Stress and Fatigue Analysis in Diecasting

Marco Aloe, Calcom ESI, Switzerland
Mark Samonds, ESI Software, France
Lorenzo Valente, ECOTRE sas, Italy

Abstract

Throughout the manufacturing industry, casting process simulation is now widely accepted as an important tool in product design, process development, improving yield and in solving processing problems. Die casting process issues related to hot tearing and cracking of the casting, thermal fatigue of dies, and prediction of the final part dimensions can however be a challenge. Powerful, multi-physics simulation tools are now available to address such issues. New dies can be designed on the computer, thereby eliminating expensive trial-and-error retooling procedures and achieving drastic cost savings in new process development and with the improvement of current production.

This paper will consider some of the factors influencing the accuracy of a coupled thermal, fluid and stress analysis of casting. After reviewing the different models implemented in the ProCAST software, various applications will be used to illustrate how simulations can be used to assess hot tearing, die fatigue and dimensional tolerances.

Keywords: FEM, casting simulation, thermo-mechanical coupling, die fatigue, hot tearing, cracking, ProCAST.

Introduction

Besides the defects related to filling and solidification, there are a number of stress related issues which can affect the final integrity of the die-cast component, as well as result in die failures.

Factors which influence the stress behavior and fatigue life of the die include geometry, thermal history, thermo-mechanical properties of the die and casting, thermal/mechanical contact algorithm, and external forces and pressures.

In order to accurately simulate the stress behavior, one should consider the full coupling between the thermal, fluid and mechanical stress analysis of all the relevant materials, including casting, cores and dies. The gap formation caused as a result of shrinkage during solidification and inversely contact pressure, will affect the heat transfer between the casting and the dies and needs to be taken into account.

Furthermore, dies may experience some local plastic deformation and thus one needs to consider both the elastic and plastic behavior of the die. Any local plastic deformation in the die would severely limit its life time and should therefore be avoided. Even when dies operate within the elastic region, their life time is influenced by the cyclic stresses which occur during processing.

A realistic assessment of these issues requires a fully coupled thermal-fluid-stress simulation. The finite element method [1] has been found to be superior for this type of simulation. Some of the considerations involved in the implementation of such a program include; 1) use of an appropriate material model, 2) unstructured mesh 3) thermal/mechanical contact algorithm, 4) implementation for mold filling and solidification, 4) fatigue life prediction, 5) hot tearing prediction, 6) cracking prediction, and 7) inverse displacements.

Material models

In order to simulate a variety of materials, several mechanical material models have been adopted in ProCAST. For cast parts and molds, the models include a thermo-elasto-viscoplastic model of the Perzyna type [2], a thermo-elastoplastic counterpart and an elastic model.

The elastoplastic model and elasto-viscoplastic model, in which all the parameters and functions are temperature dependant, are described in [3].

The first example demonstrates the importance of using proper material models in the stress analysis. The problem considered is an aluminum casting in a sand mold. The mold material model is chosen as elastoplastic with linear strain hardening. The casting material model is treated with two alternatives, elastic and elasto-viscoplastic. An isotropic linear hardening law is assumed for the elasto-viscoplastic model. The initial temperature of the casting is taken as 650°C and the mold temperature as 25°C. All material data are temperature dependent. The results in Figure 1 show the accumulated plastic strain for both material models. Naturally, with an elastic model for the casting, on the left, the only plastic strain occurs in the mold. Figure 2 depicts the corresponding final effective or von Mises stress. The elastic model results in a maximum stress in the casting more than twice that in the other model. The viscoplastic model can relieve stress through plastic deformation. Thus, if the absolute value of the stress in a casting is desired, it is necessary to utilize one of the nonlinear material models.

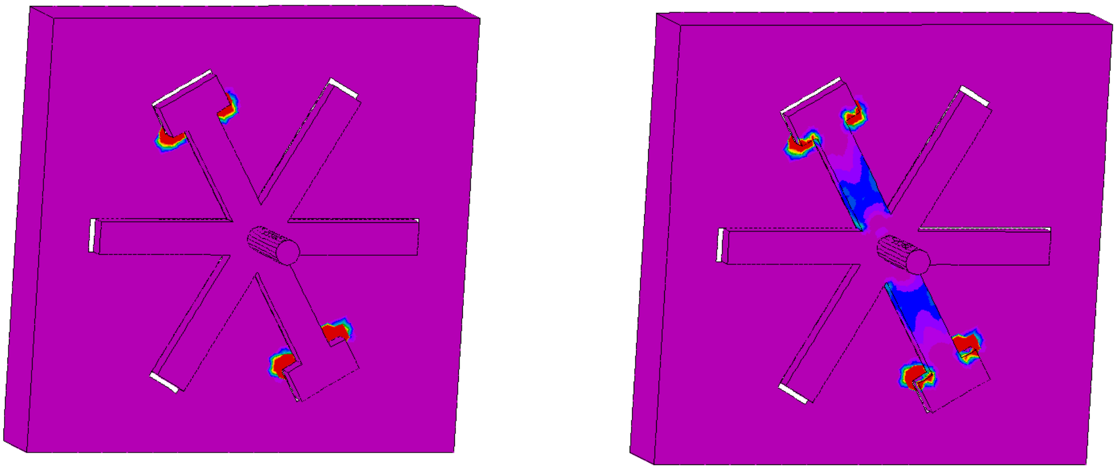


Figure 1 : Accumulated Plastic Strain, Elastic Model (left) and Viscoplastic (right) (ProCAST)

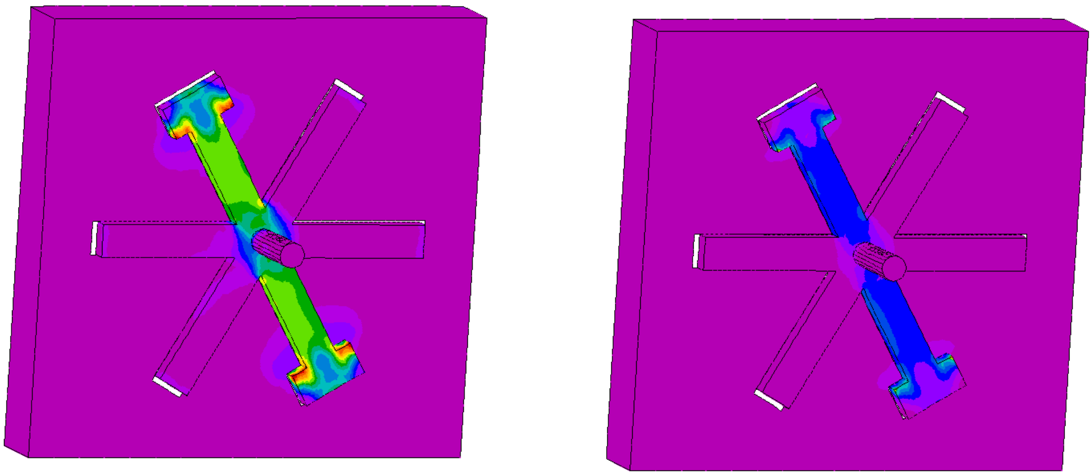


Figure 2: Effective Stress, Elastic Model (left) and Viscoplastic (right) (ProCAST)

Unstructured mesh

The Finite Element Method, based on unstructured meshes, has its roots in mechanical engineering and all major software for the simulation of stress and deformation are using this method today. Since structured meshes (used in FDM) are constrained to follow the coordinate axes, deformation calculations with such meshes are limited to small deformations, often in the elastic regime (see figure 3 (right) illustrating the problem of stair-like interfaces). As is well known, deformation of metals during cooling occurs to a large extent in the viscoplastic regime and this component must be absolutely considered if realistic simulations are to be obtained. This is necessary in particular to handle the loss of contact of two parts of a casting (e.g. the metal and the mould) when an air gap forms or the friction between them when they are in contact, thus influencing heat transfer (see figure 5). With unstructured meshes, the new position of the mesh points can be calculated at each time step. Thus, the mesh can be deformed and the contact/loss of contact events can be detected.

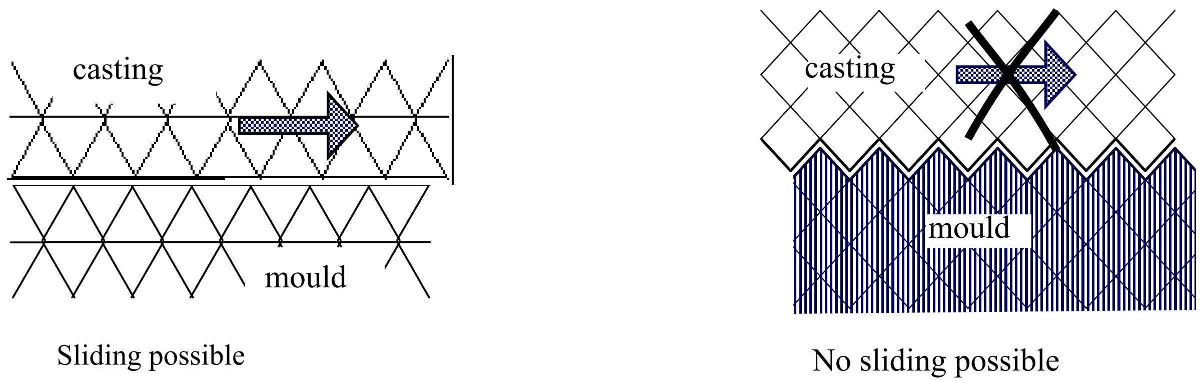


Figure 3 : Comparison between unstructured mesh used in FEM (left) and structured mesh use in FDM (right) in regards to stress calculations issues.

Thermal and Mechanical Contact of Casting and Mold

As described above, one of the critical aspects of the calculation is the treatment of the interfaces between the casting and mold, considering both thermal and mechanical aspects.

A multi-body mechanical contact algorithm is employed to compute the contact and gap formation between the casting and mold parts. Contact between different mold parts is also considered. An augmented Lagrangian type method [4] is used in the contact algorithm. Such a technique greatly enhances the stability and robustness of the contact computation algorithm.

Thermal contact between parts is considered by adjusting the interface heat transfer coefficient with respect either to the air gap width or the contact pressure as computed by the mechanical contact algorithm.

For demonstration purposes, a simple T shaped casting of A356 in a H13 mold is simulated, as shown in Figure 4. The effective interface heat transfer coefficient at two different points on the casting is plotted in Figure 5. The top curve is from a point experiencing increasing contact pressure as the casting contracts. The middle curve is from a point where a gap is opening up between casting and mold, assuming the presence of air. The bottom curve is from that same point, but assuming a vacuum. The large variation in the coefficient illustrates the importance of accounting for local conditions. In addition, this example illustrates the value of the reverse coupling of the mechanical deformations with the energy solution. This effect can be seen in Figure 4 on the right where the heat flux contours are plotted. The heat flux is greatest where the contact pressure is highest.

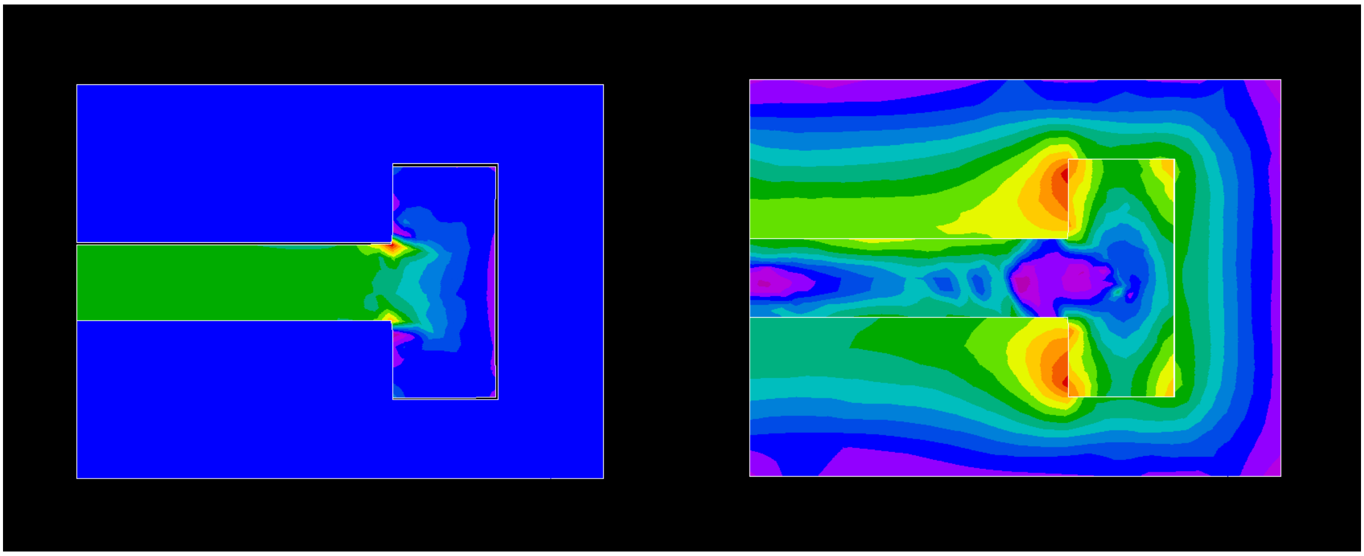


Figure 4: Principal Stress 1 and Heat Flux Contours (ProCAST)

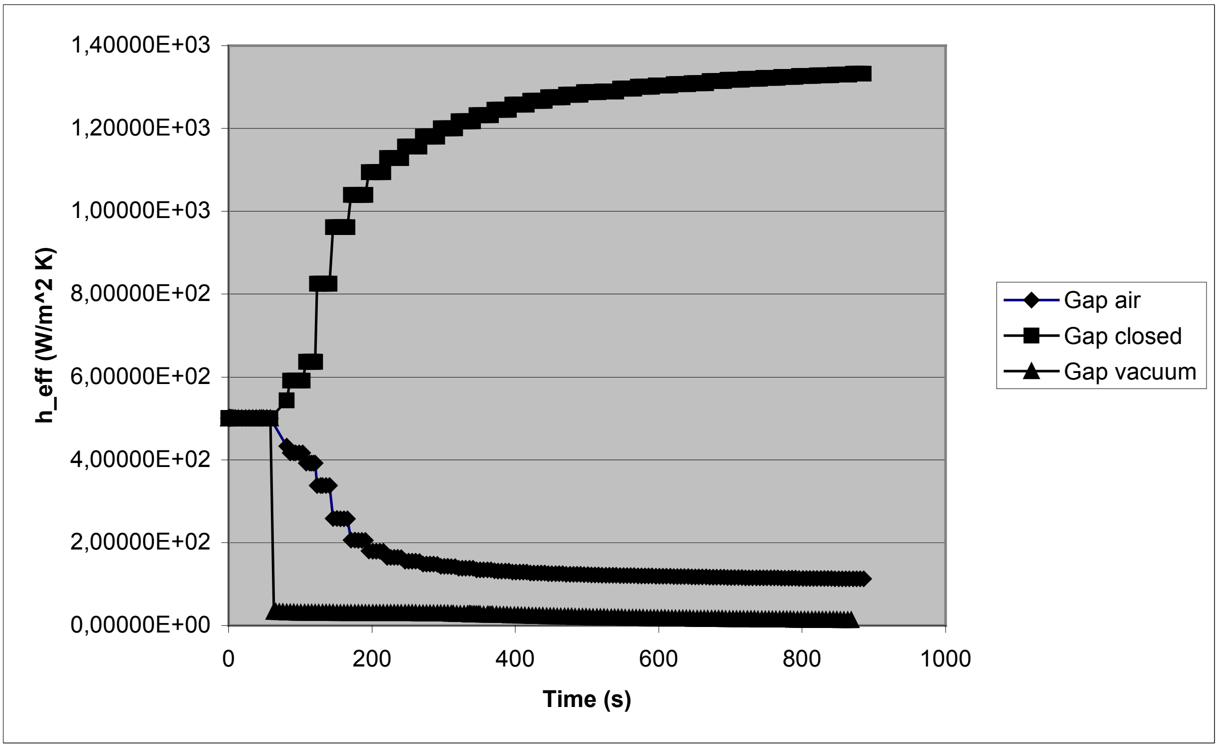


Figure 5: Interface heat transfer coefficients adjusted for mechanical contact

Implementation for mold filling and solidification

The casting process is simulated by a coupled thermal-fluid-stress analysis using the finite element method in an Eulerian-Lagrangian framework. Different types of elements can be used in the finite element discretization [1]. We refer to [5] for details of the elements used in ProCAST as well as for the implementation of the numerical algorithms.

When free surface flow is involved, as in filling, it is of course necessary to skip over the empty elements in the stress analysis. Care has also to be taken in the treatment of the liquid elements. Those elements that are connected by some path to a free surface can also be skipped. The volumetric change in those elements, due to thermal contraction and phase change, will be accounted for by the free surface algorithm. However, those liquid elements that are in a volume enclosed by solid need to be included in the stress calculation because that volumetric change will affect the stress state in the surrounding elements. For example, contraction in the liquid elements will result in a tensile stress that can deform a surrounding solid shell.

Fatigue life prediction

Designing a die to avoid fatigue failure is one of the more important and difficult tasks an engineer faces. Many factors are involved in the repetitious loading that causes fatigue failure. The model within ProCAST is based upon a "strain-driven" approach and a power law relationship, which corresponds to low cycle fatigue derived from the SAE J1099 Standard [6].

During the calculation, the accumulated plastic strain (if any) is recorded at each location of the die. If there is no plastic strain, then the elastic strain is recorded and the life of the die is calculated with another power law relationship.

This model can be used as an indicator for different steel grades generally used for molds. It should be mainly used to compare different designs with the same mold material (e.g. to compare the effect of cooling channels or of cycling time).

The fatigue life model is applied to a simple example of a high pressure die cast aluminum alloy component (see Figure 6), cast at 720°C, with one die half having a cooling channel positioned at the end of the casting. The full cycle includes filling, solidification, ejection and spraying. In a first scenario, we consider the cooling channel at 20°C and in a second scenario we remove the cooling channel. The effect of the cooling channel on the effective stress, as well as on the die fatigue, is clearly evidenced on Figure 7. The increased temperature gradient between the casting/die interface and the cooling channel increases cyclic stresses in the die. In the second scenario, as shown in Figure 8, the high stress regions have disappeared with the cooling channel and an improvement in fatigue life prediction is obtained.

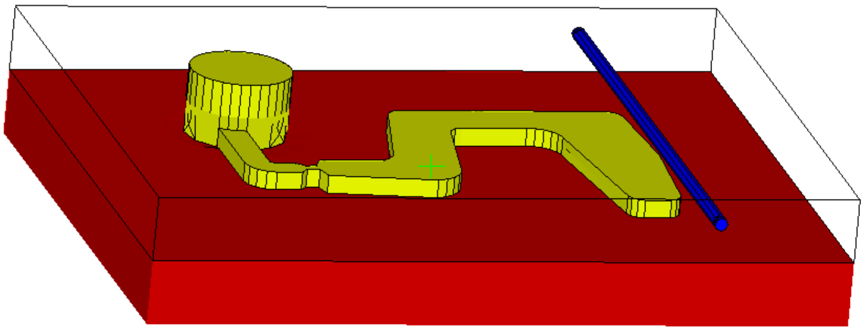


Figure 6: Geometry showing casting (yellow), cooling channel (blue) and dies (red).

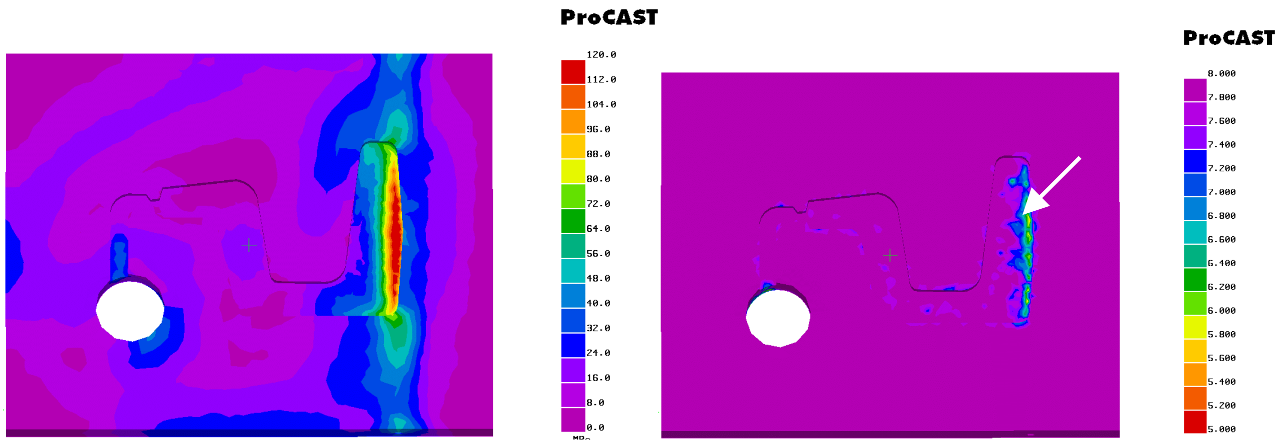


Figure 7: Effective stress in bottom die (left) showing high stress and fatigue life prediction (right) showing regions with limited fatigue life (with cooling channel).

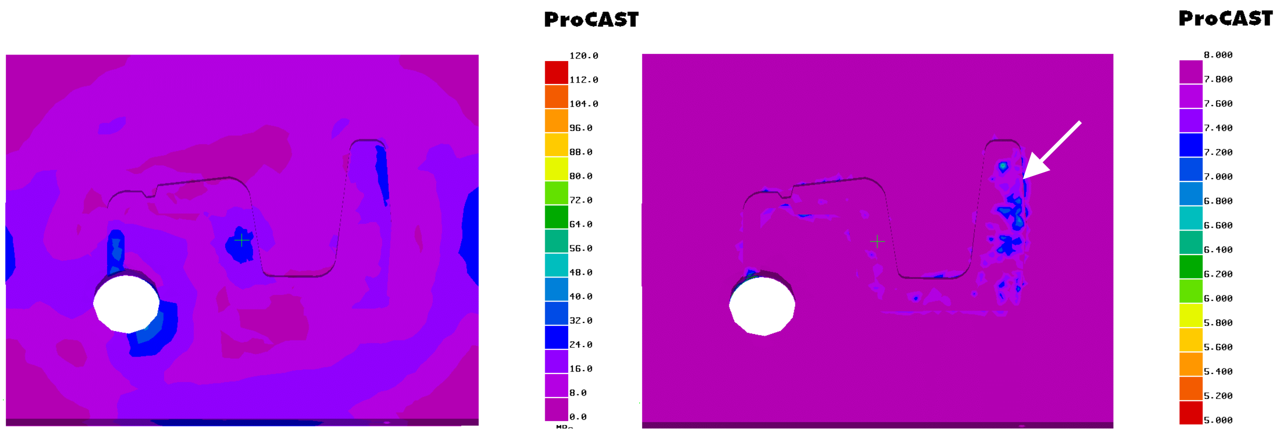
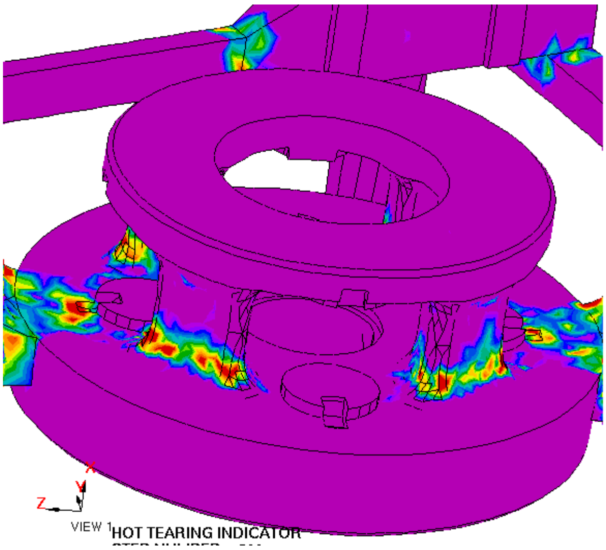


Figure 8: Effective stress in bottom die (left) showing limited stress and fatigue life prediction (right) showing regions with limited fatigue life (w/o cooling channel).

Hot tearing prediction

Hot tearing occurs when the strains that appear while the metal is still partially solidified cannot be compensated by liquid feed metal due to the low permeability of the mushy zone [7]. Longer freezing range alloys, where a liquid film persists between grain boundaries for a greater time, are more prone to hot tearing. Whether or not it occurs depends on the mechanical loads that develop due to thermal contraction and the contact constraints of the die wall.

We have found that the total strain, plastic plus elastic, that accumulates between a critical value of fraction solid and 1. is a useful indicator of hot tearing. Relatively high values of this quantity correlate well with the probability of hot tearing.



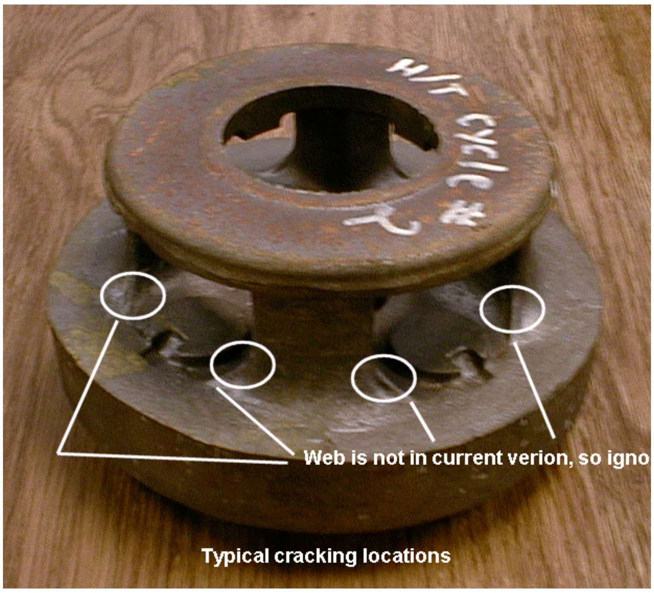


Figure 9: Industrial validation of a hot tearing prediction within ProCAST.

Cracking prediction

The cracking indicator model of ProCAST corresponds to cracks occurring after completion of solidification. The model is based upon the modified Gurson model. It corresponds to a plastic strain driven model where accumulated plastic strains allow cracks to nucleate and grow. All the plastic strain is considered, including plastic strains formed in the mushy zone. The model couples the stress calculation with the porosity calculation. The presence of porosity, corresponding to a void fraction indicator, will increase the risk of cracking.

Inverse displacements

One of the more challenging tasks of designing a die casting is figuring out the shrinkage allowance to add to the casting geometry. With a complex 3D geometry, shrinkage will be non-uniform. The presence of cores, inserts, or re-entrant corners of the dies further complicates the task.

A very powerful technique for coming up with an initial die geometry is afforded by the coupled casting simulation, starting with a CAD model of the desired net shape of the casting. It is meshed and simulated in a direct way, starting from filling, through ejection, and then cooling down to room temperature. This results in displacement values at every node in the mesh due to contraction and distortion. The software then inverts those displacements, applying them to the original mesh to produce an expanded initial geometry. This new initial geometry produces a casting that shrinks quite accurately to the desired net shape.

In Figure 10, a simple example of an aluminium male cross sign is used to demonstrate the method for correcting the distortions of the part. On the left, a part is shown distorted after casting due to constraints from the die. These distortions were automatically inverted in order to determine the correct die shape. On the right, the final corrected shape of the part is shown after casting.

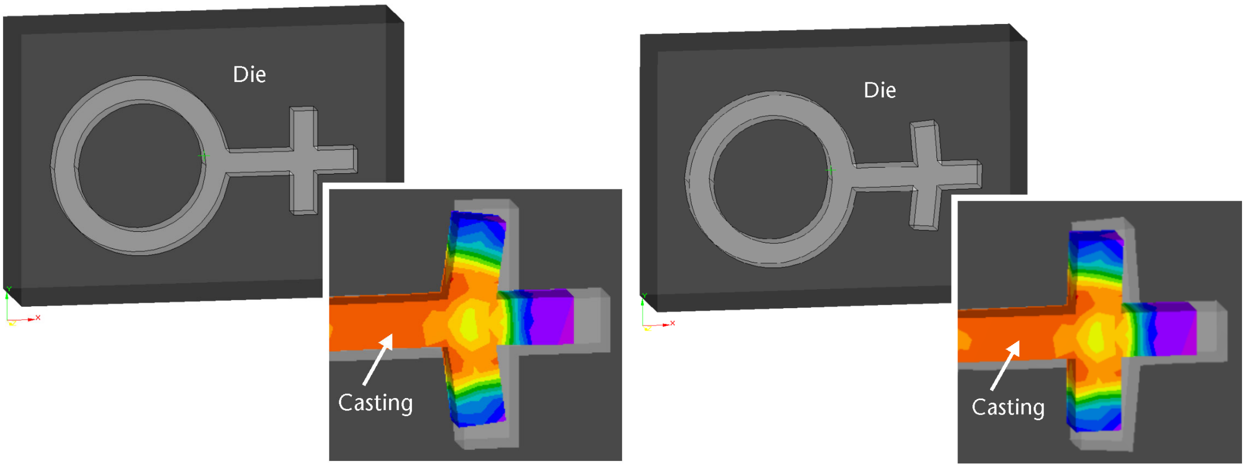


Figure 10: Effective stresses in the part after casting (left) and effective stresses in the part after modifying the die cavity in order to produce the required part shape (right). (ProCAST)

Industrial applications

An A390 alternator housing cast in H13 steel dies. Figure 11 shows the stress levels in the bottom die at a certain time during filling. These stresses occurring at an early stage of the process result in dimensional changes of the dies and a reduction of the casting volume.

The stress contours in the casting before and after ejection are shown in Figure 12. Because of the mechanical constraint of the dies, the stress levels in the casting can be quite high before ejection. The stress levels are substantially reduced after ejection when the contact constraint is removed.

The plastic strain in the casting is shown in Figure 13 (left). Plastic strain occurs when the local stress exceeds the yield stress. This results in a permanent deformation, unlike elastic strains which are recoverable after unloading. Hot cracking can occur if the ultimate tensile stress is exceeded. Figure 13 (right) shows the hot tearing indicator. Areas with higher values are more likely to produce hot tearing.

Finally, Figure 14 shows the fatigue life prediction in the two die halves. Lower values indicate shorter life expectancy.

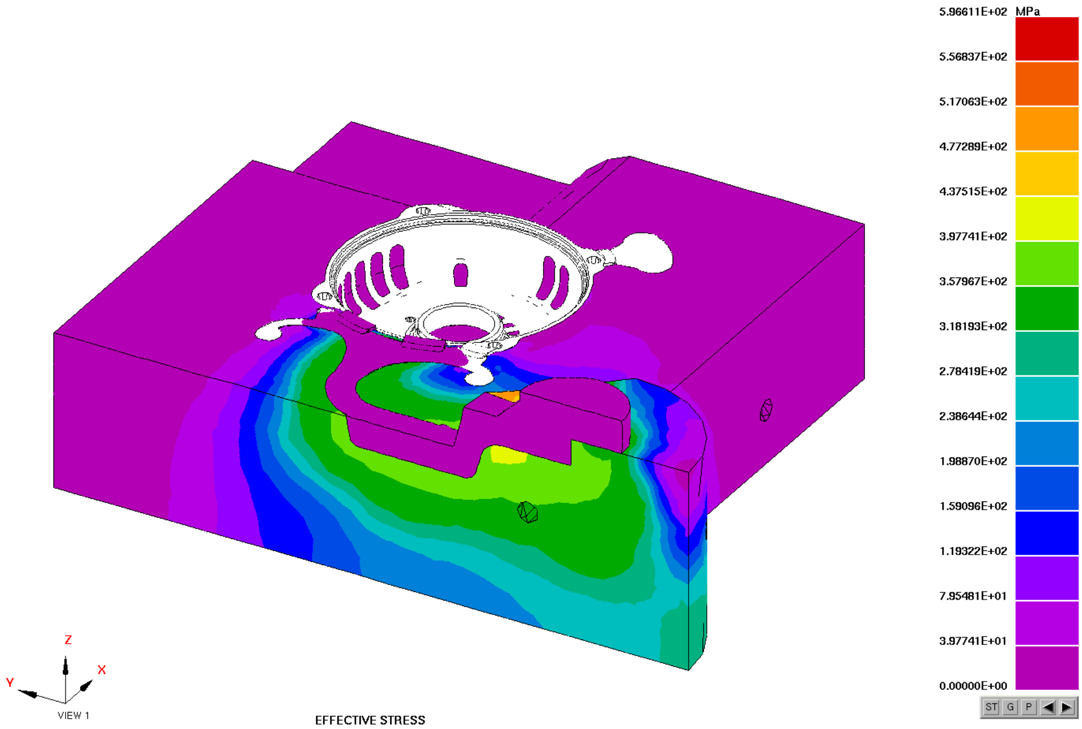


Figure 11: Stress development in the die during filling. (ProCAST)

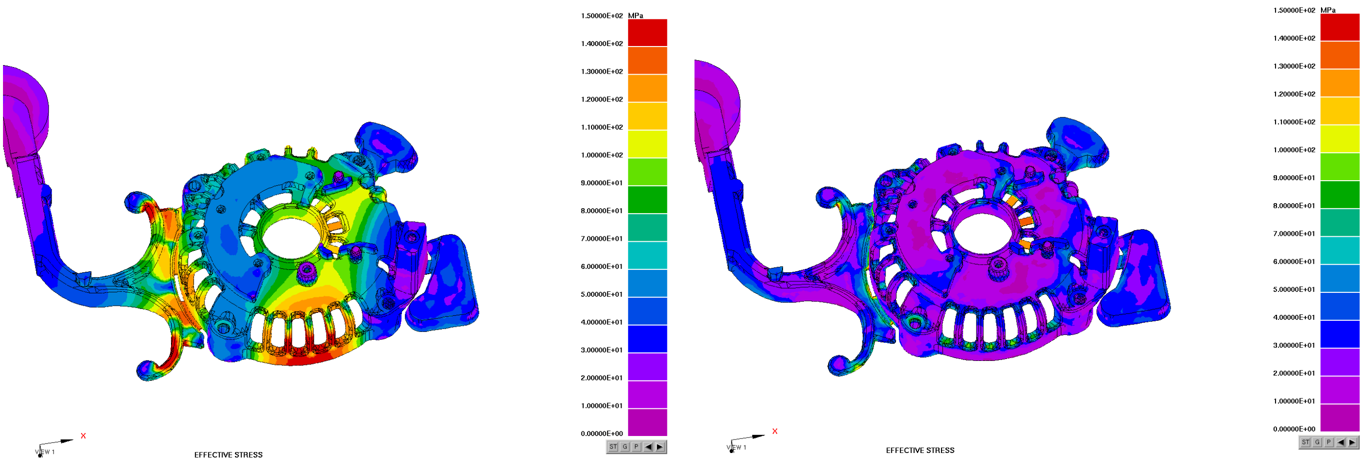


Figure 12: Stress in casting before ejection (left) and after ejection (right). (ProCAST)

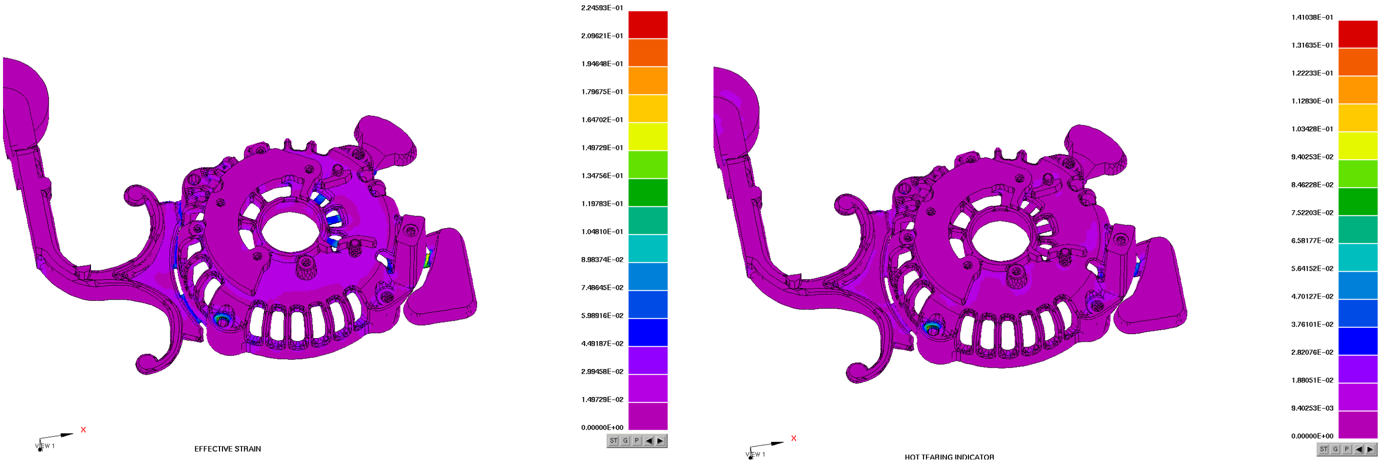


Figure 13: Plastic strain in casting after ejection (left) and hot tearing propensity (right). (ProCAST)

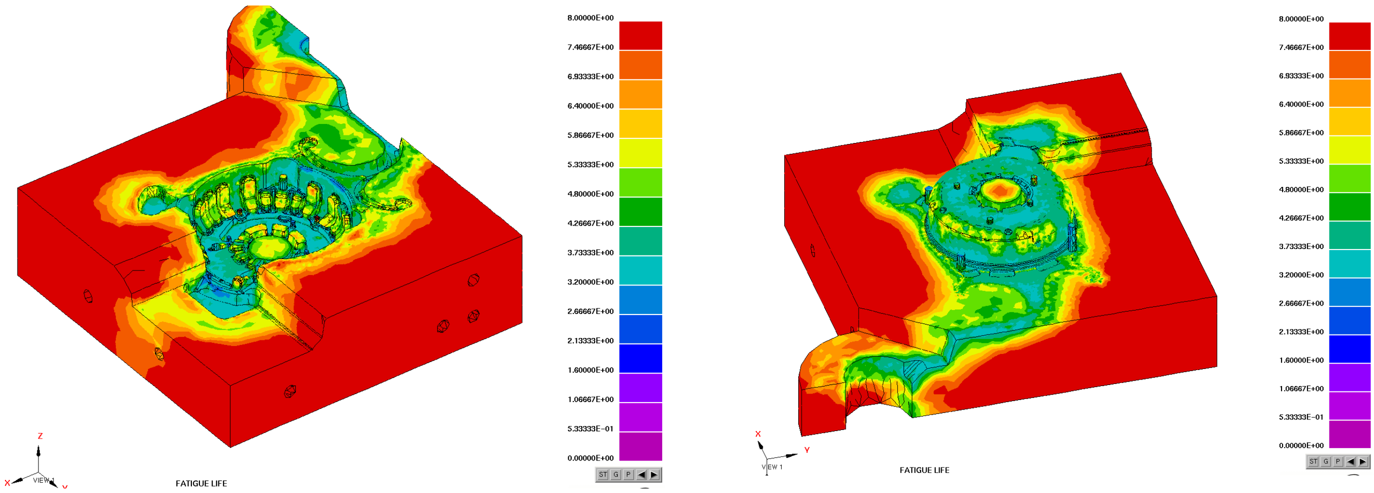


Figure 14: Fatigue life prediction in bottom die (left) and in top die (right). (ProCAST)

Conclusion

Casting process simulation has now reached a state where a relevant input for the design of a die can be given to the process engineers. Gating systems, overflows, venting channels can be optimized using numerical simulation. Solidification related defects can also be predicted taking into account cooling channels and die cycling so as to accurately reproduce production conditions.

ProCAST readily addresses all these issues but also includes advanced features to better assess the casting quality. These advanced features include fully coupled thermo-mechanical analysis with hot tearing, cracking and fatigue life predictions. The generalization of CAD modeling and the increase in performance of computers now allows for these technologies to be applied by the casting industry to full industrial applications.

References

1. O.C. Zienkiewicz and R.L.Taylor, 1991, The Finite Element Method, Volume 2, McGraw-Hill.
2. P.Perzyna, 1966, 'Fundamental Problems in Viscoplasticity', Advance in Applied Mechanics, Vol.9, pp. 243-377.
3. Mark Samonds, J.Z. Zhu, Adi Sholurwalla, "Integration of Thermal Stresses Simulation with Process Development in the Modern Foundry", Nadca 2002.
4. J.C. Simo and T.A. Laursen, 1992, 'An augmented Lagrangian treatment of contact problems involving friction', Comput. & Structures, Vol. 42, pp.97-116.
5. ProCAST User Manual & Technical Reference, 1998-2004.
6. Technical Report on Low Cycle Fatigue Properties, J1099, Society of Automotive Engineers, Warrendale, PA, 1998.
7. John Campbell, 1993, Castings, Butterworth-Heinemann Ltd.