Integration of manufacturing process simulation in to the process chain

Closing the gap between CAE supported design and manufacturing process simulation

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Summary

CAE techniques from CAD to lifetime prediction are essential support tools to the design process for automotive castings, particularly for power train parts. Substantial savings in development time, costs and risks gained by an increasing grade of integration between the different CAE tools, have been reported. Technical effects are clearly visible as well: filigree casting structures, fulfilling increasing demands for mechanical durability, have been created. But with more and more sophisticated designs, the risk of failure during durability tests or in the field, caused by wrong simulation results, increases as well. This point is also reported.

This might be boosted by lack of focus on manufacturing process specifics within the design process chain. This contribution aims to clarify, how specifics like residual stress in castings or an inhomogeneous distribution of mechanical properties can be found by manufacturing process simulation, and be integrated with the CAE tools which support the casting design process.

As example, the casting process of a FORD V6 iron engine block was simulated. In detail, the phase distribution being formed during solidification and further cooling were simulated, and based on this the distribution of mechanical properties like the Youngs Modulus was calculated and prepared to be transferred to FE analysis. Also based on the “thermal history” of the casting, the residual stress distribution was simulated and then transferred from the structured mesh which is used for the casting simulation to an FE mesh for the simulation of stress rearrangement during machining of the block.

Keywords

Casting simulation, process simulation, FE analysis, residual stress, mechanical properties, integration

0. Design process ignores manufacturing specifics

The design process for automotive castings is, particularly for power train parts, supported by CAE techniques from CAD to lifetime prediction. State of the art is a quite developed grade of integration between the different CAE tools, what already leads to substantial savings in development time, costs and risks.
Today, there is a lot of trust in the simulation technologies being incorporated in the design process. This means that, for example in the case of automotive power train castings, no part will be released without extensive validation by all kinds of acoustic, flow, stress/strain or fatigue simulations. But with the trust in these simulation comes the risk: wrong simulation results can forward an effect far into production. This risk exists particularly, if manufacturing process specifics are not considered in the design process to the right extent. Such specifics, characteristic for castings and almost not avoidable, are for example residual stress and inhomogeneous mechanical properties.
The reasons why these manufacturing process characteristics are often ignored in the design process are some missing links between CAE tools for design and manufacturing process layout, and the lack of focus of designers on the manufacturing specifics.
The motivation for this contribution is to show, based on an example of an iron V6 cylinder block, how the simulation of the manufacturing process can deliver extremely important information for the FE analysis during the design process. As example for the information, which can be integrated into the design process, the distribution of both residual stress and mechanical properties is shown. Since this contribution is not focused on FE analysis, the residual stress rearrangement during the machining process, simulated on a FE mesh, is used as example for the integration between different simulation tools with different meshes.

1. Simulation of the manufacturing process of engine blocks

Casting simulation has become quite well accepted, mainly in the casting supplier industry. There the simulation is used to design or optimize the casting process, while part design and specifications often are already fixed. The simulation can generally be divided into mould filling, solidification, properties and residual stress calculations [1].

1.1. Mould filling simulation

The geometries of casting, runner and riser system, and the mould are usually directly taken from 3D CAD data. For mould filling simulation, state of the art is to use Navier-Stokes, coupled with Fourier approaches. The flow will generally be treated as laminar flow, while turbulence effects are considered using a modified k/ε method. Today, enmeshments for a complete setup consisting of casting, runner and riser systems and mould have up to 180 Million control volumes. Figures 1.1 and 1.2 show some results from a mould filling simulation for a FORD V6 iron block.

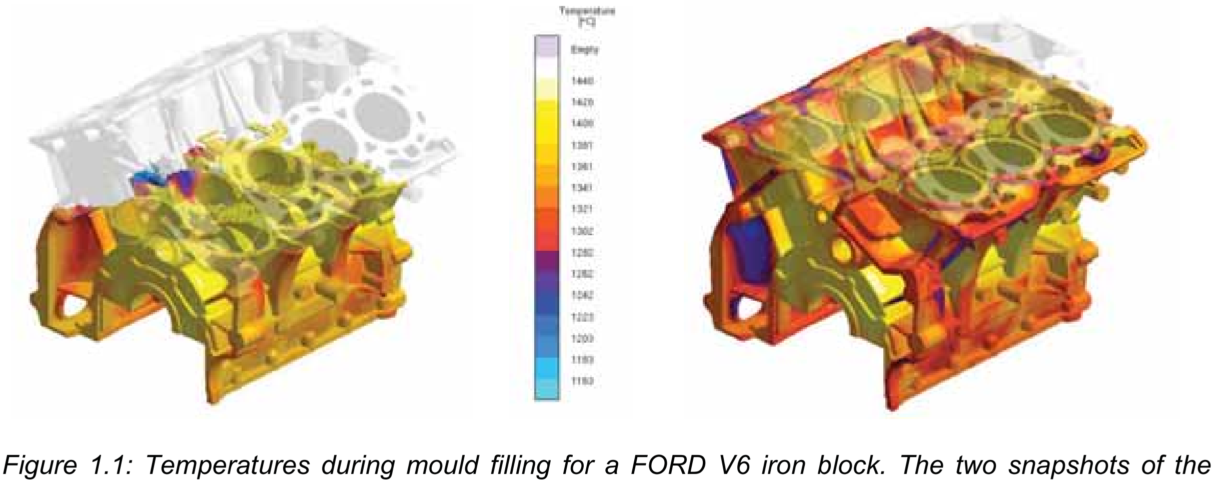

Figure 1.1: Temperatures during mould filling for a FORD V6 iron block. The two snapshots of the mould filling process shown here clearly document the temperature loss of the melt during filling. The temperature distribution at the end of filling is an initial boundary condition for the subsequent solidification simulation.

1.2. Solidification simulation

The simulation of the solidification is usually directly attached to the mould filling simulation. The temperature distribution of the casting and the mould at the end of the mould filling process is an initial condition for the solidification simulation. The models for cast iron take into consideration, that local undercooling and therefore the phase formation depends on the alloy constitution, the nucleation conditions and the local cooling rates. The results, which could be gained from the solidification simulation, are the temperatures during solidification, Figure 1.2.1 and critical sections for feeding, which indicate locally weakened microstructure, Figure 1.2.2.

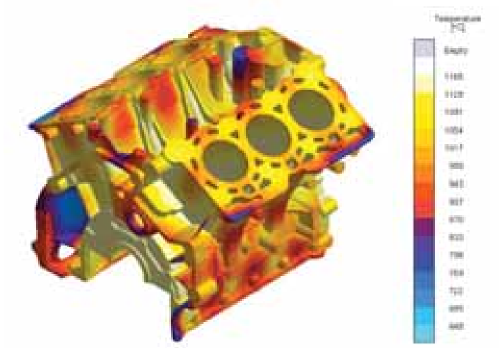

Figure 1.2.1: Temperatures during solidification for a FORD V6 Lion block.

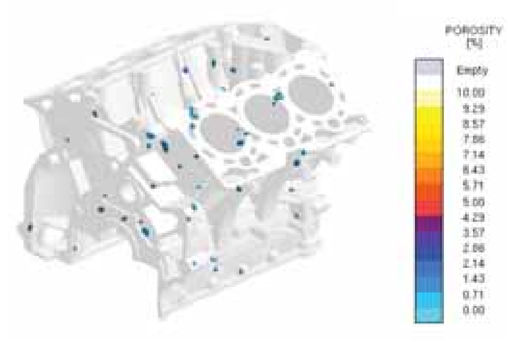

Figure 1.2.2: critical sections for feeding for a FORD V6 Lion block.

2. Determination of manufacturing process specifics

Based on the “standard” casting simulation results as described above, the inhomogeneous mechanical properties distributions as well as the residual stress distribution can be calculated. The “first level” simulation results as temperatures, cooling rates and temperature gradients are the basis for these “second level” simulation results.

2.1. Casting properties calculations

The formation of microstructure and, based on this, of mechanical properties depends of the casting alloy and several metallurgical and process related conditions such as nucleation, local cooling rate and local undercooling of the melt [2]. If the simulation model takes this into consideration, it is possible to calculate the distribution of phases, Figure 2.1.1, as well as the resulting distribution of mechanical properties, Figure 2.1.2.

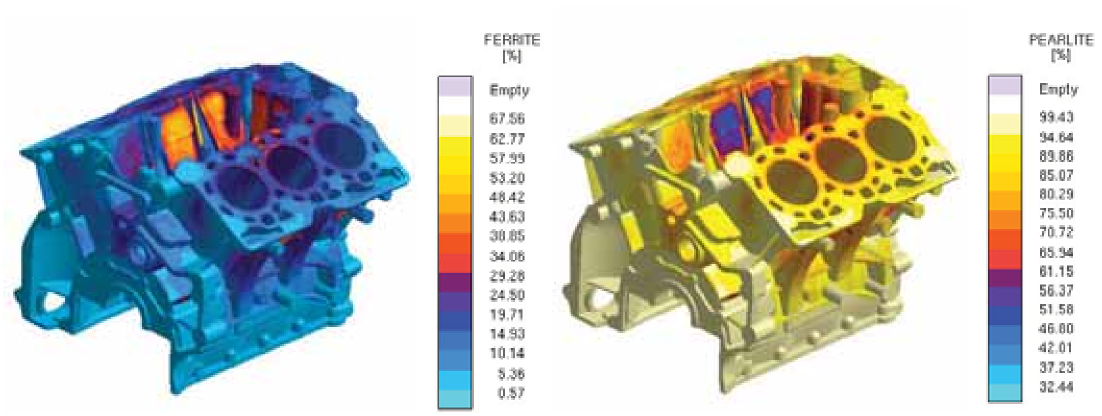

Figure 2.1.1: Ferrite (left) and Pearlite (right) distribution in the casting. This microstructure distribution has a big influence on the mechanical properties (see Figure 2.1.2 below)

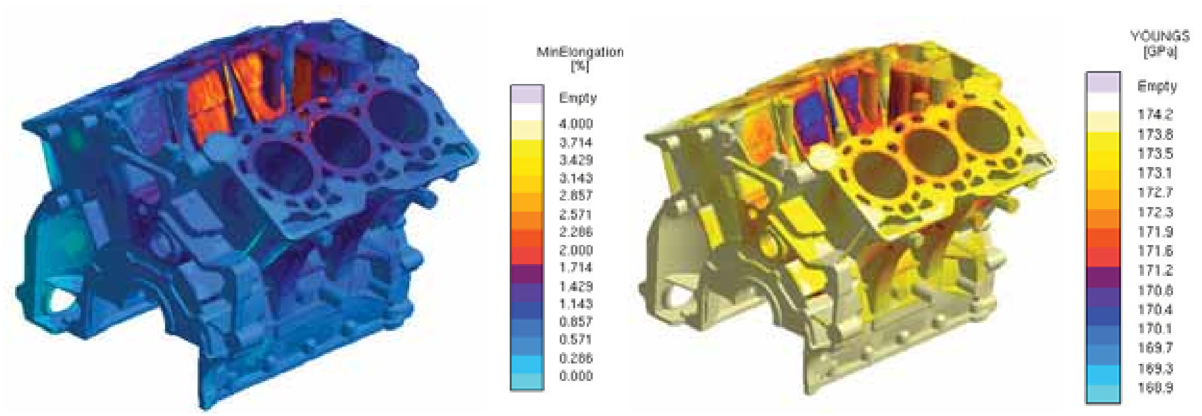

Figure 2.1.2: Distribution of minimum elongation (left) and Young's Modulus (right) in the casting. These mechanical properties correspond with the microstructure distribution (see Figure 2.1.1 above). With increasing Ferrite content the minimum elongation increases, while with increasing Pearlite content the Youngs Modulus increases.

2.2. Residual stress calculations

Nearly any metal alloy shrinks during solidification and further cooling down to room temperature. This causes, depending on the expansion coefficients, the shape of the part and to a smaller extent on manufacturing process conditions the residual stress, which could be found in any casting. Proceeding from the "temperature history" of the casting, which is known from the solidification calculation, the residual stress formation for the raw casting can be calculated, Figure 2.2.1. The model uses a non linear, temperature dependent elasto plastic approach with isotropic hardening.

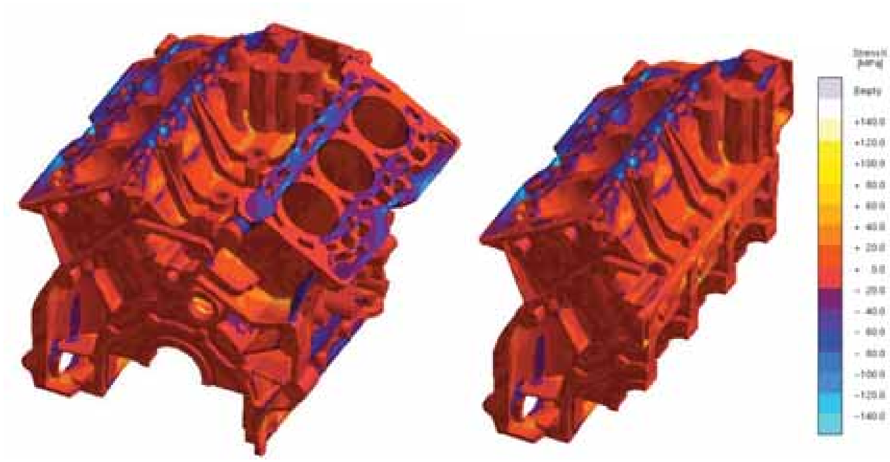

Figure 2.2.1: Residual stress distribution in the raw, not machined casting in direction of the crankshaft (X-direction). Values go up to 80 MPa.

3. Transfer of residual stress and mechanical properties into FE analysis

The simulation of the manufacturing process has shown, that quite substantial residual stresses as well as an inhomogeneous distribution of mechanical properties have to be expected in the casting. Any FE analysis ignoring this, carries the risk of being wrong and misleading the development. In this contribution the usage of existing interfaces between simulation software applications should demonstrate, that the integration of the CAE tools which follow the process chain, could be state of the art. In the case of the project presented here, the simulation of the manufacturing process was performed using a Finite Volume method and a structured grid enmeshment. All calculations were made with the model of the complete casting. This procedure is best practice for casting simulation. The FE analysis was made using a tetraeder enmeshment, what is state of the art for this type of simulation. The local resolution of the Finite Volume mesh for casting simulation usually has a finer resolution than the appropriate FE meshes of the same part. The mapping algorithms have to consider this and to take care, that particularly critical high values of the residual stress do not get lost, Figure 3.1.

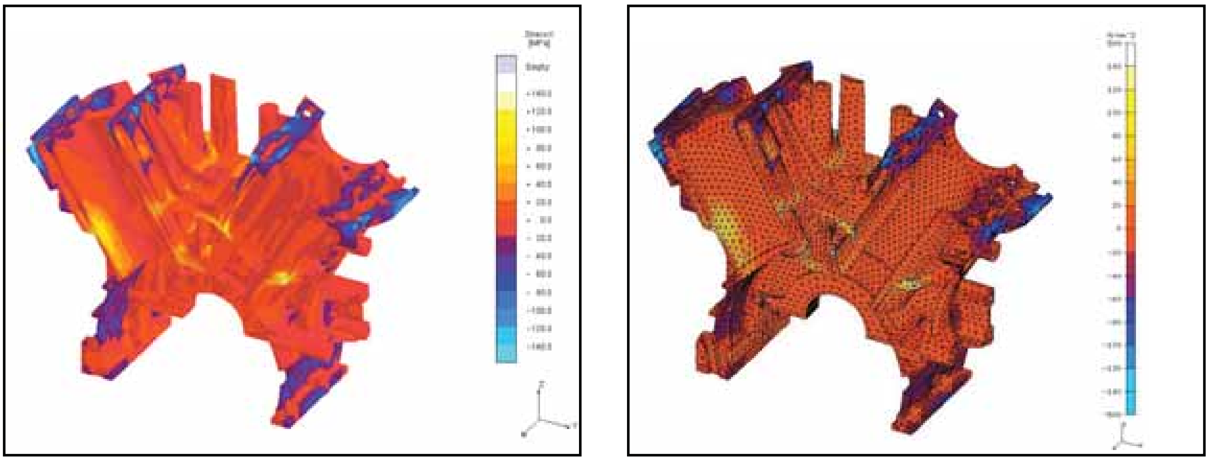

Figure 3.1: Residual stress distribution in the section of the raw casting being subject of the FE analysis. The values were transferred (mapped) from MAGMASOFT® (left) to an unstructured FE mesh (right) without loosing the critical high values and gradients.

Mechanical properties as Young's Modulus or the minimum elongation, see Figure 2.1.2 above, can be transferred in the same manner.

4. The influence of machining on residual stress in the casting

Since machining can have an important influence on the residual stress distribution, it is necessary to simulate the effect of this process. To do this, the residual stress distribution of the raw casting has to be mapped from the structured enmeshment, which was used for the casting simulation, to the unstructured FE - enmeshment to be used for further durability calculation. Therefore we need two geometry models, one for the raw casting and the other for the machined casting, where the "difference" is the machining allowance, Figure 4.1.

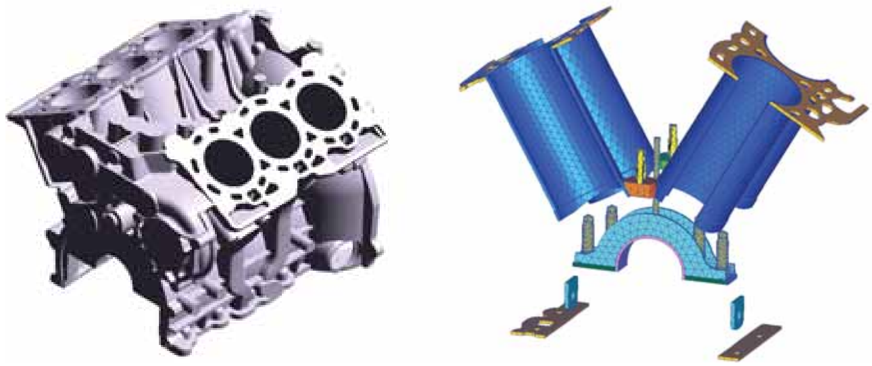

Figure 4.1: 3D CAD model of the casting (left) and enmeshment of the machining allowance (right).

The effect of the machining process on the residual stress distribution of the casting can then be considered by the residual stress rearrangement when subtracting the machining allowance, Figure 4.2.

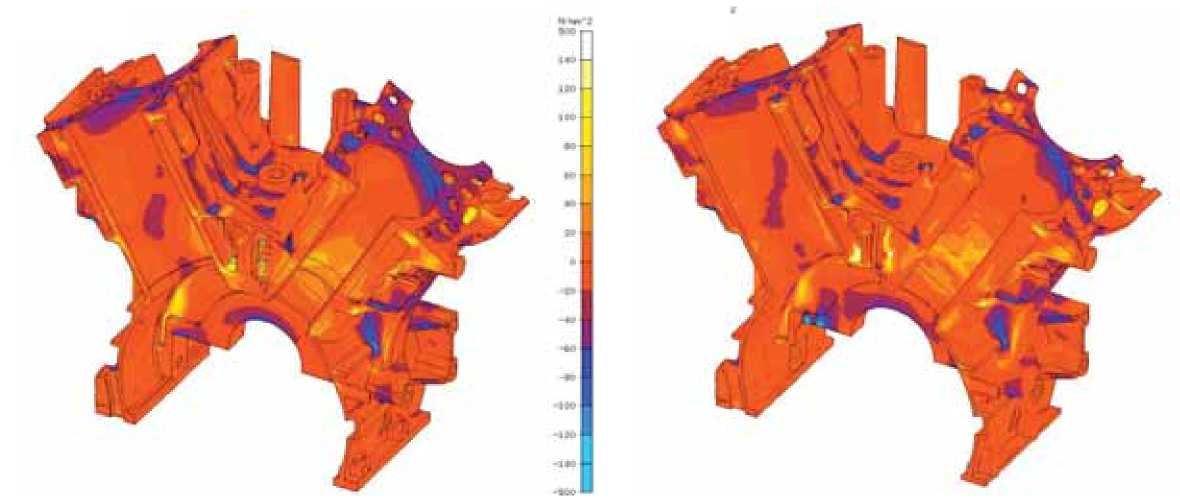

Figure 4.2: Residual stress distribution before (left) and after (right) machining. In some critical sections the residual stress values differ up to 20%.

Conclusions and remarks

The power train castings of today, which have to combine low weight with very high resistance against mechanical loads, very often have quite sophisticated designs. The FE analysis has supported the tendency, that a design just fulfils the specifications, and that the safety margins have been reduced more and more. On the other hand this means, that the castings should have no defects weakening the structure, and that the casting properties should have a homogeneous distribution, as assumed in the FE analysis. Both is generally not possible. For this reason it seems to be mandatory to gain information about the manufacturing process by casting simulation, and to transfer the critical values such as residual stress or an inhomogeneous Young's Modulus distribution from casting simulation to FE analysis. The example in this contribution shows that this is possible. The low grade of integration being practice for most of the casting design processes is more caused by the low level of integration between departments and people, who are involved in design processes then by missing links between the used CAE tools.

Nevertheless it should be made clear, that there is still a long way to go until all necessary mechanical properties of castings of all technical alloys can be predicted. The best status today is with iron castings, where the microstructure can be simulated quite accurately and where the microstructure is dominant for the mechanical properties. Light alloys are much more difficult, because their casting defects such as micro- and macro porosity influence the mechanical properties more than the microstructure. And these casting defects can not yet be determined in appropriate accuracy using the state of the art simulation techniques.

References

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[2] Svensson, I.L., M. Wessén: " Foundry Of Cast Irons : Processing and Simulation ", Numerical Simulation of Foundry Processes, S. 87-145, September 2001