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Comparison of two hot tearing criteria in numerical modelling of arc welding of stainless steel AISI 321

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ABSTRACT

Two hot cracking criteria have been tested: the RDG criterion, based on the prediction of liquid cavitation as a precursor of crack formation, and a strain-based solid mechanics criterion. Both criteria have been implemented in a finite element thermo-mechanical simulation of gas tungsten arc welding. After comparison with experimental results obtained in a test campaign on stainless steel AISI 321, both criteria have shown good ability to predict crack occurrence. Yet, the best response in terms of cracking prediction was obtained with the strain-based solid mechanics criterion.

1. Introduction

Hot cracking is a common defect occurring during solidification and welding of metallic alloys. In industrial welding practice, a lot of prototype tests are realized to define operating parameters (welding heat input, chemical composition) in order to avoid hot cracking. Such tests are expansive and time consuming. In addition, as they do not cover all real industrial welding configurations, they do not guarantee absence of cracking. Alternatively, it might be expected that the progress in the numerical modelling of welding processes could be used in hot cracking sensitivity prediction. The aim of this contribution is to study the capacity of two hot cracking criteria to predict such a defect. In a first section, we will proceed to a brief reminder of what is hot cracking and what are the main physical phenomena involved. The two main classes of hot cracking criteria that can be found in the literature will be introduced. In a second part, the main equations governing the thermomechanical analysis of welding will be presented. A third section will present the experimental results obtained by GTA (gas tungsten arc) welding on rectangular plates of stainless steel AISI 321. The numerical thermal analysis of those tests will be discussed in a fourth section, showing the accurate calibration of the thermal model with respect to experimental records. Then, the thermomechanical analysis will be presented and finally the response of the two types of hot cracking criteria will be analyzed and discussed.

1.1. Hot cracking and prediction criteria

Hot cracking (also named hot tearing or solidification cracking) is a well-known welding defect occurring at the end of solidification. Readers can refer to Campbell (2003) which gave a comprehensive and synthetic description of this defect in his book on castings. During solidification, low melting point liquid exists between dendrites. At the end of solidification (high solid fraction) the stresses initiated by solidification shrinkage or by thermal gradients in the surrounding solid may be sufficient to open interdendritic spaces not yet completely solidified and create intergranular cracks that liquid feeding cannot fill. Among many authors, Eskin and Katgerman (2007) studied and established a comprehensive review of the different physical phenomena leading to this defect. Alloys are considered the most vulnerable in the so-called Brittleness Temperature Range (BTR). This temperature interval – the name of which expresses that hot cracking may be seen as a ductility loss – is between the coherency and the coalescence temperature. The coherency temperature can be defined

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when dendrites begin to transmit forces but with low rigidity. Above coherency temperature, any deformation or displacement of solid dendrites can be easily compensated by the circulating liquid phase. The coalescence temperature is reached when dendrites are strong enough to accommodate strain, while numerous solid bridges limit the risk of crack propagation. In between these characteristic temperatures – or equivalently characteristic solid fractions – that is when liquid cannot flow any more through interdendritic spaces, the mushy zone is susceptible to hot cracking. Farup et al. (2001) provided spectacular evidences of the combination of phenomena leading to hot cracking: liquid cavitation, lack of liquid feeding, and plastic deformation of solid bridges.

From the previous considerations, it can be deduced that a given alloy will be more or less prone to solidification cracking depending on its thermophysical and rheological properties and on local specific solidification conditions determining for instance dendritic spacing and, as a consequence, mushy zone permeability. In addition, Cross and Coniglio (2008) showed like other researchers the existence of a critical strain, below which no solidification crack occurs, and the influence of strain-rate. Regarding the prediction of hot cracking, models can be grouped into two great families that are presented in the next two sections.

1.2. Liquid cavitation approach: RDG criterion

The so-called RDG criterion (so-called from the initials of their authors) was proposed by Rappaz et al. (1999). The authors considered the mass balance between solidification shrinkage and liquid feeding through the permeable solid dendritic network. Hot tearing was supposed to occur due to a deficit of liquid feeding through the mushy zone, leading to cavitation in the interdendritic liquid, and then to crack initiation. Assuming a thermal gradient oriented along x direction, also the direction of columnar dendritic growth, the mass balance equation was approached as

$$\left(1+\beta\right)\left(\dot{\varepsilon}_{yy}+\dot{\varepsilon}_{zz}\right)f_s+\beta\frac{\partial f_s}{\partial t}=\frac{\partial}{\partial x}\left(\frac{K}{\mu}\left(\frac{\partial p}{\partial x}-\rho_l g_x\right)\right) \tag{1}$$

where $\beta=\frac{\rho_s}{\rho_l}-1$ is the solidification shrinkage coefficient, f_s is the solid fraction, ε_{yy} and ε_{zz} are solid strain rate components perpendicular to the growth direction. The two terms summed in the left hand side of Eq. (1) are associated with the mechanical deformation and the solidification shrinkage, respectively. The deformation parallel to the dendrites was ignored, as it could not induce hot tearing, and the densities of the two phases, liquid and solid, were assumed constant. The right hand side term expresses the liquid feeding governed by Darcy law, where K is the permeability, μ the liquid viscosity and p the liquid pressure.

The permeability K may be expressed by the Carman–Kozeny equation:

$$K={\lambda_2}^2\frac{(1-f_s)^3}{180{f_s}^2} \tag{2}$$

in which λ_2 denotes the secondary dendrite arm spacing (SDAS). This value is often determined experimentally by metallurgical expertise. It increases with solidification time (the time spent in the solidification interval) by dendrites maturing. This phenomenon, which is due to the diffusion of atoms from high to low curvature zones in order to minimize the chemical potential, decreases the number of secondary branches and thus increases the interdendritic space. This explains why the distance between dendrites depends strongly on the cooling rate. The SDAS can be estimated by power law type expressions as a function of the solidification time t_f, such as introduced by Kurz and Fisher (1986) :

$$\lambda_2=M{t_f}^{1/3} \tag{3}$$

where M is a material constant.

Rappaz et al. (1999) proceeded to the integration of the mass balance equation along the length of the mushy zone, which lead to a relationship between the tensile strain rate ε applied perpendicular to the solidification direction on one hand, and the liquid pressure drop through the mushy zone $\Delta p=p_m-p$ on the other hand, p_m denoting the metallostatic pressure in the liquid pool, at dendrite tips. The liquid pressure p continuously decreases in the mushy zone, from the tips to the roots of primary columnar dendrites. Close to dendrite roots, that is below the coalescence temperature, near the full solid region, the liquid pressure may reach the cavitation pressure. The comparison of this pressure drop to its critical value $\Delta p_{crit}=p_m-p_C$, where p_C is the cavitation pressure, leads to a critical strain rate ε. According to Rappaz et al., hot cracking was then supposed to initiate when:

$$\dot{\varepsilon}>\frac{G}{B}\left[\frac{G\lambda_2^2}{180\mu\left(1+\beta\right)}\Delta p_{crit}-v_T\frac{\beta}{\left(1+\beta\right)}A\right] \tag{4}$$

where G is the norm of the temperature gradient in the mushy zone, v_T is the speed of the solidification front, A and B are integrals that depend on the solidification path of the alloy, the bounds of the integrals hereunder being the bounds of the BTR, upper bound T_{coh}, lower bound T_{coal}:

$$A=\int_{T_{coal}}^{T_{coh}}\frac{f_s^2}{(1-f_s)^2}dT \qquad B=\int_{T_{coal}}^{T_{coh}}\frac{f_s^2}{(1-f_s)^3}\left(\int_{T_{coal}}^{T}f_s dT\right)dT \tag{5}$$

In the context of welding, note that the metallostatic pressure can be neglected, so that $\Delta p_{crit}=-p_C$. It can be seen that using this model, the critical strain rate can be determined by thermal analysis. A central parameter for the application of the RDG criterion is the liquid cavitation pressure, corresponding to the critical cavity size leading to hot cracking.

1.3. Mechanical approach: strain-based criteria

In mechanical criteria, the physical phenomena associated with cracking are not explicitly described. Such models are based on a mechanical load limit, which is generally expressed in terms of a critical strain cumulated through the BTR. Below this limit, welding is assumed to be free from hot cracking. In practice, the Hot Cracking susceptibility Index (HCI) is often considered and is expressed as the difference between the cumulated strain $\bar{\varepsilon}_{BTR}$ in the brittle temperature range and a reference value ε_{crit}. Yamanaka et al. (1990) was the first one to express such a simple mechanical criterion:

$$HCI=\bar{\varepsilon}_{BTR}-\varepsilon_{crit} \quad \text{with} \quad \bar{\varepsilon}_{BTR}=\int_{BTR}\dot{\bar{\varepsilon}}dt \tag{6}$$

Hence, positive values of HCI indicate hot cracking risk. In the summation, $\dot{\bar{\varepsilon}}$ denotes a scalar measure of the strain rate components in the direction perpendicular to the thermal gradient. Generally, compressive strain rate components are not taken into account because they do not have significant effect on hot cracking. This is why Bellet et al. (2009) proposed two different expressions for this measure (von Mises type or largest positive eigen value). Note that these remarks also apply to Eq. (4) when using the RDG criterion.

It can be seen from Eq. (6) that, using this simple approach, the associated criterion has only three parameters which are on one hand the upper and lower limits of the BTR, expressed in terms of temperature or corresponding solid fraction, and on the other hand the strain limit ε_{crit}.