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Implementation of Casting Simulation for Increased Engine Performance and Reduced Development Time and Costs – Selected Examples from FORD R&D Engine Projects

Abstract

The application of CAE is continually gaining in importance in all areas of engine development. This is especially true for the simulation of the casting process as well as for the following heat treatment. Although the durability analysis of the finished component has long been an established part of the development process, CAE-technologies for the simulation of the manufacturing process have only recently come into focus.

The advantages of simulation at an early stage are obvious. Only by using the simulation of the manufacturing process is it possible to determine the distribution of inhomogeneous mechanical properties (hardness, elongation and yield strength) as well as residual stresses and to consider these properties in the design optimization process, especially in FEM calculations. The quality of the CAE analysis is significantly improved, therefore the full potential of the cast material can be taken advantage of in early design stages. On the other hand, through the optimization of heat treatment using simulation, the performance of the engine can, for example, be increased without cost-intensive design changes within the existing design concept.

In this paper the involved companies, using selected examples from continuing R&D projects, will illustrate the potential to reduce the development time while simultaneously increasing the quality of the component. The methodology of simulating the casting process has been integrated as a key technology into the development process of cylinder heads and blocks at Ford Motor Company and has led to a significant reduction in development times and costs.

1. Introduction - Requirements for Engine Development

Engine development has undergone a tremendous development process in the last three to five years. The cornerstones of this development are weight, design space and performance; features that have been enhanced with a development rate that has not been experienced in the decade before (Fig. 1). Depending on the development goal, engines went into production with the following improvements:

- performance increase by 50% with same total weight, or
- reduction of engine weight and design space by 25% with same performance.

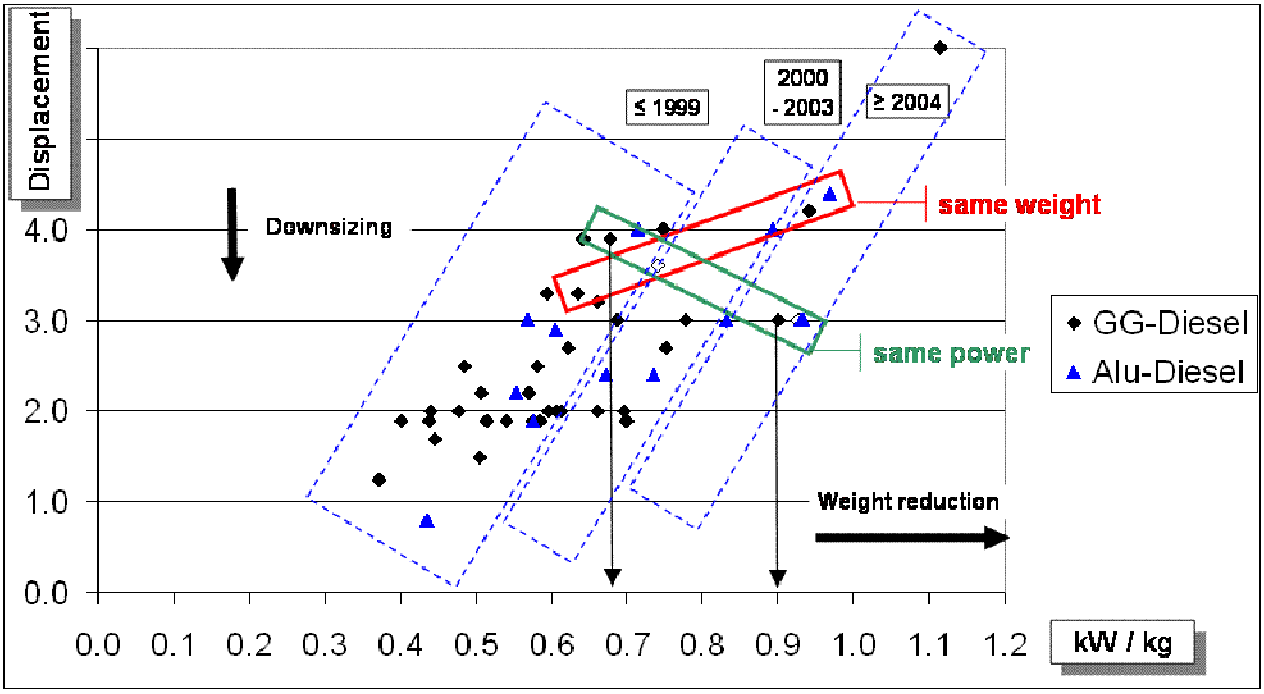

Figure 1: Development trends regarding specific power output and displacement

The customer highly appreciates and honors these improvements, where especially resulting features like reduced gasoline consumption, crash security, and the overall driving fun deliver **high customer value**. The next development goals are gasoline engines with 90 kW/L, 140 bar, and diesel engines with 80 kW/L, 200 bar, respectively. With this 'quantum leap' in engine development, companies are forced to break new ground in many areas. However, these ambitious goals can not be met with **common procedures**. **New processes and methods** are required to successfully enter new territory.

2. Future Development Process

The general **development targets** have not really changed:

- Reducing development times
- Exploiting the potential of design and material
- Reducing costs in the development process
- Reducing component costs and production costs

The approach to support physical component tests with numerical processes has successfully been used before and led to an **extensive use of CAE** in today's engine development process:

- Structural analysis (durability, acoustics/ NVH)
- Flow simulation (intake/exhaust gas system, in-cylinder flow, simulation of oil circulation and water jacket, crank case/ PCV system)
- Dynamics of multibody systems (valve train, timing gear, crankshaft, piston)
- Simulation of friction and wear, bearing calculation

The individual CAE methods have reached such a quality and accuracy level that aspects like production influences, tolerances, and parameter variation in production have increasingly more impact. Consequently, current **CAE developments** are mainly focused on production processes:

- **Failure hypotheses -** considering local properties (microstructure, material defects, inhomogeneities) and more accurate material data (chemical composition, elevated temperatures)
- **Manufacturing simulation -** casting, forging, heat treatment, machining, joining etc.

This is the basis for the future development process: not only further development but **integration of CAE methods**, i.e. a complete and Closed Loop CAE Procedure for the simultaneous optimization of component and production process. This is the only way to reach the required quality level in the development process to achieve **zero prototyping**, substantially reducing development time as well as development costs (Fig. 2). At the same time, the Closed Loop CAE Procedure together with the resulting improved analysis quality is the prerequisite to develop next generation high performance components.

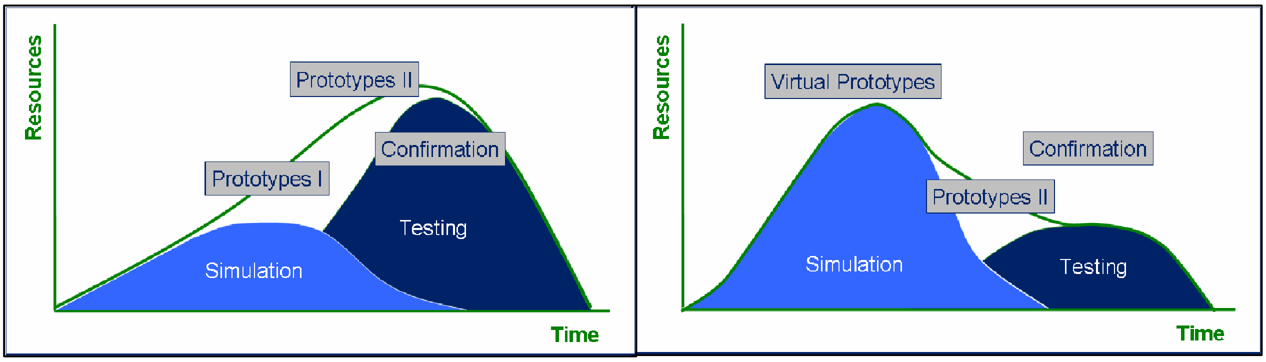

Figure 2: Resource shift following the Integrated CAE Development Process

3. Casting Process Simulation for the Optimization of the Development Process

An important part of the zero prototyping development process for engine components is the simulation of casting processes and heat treatment if applicable (Fig. 3). The objective is to identify the inhomogeneous distribution of material properties, residual stresses, the influence of component design, process parameters and their variations, and last but not least the influence of the cast alloy. The simulation of the complete casting process provides results like

- Hardness (required optimization parameter regarding the machining of iron castings that are of increasingly lightweight structure)
- Yield limit, tensile strength, SDAS, and further microstructural characteristics (important parameters for the component behavior under load as well as for failure life calculations)
- Porosities (influence on function and fatigue life)

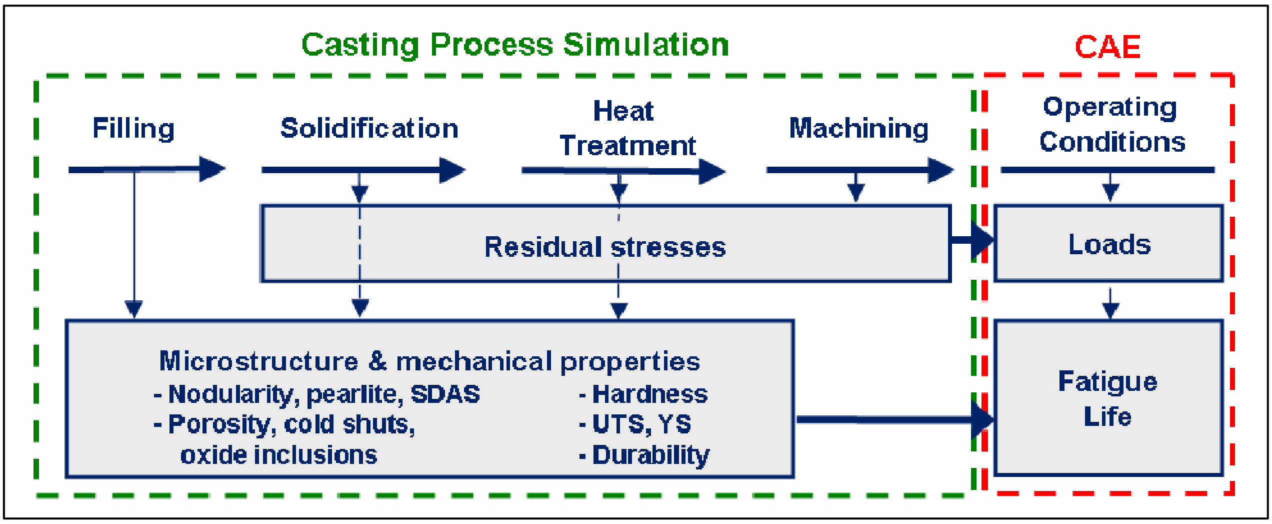

Figure 3: Impact of casting and manufacturing processes on the component performance

Residual stresses are computed by simulating the casting or heat treatment process and are being implemented in the fatigue calculation as 'pre-load of the component'.

The casting process simulation is easily integrated into the conventional CAE procedure. Due to the parallel integration the development process is not prolonged in spite of the significant quality improvements (Fig. 4).

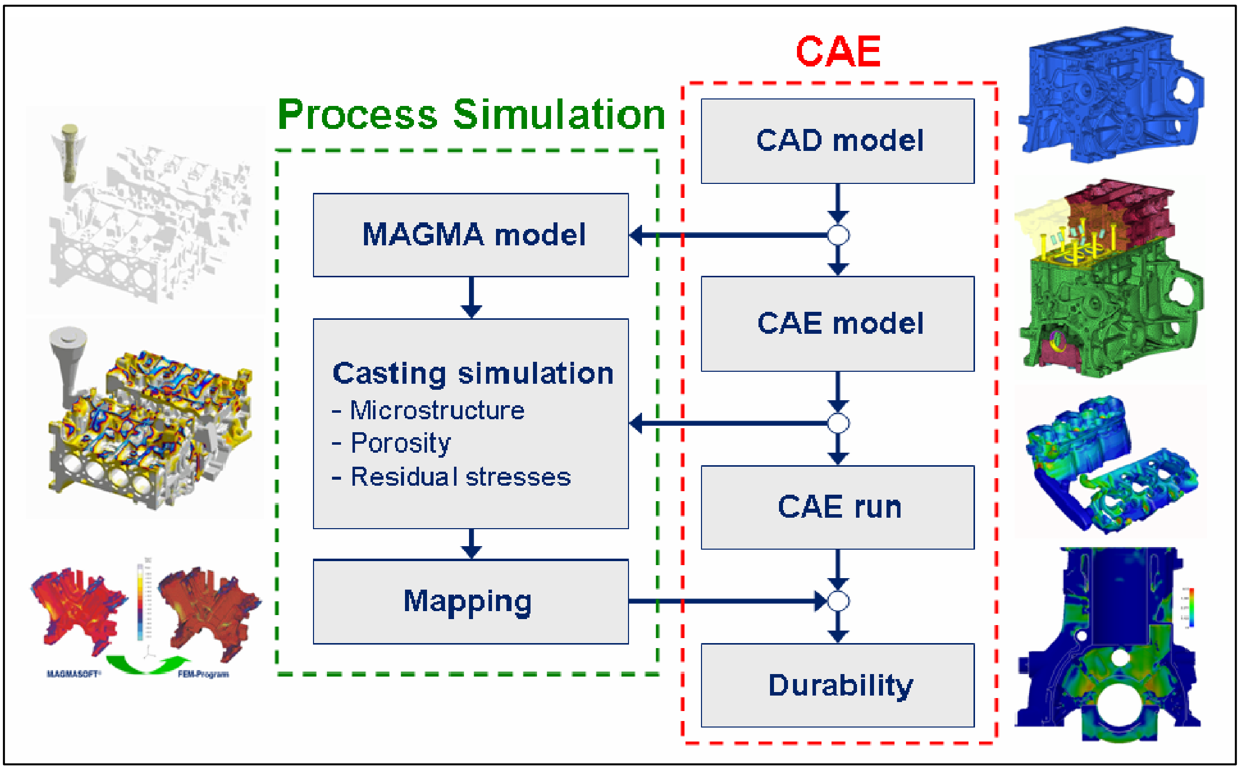

Figure 4: Integration of CAE and casting simulation

4. FORD Engine Development - Examples

The potential of casting simulations covers all iron and nonferrous alloys as well as all casting processes. Foundries use casting simulation on a regular basis for the optimization of casting technology and production parameters. The objective is to avoid cold laps, porosities and inclusions, and in the case of cast iron components also to analyze the microstructure for the calculation of hardness and yield point. The main parameter for CGI (compacted graphite iron) is nodularity (Fig. 5).

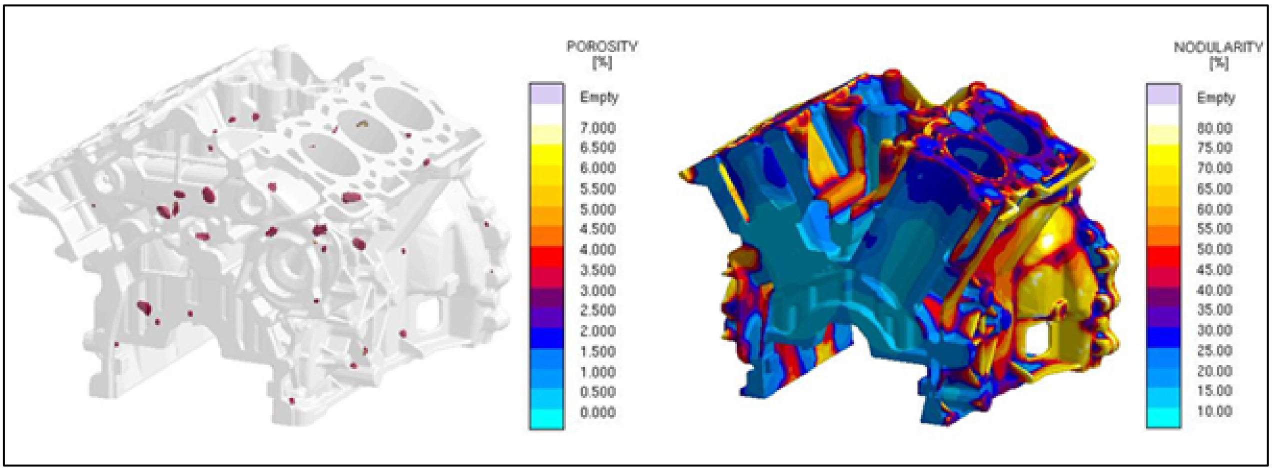

Figure 5: Porosity and nodularity distribution (section) in a CGI block

Affected by the design, some areas cool down much faster than others leading to locally increased hardness values in cast iron (Fig 6). The simulation identifies this problem making it possible to respond as early as in the virtual development phase. Additionally, because of the high sensitivity of the MAGMA simulation it is possible to calculate the influence of alloy modifications even in the range of process variations. Consequently, the Closed Loop CAE Procedure is the way to identify the optimal alloy considering the locally increased hardness values.

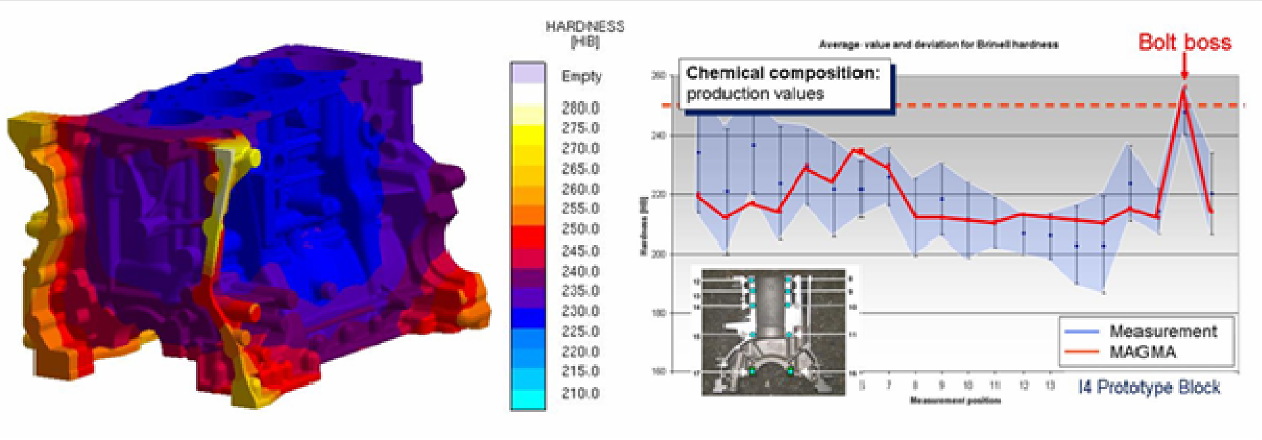

Figure 6: Hardness distribution and simulation sensitivity for GJL

What is more, inhomogeneous cooling rates cause inhomogeneous mechanical properties (Fig. 7) that cannot be neglected in the new generation of high performance components and hence need to be considered in the Closed Loop CAE Procedure. The challenge is to combine production simulation and failure life calculations in an integrated CAE tool.

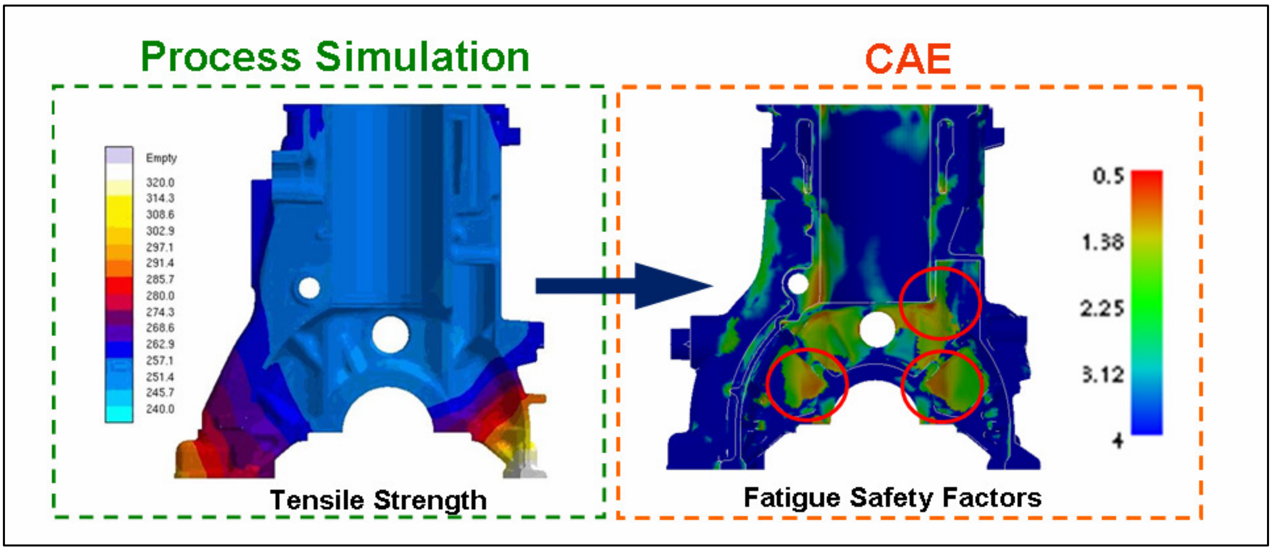

Figure 7: Local mechanical properties and fatigue safety factor prediction

The zero prototyping development process adds the calculation and integration of **residual stresses** to the simulations that are traditionally rather foundry-relevant. The residual stresses in engine blocks are often as high as the assembly and operating loads themselves. However, the formation of residual stresses follows completely different principles than the formation of thermal and mechanical operating stresses. Consequently, superposing these stresses does not only lead to increased stresses but also to compensations, with the according **impact on fatigue life**.

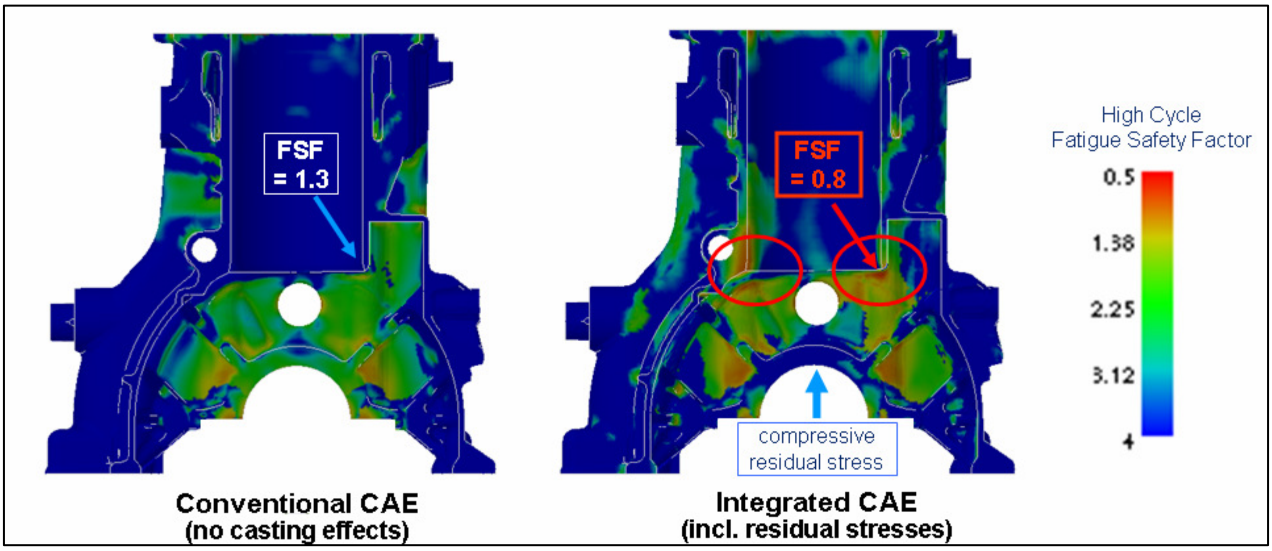

Figure 8: Impact of residual stresses on failure life prediction

The **integrated CAE procedure** includes residual stresses as the fourth load case with the same importance as the three traditional load cases assembly, temperature, and peak pressure. The local mechanical properties are considered in the failure life calculations (Fig. 9).

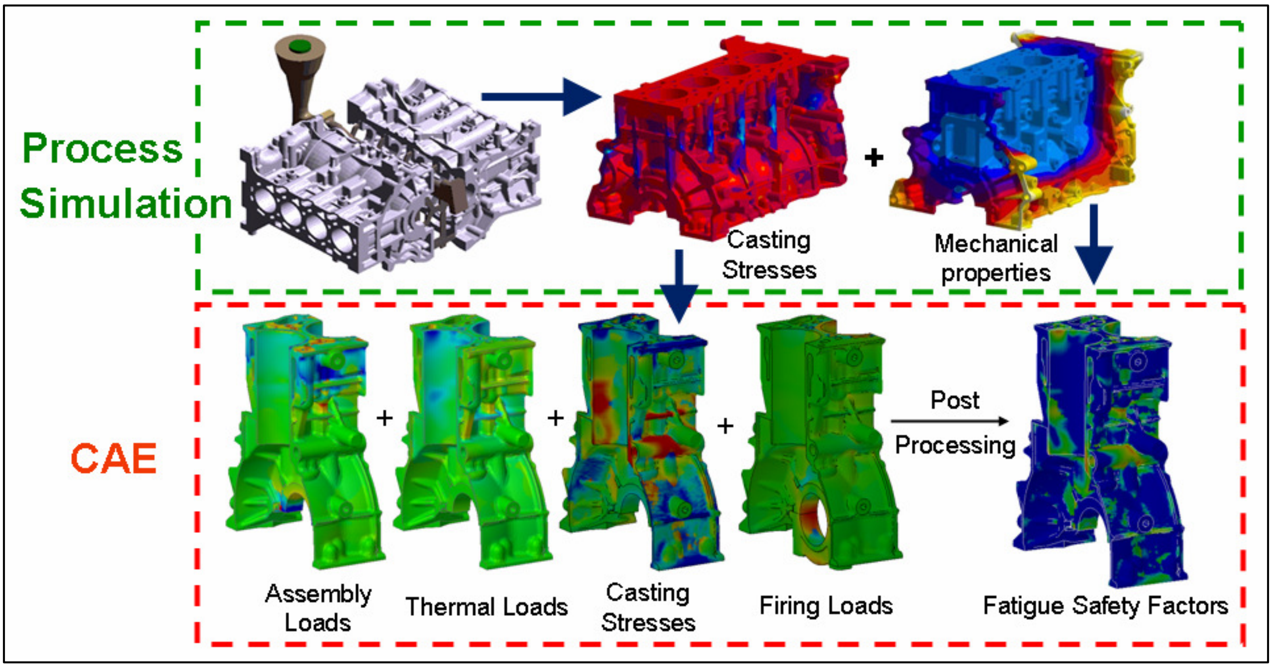

Figure 9: Integrated CAE procedure

Slightly modified, this procedure is also used for cylinder heads and other heat treated components, where the dominant residual stresses are created during the quenching process due to the significant temperature differences in the component (Fig. 10). The simulation considers the heat transfer in the quenching medium and the resulting cooling behavior.

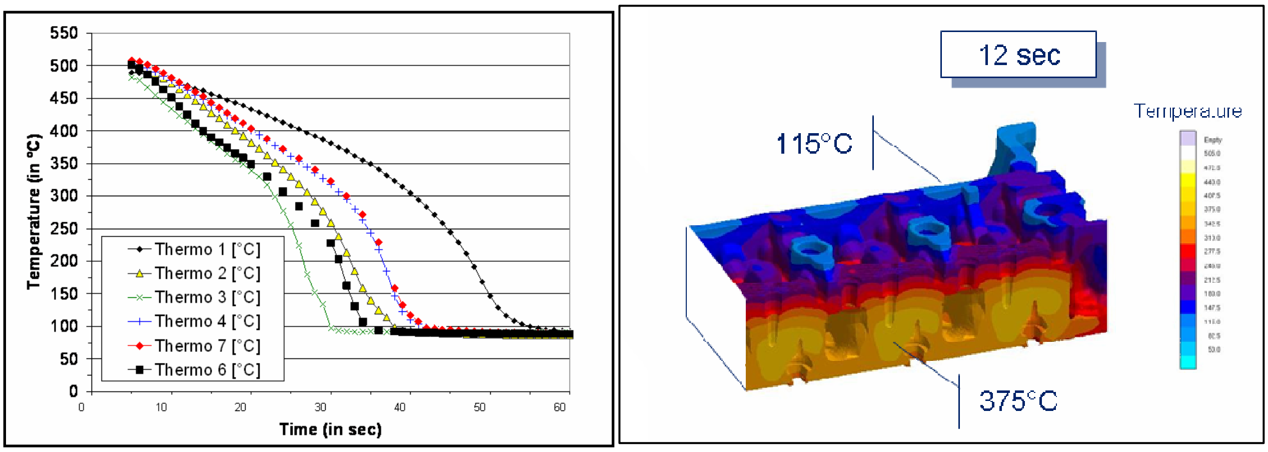

Figure 10: Cooling curves and temperatures in a cylinder head during water quench

Residual stresses in high-strength heat treated cylinder heads are in some cases so close to failure limit that prototype failure can already be explained with a simple residual stress analysis. (Fig. 11). Thus, also for the consideration of heat treatment in the development process of high performance components, the integrated CAE procedure is indispensable.

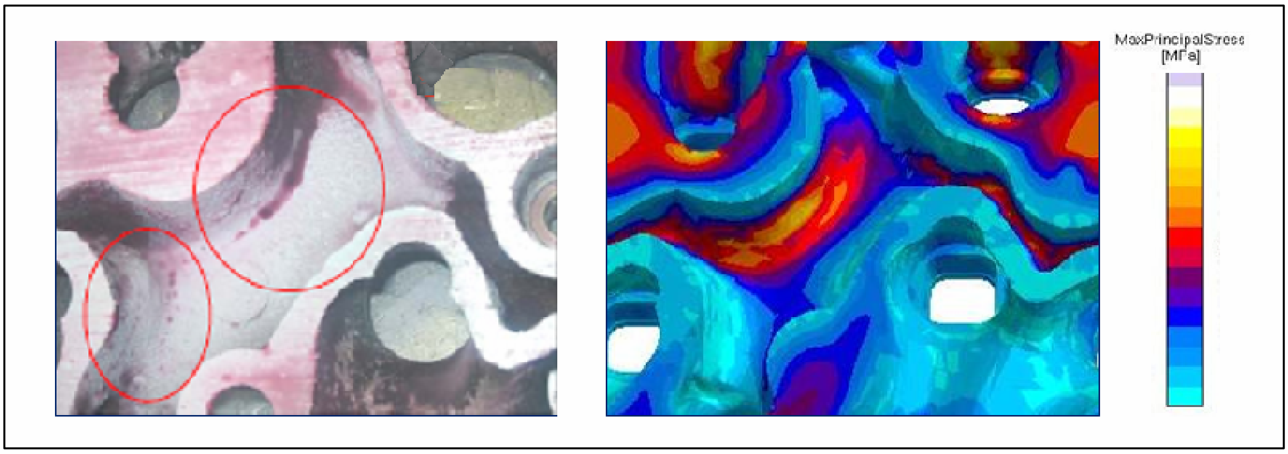

Figure 11: Test result and virtual residual stress analysis of a prototype cylinder head

Aluminum cylinder blocks with gray cast iron inserts show a similar picture. The residual stresses in the cylinder bridges are the reason for bridge cracks during machining. The appropriate actions to address the bridge cracks can be taken during the production process development. However, residual stresses will still be present in the component and will have an impact on the fatigue life of these future high performance engines (Fig. 12). Consequently the integrated CAE procedure is essential for the development of highly stressed aluminum engine components, whether they are heat treated or not. This is especially true when dealing with hybrid components.

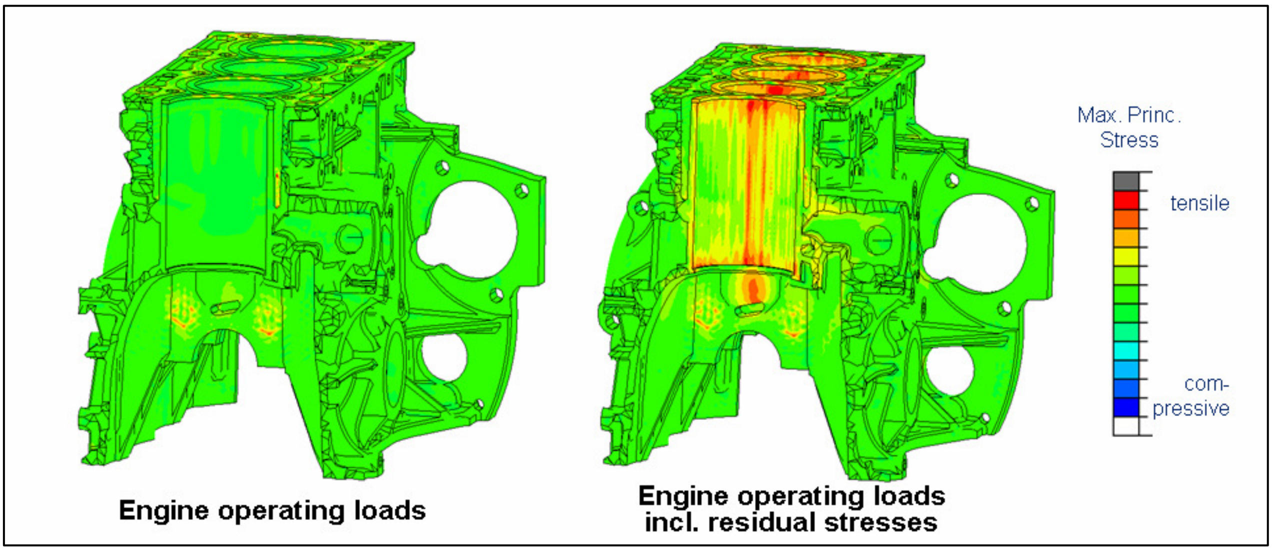

Figure 12: Impact of residual stresses on total stresses during engine operation

Another topic is the use of a virtual DoE (Design of Experiment) for the development of new technologies. The robust design of aluminum crank cases with cast iron cylinder liner inserts requires e.g. to address the following tasks:

- Optimum wall thickness ratio of liner and bore bridge
- Controlled preheating of the liners in the core package or a high pressure die casting die.
- Using the appropriate casting parameters to avoid cold laps

- Securing optimum heat transfer at operating temperature with the aluminum shrink-on process
- Ensure sealed bond between liner and aluminum structure

Compared with the 'conventional' process that includes various process steps like design, trial castings, analysis of prototypes, engine tests, and pulser tests, including the necessary optimization loops covering the whole process, the new Closed Loop CAE Procedure is much quicker and more efficient:

- Designing geometry for minimum wall thicknesses
- Strength calculation and casting simulation
- Optimization loops with repeated calculation of strength, casting properties, and residual stresses
- Producing prototype components
- Verifying design in engine trials and pulser tests

Casting simulation does not only deliver all relevant information for the layout of design and process (Fig. 13); it now represents a powerful and robust feature that allows the use of a virtual DoE to analyze the interdependencies of its parameters. Not only the significantly reduced development times and costs, but also and especially the extended gained knowledge regarding component load capacity as well as process sensitivity can be seen as important advantages providing a considerably improved basis for future developments.

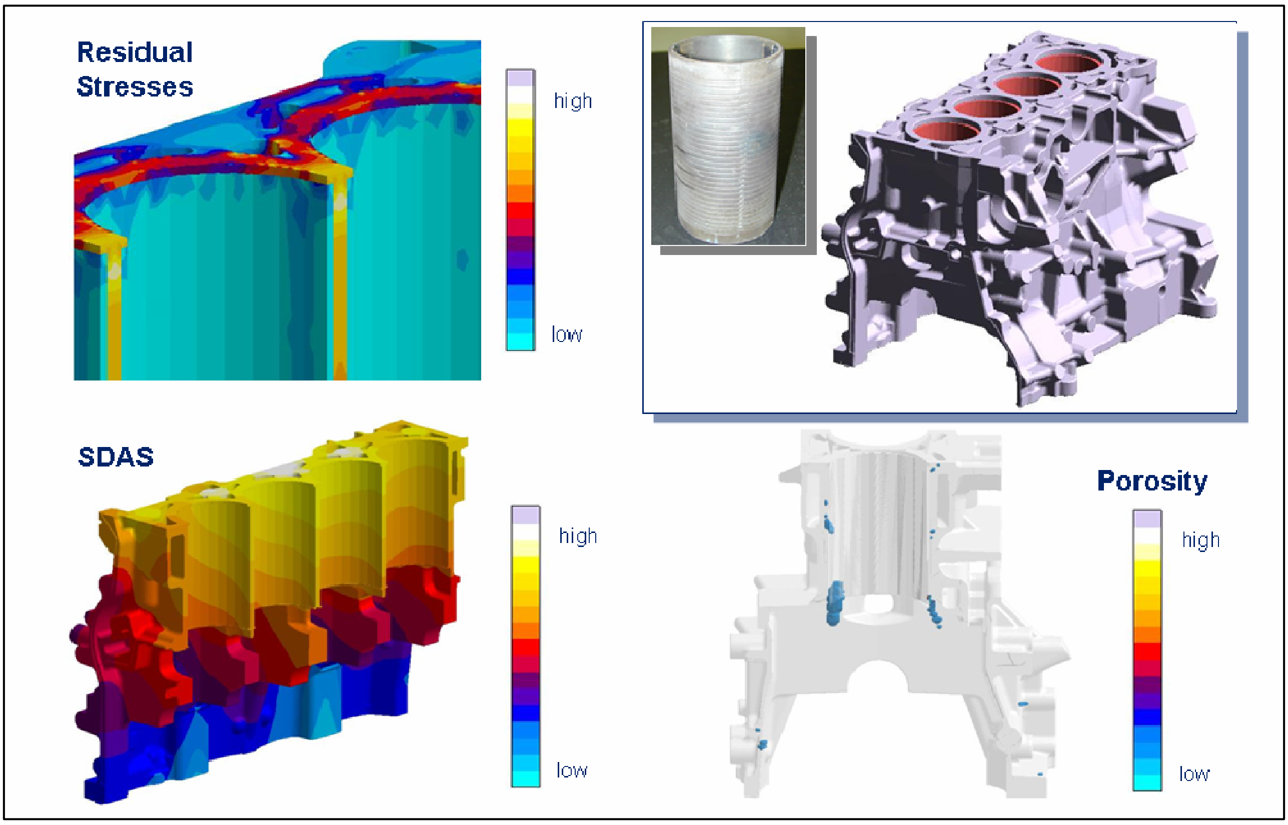

Figure 13: Casting simulation supporting new technologies

5. Potential for the Development Process

The previous chapter demonstrates the integrated CAE procedure as a powerful and effective tool to reduce development time and costs as well as to optimize quality. This applies to new technology concepts as well as to product development.

The main potentials for quality improvements and cost savings are: casting trials (filling, solidification, cold laps, porosities), prototype manufacturing, component and material analyses (residual stresses, properties), test runs including result evaluation, machining trials (hardness, cracks), and last but not least the definition of robust production parameters (casting parameters, alloys, insert temperatures).

5.1. Developing New Technologies With Minimum Effort

The integrated CAE procedure provides significant advantage in the advanced design phase for **concept studies** as part of the development of new technologies. In the past, this applied to the development of iron inserts, alternative heat treatment processes, or material substitutions. In the future, targets are more widespread topics, starting from thin wall castings via machining clamp loads and die lifetime up to alloy development.

The saving potential is explained in the complete substitution of the experimental DoE with a virtual DoE. In the advanced design phase the time for technology development can be reduced **down to 50% - 25% of the normal time** and costs can be reduced **by up to 50 %** due to omitting extensive work for sample production and machining, for tests, and for component checks.

The distinctive feature of the virtual DoE is the ability to address **bigger development steps** regarding design, material, and process, which is due to the fact that a much higher number of parameters can be considered including the influence of their interdependencies.

5.2. Reducing Engine Product Development Times and Costs

The first step to introduce the integrated CAE procedure into product development is the consequent parallelization of component CAE and manufacturing simulation. This measure already reduces the development time by **ca. 3 months**, as the development of casting prototypes can be finished in time with the last design step. The increased effort for simulation and coordination during the simultaneous optimization creates additional costs; however, these costs are more than compensated by the early consideration of production related influences and the reduced effort for test bed runs. Further development focuses on the completion of material data and models for the whole range of applied materials.

The second step is the **total substitution** of the physical prototypes and their related test bed runs with virtual prototypes in the series-1-phase (Fig. 14). The result is the reduction of engine development time by **approximately 6 months** as well as the corresponding cost reduction with synergy effects having impacts on several process steps including engine machining. The challenge here is shifting the core engineering resources towards CAE evaluation.

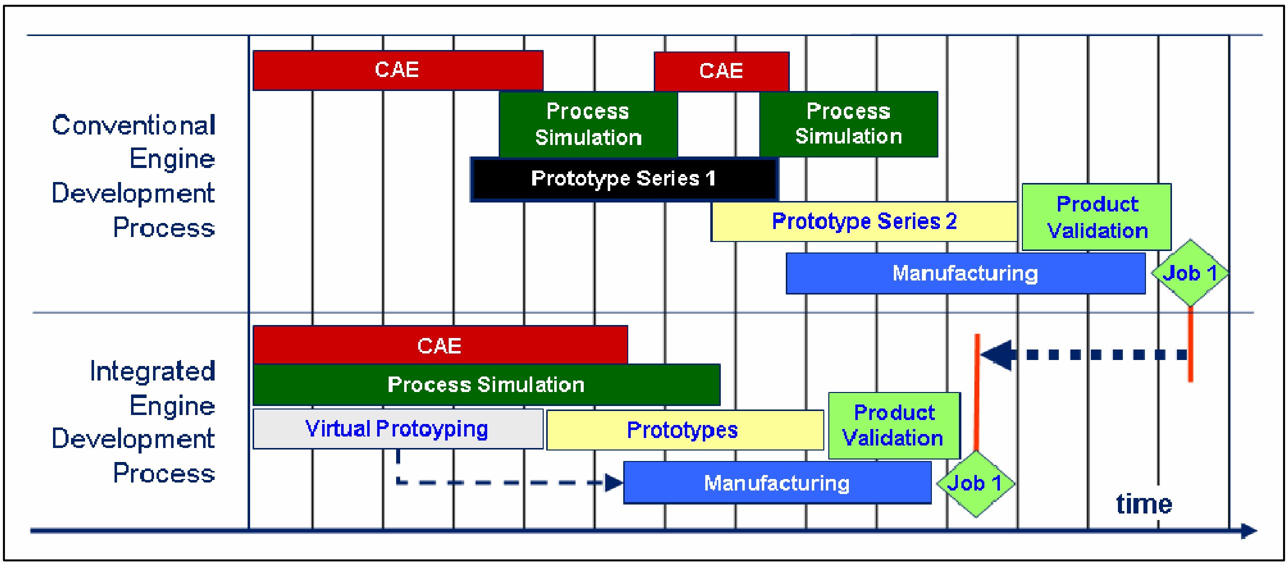

Figure 14: Savings in development time due to integrated CAE processes

6. Conclusion

The comprehensive integration of manufacturing process simulation into the engine CAE development procedure (Fig. 15) is the key to success for the accelerated realization of engine downsizing and increased performance that comes along with a reduction in development time and costs at the same time. It is the prerequisite for zero prototyping.

Our examples show the tremendous opportunities in the integrated CAE procedure, exceeding by far the savings achieved by the general and more traditional approaches. The result of this concept is like a 'breakthrough' that has rarely happened before in engine development and that will prove to be a cornerstone for all future developments.

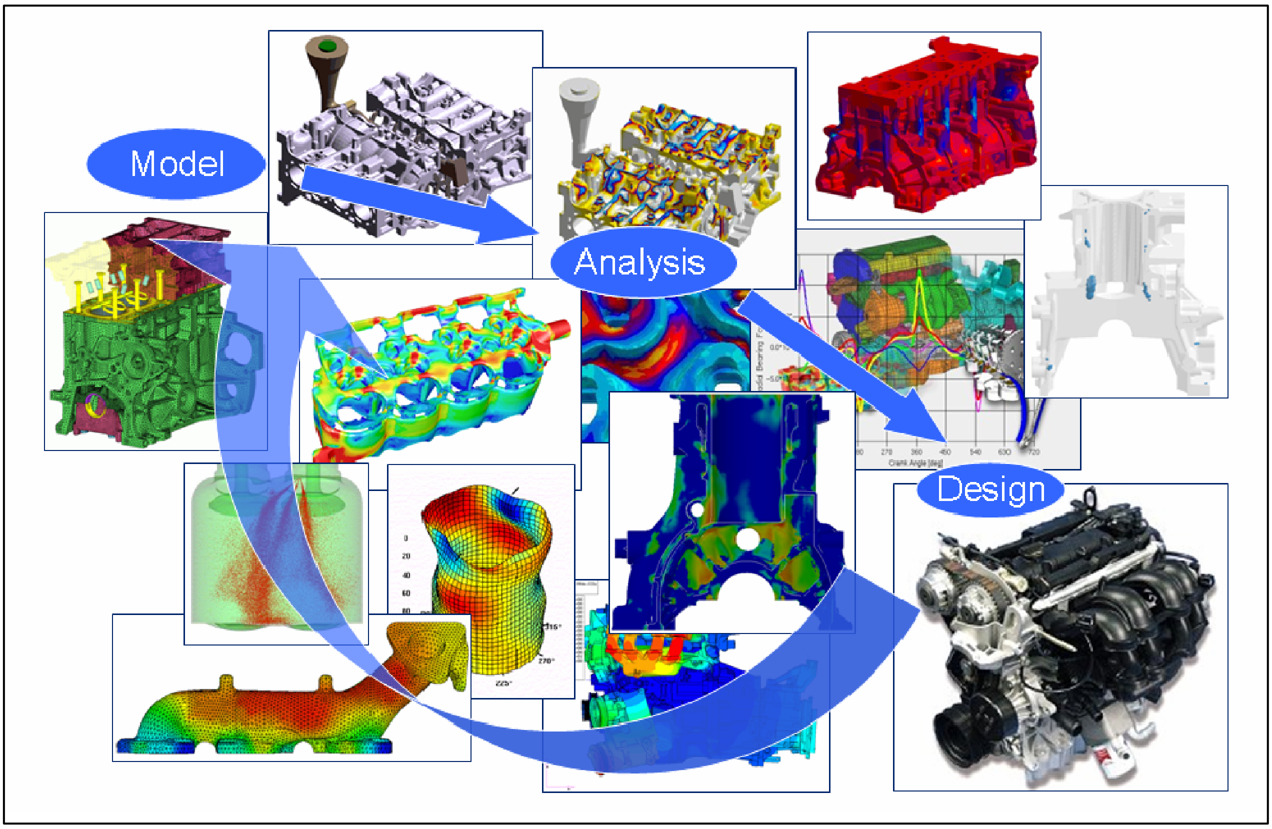

Figure 15: Integrated CAE process applied to engine development