Formation of Porosities during Spot Laser Welding: Case of Tantalum Joining

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Abstract: During the welding of tantalum with a ND: YAG pulsed laser, a deep and narrow cavity, called the keyhole, is formed. At the end of the process, surface tension forces provoke the collapse of the keyhole. For important interface deformations, gas bubbles can be trapped into the melting pool. If the solidification time is insufficient, these bubbles give birth to residual porosities. The aim of the study is to predict the porosities diameters depending on the keyhole shape. The level set method has been first used to compute the dynamics of the interface position during the keyhole collapse. A comparison with the phase field method has then been performed for particular conditions.

Keywords: laser welding, porosities, level set, phase field, multiphase flow.

1. Introduction

Spot laser welding offers several advantages in industrial manufacturing. Indeed, localized temperature gradients induce weak workpieces distortions. Unfortunately, the operating parameters leading to defect-free welded joins are difficult to obtain. Consequently, unsafe welded joins are repeatedly encountered, polluted by micro or macro pores defects. The aim of the study is to predict the formation of such defects in the case of tantalum joining with a ND : YAG pulsed laser.

The formation of porosities depends on complex thermohydraulic phenomena. During the interaction, a melted zone is formed. When one reaches the vaporization point, the ejected vapor induces a pressure, called the recoil pressure, which inserts the liquid-gas interface as a piston: it tends to form a deep and narrow cavity called the “keyhole”. At the end of the interaction, surface tension forces provoke the keyhole collapse. For important interface deformations, gas bubbles can be trapped into the melting pool (figure 1). If the solidification time is insufficient, these bubbles give birth to residual porosities (ref [1], ref [2]).

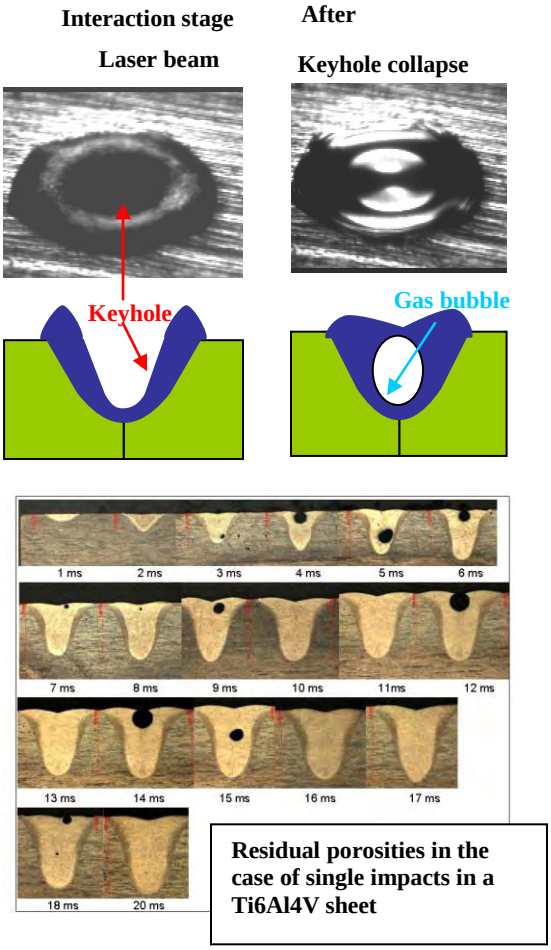

Figure 1: porosities formation mechanisms

As physical phenomena during the interaction stage strongly depend on the liquid-gas interface geometry, a predictive approach of the whole process appear quite complex. Indeed, the laser beam is trapped into the keyhole, and consequently, the rate of absorbed power evolutes at each moment (ref [3]). Moreover, the liquid-gas interface temperature determines the recoil pressure (ref [4] and [5]).

That's why, for our problem, we have focused our attention on the cooling stage. The mechanisms of keyhole collapse have been apprehended thanks to a hydraulic model. Following a parametric analysis, we are trying to find a depth limit, from which gas bubble are always trapped. The following model have been originally developed by K. Girard and J. Nadal (ref [6]) in the software FLUENT. Unfortunately many numerical problems have been encountered by the authors, especially induced by interface instabilities.

2. Physical model

2.1 Shape of the keyhole at the end of the interaction

As we only model the cooling stage, the geometry ok the keyhole at the end of the interaction must be determined.

First of all, the position of the fusion isotherm is deduced from a metallurgical analysis, as shown on figure 2. Moreover, the keyhole's ray, and the volume of metal accumulated at the surface, is measured according to visualizations of the melting pool with a high speed camera (figure 3). At last, K. Girad (ref [6]) proposes a good approximation of the liquid film dimension at the bottom of the keyhole (about 40 µm in our case).

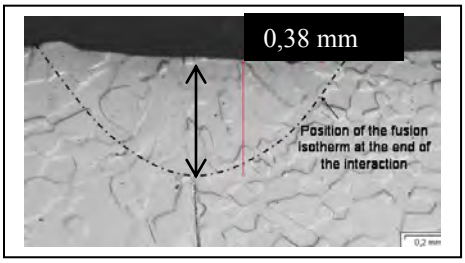

Figure 2: metallurgical analysis

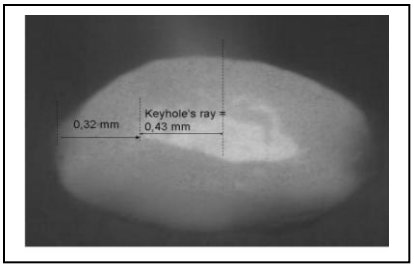

Figure 3: visualization of the keyhole

In the model, we admit that the shape of the keyhole is ½ elliptic and that the metal accumulated at the surface tends to form a tore. By writing that the volume of the ½ tore is equal to the ½ ellipse' one, we are able to deduce all the problem dimensions.

2.2 Materials properties

In the case of liquid tantalum, the density ρ is equal to 15630 kg/m^3 and the dynamic viscosity µ is equal to 8.032e^{-3} Pa·s. The surface tension coefficient is taken equal to 2.168 N.m^{-1}.

1.2 Hypothesis

The surface tension coefficient is supposed constant during the collapse stage. Characteristic dimensionless numbers calculation shows that:

- the flow is laminar;
- capillary effects are important compared to viscous ones:

$$Ca = \frac{\mu V}{ts} = 2.10^{-3}$$

- gravity effect can be neglected:

$$Bo = \frac{\rho g.L^2}{ts} = 8.10^{-4}$$

3. Governing Equations

The level set method has been first used to determine the evolution of the interface position. A comparison with the phase field method has then been performed for particular conditions.

The Level Set application mode is largely described in ref [7]. The method enables to find the fluid interface by tracing the isolevel of the level set function, Φ. The isocontour Φ =0.5 determines the position of the interface. The equation governing the transport of Φ is:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla \cdot \left(\varepsilon \nabla \phi - \phi(1-\phi) \frac{\nabla \phi}{|\nabla \phi|} \right)$$

where u (m/s) is the fluid velocity, and γ (m/s) and ε (m) are numerical stabilization parameters. The ε parameter determines the thickness of the layer around the interface where

Φ goes from zero to one. ε is generally taken equal to hc/2, where hc is the characteristic mesh size in the region passed by the interface.. Generally, a suitable value for γ is the maximum velocity magnitude occurring in the model.

In the Phase Field application mode (largely described in ref [7]), the two-phase flow dynamics is described by the Cahn-Hilliard equation. The method consists in tracking a diffuse interface separating the immiscible phases (region where the dimensionless phase field variable Φ goes from −1 to 1). The Cahn-Hilliard equation is solved in two times:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi$$

$$\psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1)\phi$$

where u is the fluid velocity (m/s), γ is the mobility (m3·s/kg), λ is the mixing energy density (N), and ε (m) is the interface thickness parameter. The mixing energy density and the interface thickness are related to the surface tension coefficient through the relation (réf 8):

$$\sigma = \frac{2\sqrt{2}}{3}\frac{\lambda}{\varepsilon}$$

ε is usually set to half the characteristic mesh size in the region passed by the interface. The mobility parameter γ determines the time scale of the Cahn-Hilliard diffusion and is generally taken equal to ε^2.

In both the two methods, the transport of mass and momentum is governed by the incompressible Navier-Stokes equations, including surface tension:

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \nabla \cdot \eta(\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \rho \mathbf{g} + \mathbf{F}_{st}$$

In the above equations, ρ (kg/m3) denotes the density, u the velocity (m/s), t the time (s), p the pressure (Pa), and η denotes the dynamic viscosity (Pa·s). The momentum equations contain gravity, ρg, and surface tension force components, denoted by Fst. But, in our case, gravity is neglected.

The surface tension force is implemented differently in the Level Set and Phase Field application modes (ref [7]). The Level Set application mode computes the surface tension as:

$$\mathbf{F}_{st} = \nabla \cdot \mathbf{T} = \nabla \cdot [\sigma\{\mathbf{I} + (-\mathbf{n}\mathbf{n}^T)\}\delta]$$

where ζ is the surface tension coefficient, I is the identity matrix, n is the interface unit normal, and δ is a Dirac function, nonzero only at the fluid interface. The interface normal is calculated from:

$$\mathbf{n} = \frac{\nabla \phi}{|\nabla \phi|}$$

The level set parameter Φ is also used to approximate the delta function by a smooth function defined by:

$$\delta = 6|\phi(1-\phi)||\nabla \phi|$$

In the Phase Field application mode, the diffuse interface representation implies that it is possible to compute the surface tension by:

$$\mathbf{F}_{st} = G \nabla \phi$$

where Φ is the phase field parameter, and G is the chemical potential (J/m3):

$$G = \lambda\left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\varepsilon^2}\right] = \frac{\lambda}{\varepsilon^2}\psi$$

4. Numerical Model

4.1. Initial state

The initial state is deduced from observations and hypothesis made in paragraph 2.1. The initial interface geometry is described in figure 4.

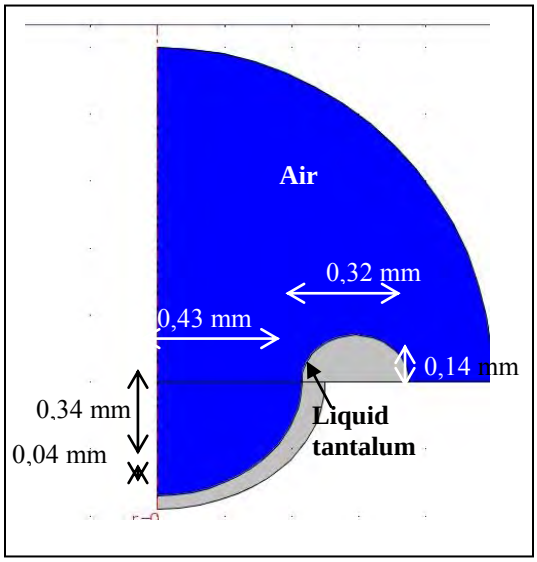

Figure 4: initial state

4.1. Boundary settings:

The boundary conditions are presented on figure 5.

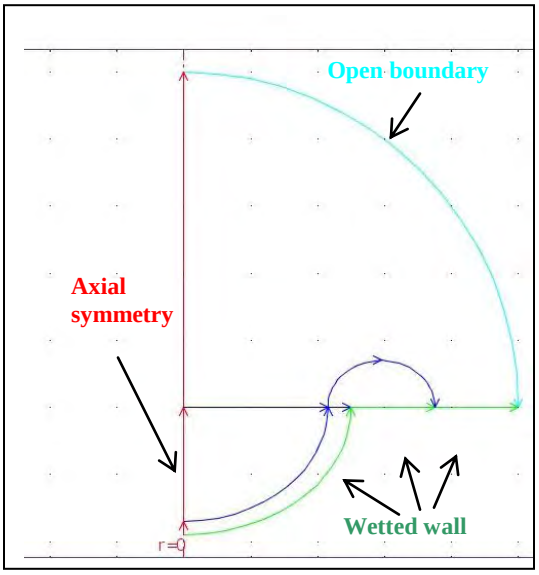

Figure 5: boundary settings

For the level set method, the wetting phenomena are determined by the contact angle and the slip length. The velocity component normal to the wall is set to zero:

$$\mathbf{u} \cdot \mathbf{n}_{wall} = 0$$

One adds a frictional boundary force:

$$\mathbf{F}_{fr} = -\frac{\eta}{\beta}\mathbf{u}$$

β is called the slip length. The angle between the wall and the fluid interface, called the contact angle θ, is supposed constant equal to pi/2. By default, the slip length is equal to the mesh element size, h. We will see thereafter the consequences of this dependence.

For the comparison between the level set and the phase field method, the condition "wetted wall" has been replaced by a "slip wall" condition.

4.2. Meshing

The mesh must be homogenous along the liquid – gas interface in order to initialize correctly the problem. In order to analyse the model spatial convergence, the mesh size has been progressively reduced. When the mesh is consequently refined, the air domain size must be extended to obtain a converged solution.

4.4 Choice of level set parameters

In the present model, the mesh size is inferior to 1e-5. Consequently, the value of ε has been fixed to $5e^{-6}$ and γ is equal to 1. Indeed, thanks to experimental measure, the velocity of the fluid doesn't exceed 1 $m.s^{-1}$.

4.3. Transient initialization:

Before starting the fluid flow calculation, the level set function must be initialized. The initialization time is fixed to 5ε/γ.

5. Results and discussion

Firstly, the numerical behaviour of the model has been tested for a high dynamic viscosity (8 Pa.s). This allows a better model convergence. Some results are presented on the figure 6.

The filling of the keyhole can be divided into two stages: a "detachment stage", illustrated on figure 6.c, and a "filling stage", illustrated on figure 6.d.

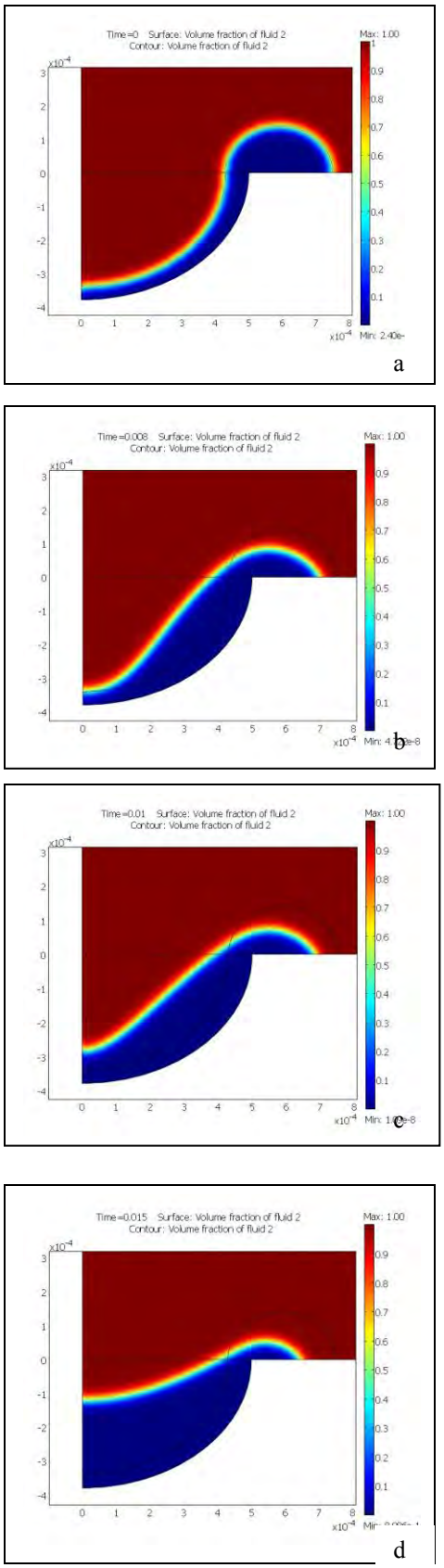

Figure 6: numerical results: keyhole collapse

The results are stable while reducing the mesh size from $1.3.10^{-5}$ to $3.1.10^{-6}$. Nevertheless, the detachment stage length increases while refining the mesh (board 1). It can be explained by the dependence between the mesh size and the slip length. Consequently, the slip length will have to be determined by comparison with experimental data (figure 7).

Minimum mesh size	detachment stage duration	Filling stage duration
1.3e-5	5	10
6.4e-6	6	11
3.1e-6	7	13

Board 1: spatial convergence

Thanks to a parametric analysis, it is confirmed that the gravity has no influence. The flow is laminar, with a maximum velocity of 0.5 $m.s^{-1}$. It asserts the good choice of $\gamma = 1$.

The complete filling time, about 20 ms, is longer than expected. Indeed, a high speed camera film shows that the keyhole collapse doesn't exceed 1 ms (figure 7). This can be explained by the non physical value of the fluid viscosity.

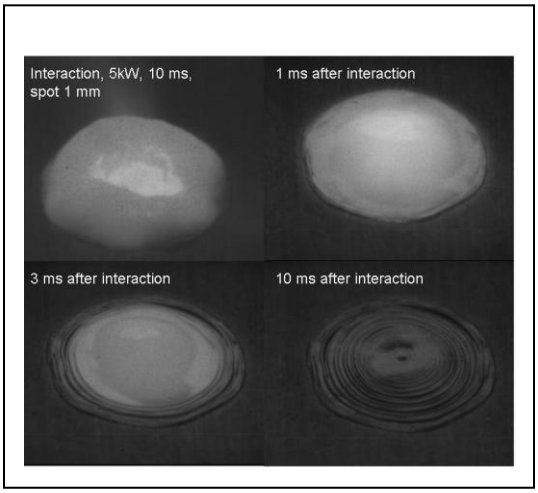

Figure 7: experimental results: keyhole collapse

A computation has then been performed with the phase field method. Neglecting the wetting phenomena, it confirms the interface shape

obtained by the level set application mode. The sliding condition between the solid and the fluid induces a collapse time of 8 ms in the two cases.

Considering the real viscosity of the fluid ($8.032e^{-3}$ $Pa.s^{-1}$) makes the model convergence difficult to obtain. Indeed the liquid film undergoes a thinning (figure 8) and the mesh size must be consequently reduced to allow the convergence. The results are stable while refining the mesh. Nevertheless, the interface shape does not seem physically correct, and this part of the study will have to be reconsidered.

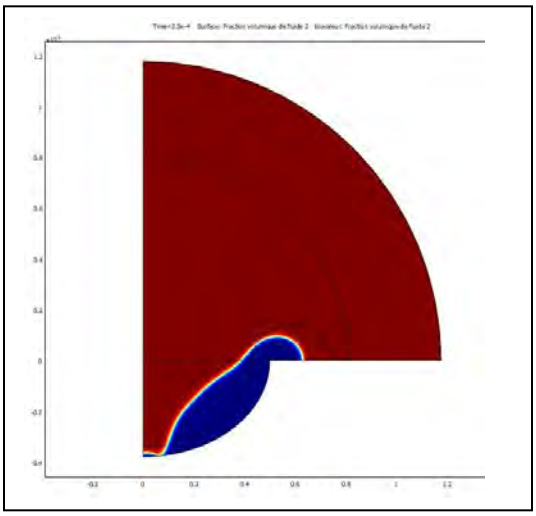

Figure 8: interface shape with the real viscosity

6. Conclusions

In order to predict the risk of porosities formation during tantalum welding, a model has been developed to simulate the keyhole collapse. Two Eulerian methods have been used and compared: the Level set and Phase Field methods.

If the interface shape seems to be physically correct for a high fluid viscosity, the liquid film undergoes a thinning when considering the real tantalum viscosity (8.032e-3 $Pa.s^{-1}$). This phenomenon has to be studied, especially by comparing different numerical methods.

In order to evaluate the diameter of the pores that may affect our welded joints, we are currently working on a second model to simulate the bubbles up rise simultaneously with the solidification front progress (thermo-hydraulic approach).

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