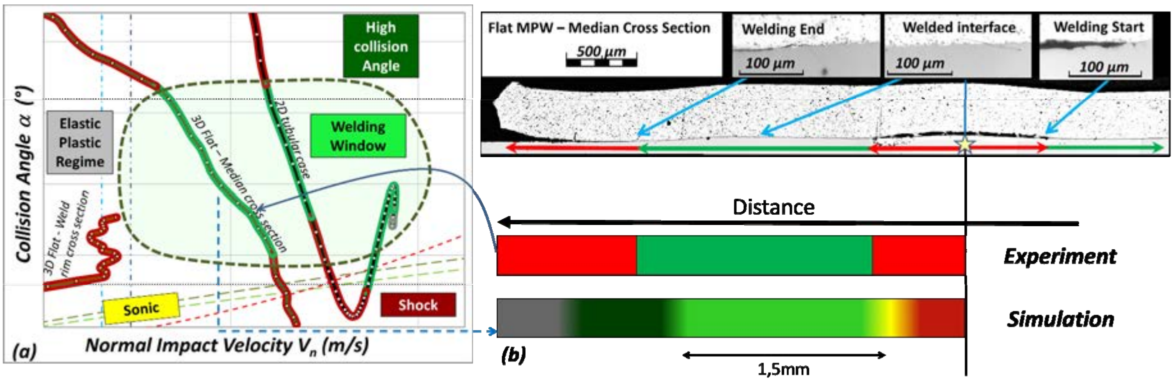

Figure 11: Experimental/Numerical comparison of the welded lengths on the 2D median cross section (b); Experimental welded zone retro-projection on the Welding Window (a)

An additional curve is taken from a cross section on the rim of the welded zone (see white dashed line in Figure 10). This allows us to accurately characterize a boundary of the Welding Window. This lower velocity limit is in good agreement with the theoretical elastic-plastic/hydrodynamic vertical limit.

More generally, the comparison between numerical and experimental ballistic data in 2D and 3D can be useful to refine the Welding Windows, especially for high angles and velocities. Figure 11 (left) illustrates this by projecting the experimental welded/unwelded lengths on the corresponding ballistic curve. In this case, three curves are processed. The 2D tubular case and the 2D cross sections from the planar MPW case give complementary results, as their respective ballistic curves are located in different regions of the graph.

4 Conclusion

This paper demonstrated the most recent modeling developments performed at Bmax dedicated to Magnetic Pulse Welding. The work is based on the post-processing of 3D impact conditions. The simulations are performed using the multi-physical LS-DYNA® code that makes it possible to accurately model induced Lorentz forces leading to high velocity impacts. The resulting collision parameters, angle and velocity, can be compared with the theoretical and experimental Welding Window for the combination of 2 materials. Two possibilities have been demonstrated, depending on the complexity of the case. For simple geometries, ballistic data can be plotted in the welding window graph as the collision point follows a curvilinear path. For a more complex 3D case, where it is no longer possible to easily use the results, the Welding Window can be reciprocally projected on the geometry. This provides a direct observation of predicted welded zones. This method has been validated using several experimental results associated to micrographs, in different geometries (cylindrical and planar). In both cases, simulated MPW data have shown a good match between experimental and theoretical welding windows. These tools provide not only the ability to efficiently refine the welding windows, but also to optimize coils and gaps in order to increase welding areas and thus the strength of assemblies. In addition this method facilitates a better understanding of the related physical phenomena. Practically, this analysis can be extended to more complex shapes, more in line with customer’s requirements.

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