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PREDICTION AND VALIDATION OF HOT TEARING IN PERMANENT MOLD STEEL CASTING USING A VISCOPLASTIC DAMAGE MODEL

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Abstract

Hot tears are unacceptable defects, which can be found in final steel casting products. It is believed that a hot tear forms at the mushy zone with a high fraction of solid due to an applied tensile strain. In this work the simulation of the solidification and deformation processes are carried out using commercial software combined with a user-defined constitutive model. The shrinkage porosity information is coupled to the constitutive deformation model in the solid state to calculate the materials damage, where a viscoplastic model can predict the hot tear formation in permanent mold steel alloy casting. A good correlation between experimental findings and predicted damage is observed.

Key words: hot tear, casting, steel alloy, viscoplastic, damage, solidification

1. INTRODUCTION

Hot tearing has been studied by means of experiment and simulation in many scientific disciplines such as welding, casting processes of ferrous and nonferrous alloys as well as in continuous casting of aluminum or steel (Pierer et al., 2009). Hot tearing is one of the most common defects for casting. These defects in steels are repaired by removing defect areas from the casting followed by welding. Furthermore, pre- and post-weld heat treatment is necessary, leading to extensive procedures and high costs. Generally, theoretical approaches assume that a hot tear forms during solidification at or just above the solidus temperature due to residual liquid films along dendritic interfaces (Apblett & Pellini, 1954; Bhattacherya et al., 1954; Pellini, 1952). The porosity can be formed in the last stage of solidification due to shrinkage and may act as nucleation site for hot tears. The formation of hot tears can be also attributed to insufficient feeding of liquid in the mushy zone and simultaneous thermal and mechanical loading of the dendritic network (Campbell, 1991; Clyne & Davies, 1981; Rappaz et al., 1999). This loading, caused by the contraction of the casting and by geometric constraints of the mold, produces thermal and mechanical strains, which causes additional voiding called damage. Also other parameters such as, alloy composition, mechanical properties and cooling history can affect the formation of hot tearing (Gou & Samonds, 2010). A detailed review of hot tearing has been published by Eskin and Katgerman (2007). In the present work a newly developed viscoplastic model that calculates deformation and damage in the presence of voids (porosity) is implemented in the UMAT user subroutine of

36 – 42

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ABAQUS in the simulation of the solidification of steel casting to identify the potential hot tear sites. Finally, the model is validated using experimental results. The modeling approach and damage model are introduced in the following chapters.

2. MODELING APPROACH

In this approach, the temperature and porosity distribution are simulated using the finite difference method based software MAGMASoft. In the next step, the calculated temperature history and the feeding results (porosity) are introduced to the solid mechanics finite element program ABAQUS using MAGMALink to compute the deformation of the solid phase. The damage porosity produced by viscoplastic dilatation is calculated as a function of the visco-plastic strain rate and the solid fraction. Figure 1 shows a graphic illustration of the one - way calculation flow.

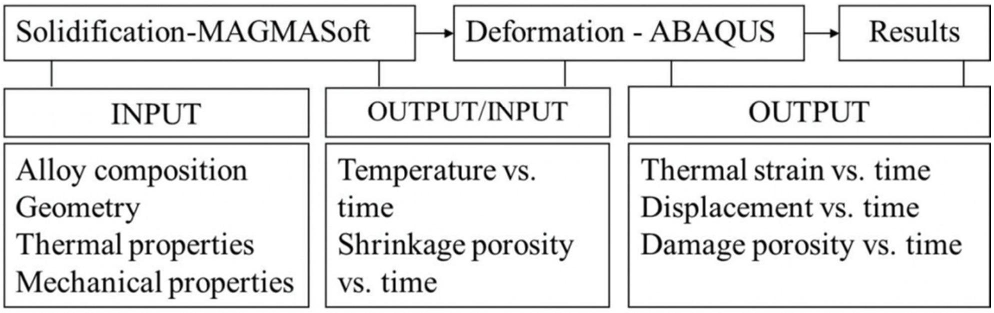


Fig. 1. *One - way path from the solidification results to the deformation and then to results.*

The coupling of the deformation of the solid phase during solidification is not taken into account in this work.

3. DAMAGE BASED VISCOPLASTIC MATERIAL MODEL

The material behavior in the semi solid state by the presence of voids (porosity) can be described by the Monroe-Beckermann constitutive damage based visco-plastic material model (Monroe, 2008; Monroe et al., 2009), which is based on the quadratic yield function from Cocks (1989). The volume averaged model accounts for the presence of three phases: solid f_s, liquid f_l and pores f_p, (Carlson et al., 2003). The sum of all these phase fractions is one. The porosity fraction is split into shrinkage porosity $f_{p,sh}$ and damage porosity $f_{p,d}$, which are calculated separately. The calculation of liquid flow and shrinkage porosity is done with the finite difference method based software MAGMASoft using the model presented in Carlson et al. (2003). The influence of the solid deformation on liquid flow and of the liquid pressure on solid deformation is neglected. The total strain ε_s consists of elastic ε_s^e, thermal ε_s^{th} and viscoplastic ε_s^{vp} terms:

$$\varepsilon_s=\varepsilon_s^e+\varepsilon_s^{th}+\varepsilon_s^{vp} \tag{1}$$

The elastic strain is determined by the Hooke's law:

$$\tilde{\boldsymbol{\sigma}}_{\mathbf{s}}=\mathbf{C}_{\mathbf{e}}\boldsymbol{\varepsilon}_{\mathbf{s}}^{\mathbf{e}} \tag{2}$$

where $\mathbf{C}_e$ denotes the elastic stiffness tensor, defined by the Young's modulus, E, and Poisson ratio, v, which are depending on both temperature and solid fraction (Hardin & Beckermann, 2007; Roberts & Garboczi, 1989). $\tilde{\boldsymbol{\sigma}}_{\mathbf{s}}$ is the effective stress tensor for solid which is derived in the porous media theory (Martin et al., 1999) and is given by:

$$\tilde{\boldsymbol{\sigma}}_{\mathbf{s}}=f_s\boldsymbol{\sigma}_{\mathbf{s}}+f_s\mathbf{p}_{\mathrm{l}}1 \tag{3}$$

where $\boldsymbol{\sigma}_S$ is the stress in the solid, and I is the identity tensor. The thermal strain ε_s^{th} is governed by the temperature dependent density ρ_s. The integration finishes at the current temperature T_c:

$$\boldsymbol{\varepsilon}_{\mathbf{s}}^{\mathbf{th}}=\left(\int_{T_s}^{T_c}-\frac{1}{3\rho_s}\frac{d\rho_s}{dT}dT\right)\mathbf{1} \tag{4}$$

with T as the temperature. The visco-plastic strain is calculated with the associative flow rule, which is given by Simo & Hughes (1998):

$$\dot{\boldsymbol{\varepsilon}}_{\mathbf{s}}^{\mathbf{vp}}=\dot{\gamma}\frac{\partial\Phi}{\partial\tilde{\boldsymbol{\sigma}}_{\mathbf{s}}} \tag{5}$$

where $\dot{\gamma}$ is the scalar flow parameter, and Φ is the associated yield function. The quadratic yield function from Cocks (1989) is adopted as:

$$\Phi=q_s^2+A_1p_s^2\text{-}A_2\sigma_{dy}^2\leq 0 \tag{6}$$

The solid pressure p_s in the yield function is given by:

$$p_s = -\frac{1}{3}(\tilde{\boldsymbol{\sigma}}_{\mathbf{s}}:\mathbf{1}) \tag{7}$$

and the von Mises stress q_s by:

$$q_s = \frac{2}{3}|\tilde{\boldsymbol{\sigma}}_{\mathbf{s}} + p_s\mathbf{1}| \tag{8}$$

The parameters A_1 and A_2 depend on the solid volume fraction:

$$A_1 = \left(\frac{9(1-f_s^*)}{2\left(2-f_s^*\right)(1+m)\left(1+\frac{2(1-f_s^*)}{3}\right)}\right), \quad A_2 = \frac{f_s^{*\frac{2}{(1+m)}}}{\left(1+\frac{2}{3}(1-f_s^*)\right)} \tag{9}$$

and also on the strain rate exponent m and the scaled solid fraction f_s^*, that are both determined experimentally and theoretically (Cocks, 1989; Leblond et al., 1994; Michel & Needleman, 1994). This model is reduced to the von Mises yield model if the solid fraction f_s reaches one (100% solid). The scaled solid fraction is defined as (Tvergaard & Needleman, 1984):

$$f_s^* = f_s^{coal}\left(\frac{f_s - f_s^{coh}}{f_s^{coal} - f_s^{coh}}\right) \tag{10}$$

in order to use this model for the coherent part of the mushy zone. The coherent solid fraction f_s^{coh} occurs initially when the solid pieces contact and when the secondary dendrite arms interlock, respectively. For $f_s < f_s^{coh}$, the mush does not experience any stress and strain, because the solid pieces are not interconnected in the liquid. The scaling of the solid fraction was carried out only below the coalescence solid fraction, f_s^{coal}. Above this solid fraction the mush is very soft and the formed voids can coalesce due to tensile strain. At the coherent solid fraction the coalescence solid fraction becomes zero. The parameter and constants used for the determination of f_s and f_s^* considered in equation 10 and to model the solid deformation are provided in table 1. The evaluation of f_s and f_s^* in a steel cast GX8CrNi12 which is applied in this work, is seen in figure 2**.** The solid fraction was determined using JMatPro by a back diffusion thermodynamic calculation based on 1K/s cooling rate.

The dynamic yield stress σ_{dy} used in the yield function is given by Monroe & Beckermann (2007):

$$\sigma_{dy}(\varepsilon_{eq}, \dot{\varepsilon}_{eq}, T) = \sigma_0(T)\left(1+\frac{\varepsilon_{eq}}{\varepsilon_0(T)}\right)^{n(T)}\left(1+\frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0(T)}\right)^{m(T)} \tag{11}$$

with the initial yield stress $\sigma_0(T)$, the reference strain $\varepsilon_0(T)$, the hardening exponent $n(T)$ the reference strain rate $\dot{\varepsilon}_0(T)$ and the strain rate exponent $m(T)$. This model includes both the isotropic hardening parameter and creep (strain rate) dependency (Pokorny et al., 2008). The equivalent strain ε_{eq} and the equivalent strain rate $\dot{\varepsilon}_{eq}$ are derived from the scalar dissipation of energy by:

$$\varepsilon_{eq} = \int_{\mathrm{T_s}}^{\mathrm{T_c}} \frac{\tilde{\sigma}_s:\dot{\varepsilon}_s^{vp}}{g_s\sigma_{dy}}\,\mathrm{dt} \tag{12}$$

Table 1. *Parameters to model solid deformation in steel cast GX8CrNi12.*

Parameters and Constants	
Quantity	Value
Solidus temperature T_S	1455°C
Liquids temperature T_L	1505°C
Coherent solid fraction g_s^{coh}	0.5
No feeding solid fraction g_s^{nf}	0.75
Coalescence solid fraction g_s^{coal}	0.85

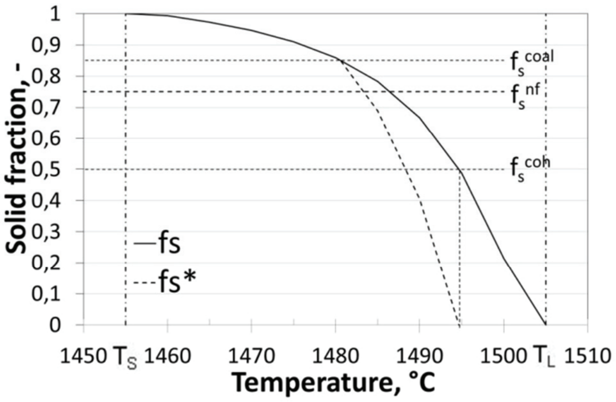


Fig. 2. *Variation f_s, and f_s^* with temperature for steel cast GX8CrNi12 calculated with JMat Pro based on 1K/s cooling rate and a back diffusion thermo-dynamic calculation.*

where the integration starts from the solidification temperature and ends at the current temperature. The damage porosity is calculated by integrating the volume fraction of porosity by visco-plastic dilatation over the solid fraction f_s^{nf}:

$$f_{p,d} = \begin{cases} 0, & f_s < f_s^{nf} \\ \int f_s \dot{\boldsymbol{\varepsilon}}_{\mathbf{s}}^{\mathbf{vp}}:\mathbf{1}\mathrm{dt}, & f_s > f_s^{nf} \end{cases} \tag{13}$$

f_s^{nf} (no feeding solid fraction) represents the solid fraction at which the liquid flow in the mushy zone is difficult or does not take place. In this paper, when the solid fraction reaches 0.75, the flow of liquid is assumed to be disrupted. The final damage model was implemented in the finite element code of ABAQUS. The calculated damage indicates the potential hot tears locations and is considered as a hot tear criterion.

Table 2. *Thermo physical data for simulation in MAGMA and ABAQUS.*

	Category	Parameter	Unit	Determination
MAGMA	Solidification simulation	Solid fraction in solidification interval g_s Specific heat capacity c_p Density ρ Thermal conductivity λ Viscosity μ Material composition	[-] [J/kgK] [kg/m^3] [W/m^{2}K] [m^2/s] [weight%]	JMatPro/MatCalc JMatPro/MatCalc JMatPro/MatCalc JMatPro JMatPro given
ABAQUS	Stress and Damage simulation	Yield stress $R_{p0,2}$ E-modulus E Coefficient of thermal expansion α Poisson ration v Hardening coefficient (exponent) n Strain rate exponent m	[MPa] [MPa] [1/K] [-] [-] [-]	Gleeble 1500 Gleeble 1500 JMatPro/MatCalc JMatPro Gleeble 1500 Gleeble 1500

4. THERMO PHYSICAL AND MECHANICAL PROPERTIES DETERMINATION

For the solidification simulation in MAGMASoft and the deformation simulation in ABAQUS the thermo-physical material data from the fully liquid temperature to room temperature are required. Table 2 summarizes the necessary data for both softwares. The thermo-physical properties of the steel cast GX8CrNi12 were calculated using JMatPro and MatCalc. The thermo-mechanical properties were determined experimentally using a Gleeble ® 1500 simulator.

5. APPLICATION

In order to validate the damage model proposed above, the experimental results of a hot tearing test named 'Crickacier' developed by Cerri et al. (2008) were compared. This experiment was performed to study the hot tear formation during solidification of steels in a permanent steel die. It is basically a constrained shrinkage test consisting of a feeder, water-cooled chills, a mold insert and a permanent steel mold. See figure 3 for the schematic experimental setup. The water cooled chills are placed at the two ends of the cast specimen, so that the solidification initiates first around the chills and then proceeds toward the cast center with a direction of growth perpendicular to the mold surface. The white arrows illustrated in figure 4a shows the direction of the solidification. The specimen is designed such that the section is bigger in the mold center in order to build a hot spot in the central region. During solidification the constrained ends create a mechanical loading orthogonally to the dendritic growth, which produces tensile stresses in the central hot spot. In order to control the thermal evolution, a steel insert in the central part of specimen is used. Its use causes a crack initiation at the center of specimen in the bottom part. The crack location is illustrated by a white line in figure 4b.

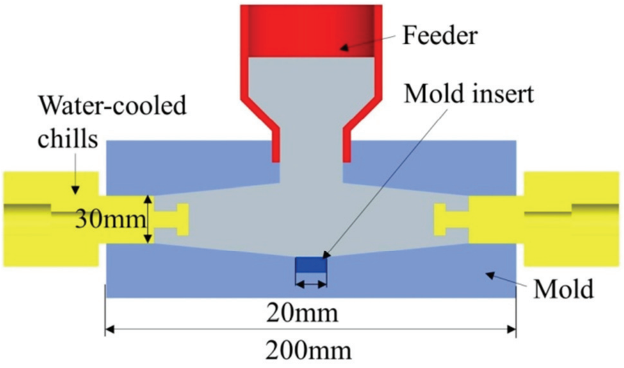


Fig. 3. *Schematic view of experimental setup (Cerri et al., 2008).*

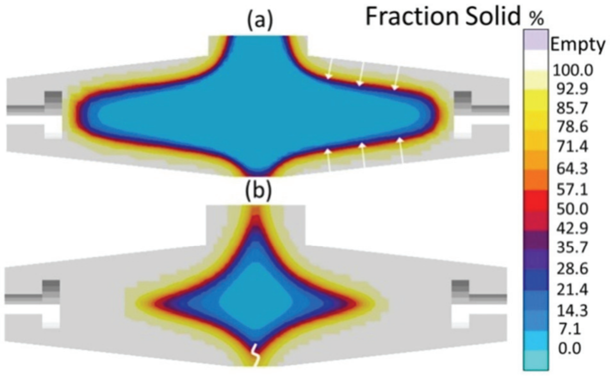


Fig. 4. *Solidification simulation of steel cast GX8CrNi12 in MAGMASoft - (a) solid fraction distribution after 30sec, 62% solidified regions, direction of growth illustrated with white arrows and (b) solid fraction distribution after 50sec, 85% solidified regions; white line indicates possible crack.*

Considering the symmetry in the part, one quarter of the set up is modeled. The contact between cast and mold, mold insert and chills were also simulated using the models implemented in ABAQUS. Figure 5 shows the experimental results of hot tearing in the casting specimen (Cerri, 2007). The calculated potential hot tearing locations by using the here applied damage model are shown in figure 6. The simulated hot tearing agrees well with the observation of visible cracks.

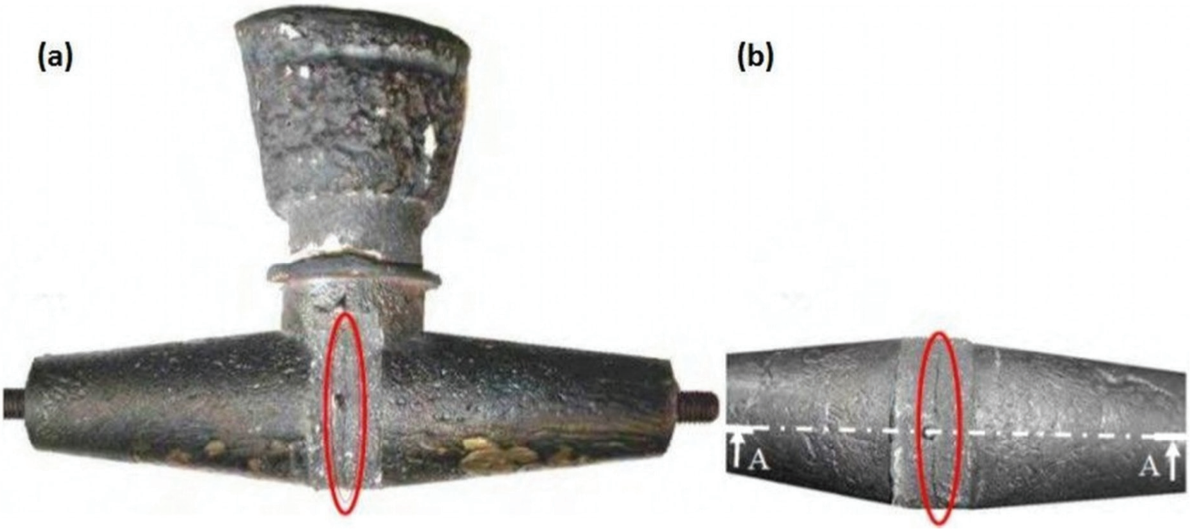


Fig. 5. Location of hot tears in 'Crickacier' with (a) Front view and (b) bottom view (Cerri, 2007).

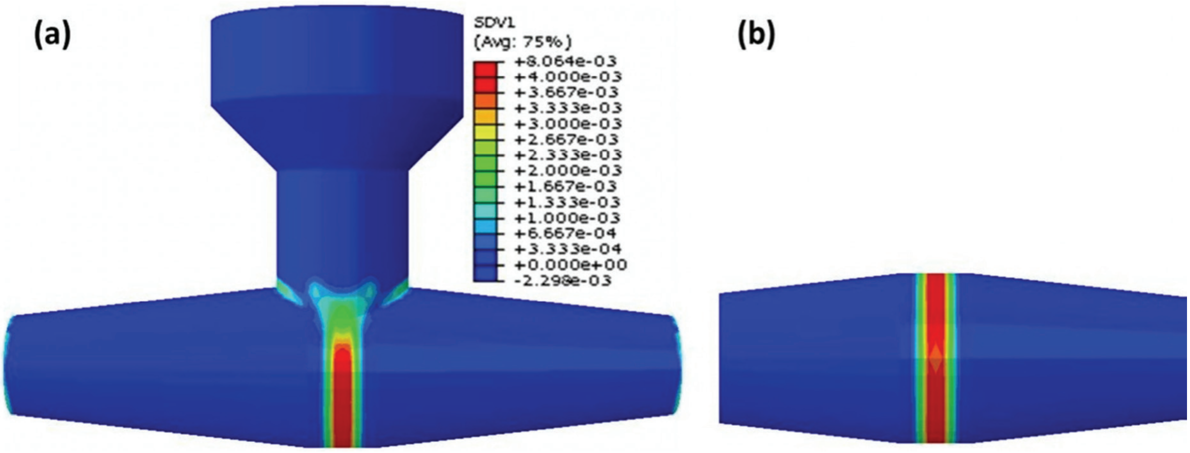


Fig. 6. Simulated damage in 'Crickacier' wtih (a) front view and (b) bottom view.

The hot tear mechanism was analyzed in detail at the elements 13522 and 5575 (see figure 7). The evolution of the tensile stresses, the solid fraction and the damage of this selection are illustrated in figure 8. The element 5575 was taken from the region of actual crack, while element 13522 corresponds to the region where the simulation showed a high hot tearing tendency. The evolution of solid fraction of element 5575 (see figure 8a) shows that the liquid metal begins to solidify after about 18 seconds. After further solidification at 40 seconds, deformation begins inducing local stresses. At this point the liquid metal can feed the damage porosity. After a solid fraction of 0.75 is reached at approximately 50 seconds, the liquid is not able to fed anymore the remaining pores and damage starts to accumulate, thus voids can grow and coalesce. During the solidification the stress is low: about 5MPa. At the regions where high damage is predicted, hot tears can form. Under high tensile stress the hot tears can grow to cracks. The damage at element 13522 is lower than at element 5575, even though the tensile stress is a little bit higher and the liquid starts to solidify later, figure 8b. This is because the solidification at element 5575 from the moment when stress begins to accumulate takes longer than at element 13522 and damage is the integration of the visco-plastic strain over time starting when the feeding with liquid is suspended (0.75 solid fraction). Therefore the total damage is higher in element 5575.

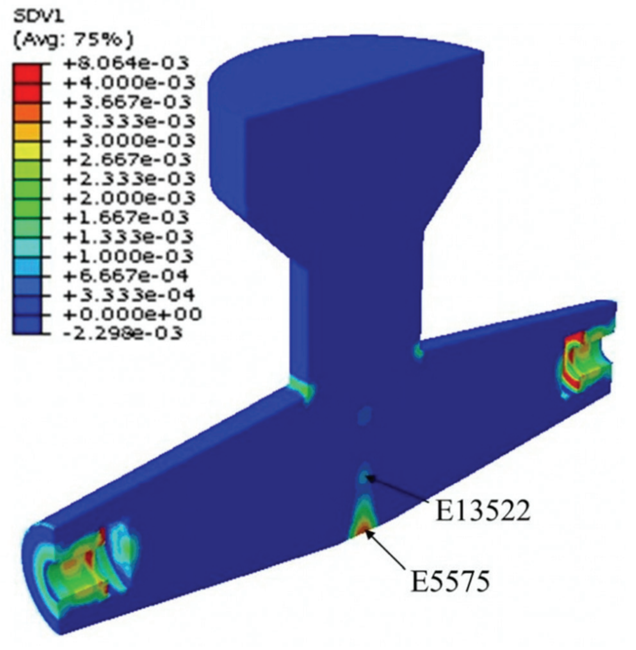
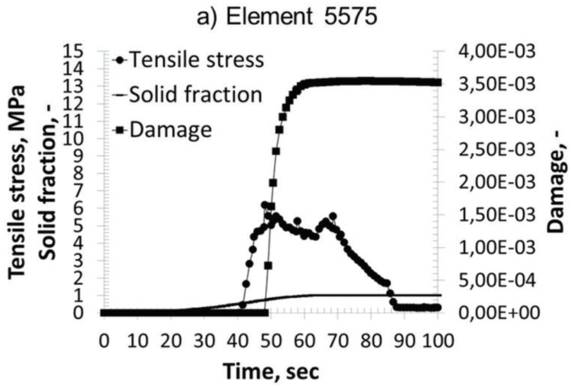


Fig. 7. Damage distribution in the cross section of 'Crickacier'.


a) Element 5575

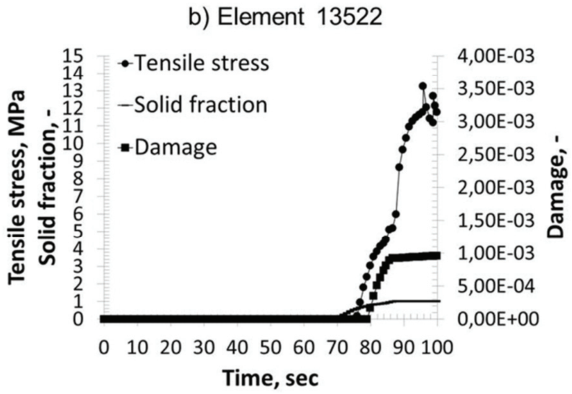

b) Element 13522

Fig. 8. *Tensile stress, solid fraction and damage evolution with time in the hot tear regions at elements a) 5575 and b) 13522.*

6. CONCLUSIONS

A damage model for hot tearing prediction has been applied, based on Cocks constitutive model. It describes internal damage of the solid fraction by the consideration of shrinkage porosity and growth of voids in the last stage of solidification in the mushy zone during casting. The validation of the computed damage model for steel was shown by experiments from literature. It was seen that the hot tearing susceptibility can be predicted accurately in permanent mold steel casting by applying the model in the numerical simulation of steel casting process. Further validation of damage model in collaboration with voestalpine Gießerei Linz for steel cast GX8CrNi12 is planned.

REFERENCES

Apblett, W.R., Pellini, W.S., 1954, Fracture Which Influence Weld Hot Cracking, *Welding Research*, 19, 83-90.

Bhattacherya, U.K., Adams, C.M., Taylor, H.F., 1954, Stress Required to Hot Tear Plain Carbon Cast Steel, *Trans. AFS*, 62, 557.

Campbell, J.C., 1991, *Castings*, Butterworth Heinemann, Oxford.

Carlson, K., Lin, Z., Hardin, R., Beckermann, C., Mazurkevich, G., Schneider, M., 2003, Modeling of Porosity Formation and Feeding Flow in Steel Casting, *Mod. Cast. Weld. Adv. Soli. Proc., X, PA*, 295-302.

Cerri, O., Chastel, Y., Ballet, M., 2008, Hot Tearing in Steels During Solidification: Experimental Characterization and Thermomechanical Modeling, ASME, *J. of Eng. Mat. Techn*., 130, 1-7.

Cerri, O., 2007, *Rupture a chaud dans les aciers au cours de leur solidification - caracterisation experimentale et modelisation*, PhD thesis, Mines ParisTech, Paris (in French).

Clyne, T.W., Davies, G.J., 1981, The Influence of Composition on Solidification Cracking Susceptibility in Binary Alloy Systems, *Brit. Found*., 74, 65-73.

Cocks, A.C.F., 1989, Inelastic deformation of porous materials, *J. Mec. Phy. Sol*., 37, 693-715.

Eskin, D.G., Katgerman, L., 2007, A Quest for a New Hot Tearng Criterion, *Met. Mat. Trans. A*, 38A, 1511-1519.

Gou, J., Samonds, M., 2010, Modeling of casting and solidification procesing, *Fund. for Met. Proc. Mod*, 22A, ASM handbook

Hardin, R.A., Beckermann C., 2007, Effect of porosity on the stiffnes of cast steel, *Met. Mat. Trans. A*, 38, 2992-3006.

Leblond, J.B., Perrin, G., Suquet, P., 1994, Exact result and approximate models for porous viscoplastic solids, *Inter. J. of Plast*., 10, 213-235.

Martin, C.L., Favier, D., Suery, M., 1999, Fracture behavior in tension of viscoplastic porous metallic materials saturated with liquid, *Inter. J. of Plast*., 15, 981-1008.

MatCalc, The scientific tool box for enjoyable computational materials engineering, Favoritenstraße 9-11 / E308, 1040 Viena, Austria, http://matcalc.tuwien.ac.at

Michel, J.C., Needleman, A., 1994, An analytical and numerical study of overall behaviour of metal-matrix composites, *Mod. Simul. Mat. Sci. Eng*., 2, 637-658.

Monroe, C.A., 2008, *A Modeling and Experimental Study of Deformation and Hot Tearing in Steels*, PhD Thesis, The University of Iowa

Monroe, C.A., Beckerman, C., Klinkhammer, J., 2009, Simulation of Deformation and Hot Tear Formation using a visco-plastic Model with Damage, *Mod. Cast., Weld. Adv. Solid. Proc*. XII, 313-320.

Monroe, C.A., Beckermann, C., 2007, Deformattion During Casting of Steel: Model and Material properties, *Proc. 61st SFSA Techn. Oper. Conf. Chicago*, Steel, Paper No. 5.6.

Pellini, W.S., 1952, Strain theory of Hot-tearing. *Found.*, 80, 124.

Pierer, R., Griesser, S., Reiter, J., Bernhard, C., 2009, *Über die Bildung von Heißrissseigerungen in Stahl: Metallografische Analyse und Chrakterisierung*, Springer-Verlag, 346-353 (in German).

Pokorny, M., Monroe, C., Beckermann, C., Bichler, L., Ravindran, C., 2008, Prediction of Hot Tear Formation in a Magnesium Alloy Permanent Mold Casting, *Inter. J. of Metalcast Fall*, 08, 41-53.

Rappaz, M., Drezet, J.M., Gremaud, M., 1999, A New Hot Tearing Criterion., *Met. Mat. Trans. A*, 30A, 449-455.

Roberts, A., Garboczi, E., 1989, Elastic properties of model porous ceramics, *J. Mech . Phys. Solids*, 37, 693-715.

Simo, J.C., Hughes, T.J.R., 1998, *Computational Inelasticity*, Springer Verlag, New York.

Tvergaard, V., Needleman, A., 1984, Analysis of the cup-cone fracture in a round tensile bar, *Acta. Metall.*, 32, 157-169.

PRZEWIDYWANIE I WERYFIKACJA PĘKANIA W WYSOKICH TEMPERATURACH ODLEWÓW STALOWYCH PRZY UŻYCIU LEPKOPLASTYCZNEGO MODELU USZKODZEŃ

Streszczenie

Pękania są uszkodzeniami dyskwalifikującymi wyrób, mogącymi występować w produktach końcowych odlewania stali. Uważa się, że pękanie powstaje z powodu powstających naprężeń rozciągających w strefie pół-ciekłej przy wysokim tarciu ciała stałego. W niniejszej pracy symulacja krzepnięcia i proces deformacji przeprowadzone zostały przy zastosowaniu przemysłowego oprogramowania w połączeniu z określonym przez użytkownika modelem konstytutywnym. Informacja o powstałej w wyniku krzepnięcia rzadziźnie jest włączona do modelu konstytutywnego odkształceń w stanie stałym, co pozwala obliczyć uszkodzenie materiału. W tym przypadku model lepkoplastyczny może przewidzieć tworzenie się pęknięcia przy odlewaniu stopów stali do formy. Zaobserwowano dobrą korelację między wynikami doświadczalnymi i uszkodzeniami przewidywanymi przez model.

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