USING STRESS SIMULATION TO TACKLE DISTORTION AND CRACKING IN CASTINGS

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Abstract

The use of stress simulation in casting design and manufacturer has found wide spread use in not only the automotive industry but also more general engineering castings. The development of light-weight body structures in the automotive industry has lead to a new generation of large thin walled complex aluminium and magnesium castings with demanding dimensional and stiffness tolerances, which require particular attention to casting design and production techniques. To achieve economic production long die tool life is required and thermo mechanical fatigue cracking 'heat checking' is often the limiting factor. Minimum distortion and maximised die life can be achieved by using simulation tools and optimisation techniques during casting design and production. A group of companies with competences in casting simulation, material testing, design and high pressure die casting has worked together on the overall design and manufacturing process and examples will show the success of this approach. The paper will give a review of the current capabilities of the application of a numerical simulation to stress related problems in casting manufacture.

Riassunto

Il presente lavoro aspira a validare un modulo software di nuova concezione, e aggiuntivo al pacchetto commerciale di software di simulazione, che permette la predizione della microstruttura e delle proprietà meccaniche di leghe in alluminio in differenti condizioni di colata. La simulazione del processo di colata e delle risultanti microstrutture e proprietà meccaniche, permette la riduzione delle prove sperimentali e provvede al miglioramento della selezione di materiali e processi, consentendo inferiori costi di progettazione e sviluppo.
I risultati della simulazione vengono comparati con le indagini microstrutturali e di comportamento meccanico di una testa cilindri grezza in alluminio prodotta per colata a gravità. Si dimostra che le predizioni ricavate dalla simulazione sono comparabili con i risultati sperimentali. Al fine di migliorare ulteriormente la qualità degli strumenti simulativi, è vitale acquisire maggiori esperienze dal confronto con getti di maggiore complessità geometrica e in differenti leghe di alluminio, dove sia le microstrutture che le proprietà meccaniche siano attentamente analizzate.

KEYWORDS

Casting Simulation, Distortion, Hot Tearing, Residual Stresses, Die Constraints, Heat Treatment, Visco-Plastic Simulation, Heat Checking, Die Life.

INTRODUCTION

With the production of thin walled structural components the foundry industry has been able to substitute classic pressed parts with castings. The generally large surface area complex castings with demanding dimensional and stiffness requirements place high demands on design and production by high pressure die casting. Along side the formation of hot tears, the distortion places great demands on the process.
Certain parts that are particularly prone to hot tearing which has lead to the replacement of non heat treatable alloys to ones requiring heat treatment. This increases the productions cost due to the addition of heat treatment, which can also lead to distortion of component.
Tackling the distortion requires an accurate understanding of the distortion mechanism of each individual production stage as well as how they interact. Due to the numerous parameters, simulation of the complete production process is a powerful tool. With this in mind a group of companies with expertise in simulation, materials testing, design and production of die casting dies formed a consortium as part of a BMBF funded research project. Some of the results of this project are presented in this paper. The knowledge gained in the project has been applied to some additional high pressure die casting components for the prediction of hot tearing tendency and is presented here.

FORMATION OF RESIDUAL STRESSES AND DISTORTION IN CASTINGS

The formation of residual stresses and distortion can be easily understood by the simple example given in figure 1. The solidification and cooling to room temperature of all castings occurs with an inherent inhomogeneous temperature distribution. When areas which are cooling faster, such as the thinner side arms of the lattice, thermally contract and are constrained, tensile stresses are formed. At high temperatures where yield stress is low thermal stresses are relieved to some degree by plastic deformation. The highest stresses and plastic deformation occur when the temperature difference between faster and slower cooling rate areas is at a maximum (figure 1 $t=t_1$). As cooling proceeds, the temperature difference between the two areas decreases. This initially leads to stress relief (reduction in tensile stress level) and then to a change in the stress state from tensile to compressive in the thinner, faster cooling outer arms. In the slower cooling thick arm the initial compressive stress changes to tensile. This stress transition is due by plastic deformation at high temperatures. After complete cooling to room temperature, figure 1 $t=t_2$, compressive residual stresses arise in the thin side arms areas, whereas tensile residual stresses arise in the thick central arm /1/.
The residual casting stresses can be affected by subsequent processes such as clipping, straightening, heat treatment, machining and shot blasting. The residual stresses can be redistributed during clipping and machining but additional tensile and compressive stresses can be introduced into the casting by machining and clamping forces or heat treatment. In the worst case cracks can form in the casting during machining /2/.

The calculation of residual stresses caused by the casting process is carried out in a decoupled 2 stage process. Firstly, the temperatures in casting and die casting tool are calculated by a filling and solidification simulation. Secondly, these temperatures are used for the stress calculation. A knowledge of temperature and microstructure dependent thermal and mechanical properties of the casting material as well as the consideration of the shrinkage constraints caused by the tool are crucial parameters for the accurate calculation of residual stresses.

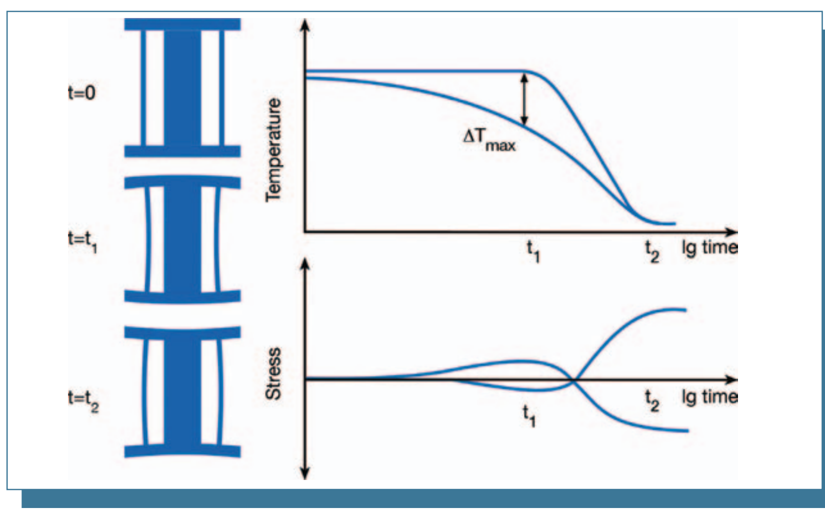

Fig. 1: Formation of residual stresses and distortion in a stress lattice

HEAT TREATMENT RESIDUAL STRESSES FORMATION AND DISTORTION

Most structural castings do not meet the required mechanical properties after casting and subsequent heat treatment is used, which usually consists of a solution anneal, quenching and artificial ageing or precipitation treatment. During the solution anneal process, the casting is heated up to a temperature below solidus temperature. The yield stress of material reduces with increasing temperature and residual stresses are relieved by plastic deformation. At these temperatures the casting can deform under its own weight. In the subsequent quenching inhomogeneous cooling again leads to the formation of new residual stresses /3/ - /5/. These stresses can lead to further distortion. In the subsequent ageing process, the residual stresses can be reduced by 20-30% due to creep and plastic deformation, causing further distortion. The level of stress relief and distortion is dependent on the residual stress after quenching, the ageing temperature and the ageing duration.

SIMULATION OF THE DISTORTION OF A STRUCTURAL COMPONENT

Starting point for any simulation is a three-dimensional geometry model of the casting, the runner and overflows, the die casting tool with the die heating and cooling circuits. Figure 2 shows a die cast rear door lock panel for a passenger car. The whole geometry model is subsequently enmeshed for the calculation.

The simulation considers all relevant process conditions, including the shot profile, the temperature of melt, inhomogeneous die temperature and die cooling, die spraying as well as the casting cycle time. The simulation should reflect the steady state condition of the process after sufficient 'preheating' cycles as is carried out in die casting production. Once steady state is reached, the filling, the solidification, and the cooling of the casting are simulated.

The calculated temperatures over time are applied to casting and runners as external loads in the subsequent stress calculation. The areas, that cool down fastest, solidify and start to contract rapidly. The contraction is at least partly constrained by the die. Consequently tensile stresses form. Immediately before ejection from the die, tensile stresses occur in nearly the whole component, Figure 3.

After ejection, the shrinkage constraint caused by the die is removed and the casting and runner can

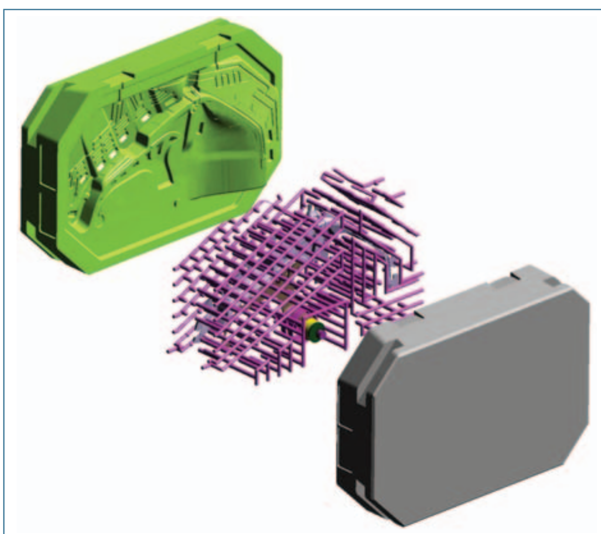

Fig. 2: Geometry of the component including runner system, water cooling and oil tempering control channels, and the two die halves.

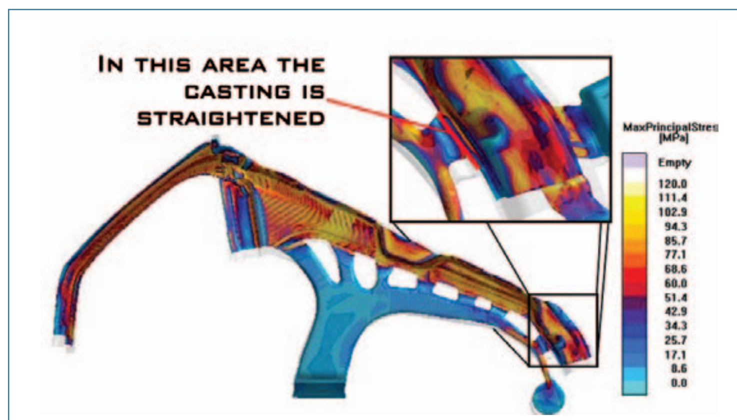

Fig. 3: Maximum Principle Stress in the rear door lock panel casting just before ejection. The original geometry is shown as semi transparent grey, as well as the deformed geometry showing the relative shape change and areas of contact and constraint.

now contract freely. The runners and gates influence the contraction of the casting, with the casting being bent towards the shot slug. The temperature field at ejection, figure 4, is the basis for the formation of stresses and deformation during cooling down to room temperature.

As the runner is generally hotter, it contracts more in the subsequent cooling phase and pulls the casting inwards towards it, Figure 5. The swan neck moves in an upwards direction, as the upper side of the casting, which faces the shot slug, has a higher temperature than the lower side after ejection.

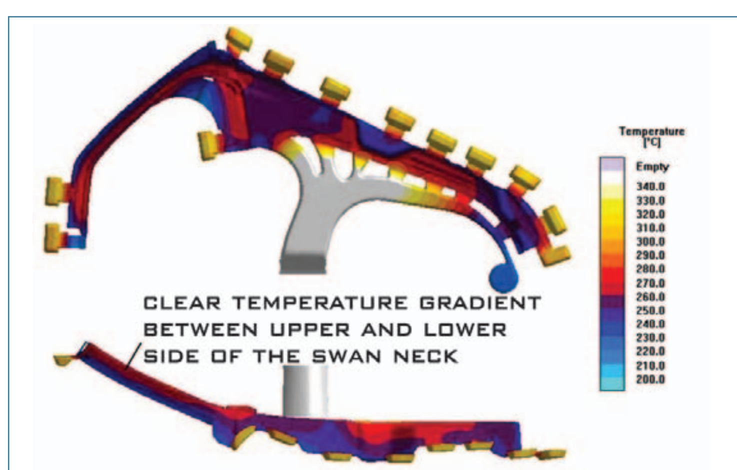

Fig. 4: Temperature distribution in the casting and runner at ejection.

Figure 6 shows the deviation from the required dimension for a contour of 23 measurement points after casting. The diagram displays the average value of all measurements (15 castings, blue line), the upper and lower limit of the measurements (dashed lines), and the results of the simulation (red line). The datum points are also shown in the diagram. It can easily be seen that the calculated distortion corresponds well to the measured.

After the removal of the runners and gates during clipping, the component opens outwards towards its starting point slightly, Figure 7. However, a certain bending towards the gate can still be seen. The correlation between the measured and simulated distortion values is still very high after clipping.

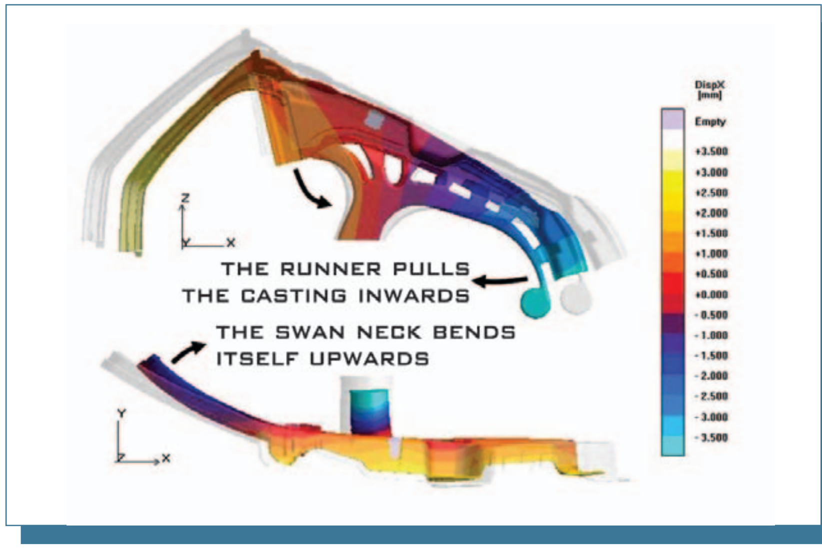

Fig. 5: Deformation of the casting after cooling to room temperature shown as displacement from the starting point in the x direction. The original geometry is shows as semi transparent grey with the deformed geometry coloured.

SIMULATION OF HOT TEARING IN HIGH PRESSURE DIE CASTING

In addition to the prediction of distortion, the prevention of hot tears is another challenge to tackle in the high-pressure die casting process.

Hot tears are tensile cracks that occur during the solidification. They often form in thicker sections, which are harder to feed and are subjected to mechanical loading due to solidification contraction, which is in turn influenced by the die constraints. Hot tearing tendency is also alloy dependant and alloys with a high solidification contraction levels and a long solidification range are more likely to develop hot tears.

Areas with a tendency to develop hot tears can be identified by casting simulation using certain hot tear criteria. Figure 8 shows the result of a hot tearing calculation for a flywheel and the associated cracked areas of the real part. The formation of hot tears can often be prevented by modifying process parameters and cooling conditions, or by minor changes in the geometry.

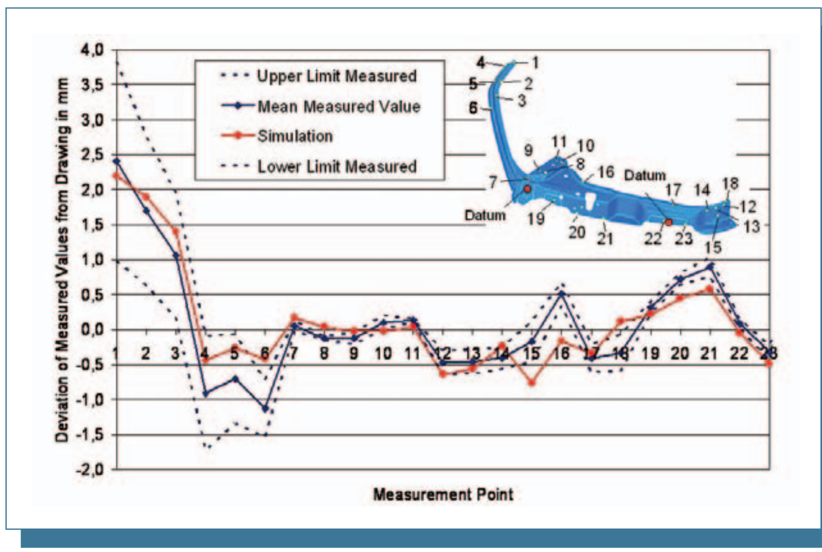

Fig. 6: Comparison of the measured and calculated deviation from the required design geometry for 23 measuring points of the rear body lock panel.

SIMULATION OF DISTORTION DURING HEAT TREATMENT OF A CAST BULK HEAD

The production process for automotive high pressure die cast components often includes a heat treatment stage. The reduction in as cast residual stress levels occurs as the heating of the casting during annealing reduces the necessary stress level to initiate creep deformation. Using a new

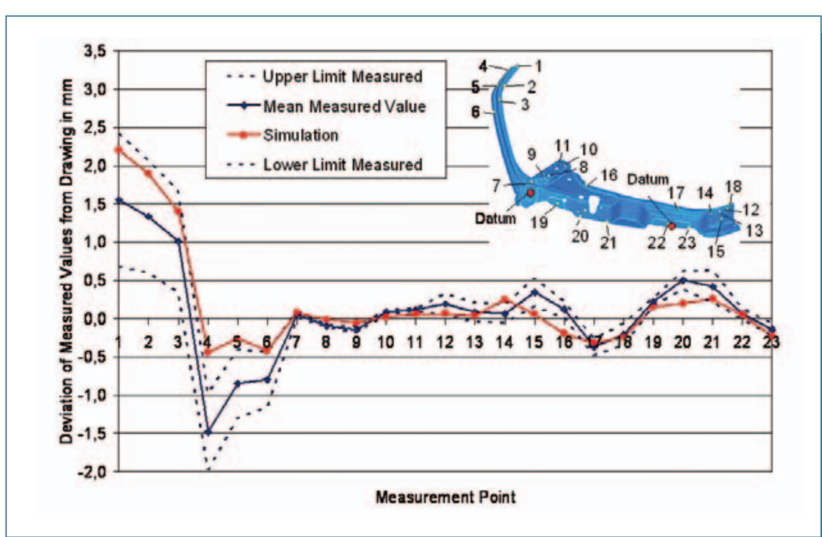

Fig. 7: Comparison of calculated and measured distortion after clipping.

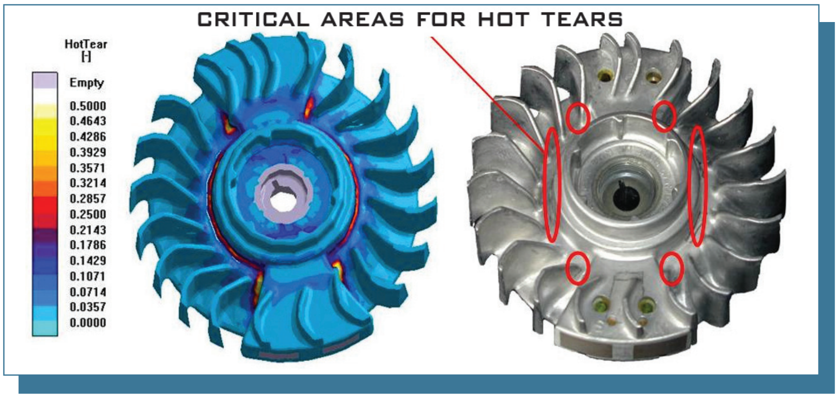

Fig. 8: Prediction of areas with a tendency to develop hot tears for a flywheel casting using a hot tear criterion.

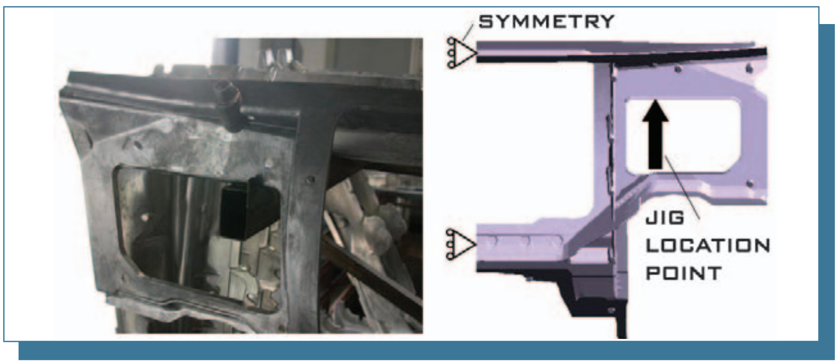

Fig. 9: Jig location points the bulk head during heat treatment.

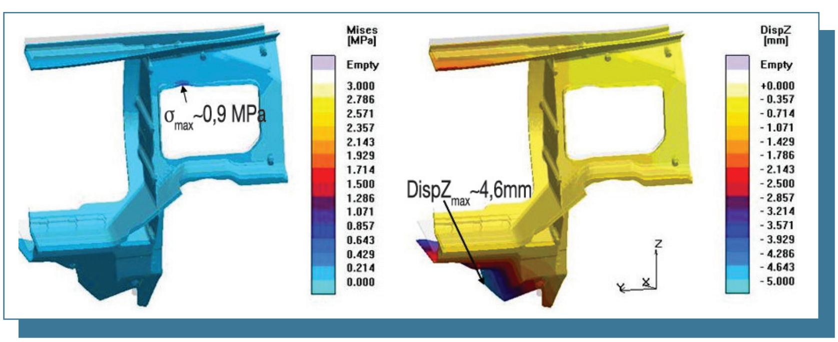

Fig. 10: Stresses and deformation of the bulk head after solution heat treatment. The original geometry of the bulk head is shown in semi transparent grey.

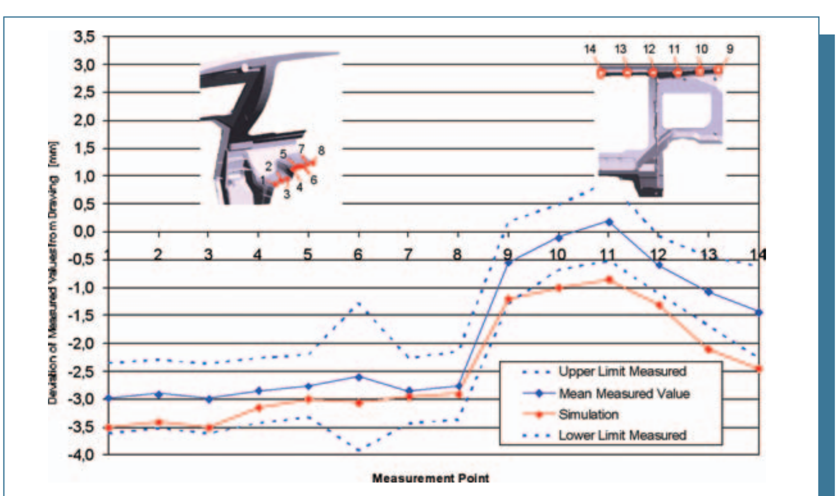

Fig. 11: Comparison of the calculated and measured distortions of the bulk head after heat treatment.

simulation model, visco-plastic strain has been taken into account for the first time. As an example the annealing of a 'bulk head' casting is shown here. During heat treatment the casting is mounted on a horizontal bar on both sides, as it can be seen in Figure 9. The simulation considered the symmetry of the geometry and only half the model is shown and was simulated.

After analyzing measurement data, it was found that the 'solution anneal' process has the largest and most significant influence on the overall distortion. This process step was simulated using the visco-plastic model which can also simulate creep in castings at elevated temperatures, as occurs in annealing. Figure 10 shows the stresses and deformation after solution annealing. The maximum stresses in Figure 10 are only ~0.9 MPa. This is can be compared to typical stress after casting of 20 to 50MPa. The distortion which occurred during the heat treat anneal is also shown with the maximum displacements of approximately 4.6 mm.

The simulated dimensional deviations from the nominal, as well as the average, the lower and upper measured values are displayed in Figure 11. It can be seen that the simulated distortion value of the casting correlates well with the measured average values. Without the inclusion of the visco-plastic material law, an accurate simulation would have not been possible.

FATIGUE LIFE OF HIGH PRESSURE DIE CASTING TOOLS

Die casting tools usually have a limited life due to the thermal fatigue cracking or 'heat checking' of the die surface, which is caused by high cyclical thermal loads. The main features of the temperature and stress cycling are shown in figure 12. The surface of a die is exposed to a rapid increase in temperature as the metal fills the die and the casting solidifies. After ejection the die surface cools as the source of heat, the casting, is removed. If as is normally the case, the die surface is sprayed and experiences very rapid cooling as the water base of the die spray evaporates. As the die heats up during filling and solidification compressive stresses develop in the surface of the die as it tries to expand but is constrained by the cooler subsurface areas. After ejection the compressive stress level reduces and as spraying occurs the stress becomes tensile, peaking just after the end of spraying, as the surface tries to contract but is constrained by the now hotter subsurface areas. This process repeated over a few thousand cycles causes thermal fatigue cracking in the surface of the die and the appearance of heat checking. The cracks that form are effectively stress relieving the die surface.

Not only the thermal load plays an important role in tool life, but also the manufacturing stages of die machining, eroding, finishing, hardening, the die steel used, the casting alloy, as well as the design of the die /6/-/8/.

The calculation of the anticipated tool life of high-pressure die casting dies consists of three steps. Firstly, the temperature distribution in the die during filling, solidification, cooling, and spraying is calculated. Secondly, these temperatures are applied as external loads for the calculation of thermal stresses in the die tool. Thirdly, an analysis is performed of how the calculated cyclical stress loading is expected to influence the onset of heat checking.

The thermal stresses of the die casting tool of the earlier described rear door lock panel (figures 3 to 5) were calculated for one casting cycle. Based on the results, the expected life time of the tool is established. The calculated life times were compared with the crack patterns of the actual die after 50,000 cycles, Figure 13. Critical areas are shown in the evaluation in blue, less critical areas in yellow to white.

As can be seen in Figure 13, the area around the ejector pins on the runner shows radial cracks, with a calculated life time of about 2,000 cycles. A critical area is where the runner splits and has it largest cross section. The areas on the right of the die photo and simulation image in the figure 13 also shows a critical area where the runner splits into 3 ingates, light blue. Figure 13 also shows a critical area in the swan neck of the casting. The geometry has 3 notch type features. The notch effect will lead to higher stress concentrations and lower tool life time which is seen in the resulting die photo and in the lower calculate life cycles.

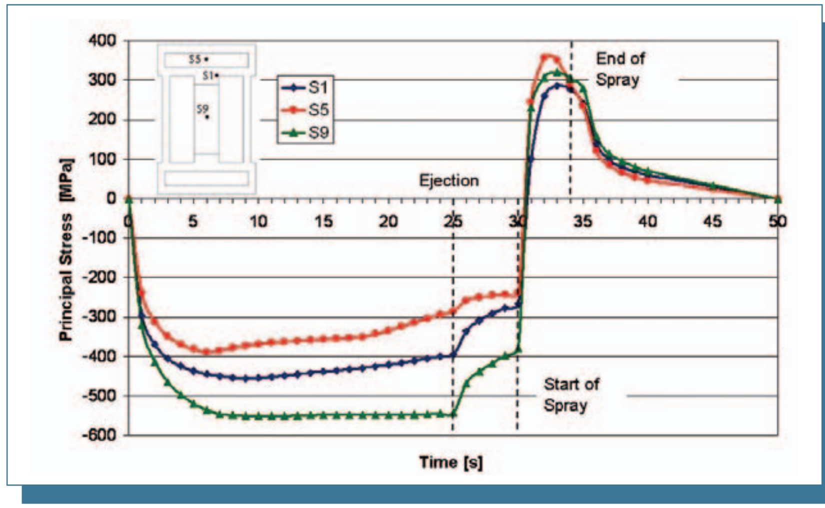

Fig. 12: Typical stress changes for three points in the die surface during one casting cycle.

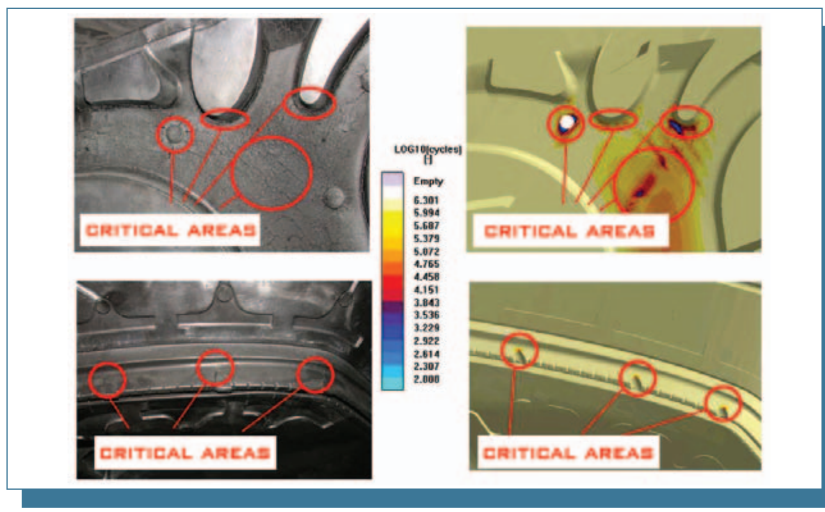

Fig. 13: Comparison of the calculated die life (right) with the actual crack pattern in the area of the gate and the swan neck (left). The most critical areas are marked with red circles.

CONCLUSION

The control of the distortion of large thin walled structural components places great demands on the producers of such castings. For a successfully approach, a prerequisite is an exact understanding of the mechanism by which the distortion occurs as well as its design dependant effects. With the help of the latest methods of casting simulation, it is now possible to accurately predict the deformation due to the casting, clipping and heat treatment processes. Based on this understanding and capability it is also possible to determine preventative actions to distortion such as a pre-emptive deformation of the designed geometry, *'bend the die to straighten the casting'* and pre-emptive development of heat treatment orientations and jigging.

As well as prediction of residual stress and distortion, today it is possible to predict areas prone to hot tearing and thermal fatigue stress 'heat checking' in die tools. With these developments simulation can support the high pressure die casting in securing an increased field of application in thin wall cast structural components.

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