Finite Element Modelling of Porosity during Solidification

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Abstract: *The present paper describes the computational framework for a fully coupelled macroscopic thermomechanical damage model which can predict the nucleation and growth of shrinkage porosity in a casting during its solidification.*
The numerical analysis results obtained from the model indicate that the combination of an apropriate thermal nucleation criteria and a Gurson's compressible growth model provide a reliable tool for the prediction of shrinkage cavities in geometrically complex castings.

1 INTRODUCTION

Casting may be defined as a classic metal forming process in which, a definite volume of the melt conformed to the shape of the mold cavity, hardens by losing its heat content to the environment, producing a stable solid part. This definition leaves behind in time history the melting and filling operations performed in the foundary practice, and only considers reflecting their effects in the initial and boundary value conditions of the thermo-mechanically coupelled solidification problem[i]. For which the application of the finite element approximate solutions of the problem, to describe the plastic and viscoplastic behaviour of the phase transformation are generally considered appropriate[ii,iii].

Despite successful continuous single crystal growth from the melt of some slow growth rate pure materials, in practice, even during the filling of the cold mold with the melt of a pure metal, many dendritic crystallites will form initially, and then the growth will generally proceed inwards from the wall, as heat is extracted. For an alloy it is even more complicated because the dendritic structure depends on the coupelled diffusion of heat and a competitive diffusion of chemical elements[iv].

Within the solidification body, because of the thermal and phase change contraction and/or expansions, once a solid skin is formed, porosity occurs because of the inability of the melt to feed localized regions in the casting[v,vi], and presence of the dissolved gases trapped in the melt[vi]. Cavitation can also occur when there is a negative pressure in the melt[iii]. Coalecense and pore diffusion can easily occur at these high temperatures of solidification[vii].

2 THERMAL NUCLEATION CRITERION

During the solidification phase transfer, thermal contractions and expansions, morphological evolution, and mechanical properties are all strongly temperature dependent. Consequently, after detailed careful analytical evaluation of the existing thermal criteria functions in the literature[iii,ix,x], the following thermal porosity function was formulated to be used in the damage model;

$$TPC = \wp = 1 - \exp(-\alpha.\sqrt{t}\left(\frac{Rate}{\sqrt{GradT}}\right))$$

Here, $\wp$ is the Thermal Porosity Criterion function, in which t is the solidification time, $GradT$ is the temperature gradient and $Rate$ is the rate of cooling for an element of material. This function combines the Niyama[ix] thermal criteria variables and Lee's[x] local solidification time. In this function α is an adjustable parameter which depends on the material. The value of α taken in the present analysis is $\alpha = 0.005$.

$\wp$ can vary within the range of $0 \leq \wp \leq 1$. And the probability of shrinkage cavity formation increases with the increase of this variable, reaching the maximum when $\wp = 1$. It is considered that the total fraction of porosity for each element will be;

$$f_{tot} = f_n + f_g$$

Where, sub-indices tot, n and g indicate total, nucleation and growth respectively.

3 GURSON VOID MODEL

Gurson formulated the following mathematical expression of the yield surface for a Vom Mises perfectly plastic material;

$$\Phi\left(J_2(s), tr\sigma, \sigma_M, f\right) := J_2(s) - \frac{1}{3}\left\{1 + f^2 - 2f \cdot Cosh\left(\frac{3p}{2\sigma_M}\right)\right\}\sigma^2{}_M$$

Where, f is the porosity fraction and the damage variable, p is the pressure, σ_M is the actual uniaxial yield stress of the material matrix in tension , and $\sigma_M = \sigma_0 + K(R)$ in which σ_0 s the initial yield stress, $K(R)$ is a hardening function depending only on a single parameter R.

This yield surface allows the desired expansion and contraction of the matrix material.

Details of the theory and its implementation within a general framework of the plasticity, are given in previous references[3].

It can be seen from the form of the yield function that when the fraction of porosity is at zero percent, then the Gurson yield criteria returns to its original Von Mises condition. Also, we assume that the softening effect of the porosity growth is independent from the thermal hardening during each time step.

Figure 1. The 2D and 3D Sections of the meshed sreel bar in the sand mold.

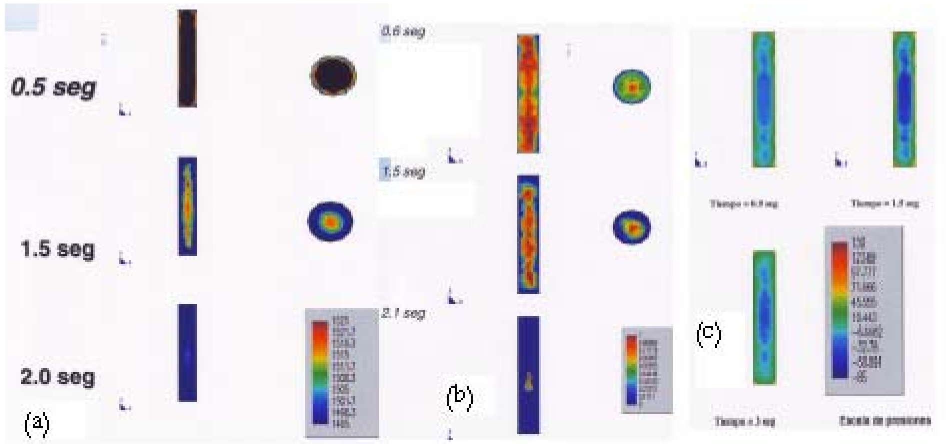

Figure 2. (a)Mushy zone evolution. (b) TSC evolution. (c) Local pressure evolutions.

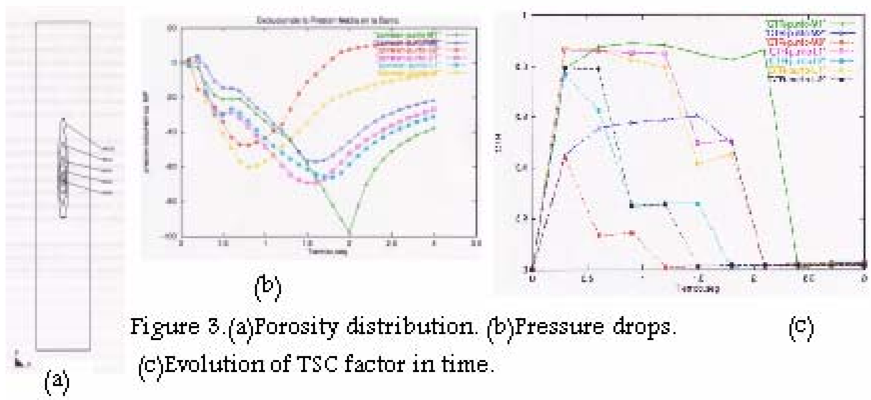

Figure 3.(a)Porosity distribution. (b)Pressure drops. (c)Evolution of TSC factor in time.

4 ALYSIS and RESULTS

Solidification process of a simple cylindrical, low carbon steel bar in a sand mold has been analysed employing the Vulcan thermo-mechanical code in which the present gurson damage model has been implemented [iii] .

In Figure 1, sections of the meshed geometry of the solidification analysis sample has been shown. The diameter of the bar is 10 mm and its length is 60 mm, cast in a cylindrical sand mold.

A further meshing sub-structure, that is cylinders within cylinders inside the 10 by 60 mm steel bar has been imposed, to help with the iniciation and propogation of porosity nucleation during the course of the analysis. The right hand side image shows the meshing sub-structure of cylinders in the steel bar, and identifies three points across the mid-height section of the bar. These points have been used to follow the evolution of the variables during the analysis. The solidification temperature range for this steel bar has been taken to be between 1525 (solidification starts) and 1495 degrees centigrade (ends). More complete details of the thermal and mechanical properties used in the present work can be found in references available at cimne [iii] .

In Figure 2, three time evolution results obtained from the analysis have been shown, (a) shows the advancing mushy zone at different times of the solidification analysis. (b) shows the evolution of the Thermal Porosity Criterion (TPC) values, which have been used here to indicate the starting time and location of nucleation in a material element in the bar, by triggering the damge growth model. (c) shows the average pressure distributions in the bar at different times during the solidification. The concentration of the negative hydrostatic pressures at the center of the bar can be observed.

Figure 3, (b) and (c) show the relative evolution graphs of TPC values and mean pressure values, at identified points on the axis of the bar (note the maximum pressure drop to approximately -20 MP at the center of the bar). Figure 3, (a) shows the distribution of the porosity within the solidifying steel bar.

5 DISCUSSIONS and CONCLUSSIONS

The results presented here in this paper demonstrate that:

A) The thermal criteria function, based only on the thermal results of the solidification analysis, indicates an experimentally acceptable "hot spot" at the thermal center of the cylindrical specimen as the most probable point at which the initial nucleation of the porosity can occur.

B) Demonstrate how the implementation of the Gurson damage model within the framework of the finite element formulation of thermo-plastic hardening model can produce expansion or contraction of porosity in response to the local hydrostatic pressure in the volume element material matrix. In the present context this local growth of the porosity is a consequence of the thermally confirmed TPC signal, and the propagation gradient created through the cylindrical sub-structured meshing.

We can conclude that, the nucleation followed by the porosity growth of the Gurson model, has simulated the physically logical response of the sample to the negative hydrostatic pressures in the solidifying steel bar. Considering the physical importance of the pressure terms as far as the thermodynamics of the closed and open material bodies are concerned, many useful applications of this damage model can be devised, of which casting porosity is one of the traditionally complex ones, presented in this work.

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