COMPUTATIONAL WELD MECHANICS OF HOT CRACK NUCLEATION IN NICKEL-BASED WELDS

Ahmed Nasser[1], Mahyar Asadi[2], John Goldak[3] and Abd El Halim O. Abd El Halim[4]

[1]Mechanical and Aerospace Engineering Department, Carleton University; 3135 Mackenzie, 1125 Colonel By Dr, Ottawa, ON, Canada, K1S 5B6, ahmed_nasser@carleton.ca
[2]Mechanical Engineering Department, The University of Ottawa; 161 Louis Pasteur Ottawa, ON, Canada, K1N 6N5, masadi@uottawa.ca (Corresponding Author)
[3]Mechanical and Aerospace Engineering Department, Carleton University; 3135 Mackenzie, 1125 Colonel By Dr, Ottawa, ON, Canada, K1S 5B6, jgoldak@mrco2.carleton.ca
[4]Civil and Environmental Engineering Department, Carleton University; 3432 Mackenzie, 1125 Colonel By Dr, Ottawa, ON, Canada, K1S 5B6, a_halim@carleton.ca

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Abstract

Computational weld mechanics (CWM) is used to estimate the likelihood of hot crack nucleation in a weld joint. A hot crack nucleates when the evolution of the local state of stress, strain, temperature and microstructure in the hot cracking temperature region reaches a critical value. The local evolution of state is determined by a high-resolution 3D transient CWM analysis and compared to experimental data characterizing the material resistance for each type of hot cracking. This paper evaluates the susceptibility to ductility dip cracking (DDC) and solidification cracking, separately, for single bead-on-plate welds of nickel-based alloys (FM82 and Inconel 600). An algorithm determines the hot cracking risk based on the temperature, temperature profile, strain increment, and rate of strain in the hot cracking temperature region. The critical values are obtained from the existing experimental data. The objective is to demonstrate that CWM can be used in the design stage to choose weld parameters, such as weld speed, to reduce the risk of hot cracking for a given material, weld joint and weld structure.

Hot Cracking Driving Force

The purpose of this paper is to demonstrate particulars of estimating the risk of hot cracking using CWM analyses. Comparing computed data for strain and temperature to critical values that were experimentally obtained is the basis of the technique. The ability to predict the risk of hot crack nucleation in a welded structure at an early design stage of a project's life cycle provides an opportunity to improve reliability and risk management.

In this paper the risk of hot cracking is estimated using a mechanical approach. Prokohrov [1] was one of the pioneers who used a mechanical approach by quantifying the amount of strain that causes hot cracking. The concept of a mechanical approach was greatly advanced by the work of Chihoski [2], who showed that varying welding parameters could change the deformation near the weld pool and consequently the risk of hot cracking. In addition, Matsuda et al. [3] were able to experimentally measure the localized evolution of strain in a mixed solid-liquid region by pioneering the Measurement by Means of *In-Situ* Observation (MISO) technique.

DDC and solidification cracking shall be the focus of this research. DDC occurs in a solid phase. The cause of the drop in material resistance to DDC nucleation at the ductility dip temperature range (DTR) has been explained by an accumulation of voids, element segregation to grain boundaries, grain size, grain boundary orientation or a combination of these factors [4]. In contrast, solidification cracking occurs in a mixed solid-liquid region at the brittleness temperature range (BTR). Dendrites growing into a liquid phase are covered by a liquid film due to segregation. The liquid film is the cause of the drop in material resistance [5].

CWM Analysis Method

The risk of hot crack nucleation is estimated by comparing the computed values for localized strain rates and temperature to the experimentally obtained data that characterizes the material resistance to hot cracking. In this research, results for localized strain and temperature observed during welding are computed using 3D transient macroscopic thermal and mechanical CWM analyses. These analyses assume that the material is homogeneous. The CWM analyses are capable of determining regions at risk of hot crack nucleation.

CWM simulation tests for DDC and solidification cracking during bead on plate welds of Ni-based alloys are conducted. The CWM simulation tests for DDC and solidification cracking are entirely separate. Ni-based alloys are likely to maintain the same crystal structure thereby reducing the need for the simulation of the microstructure evolution [6]. In both hot cracking tests free body motion is restrained.

The solidification cracking test was based on the experimental procedure developed by Matsuda et al. [3]. The solidification cracking test was on an Inconel 600 plate measuring 300×50×2 mm. The welding speed was 2 mm/s. This test relied on a cross-head speed (CHS) applied from the instant of time the heat source reaches mid-point of the weld path, for a maximum duration of 3 s. Different CHS of 20, 2, 0.2 and 0.1 mm/s were used.

Meanwhile, the DDC test was based on the CWM simulation conducted by Chen and Lu [7]. In the DDC test a Filler Metal 82 (FM82) plate measuring 100×100×2 mm was used. Welding speeds of 2 and 5 mm/s were used. Power input and the dimensions of the heat source model were altered to maintain the approximate size of the weld pool and the maximum temperature.

The CWM technique to estimate the risk of hot cracking was enhanced by the use of:

1. principal plastic strains at Gauss points;
2. the global post-processor for hot cracking;
3. and an equation relating constant temperature tension tests to welding;
4. the sub-model feature.

Principal Plastic Strains at Gauss Points

Hot cracks are usually caused by the maximum tensile strain component [8]. The principal strains determine the maximum tensile component of strain. A tensile strain is needed to cause crack nucleation, i.e, separate the crack edges. A compressive strain would push the crack faces together.

The direction of the principal strain is subject to change at each time step. However during the cooling phase in welding the direction of strain usually remains in the same general direction.

The risk of hot crack nucleation is determined using the plastic component of strain because it measures the irreversible damage that leads to crack nucleation [8]. The high temperatures experienced during welding result in a significant drop in yield strength. As a result the plastic component of strain is significantly larger than the elastic one [1].

The results that are used in the analyses conducted are obtained from the Gauss points in the domain. This provides the computed results directly rather than interpolating results to nodes.

Global Post-Processor

A post processor was used to assess risk of solidification cracking for every Gauss point in the domain. This post processor determines the risk of solidification cracking at each Gauss point based on the following criteria:

1. the temperature is within a specified BTR;
2. the temperature has a cooling thermal profile;
3. the tensile strain increment in the BTR region is greater than a critical value.

Relating Constant-Temperature Tension Tests to Welding

Constant temperature tests, such as hot tensile tests, do not represent the thermal cycle experienced during welding. An equation was devised in order to utilize measurements that characterizes the material resistance to hot cracking obtained using hot tensile test. This conjectured equation is based in concept on Miner's rule. The purpose of this equation/method is to map the evolution of state in a set of hot temperature tensile tests to the evolution of state at any point in a weld. This method quantifies the amount of damage at a material point caused by a tensile plastic strain increment within the temperature range at which the material is susceptible to hot cracking.

The use of this equation is based on the idea that a critical amount of damage must be accumulated for a crack to nucleate [9]. A damage parameter for any point (x,y,z) in a weld joint is computed at each of n time intervals or time steps within the duration of the weld thermal cycle. The sum of the damage parameter increments over time steps determines the accumulated damage, which is assumed to be a measure of the risk of hot crack nucleation. The value of the damage parameter is evaluated by normalizing the principal plastic strain increment within each temperature interval with the experimentally measured material resistance. This is expressed as Equation 1 for n time steps.

$$\sum_{i=1}^{n} \frac{\Delta\epsilon_f(T(\Delta t_i))}{\epsilon_f(T(\Delta t_i))} = \sum_{i=1}^{n} f_i(\Delta t_i) \tag{1}$$

where $\epsilon_f(T(\Delta t_i))$ is the experimentally measured strain to DDC nucleation in hot tensile tests, at temperature $T(\Delta t_i)$ and $\Delta\epsilon_f(T(\Delta t_i))$ is the increment in the computed principal strain in a given time interval, $\Delta t_i = t_{i+1} - t_i$, with an average temperature, $T(\Delta t_i) = (T(t_{i+1}) + T(t_i))/2$.

The condition for hot crack nucleation is shown in Equation 2 below. It is conjectured that a hot crack nucleates when the sum of the damage parameter increments, f_i, reaches 1.0. The actual value of the damage parameter at which a hot crack will nucleate must be determined experimentally.

$$\sum_{i=1}^{n} f_i(\Delta t_i) \geq 1.0 \tag{2}$$

During the welding process the increment in the principal tensile strain can be either positive or negative. The potential different effects the compressive (negative) strain increment might have on the damage parameter can be considered as follows:

1. a negative strain increment causes as much damage as a positive strain increment, thus the absolute value of the strain increment is used;
2. a negative strain is irrelevant to the damage, therefore a negative damage increment is set to zero;
3. a negative strain reduces damage or, in other other words, heals, therefore the negative sign is kept;
4. or some weighting factor can be assigned to the above options.

As an example of the evolution of the computed temperature and increment in the maximum tensile component of principal plastic strain with respect to time, the results at a Gauss point 5 mm from the weld center is shown in Figure 1. The sum of the damage parameter at a Gauss point 5 mm from the weld center and the possible effects of compressive strain are shown in Figure 1.

Sub-model

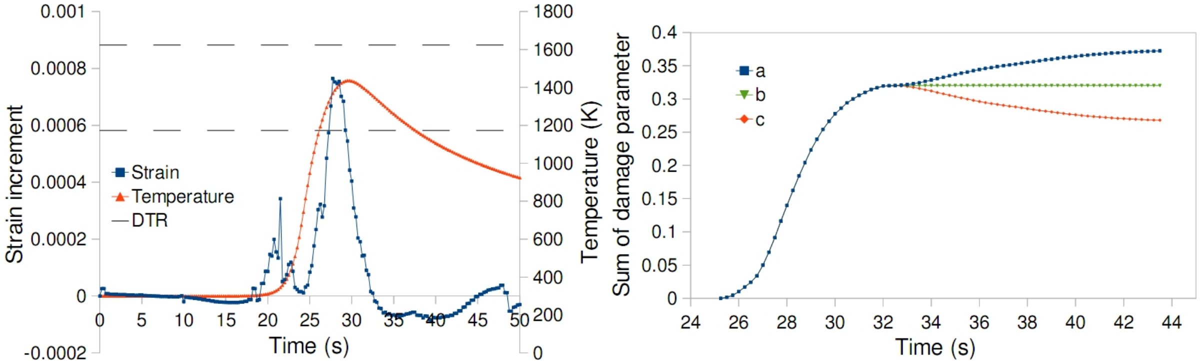

Figure 1: DDC test - data for a point 5 mm from weld centre-line and on midpoint of the weld path. On the left, temperature and principal plastic strain increment versus time. On the right, damage accumulation versus time, where: (a) absolute value of the strain increment causes damage; (b) only positive strain increment causes damage; and (c) negative strain increment reduces damage.

A sub-model is a feature in VrSuite software [10] that reduces the computational cost of high resolution models. Another benefit of sub-models is the ability to modify the mesh size in a specific region without altering the mesh of the entire domain and the need to run the CWM simulation for the entire domain repeatedly. In order to use the sub-model feature the results for the entire domain (aka parent model) must be first obtained using a relatively coarse mesh. The transient results for the entire domain are then mapped onto the boundaries of a region of interest to become the sub-model. The mesh for the sub-model region is refined by the user. A CWM simulation is run only for the sub-model using time dependent boundary conditions from the coarse mesh solution.

The sub-model in the DDC test is at the center of the plate. The sub-model in the solidification cracking test is focus on the training edge of the weld pool at the instant of the time the heat source reaches the weld path midpoint. The sub-model used in the solidification cracking test is shown in Figure 2.

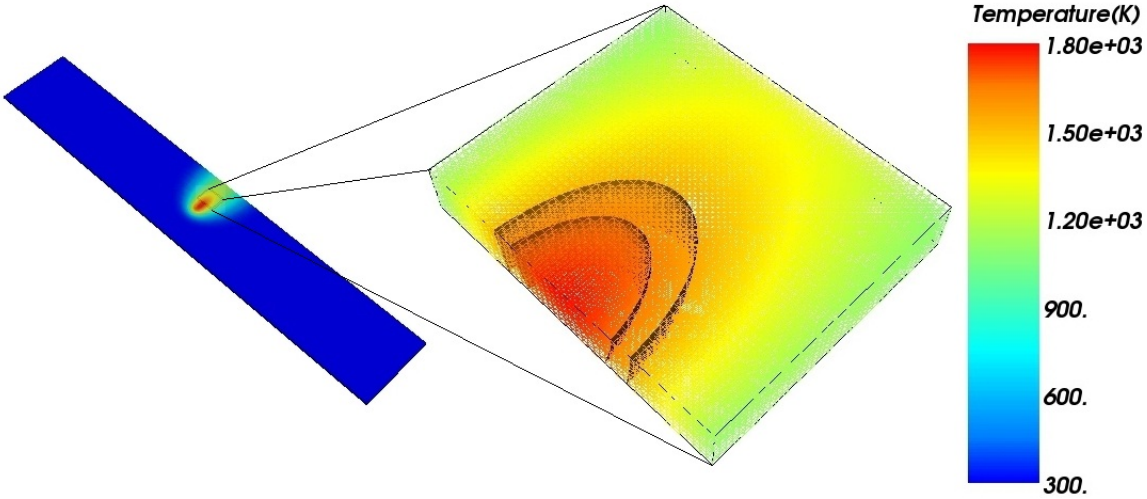

Figure 2: Solidification cracking test - temperature field and BTR iso-therms at t = 12.5 s from parent and sub-model.

Results and Discussion

In the solidification cracking test the effect of the three different CHSs on localized strain and strain rate is revealed in Figure 3. This figure is a plot of localized strain versus temperature. Experimental values for critical strain rate and ductility curves, obtained from the literature [11], are compared to values computed with CWM simulation. An intersection of the computed strain-temperature curve with the ductility curve indicates an increased risk of solidification crack nucleation.

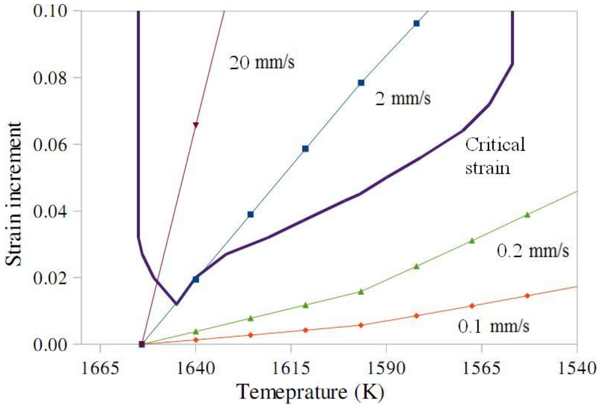

Figure 3: Solidification cracking test - strain versus temperature for different applied CHS compared to material resistance obtained from the literature [11].

In the DDC test the risk of DDC is estimated at seven Gauss points at the top and center of the plate. The points are spaced 1 mm apart in the direction transverse to welding. The tensile eigenvectors for the plastic strain between 0 and 6 mm from the weld center line for a welding speed of 2 and 5 mm/s are shown in Figures 4 and 5, respectively. The sum of the damage parameter, caused by the increment of the maximum tensile components of principal plastic strain, versus time curves for a welding speed of 2 and 5 mm/s are shown in Figures 4 and 5, respectively. A conservative approach has been used where the damage parameter is calculated based on the absolute value of strain increment.

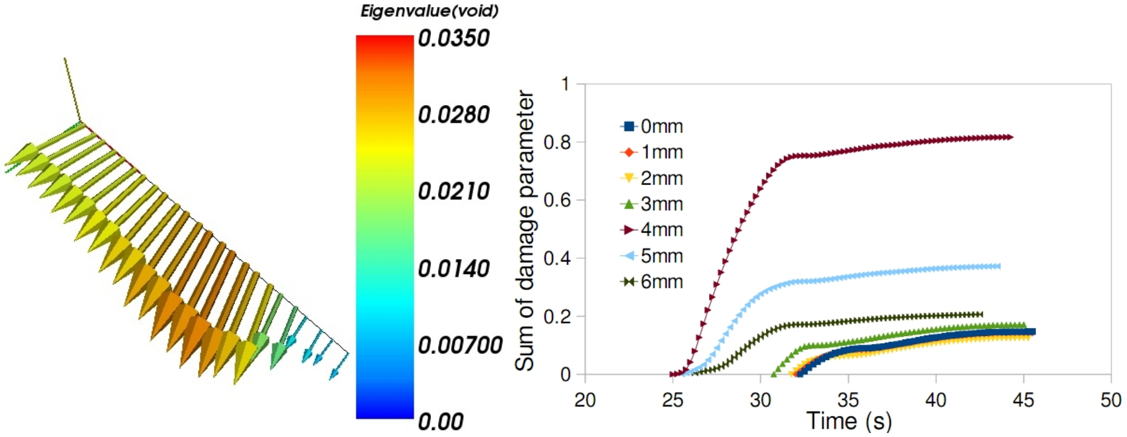

Figure 4: DDC test - on the left, eigenvectors for 3rd component of principal strain at t = 45s, from 0 to 6 mm from weld centre, for a 2 mm/s welding speed. On the right, damage parameter, caused by eigenvalue for 3rd component of principal plastic strain increment, versus time, for a 2 mm/s welding speed.

There is a difference in the method to estimate the risk of cracking between DDC and solidification cracking. Solidification cracking can nucleate only in the BTR region. Specifically, solidification cracking is considered to occur only behind the weld pool since cracks that may nucleate before the weld pool will

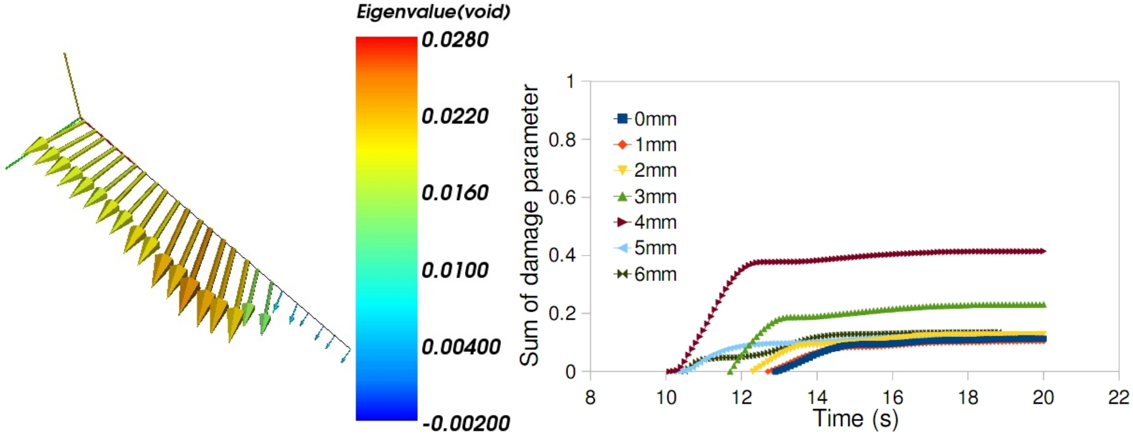

Figure 5: DDC test - on the left, eigenvectors for 3rd component of principal strain at t = 18 s, from 0 to 6 mm from weld centre, for a 5 mm/s welding speed. On the right, damage parameter, caused by eigenvalue for 3rd component of principal plastic strain increment, versus time, for a 5 mm/s welding speed.

be melted. This means that the strain increment contributing to solidification cracking is recorded during cooling only.

On the other hand, DDC can occur in DTR region, which can be in front or behind the weld pool. This means that the strain increment is recorded during heating and cooling. However, the damage caused by the plastic strain increment could be reduced, if the temperature exceeds the DTR. The risk of hot cracking can be estimated by directly comparing the tensile principal plastic strain to material resistance if data for it was obtained using a welding test.

These CWM simulations do not account for creep behavior. Creep behavior that may be exhibited during the limited time frame of the tests conducted should be negligible.

Conclusion

A methodology to estimate the risk of hot crack nucleation based on a CWM analysis was demonstrated.

1. The maximum tensile component of strain was determined by using the principal directions. The plastic component is utilized as the measure of irreversible damage that leads to hot cracking.
2. Determining the risk of solidification cracking for an entire domain was facilitated by the use of the global post processor algorithm.
3. Results for constant temperature test were applied to welding through the use of the equation based on miner's rule.
4. The high resolution model necessary to obtain accurate results for localized strain was less expensive with the use of a sub-model.

The thermal and stress analyses of the weld for both types of hot cracking are very similar. In each of the hot cracking tests the domain, material type and welding process must be defined. However, the post-processing the two types of hot cracking, which is the focus of the paper, is very different. The techniques proposed to estimate the risk of hot cracking would be best verified experimentally.

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