Predicting Hot Tearing in Aluminium Castings

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In many casting processes, some stages, such as the starting phase in the direct chill casting of aluminium alloys, are particularly critical because of the propensity of some alloys to develop either hot tears which initiate at non zero liquid fraction, or cold cracks which nucleate and grow exclusively in the solid metal. Figure 1 shows a cracked rolling sheet ingot: two hot tears initiated during the starting phase of casting have grown up as the ingot was further cast. For some very sensitive alloys, up to 10 % of the ingots present some cracks and have to be remelted.

Hot tearing

In the mushy zone, two major defects related to stresses can be encountered : porosity and hot tears. As pointed out clearly by Campbell [1], the first defect is associated with a hydrostatic depression in the mushy zone combined with segregation of gaseous solute elements (hydrogen, nitrogen, carbon monoxide). This depression is associated with the suction of the liquid in the porous dendritic region. The models developed for the prediction of microporosity formation are therefore based on the solution of the Darcy equation coupled with a mass balance and a microsegregation model of gaseous elements [2]. The formation of hot tears is also linked to a lack of feeding in the mushy zone, but for specific regions where the dendritic network is subjected to uniaxial tensile stresses [3-5]. These stresses are induced by differential thermal contraction upon cooling and might lead to the development of hot tears.

When the dendritic network is coherent [6], it can sustain, and as a matter of fact also transmit, the stresses. Above the coherency temperature, the thin film of liquid still present in-between the dendrite arms behaves like a "brittle" phase: the dendrites are pulled apart easily. If the interdendritic liquid flow can feed such regions, almost nothing is noticed except maybe for some local inverse segregation ("healed" hot tears) [7]. However, deep in the mushy zone where the permeability of the mush is very small, an opening of the non-coherent dendritic network cannot be compensated by the liquid and hot tears form. Due to the complexity of the mechanisms involved in hot tearing formation, the models developed so far are relatively simple, most of them being based upon the consideration of the solidification interval [7]: the larger the solidification interval of the alloy, the more sensitive it will be to hot tearing. The most sophisticated models use a back-diffusion model [1], for which the maximum HCS (Hot Cracking Sensivity) is dictated by the Fourier coefficient in the solid phase.

Clyne and Davies [7] have recognised that hot cracking was due to an opening of the mushy zone in a "vulnerable" region where the dendrite arms can be pulled apart easily. They introduced a Cracking Sensitivity Coefficient (CSC) which is the ratio t_v/t_r, where t_V is the time during which the mushy zone is vulnerable to hot tearing ($0.01 < f_l < 0.1$, where f_l is the liquid fraction) and t_r is the time during which stresses can be relaxed ($0.1 < f_l < 0.6$).

In order to predict the occurrence of hot tears in a solidifying part, a hot tearing criterion based on the ability of the interdendritic flow of liquid to compensate for the thermally induced deformation of the roots of columnar dendrites has been recently derived by Rappaz et al. [6]. Based upon a mass balance performed over the liquid and solid phases, this criterion accounts for the tensile deformation of the solid skeleton perpendicularly to the growing columnar dendrites and for feeding of the interdendritic liquid: it allows the calculation of the maximum strain rate that the roots of the dendrites can undergo without initiation and/or propagation of hot tears.

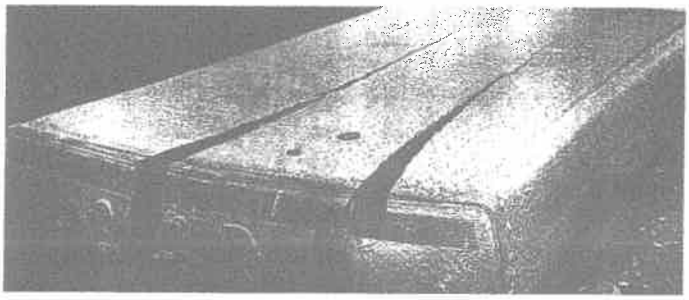

Fig. 1: cracked rolling sheet ingot.

A new hot tearing criterion

Under a given thermal gradient, G, and for a constant solidification rate, v_T, if the dendritic network is submitted to a thermally-induced tensile deformation rate, ε, the flow of interdendritic liquid should also compensate for that deformation if no hot tears form. The pressure in the interdendritic liquid will therefore decrease from the metallostatic pressure, p_m, near the dendrite tips. If the pressure falls below a cavitation pressure, p_c, a void will form and may give rise to a crack. Consequently, the criterion for hot tearing formation is:

$$\Delta p_{max} \geq \Delta p_c = p_m - p_c \qquad (1)$$

The depression in the mush has two components, one due to the solidification shrinkage and one due to the mechanical straining. Assuming that the deformation is homogeneous over the entire width of the mushy zone, Rappaz et al. [6] have derived these two components using the Carman-Kozeny model for the permeability and the back-diffusion Brody-Flemmings model for the relationship between the solid volume fraction, f_s, and the temperature, T:

$$\Delta p_{max} = \Delta p_{\varepsilon} + \Delta p_{sh} = \frac{180\mu\Delta T_0}{G\lambda_2^2}\left[v_T\beta A + \frac{(1+\beta)B\dot{\varepsilon}\Delta T_0}{G}\right]$$

$$\text{with}\quad A = \frac{1}{\Delta T_0}\int_{T_{eut}}^{T_{liq}} \frac{f_s^2\,dT}{(1-f_s)^2},\quad B = \frac{1}{\Delta T_0}\int_{T_{eut}}^{T_{liq}} \frac{f_s^2 \cdot F_s(T)}{(1-f_s)^3}dT$$

$$\text{and}\quad F_s(T) = \frac{1}{\Delta T_0}\int_{T_{eut}}^{T} f_s\,dT \qquad (2)$$

In these equations, T_{liq} is the liquidus temperature of the alloy and T_{eut} is the temperature at which interdendritic bridging occurs (i.e., coalescence of the dendrites) or the eutectic temperature if more than a given amount of eutectic has formed. μ and β are the viscosity of the liquid and the shrinkage factor, respectively. λ_2 is the secondary dendrite arm spacing. Combining equations 1 and 2 gives the maximum strain rate sustainable by the mushy zone at the root of the dendrites before a hot tear forms:

$$\dot{\varepsilon} < \dot{\varepsilon}^{max}(\mu, v, \beta, \lambda_2, G, \Delta p_c) \qquad (3)$$

Please, note that once a hot tear has formed ($\dot{\varepsilon} > \dot{\varepsilon}^{max}$), it will propagate as long as the deformation rate remains higher than the maximum value.

Application to the Al-Cu system

The hot cracking sensitivity (HCS) index, proportional to $1/\dot{\varepsilon}^{max}$, has been computed as a function of the solute content for a binary Al-Cu alloy using the parameters listed in Table 1. It is compared in figure 2 with the measurements of Spittle and Cushway for different compositions of non grain-refined Al-Cu alloys [8]. These authors measured the electrical resistance after casting the alloy into dog-bone shaped cylindrical moulds and converted this value into a hot cracking sensitivity index varying from 0 to 1 [8]. Also reported in figure 2 are the criterion of Clyne and Davies [7] based on the time spent by the mushy zone in a vulnerable stage and the solidification interval calculated with the Brody-Flemings model. To compute the criterion of Clyne and Davies and the present one, interdendritic bridging was assumed to occur at a solid fraction higher than 98% (T_{sol} = $T(f_s{=}98\%)$) or when the eutectic temperature has been reached.

μ	10^{-3} Pas	Δp_c	2 kPa	G	10^4 K/m
β	0.06	λ_2	100 μm	v_T	10^{-4} m/s

Table 1: list of parameters used in the calculations of figure 2.

The "Λ curve", typical of hot tearing in binary systems, is well reproduced by the present criterion: the rapid increase at very low solute content and the maximum at a composition around 1.4 wt. pct Cu predicted by the criterion are in relatively good agreement with the measurements of Spittle and Cushway. One can see that the maximum in hot tearing susceptibility is very close to the maximum of the solidification interval, as pointed out by Campbell [1]. The decrease of the susceptibility past the maximum is somewhat too steep although the vanishing of the hot tearing tendency at compositions higher than 3 % is well reproduced. On the other hand, the criterion of Clyne and Davies yields a too wide " Λ curve" and overestimates the HCS values as compared with experiments, especially at high concentrations. The model based simply on the solidification interval predicts an even slower decrease. It should be pointed out that the fraction at which interdendritic bridging is assumed to occur, 98 %, has a great influence on the position of the peak of the " Λ curve": the higher this fraction, the lower the concentration at maximum susceptibility index.

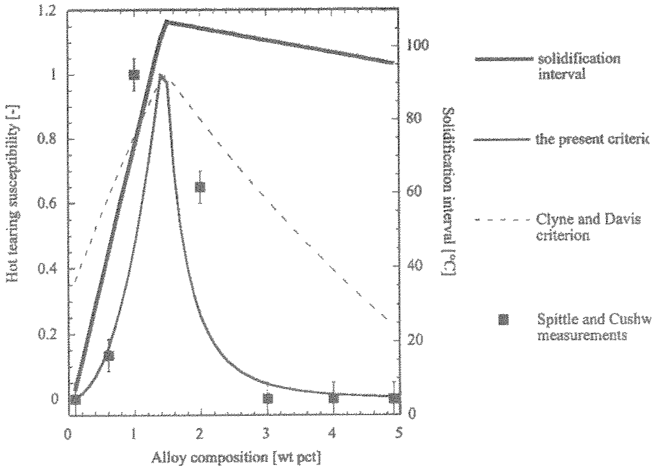

Figure 2: calculated hot tearing susceptibility as a function of alloy composition (Al-Cu system) compared with measured quantities.

The cavitation depression was set to 2 kPa in the present calculation: it is an unknown key value of the model but nevertheless it is relatively close to the depression computed by Ampuero et al. [2] for microporosity formation. It is also of the order of magnitude of the value of 1 kPa found by Drezet and Rappaz [4].

Conclusion

The new hot tearing criterion proposed here combines the capability of the mushy zone to sustain tensile deformation rate with the ability of the interdendritic liquid to feed the induced local change of volume at the root of columnar dendrites. This criterion reproduces the Λ curve typical of hot tearing in a better way than previous models. Eventually, when implemented in thermo-mechanical models of casting processes, the present hot tearing function should be very helpful in optimising the casting processes by diminishing the cracking tendency.

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Conference Diary

2001

3rd International Colloquium - FUELS. Ostfildern, Germany, January 17-18. Renate.Pfeiffer@tae.de http://www.tae.de

CAE in Polymer Processing. Ventura, California, USA, March 4-9. c-tucker@uiuc.edu http://www.grc.uri.edu

Eurotherm. Inverse Problems and Experimental Design in Thermal and Mechanical Engineering. Poitiers, France, March 5-7. euro68@ensma.fr http://www.euro68.ensma.fr

Euromech-Mecamat EMMC5. 5th European Mechanics of Materials Conference. Delft, The Netherlands, March 5-9. emmc5@wbmt.tudelft.nl http://emmc5.wbmt.tudelft.nl

Polymer'01. The New Polymers: Design, Development & Applications. Bath, U.K., April 9-11. ckie_Watts@materials.org.uk. http://www.iop.org/IOP/confs

ICIT 2001. 3rd International Conference on Industrial Tools. Maríbor, Slovenia, April 22-26. tecos@tecos.si http://www.tecos.si

PPS-17. 17th Annual Meeting. Montreal, Canada, May 21-24. pps17@gch.polymtl.ca http://gch.polymtl.ca/pps17/

Numiform 2001. 7th International Conference on Numerical Methods in Industrial Forming Processes. Toyohashi, Japan, June 18-21. numiform@plast.tutpse.tut.ac.jp http://plast.tutpse.tut.ac.jp/numiform/

ECCM-2001. 2nd European Conference on Computational Mechanics. Krakow, Poland, June 26-29. eccm@pk.edu.pl http://www.pk.edu.pl/eccm

Euro-Fillers'01 Conference. _ód_, Poland, July 9-12. eurofil@ck-sg.p.lodz.pl

International Conference on High Performance Materials Bridges. Hawaii, July 29- August 3. engfnd@aol.com

Polymers in the Third Millennium. Montpellier, France, September 2-6. conferences@chemind.demon.co.uk

2nd World Tribology Congress . Vienna, Austria, September 3-7. http://www.wtc2001-vienna.ccc.at/

AMPT'01. Intl Conference on Advances in Materials and Processing Technologies. Leganés, Spain, September 18-21. ampt01@ing.uc3m.es http://www.fundacion.uc3m.es/ampt

6th World Congress of Chemical Engineering. Melbourne, Australia, September 23-27. Chemeng@meetingplanners.com.au

ISSI. 3rd International Symposium on Structural Intermetallics. Wyoming, USA, September 23-27. hemker@jhu.edu

CCC 2001. Charpy Centenary Conference. Poitiers, France, October 3-5. sfmm@wanadoo.fr

PPS'2001. Regional Meeting. Ankara, Turkey, Oct. 22-24. akovali@metu.edu.tr http://www.poly-eng.uakron.edu/PPS/meetings.htm

APCOM'01. 1st Asian-Pacific Congress on Computational Mechanics.Sydney, Australia, Nov. 20-23 n.khalili@unsw.edu.au http://www.civeng.unsw.edu.au/conferences/apcom01

2002

13th International Colloquium Tribology Lubricants, Materials & Lubrication Engineering. Ostfildern, Germany, January 17-18. Renate.Pfeiffer@tae.de http://www.tae.de

4th European Stainless Steel Science and Market Congress. Paris, France, June 10-12. Tel. 33 1 41 25 57 28

PPS-18. 18th Annual Meeting. Guimarães, Portugal, June 16-20. pps18@dep.uminho.pt http://www.dep.uminho.pt/pps18

WCCM V. 5th World Congress on Computational Mechanics. Vienna, Austria, July 7-12. general@wccm.tuwien.ac.at http://wccm.tuwien.ac.at

Macro2002. 39th International Symposium on Macromolecules Beijing, China, July 7-12. macro2002@pdccs.org.cn http://www.chinameeting.com.cn/macro2002

IUPAC-PC2002 . Mission and Challenges of Polymer Science and Technology. Tokyo, Japan, Dec. 2-5. kokusai@spsj.or.jp http://www.spsj.or.jp

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