A method to reduce calculation time in multiphysic modelling of welding processes. Application to laser and GMAW welding.

Mickael Courtois[1*], Muriel Carin[1], Philippe Le Masson[1], Stephen Cadiou[1], Sadok Gaied[2]

[1]Univ. Bretagne Sud, IRDL, UMR CNRS 6027, F-56100 Lorient, France
[2]ArcelorMittal Global R&D Montataire, F-60160 Montataire, France
*mickael.courtois@univ-ubs.fr

Introduction

The multiphysic modelling of welding processes at the scale of the melt pool evolves each year. These models become more and more realistic, taking into account numerous physical phenomena but in general at the cost of long and heavy computations. Laser welding is particularly difficult to model because of the high energy density inducing vaporization of the metal. This vaporisation creates a vapor capillary, also named keyhole particularly difficult to model. The process involves solid, liquid and gas at the same time and all are dynamically moving. To treat the strong topological movements, level set or V.O.F. methods are commonly used. The first model fully multiphysics, including heat transfer, fluid flow, phases changes from solid to liquid, liquid to gas, and recoil pressure was developed in 2002 [1]. They used a supercomputer, that was not available to many scientists. Then, between 2008 and 2016, different models were proposed [2,3,4] with finite element and finite volume codes. But in many cases, these models are very heavy to solve (either in computing resources and/or calculation times). With this study, our goal is to propose a method to reduce calculation times based on a previous study [5] giving results in 1 month of computation. These delays are too long for an industrial environment and often, a duration of 24 hours is acceptable. Here, the code Comsol Multiphysics is used and the meshing procedure is modified to reduce drastically the number of degrees of freedom. Each equation uses one optimized mesh rather than only a unique mesh for all the equations classically used in Comsol Multiphysics. The calculation times are reduced from 1 month to 1 day for laser welding keeping all the main physics. Then, the same method is used on a standard workstation to model Gas Metal Arc Welding (GMAW) allowing a very complete calculation of a process never really fully calculated due to its complexity (to the authors knowledge).

Governing Equations

In order to model welding processes at the melt pool scale, the heat transfer equation must be solved (eq. 1). In this equation, two source terms have been introduced: S_{laser} (eq. 2), represents the energy of the laser. In laser welding, it is well known that multi-reflexions must be modelled [6] but in order to reduce calculation times a simplified approach is employed here. This method was validated in [5]. Q_{vap} represents the energy of the vaporization, this term becomes negative and very high when the temperature goes above the vaporization temperature.

Then, to represent the melt pool dynamic, the equations of momentum (eq. 3) and mass conservation (eq. 4) are solved. These equations are solved in liquid and gas, which are supposed Newtonian in laminar flow. In momentum conservation equation, sources terms are added to take into account: gravity, buoyancy effect with the Boussinesq approximation, the solid part though a Darcy condition, surface tension (because of the level set method) and the recoil pressure due to vaporization of steel (eq 5). Finally, a classical formulation for the level set transport equation is employed (eq. 6).

$$\rho\, c_p^{eq}\left[\frac{\partial T}{\partial t}+\vec{\nabla}\cdot\left(\vec{u}\,T\right)\right]=\vec{\nabla}\cdot\left(k\,\vec{\nabla}T\right)+S_{laser}+Q_{vap} \qquad (1)$$

$$S_{laser}=2.5\cos\left(\theta\right)\alpha\left(\theta\right)\delta\left(\phi\right)\frac{P_{laser}}{\pi\, r_0^2}\exp\left[\frac{-\left(x-x_0\right)^2-\left(y-y_0\right)^2}{r_0^2}\right] \qquad (2)$$

$$\begin{aligned}&\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\left(\vec{\nabla}\cdot\vec{u}\right)\right)=\vec{\nabla}\cdot\left[-pI+\mu\left(\vec{\nabla}\vec{u}+\left(\vec{\nabla}\cdot\vec{u}\right)^T\right)\right]\\&+\rho\vec{g}-\rho_l\beta_l\left(T-T_{melting}\right)\vec{g}\Phi+K\vec{u}+\gamma\vec{n}\kappa\delta\left(\Phi\right)+F_{recoil}\end{aligned} \qquad (3)$$

$$\vec{\nabla}\cdot\vec{u}=0 \qquad (4)$$

$$F_{recoil}=p_a\exp\left[\frac{\Delta H_v}{k_bT_{vap}}\left(1-\frac{T_{vap}}{T}\right)\right]\delta\left(\Phi\right) \qquad (5)$$

$$\frac{\partial \Phi}{\partial t} + \vec{u} \cdot \vec{\nabla}\Phi = \gamma_{ls} \vec{\nabla} \cdot \left[\varepsilon_{ls} \vec{\nabla}\Phi - \Phi(1-\Phi) \frac{\vec{\nabla}\Phi}{|\vec{\nabla}\Phi|} \right] \tag{6}$$

Where T is the temperature, k the thermal conductivity, ρ the density, c_p the heat capacity, $\vec{u}$ the velocity vector, θ the surface inclination, r_0 the laser beam radius, Φ the level set variable, μ the dynamic viscosity, β_l the thermal expansion coefficient, γ the surface tension coefficient, κ the curvature, δ(Φ) the derivative of Φ representing the interface, γ_{ls} and ε_{ls} numerical parameters for the transport equation, p_a the ambient pressure, H_v the vaporization enthalpy, k_b the Boltzmann constant and T_{vap} the vaporization temperature. More details for the mathematical formulation can be found in [5] and [6].

Innovating meshing approach

The main goal of this work is to reduce the calculation time. With the classical approach, to calculate 300 ms of process requires 1 month of computation [5]. With the use of only one mesh to solve heat transfer, fluid flow and the level set transport equations, the element size is driven by the level set interface that requires a finer mesh to describe correctly the interface in all the domains. However, the heat transfer and the fluid flow use also this fine mesh even if this is not needed, increasing unnecessary the calculation time. Here, we propose to use a specific mesh for each physic. This allow for optimising very precisely the element size to the local need. The level set transport equation requires a fine mesh (50 µm) in all the elements (Figure 1a). But, the heat transfer requires a finer mesh only under the laser irradiation (80µm) and so bigger elements are used far from the laser area (200µm - Figure 1b). Finally, the fluid flow uses an intermediate mesh but two times bigger than the level set equation (80 to 120 µm - Figure 1c). In this way, the number of DOF (Degrees Of Freedom) drop from 2 100 000 to 400 000 leading to a substantial reduction of calculation times.

In Comsol Multyphisics, this adaptation is not direct. Each equation, with a geometry and a mesh becomes a model. So, projection/interpolation operators must be employed to project a solution to another to perform all the couplings. Indeed, by using different meshes, the nodes do not coincide (Figure 2) and if 2 nodes are not in the same spatial position, an interpolation between the nearest points must be done. Moreover, all the couplings (advection in heat transfer, Darcy condition in fluid flow…etc) need to be re-write through the interpolation operators (called Identity operators in Comsol). All the pre-written couplings in Comsol Multyphisics are no longer usable with this method. Then, a segregated solver is used to facilitate the convergence and the projection, interpolation method (Figure 2). It is important to note that every interpolation can introduce some errors especially from a fine mesh to a coarser mesh. The solution will be slightly degraded but in a satisfactory range compare to experimental data as reference.

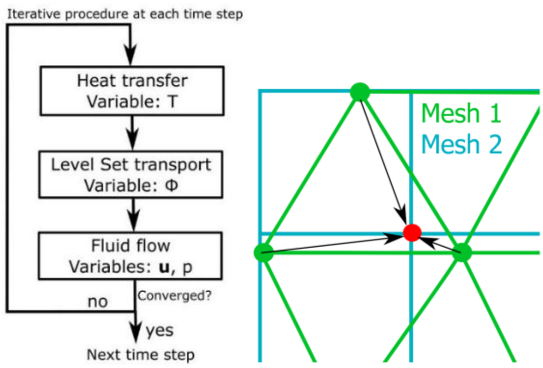

Figure 2. Iterative procedure principle allowing the use of three different meshes and the interpolation problem.

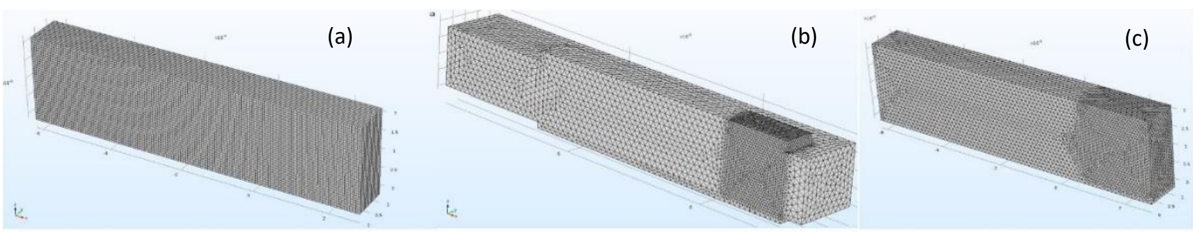

Figure 1. View of the 3 meshs used. (a) Level Set, (b) Heat transfer, (c) fluid flow

Results on laser welding

By combining the simplified formulation for the recoil pressure, the energy deposition, and especially the new meshing technic, calculations presented here are done in less than 1 day. Figure 3 presents the dynamic prediction of the keyhole creation (red) and the melt pool (yellow) growing for a 4 kW laser and a 6 m/min welding speed on a 1.8 mm DP600 sheet. A stabilization of the shape is reached at 200 ms. This configuration was fully validated with experimental data such as temperatures in solid and liquid and velocity at the melt pool surface, details of experimental data can be found in [5]. The model was used to study the keyhole depth, the maximum laser velocity possible for a full penetrating keyhole and to study fluid flow behavior around the keyhole.

Then, the same model was used for many other industrial configurations such as thickness of 3 mm, or the welding of different thicknesses. In all cases presented in figure 4, a comparison with a macrographic cut is done and shows a satisfactory agreement.

Even if the model is simplified and if the meshing method introduces some errors, the versatility of the model is proven. This model is interesting because it can predict the keyhole and melt pool behavior for many configurations using only the operating parameters as model inputs.

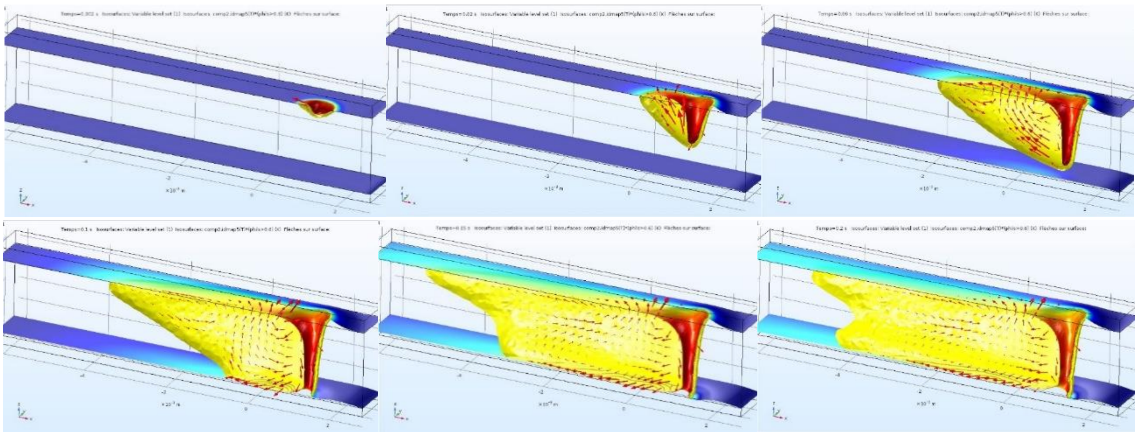

Figure 3. Keyhole and melt pool creation at 2, 20, 60,100, 150 and 200 ms.

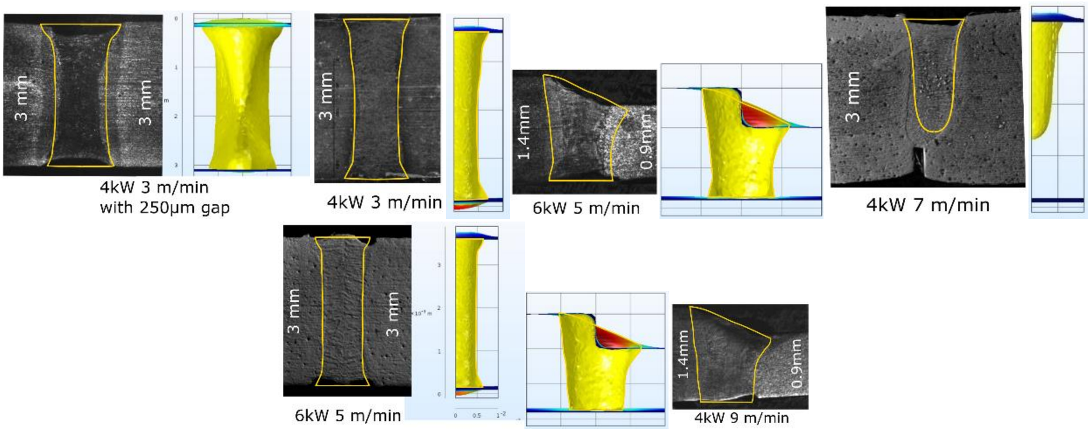

Figure 4. Comparison between model and experiment (PIMM Lab.) for 6 welding configurations.

Results on Gas Metal Arc Welding (GMAW)

The significant reduction of calculation time observed on laser welding allow to use this method on other welding processes. One of the most complicate process to model is probably the arc welding with a consumable electrode. Indeed, in addition of all the equations presented before, the electromagnetics equations (Maxwell equations) must be added (not presented in this paper). A high current is set between the electrode and the sheet, leading to the creation of an arc. Temperatures in the gas reach around 15 000 K maintaining the plasma and the melting of the feed wire. Every droplet created (CMT Cold Metal Transfer) will fall in the melt pool giving the weld seam after solidification. The very high complexity of the physical phenomena requires high computation resources, until today, despite advances in computer science.

By employing the method described above, we are able to describe completely the GMAW process in 8 days for approximatively 5 seconds of process, using 4 different meshes (electromagnetism, heat transfer, fluid flow, level set).

In this study, the CMT specific process is described with all the physics needed. The arc temperature and behavior, the droplet creation and transfer to the melt pool and the weld seam creation is dynamically predicted. All the main known phenomena are modelled like Marangoni effect, Lorentz forces in plasma and melt pool, shear stress of the gas… . To the authors knowledge, there is no equivalent model in the literature and these new developments will be detailed in a future paper.

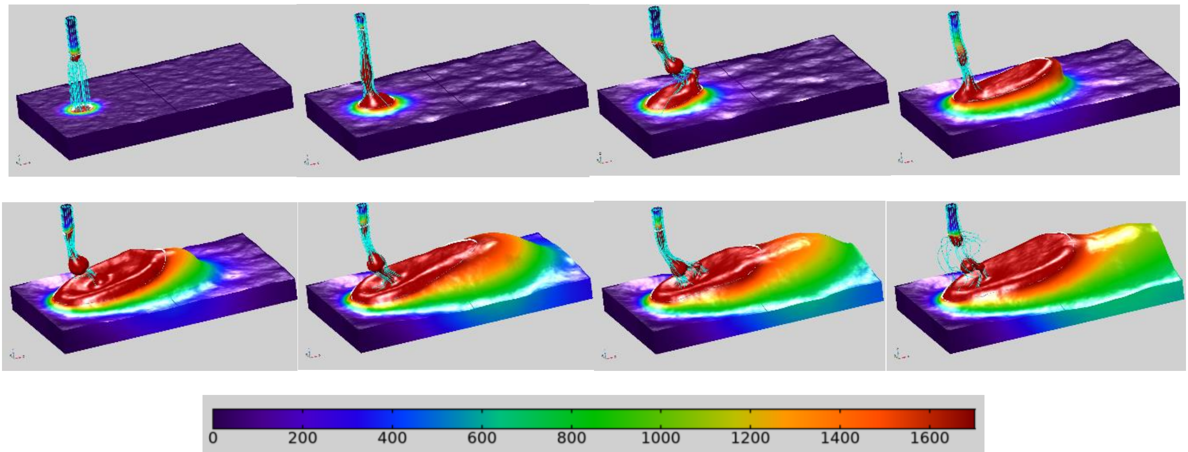

Figure 6. Global view of the material deposition at 0, 0.5, 1, 1.5, 2, 2.5, 3, and 4s. Temperature fields [K] and electrical current lines in blue.

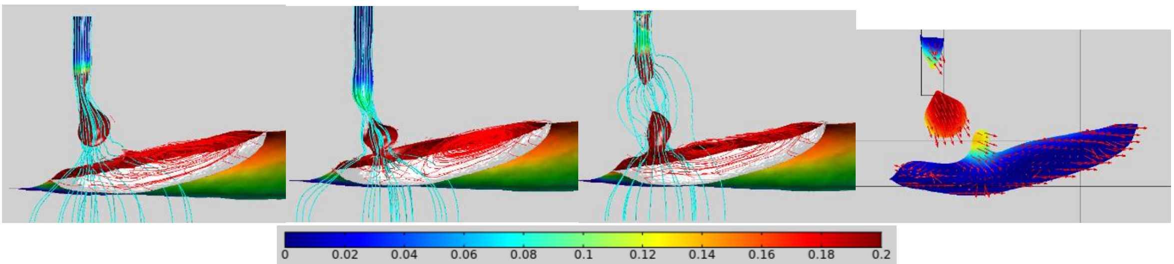

Figure 7. Mechanism of droplet creation and fall. Fluid flow streamlines in red, electrical current lines in blue, and velocity field

Conclusions

A new approach for meshing very multiphysics 3D problems like welding is proposed. The main principle is to use only the appropriate amount of elements for each physic and the size of the elements is no more driven by the most restrictive physics. This method requires the use of projection and interpolation operators available in Comsol Multiphysics reducing the accuracy but reducing also drastically the number of DOF. For example, this leads to calculation times below 1 day (vs. 1 month before) for laser welding. The model is now used to describe many operating conditions and can be easily used in an industrial environment.

Moreover, this method makes it possible to solve now more complex processes like GMA welding. In addition of heat transfer, fluid flow and level set method, all the electromagnetic problem is solved. The description of the arc behavior, the droplet generation and the melt pool is done in less than 3 weeks (before, it was not even possible for standard workstations).

This method with 3 or 4 meshes is now used on every heavy 3D model in our research group.

Acknowledgments

The authors wish to thank ArcelorMittal for the funding of a part of this study.

References

[1] H. Ki, P. Mohanty, J. Mazumder: 'Modeling of laser keyhole welding: Part I. Mathematical modeling, numerical methodology, role of recoil pressure; multiple reflections and free surface evolution', *Metall. Mater. Trans A* 33A 1817-1830, 2002.

[2] M. Geiger, K.H. Leitz, H. Koch, A. Otto: 'A 3D transient model of keyhole and melt pool dynamics in laser beam welding applied to the joining of zinc coated sheets', *Prod. Eng. Res. Devel.* 3 127-136, 2009.

[3] S. Pang, L. Chen, J. Zhou, Y. Yin, T. Chen: 'A three-dimensional sharp interface model for self-consistent keyhole and weld pool dynamics in deep penetration laser welding', *J. Phys. D : Appl. Phys.* 44 025301, 2011.

[4] W.I. Cho, S.J. Na, C. Thomy, F. Vollertsen: 'Numerical simulation of molten pool dynamics in high power disk laser welding', *J. Mater. Process. Technol*. 212 262-275, 2012.

[5] M. Courtois, M. Carin, P. Le Masson, S. Gaied, M. Balabane: Guidelines in the experimental validation of a 3D heat and fluid flow model of keyhole laser welding'. *J. Phys : D Appl. Phy* **49** 155503 (13pp), 2016.

[6] M. Courtois, M. Carin, P. Le Masson, S. Gaied, M. Balabane: 'A new approach to compute multi-reflections of laser beam in a keyhole for heat transfer and fluid flow modeling in laser welding'. *J. Phys : D Appl. Phy* **46** 505305 (14pp), 2013.