Formation of porosities during spot laser welding of tantalum

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1. Introduction

Nowadays, spot laser welding is a full-fledged part of industrial manufacturing and is routinely used due to its advantage. It generates very located temperature gradients, and therefore, induces small distortions in the pieces. Unfortunately, operating parameters leading to defect-free welded joins are difficult to obtain. That can explain that unsafe welded joins are repeatedly created, polluted by micro or macro pores defects. The aim of this 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 thermo-hydraulic 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 pushes 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]).

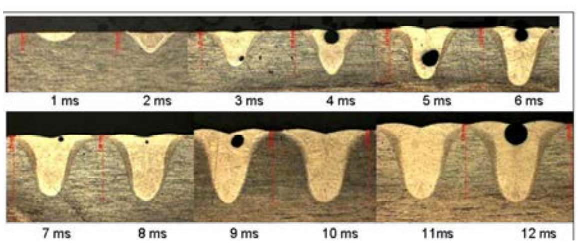

Figure 1: residual porosities for several interaction times

Physical phenomena which occur during the interaction stage strongly depend on the liquid-gas interface geometry. Therefore, a predictive approach of the whole process appears to be 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]).

For this reason, we first focus our attention on the cooling stage. The mechanisms of the keyhole collapse have been apprehended thanks to a hydraulic model, which has been presented at the COMSOL European conference in 2010.

The purpose of the present study is to model the rising bubble in the melting pool, in the case of tantalum joining. Indeed, porosities are often encountered in this material (figure 2). The problem is especially complex due to the high surface tension of the liquid tantalum (2.1 N.m-1 at the fusion temperature).

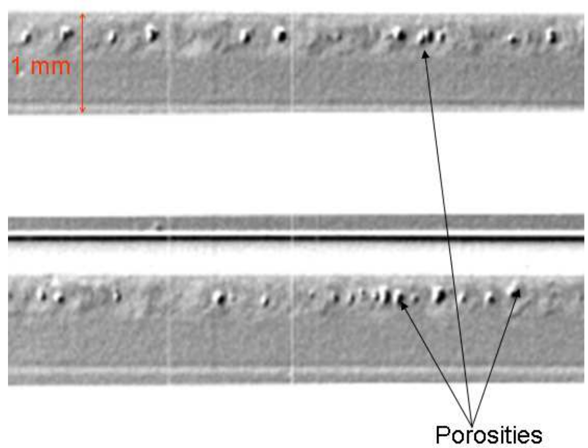

Figure 2: Detection of porosities by radiography in a tantalum welding join

2. Governing Equations

The rise of the bubble is computed thanks to an hydraulic model.

The level set method and the phase field one give the same results for low surface tension of the liquid metal (less than 0.5 N.m-1).

Unfortunately, for high surface tension coefficient, the model convergence is difficult to obtain with the Level Set method.

The Phase Field method (largely described in ref [6]), leads to an easier convergence of the problem. In this case, 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). Due to the 4^{th} order derivative in the Cahn-Hilliard equation, COMSOL solves it solving two 2^{nd} order equations:

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

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

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 related to the interface thickness (interface thickness = 3ε√2). The mixing energy density and the interface thickness are related to the surface tension coefficient through the relation (ref 8):

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

The variable χ is linked with the mobility γ and with ε by the relation χ=γ/ε2.

The choice of the phase field parameters (ε and χ) is essential to ensure the convergence and the accuracy of the model.

The transport of mass and momentum is governed by the incompressible Navier-Stokes equation, including surface tension and gravity:

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

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

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 the dynamic viscosity (Pa·s). The momentum equations contains gravity, ρg, and surface tension force components, denoted by Fst.

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):

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

3. Numerical Model

Geometry

In the model, we admit that the shape of the keyhole at the end of the interaction is ½ elliptic.

The penetration depth is taken equal to 1 mm. The gas bubble is situated at the middle of the welding pool. Its diameter is 0.3 mm.

Initial condition

The bubble and the upper part of the domain are constituted by argon, gas used to protect our welds against oxidation.

Material and properties

Concerning the liquid tantalum, the density ρ is equal to 15630 kg/m3 and the dynamic viscosity μ is equal to 8.032e-3 Pa·s.

The density of argon is equal to 0.07 kg/m3 and its dynamic viscosity μ is equal to 16.8e-3 Pa·s. The surface tension coefficient between argon and liquid tantalum is considered equal to 2.168 N.m-1 (ref (6]).

In this simulation, all the materials properties are assumed to be constant. In this first approach, no thermal considerations are taken into account.

4.2. Meshing and boundary settings

The mesh must be homogenous along the liquid – gas interface in order to initialize correctly the problem.

There is a strong dependence between the maximum element size in the region crossed by the interface (h) and the phase field parameters (ε and χ). We will discuss this point in the paragraph 4.

The boundary conditions are presented in the figure 3.

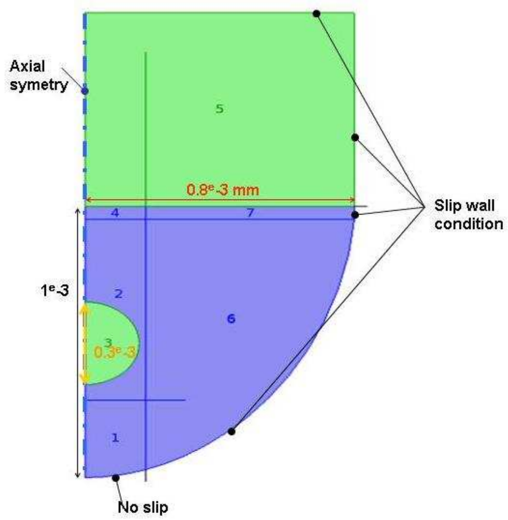

Figure 3: boundary settings

4. Results and discussion

For inadequate parameter sets (ε, χ, h), an excessive diffusion of the bubble can be observed, leading to a “numerical dissolution” of the bubble before reaching the welding pool surface.

The monitoring of conservation of the gas bubble mass constitutes a good indicator of the accuracy of the simulation.

In order to choose the phase field parameters, we propose the following approach.

1/ The surface tension coefficient is assumed to be the real one (no parametric study on this parameter)

2/ The couple (h, ε) must be chosen so that:

- The maximum element size in the region crossed by the interface is relatively small (for instance 2e-6 m for a surface tension coefficient equal to 2.1 N.m-1)
- There are enough elements in the interface thickness, which is equal to $3\varepsilon\sqrt{2}$.

3/ The parameter χ must be as small as possible to avoid an excessive diffusion around the interface. Nevertheless, a high enough value of χ must be used to obtain the numerical convergence.

In case of convergence failure, the maximum element size in the region crossed by the interface should be reduced.

The principal tests performed in order to determine possible couples of parameters (ε, χ, h) are summarized in the table 1.

ε	χ	Maximum element size in the region crossed by the interface (µm)	Mass losses of the bubble	Convergence
1	0.5	3		No
1	0.01	3		No
0.75	1	3	Total (too much diffusion)	
0.75	1	1	Total (too much diffusion)	
0.75	0.5	3	31.5%	
0.75	0.2	3		No
0.75	**0.05**	**2**	**6.35%**	**OK**
0.75	**0.01**	**2**	**3.5%**	**OK**

Table 1: Determination of phase field parameters

This parametric study shows that:

1/ Numerical convergence is difficult to obtain for values of ε superior to 0.75e-5.

2/ For value of χ higher than 0.05, the bubble diffusion is excessive.

3/ At least eight elements in the interface thickness are necessary to obtain a converged solution.

The mesh statistics are presented in the table 2 for phase field parameters ε=0.75e-5 and χ=0.05,.

Numbers of elements	149260
Element type	Triangular elements T3
Minimum element quality	0.8262
Average element quality	0.9905
Maximum element size in the region crossed by the interface (m)	h=2e-6
Maximum element size in other regions (m)	1e-5

Table 2: Mesh statistics

For a converged solution, the bubble rises due to the influence of gravitational forces. The bubble ascent can be divided into several stages, illustrated on figure 4.

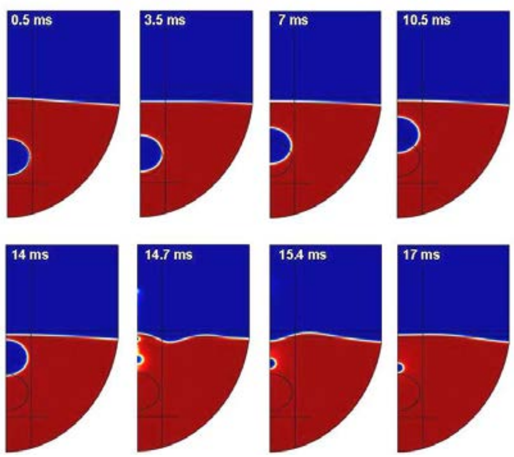

Figure 4: stages of a bubble ascent

The time to rise up is inferior to 14.7 ms.

As the bubble reaches the surface of the welding pool, the liquid-gas interface collapses. Consequently, a small gas bubble is trapped into the liquid phase. This one is trained into the melting pool because of the global velocity field.

Then, the gas-liquid interface undergoes oscillations caused by surface tension forces.

5. Conclusion

This paper presents the numerical model we have developed to study the behavior of a gas bubble trapped into a liquid tantalum pool. The numerical model is focused on an hydraulic dynamics, involving the phase field method.

The numerical results obtained with COMSOL seem to be physically realistic. In the near future, we intend to combine the present model with the solidification front progress, to evaluate the risks of generating pore defects into the welding joins.

6. References

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