Computer model for optimizing the design of cast gas turbine components

The highest gas turbine efficiencies are achieved today with single-crystal or directionally solidified blading materials. Computer modelling is used to predict whether and in what sizes the complex turbine blades can be cast economically. Working together with the Aachen Institute of Technology, ABB Corporate Research has developed and validated a design tool that allows the detailed geometry of the complex shaped components to be fully modelled. As a result, casting development can be reduced from months to weeks, with benefits that include reduced costs and a shorter 'time to market'.

To be successful in today's highly competitive market for power generation gas turbines, primary equipment suppliers have to be able to supply high-efficiency turbines at the lowest possible cost as well as respond rapidly and effectively to market changes.

One of the key components influencing gas turbine efficiency, service reliability and cost, is the turbine blading. Turbine blades are made of nickel-based superalloys using an investment casting process, also known as the 'lost wax' process.

The steady increase in turbine efficiency that has taken place over the years has been accompanied by a significant rise in temperature and more complex blading designs. Blades in modern turbines are required to operate in contact with combustion gases at temperatures higher than the melting point of the alloys used. Thus, cooling air has to be supplied to internal cooling passages within the blades, and the control of the thin superalloy wall sections has become critical for the mechanical integrity of the blading. In addition, as blade cooling has become more effective through the use of increasingly complex and convoluted internal cooling passages, the major failure mode for blading has changed from creep failure to thermo-mechanical fatigue failure.

The need for casting simulation

In their latest power gas turbine generations, manufacturers have chosen to follow the path pioneered by the aero-engine manufacturers and replace the conventional polycrystalline blading with directionally solidified or single-crystal blading 1.

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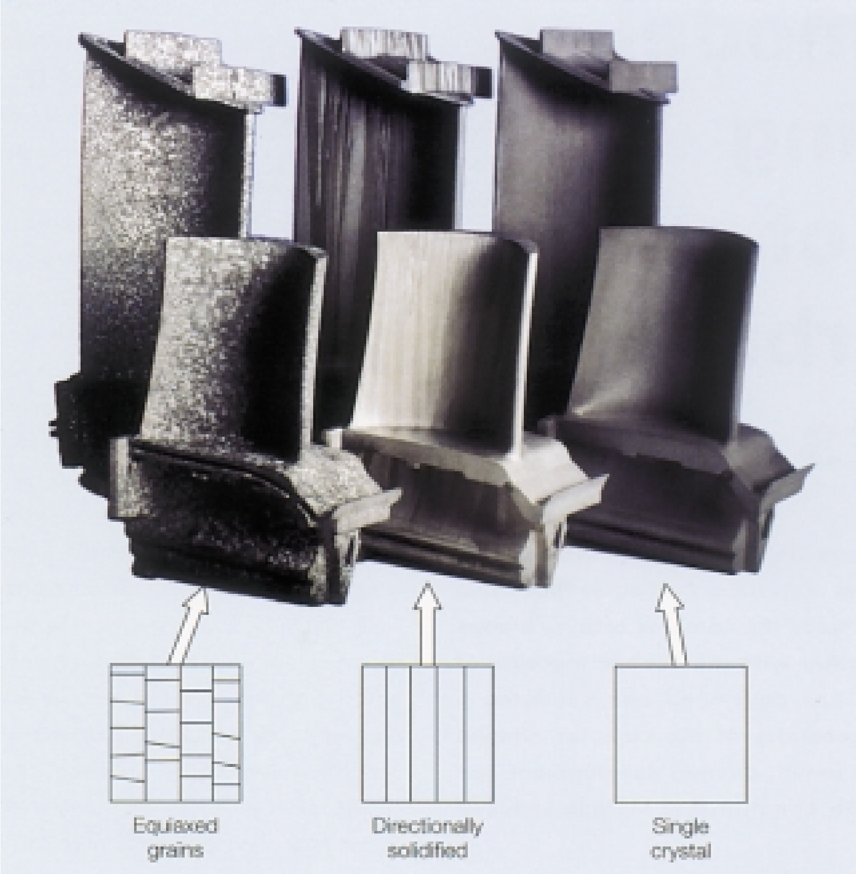
While the conventional empirical approach may be acceptable for the smaller sized and relatively larger production volume of aero-engine blades, it is not acceptable for the smaller production runs and large unit costs of the power turbine blades. In addition, the time-scale necessary to achieve an empirical solution (6 to 12 months) is not acceptable for the engine development cycle times that are dictated by market forces and engine development cost considerations. The solution to this need to be able to design inherently castable components with a low risk of generating defects, and to be able to minimize the time necessary to move up the learning curve and achieve a cost-effective manufacturing process, is to use manufacturing science in conjunction with computer simulation of the casting process during the component design and initial casting validation trials. With this approach, ABB Corporate Research and ABB Power Generation have demonstrated that casting development times can be reduced from months to weeks (equivalent to a reduction of up to 75 %) 2.

A number of casting simulation tools are commercially available, but each suffers from significant deficiencies when used for this type of optimization. ABB Corporate Research and ABB Power Generation determined in 1992 that software being developed by ACCESS e.V. at the Aachen Institute of Technology, Germany, held the most promise for development into a realistic design tool.

The specific technical advantages of this tool, called CASTS for 'Computer-Aided Solidification Technologies', are its unique viewing factor based radiation model, its capability for handling large finite element models, and the speed of the computational methodology. All these factors allow the detailed geometry of the complex shaped components to be fully modelled, and thus permit closer approaches to reality predictions.



Grain boundary orientation. In the latest generations of power gas turbines, conventional polycrystalline blading (left) has been replaced by directionally solidified (center) or single-crystal blading (right). **1**

The casting simulation model predicts the temperature field during the casting process, and includes the physics needed to predict the evolution of the component solidification during the casting process. Use of manufacturing science physical models of the casting process allows an assessment to bemade of the risk of development of typical casting defects, such as porosity, stray grains, freckles, etc. An automatic optimization of the relevant process parameters can be used to minimize solidification defects, so that casting yield rates are significantly increased. In addition, casting-related residual stresses and deformations can be calculated and the microstructure can be predicted.

Over the last few years, the model has been validated by comparisons between predictions and the physical output from casting trials. Confidence in the casting simulation is now so great that its use has been integrated into the development process for new parts, including conventional polycrystalline, directionally solidified and single-crystal components.

Casting simulation tool CASTS

Time & temperature prediction

Various input parameters are required in order to simulate the casting process. These include the geometry and physical properties of the component together with all materials involved in the solidification process (ceramic mould, core, furnace interior, etc), the initial temperatures and the boundary conditions. Also needed is an enmeshment of all the physical constituents (component, ceramic mould, core, furnace, etc) with finite elements (FE) **3**.

The computation reproduces the real-world casting sequences by first calculating the temperature field of the empty mould during preheating to 1,000–1,500 °C. This is followed by simulation of the pouring of the alloy and the determination of the transient temperature distribution in the component, mould, core and all other materials.

For directional and single-crystal solidification the mould is withdrawn from the heating chamber into the separate cooling chamber of the vacuum casting furnace (Bridgman process). The calculation of the heat transfer by radiation, involving complex and extensive computation, is therefore an essential part of the simulation.

The full temperature-time prediction is the basis for further defect, microstructure and stress-strain analysis as well as the casting process optimization.

Microstructure prediction

An alternative fully coupled temperature-grain structure simulation has been developed for accurate calculation of the grain structure for single-crystal and directionally solidified components. In addition, a fully coupled temperature-stress/strain module is under development and validation. This will permit residual stresses and dimensional accuracy to be predicted. However, both these coupled simulations take significantly more computational time than the simpler temperature field with post-processing calculation.

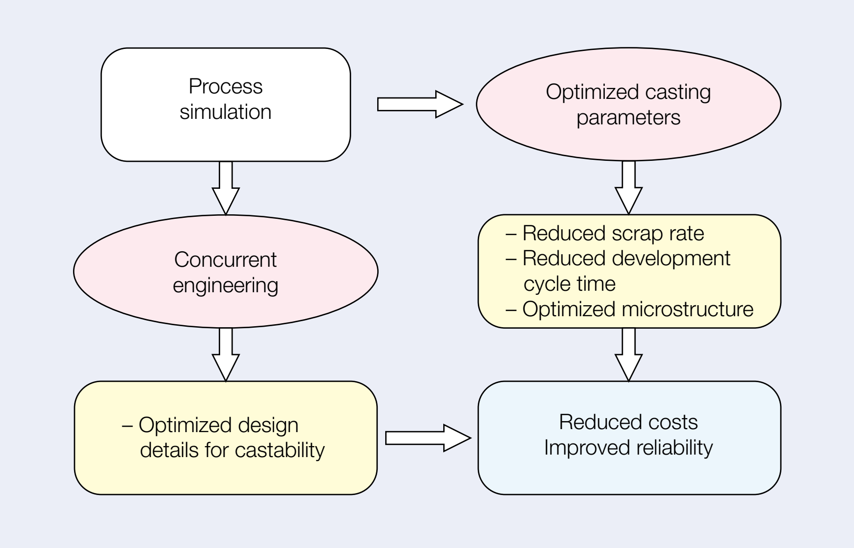
In the faster post-processing module, the microstructure calculation and evaluation is based on the temperature solution, which in turn depends on the selected solidification process (single-crystal, directional polycrystal or conventional).

The result of either coupled or post-processing structure simulation is a representation and evaluation of the whole volume, or arbitrary sections, of the casting with respect to the risk of casting microstructural features, such as porosity, quality and stability of the directionally solidified grains, freckles, stray grains, certain types of low angle grain boundaries, etc **4**. This contrasts with the output from the normal casting trials, where the volume picture has to be deduced from limited surface metallurgical evaluation, with consequential uncertainties. In fact, the casting simulation can assist in making the normal metallurgical evaluation more effective by defining sections which contain regions of high defect risk. The model has also shown that not all the components cast in a mould will always be defective in the same way. For example, a part selected for cut-up could be found to be metallurgically sound, whilst another part cast in the same mould could contain, say, an unacceptable level of porosity. Casting modelling allows the individual identification of the critical regions for cut-ups for each component within the mould cluster.

Automatic optimization

ABB has developed an automatic optimization routine, for which an analysis program performs a user-specified assessment of the quality of the microstructure. The optimization routine generates successively improved casting parameters which are evaluated by the analysis program until the maximum or defined quality is achieved. While the optimization is running, the progress of the quality improvement can be monitored interactively, enabling eventual corrections to the user-defined functions to be made immediately.

The optimization can take 20 to 200 iteration steps, depending on the number of parameters and the optimization algorithm. Each calculation of large, complexly cooled single-crystal or directionally solidified gas turbine blades takes approximately 5 hours (CPU: R10000 running at 195 MHz). Therefore, total optimization runtimes can be between 4 and 40 days. With more processors available, several calculations can be run in parallel, so that with four processors the total run-time can be reduced to from 1 to 10 days.

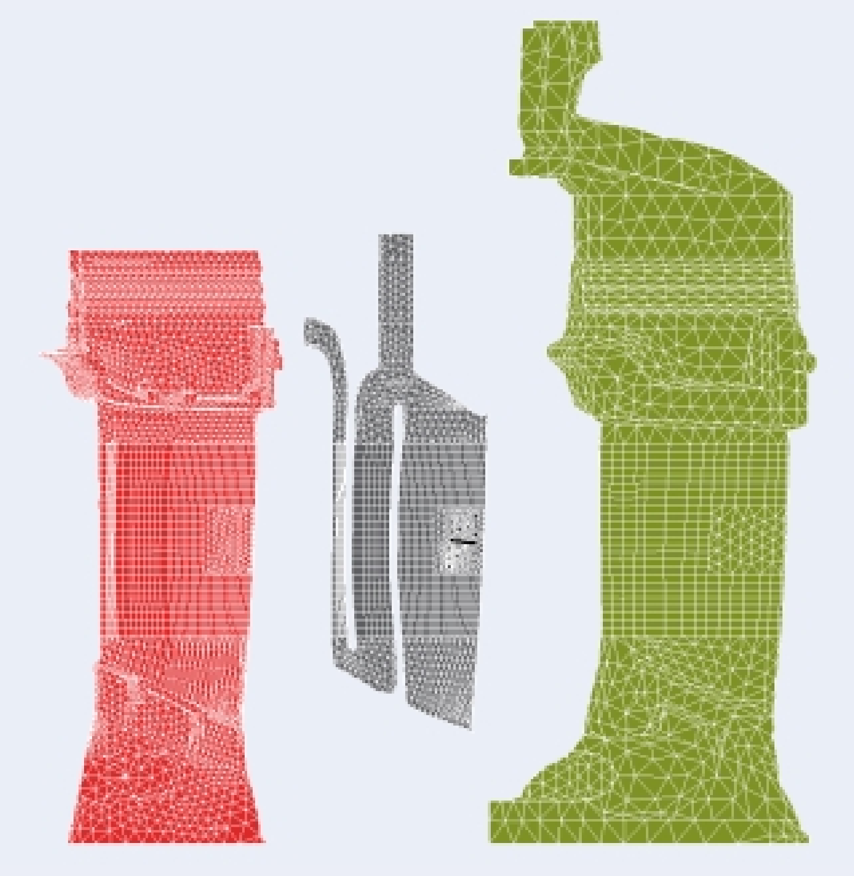


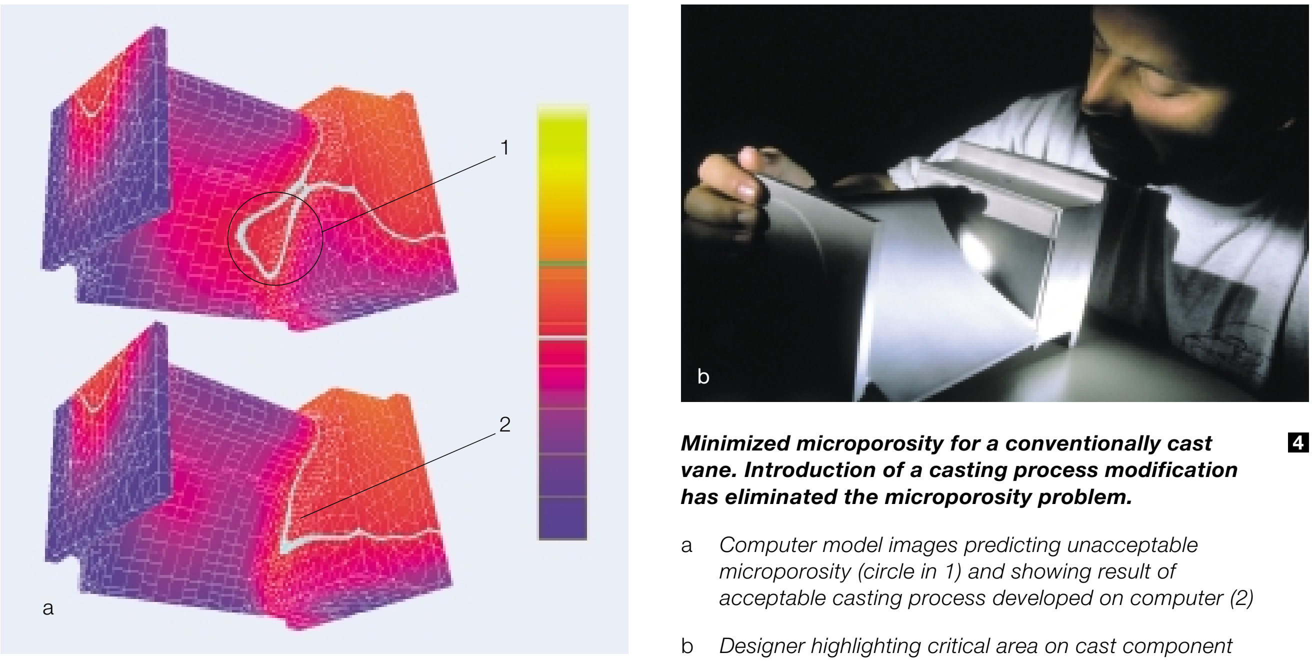
Two routes for casting process simulation: **2**

- *Concurrent design of new components*
- *Production optimization of existing components*

Finite element (FE) mesh for casting modelling of a directionally solidified blade **3**

Red *Superalloy*
Grey *Core*
Olive *Mould*





Minimized microporosity for a conventionally cast vane. Introduction of a casting process modification has eliminated the microporosity problem. **4**

a *Computer model images predicting unacceptable microporosity (circle in 1) and showing result of acceptable casting process developed on computer (2)*

b *Designer highlighting critical area on cast component*

The optimization routine can be used to minimize defect probability based on the component specification, or to improve the casting process with respect to economic and efficient production by incorporating further quality criteria, such as furnace time, alloy consumption or number of process steps.

Sensitivity analysis – identifying the critical parameters

Another advantage of casting simulation over conventional casting trials is the ability to perform meaningful sensitivity analyses. If the correct physics and parameters are used, simulation will avoid the experimental noise and permit single parameter variations to be examined, allowing the definition of critical experimental variables that need close control.

ABB has carried out parametric studies of different casting processes in order to determine how minor changes to various control parameters, such as the withdrawal rate, metal, mould and heater temperature, etc, affect the quality of the cast part. In this way it can be seen whether or not a given process is robust and stable. These evaluations would be prohibitively expensive using the traditional casting trial approach.

Applications

Low-cost production

Casting simulation is currently used for the most expensive parts with long lead times and for which there is a significant risk of cost and time overruns. This ensures the fastest return on investment.

In the course of 'lean production' the stock capacity is reduced to as low a level as possible. Thus, if there are production problems and the delayed components are on the 'critical path', there will be a delay in the delivery of a whole unit to the customer. The result can be loss of reputation, higher financing costs and reduced cash flow due to delayed payments, or contract penalties.

Because of the key role the blading plays in raising the power output and efficiency of gas turbines, it undergoes continuous development. Thus, the development time for a new design and manufacturing process can often determine the 'time to market' for a new gas turbine or upgrade. **5** highlights the considerable time advantage of casting modelling over the conventional trial & error approach. In view of this advantage, ABB uses casting simulation for all new gas turbine blading. The success and financial pay-off for casting simulation of blading is being validated, and modelling of additional complex parts, such as burners and casings, is being introduced.

Process development

A further field of application for casting simulation is in casting process development. This includes the evaluation of alternative casting techniques which enlarge the usable processing window and allow the economic production of large complex components. An example that has been modelled is the directional solidification of large gas turbine blades with liquid metal cooling (LMC). Different process alternatives are relatively easy to test on the computer, compared with the much larger effort involved in building a test facility and costly trials and product evaluation. However, new concepts outside the range of experience may require quantitative validation of the casting results.

Castability

Concept phase

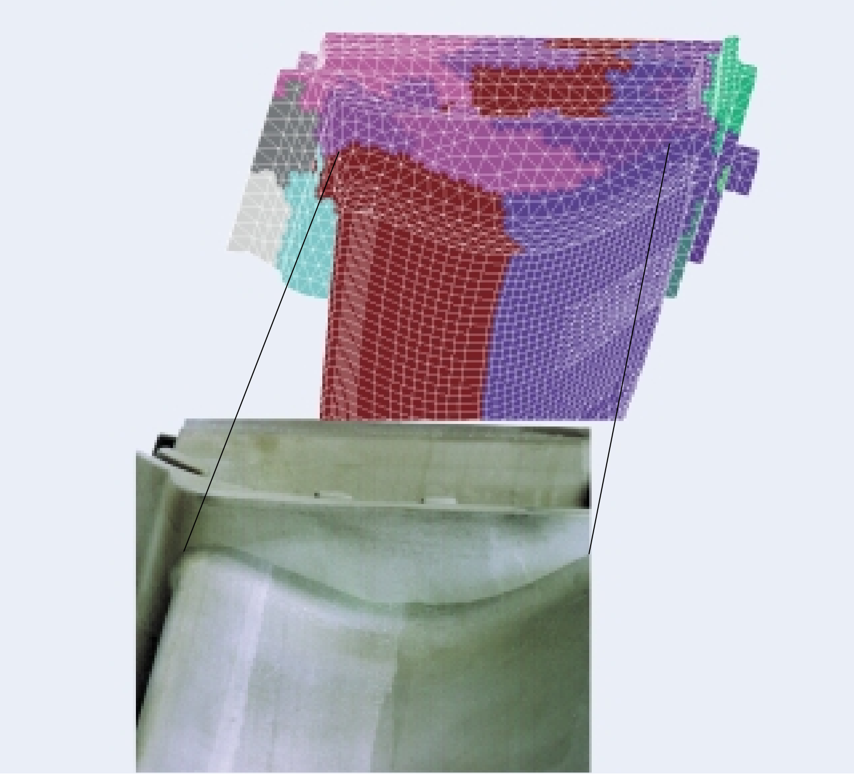
In the development of a new component, the cost impact of design changes becomes more significant the later in the development cycle the changes are implemented. Making the correct choices in the concept phase is extremely important, as it avoids problems that later may cause a significant delay and additional cost. Consequently, the casting simulation tool has the highest impact when applied during the concept phase **6**. Examples of component designs in which casting simulation has assisted during the design phase are shown in **7** and **8**. A design change after start-up of production means modifying or machining new wax and core injection tools. Depending on the extent of the changes, this can cause a delay of 2 to 6 months. Thus, in addition to losses due to the longer 'time to market' and loss of potential customers, there is also a considerable increase in direct costs for the design change, tool change, revision of the process development, and validation of the parts. In summary, it is by far easier to incorporate a correction during the concept phase than to have the casting vendor introduce changes during production development.

Design freedom

Another important aspect is the potential gain in design freedom for a component. The improved reliability of the prediction of the microstructure and the associated mechanical properties increases component safety. Also, knowledge of the local distribution of microstructural properties in relation to the distribution of the in-service component loads allows the component designer to make optimum use of all areas and features.

Tool implementation

Training classes in the use of CASTS have been organized for gas turbine designers, providing them with an introduction to the principles of the casting process as a basis for casting-friendly design. The CASTS program demonstrates, in a way which is easy to understand, how casting proceeds and is affected by design features.



Predicted (colours) and physical (shades of grey) subgrain structures for a single-crystal blade

5

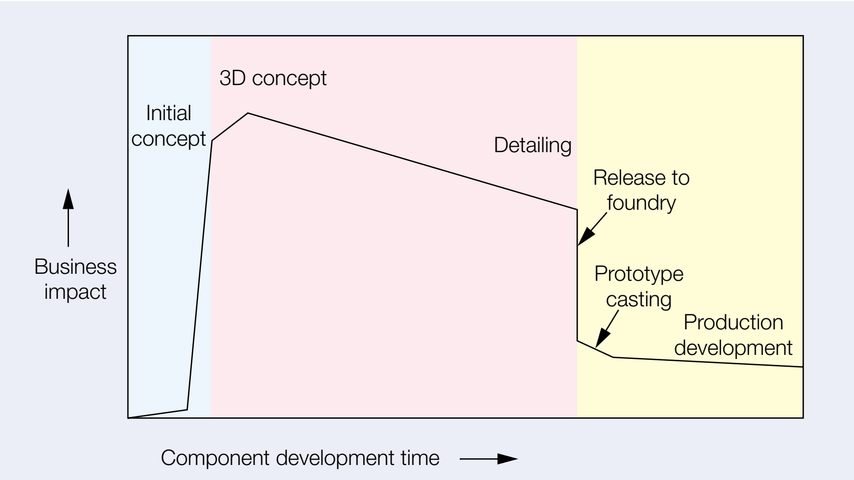
Time advantage gained with early feedback of design changes for a turbine blade: conventional trial and error (I) versus casting modelling (II).

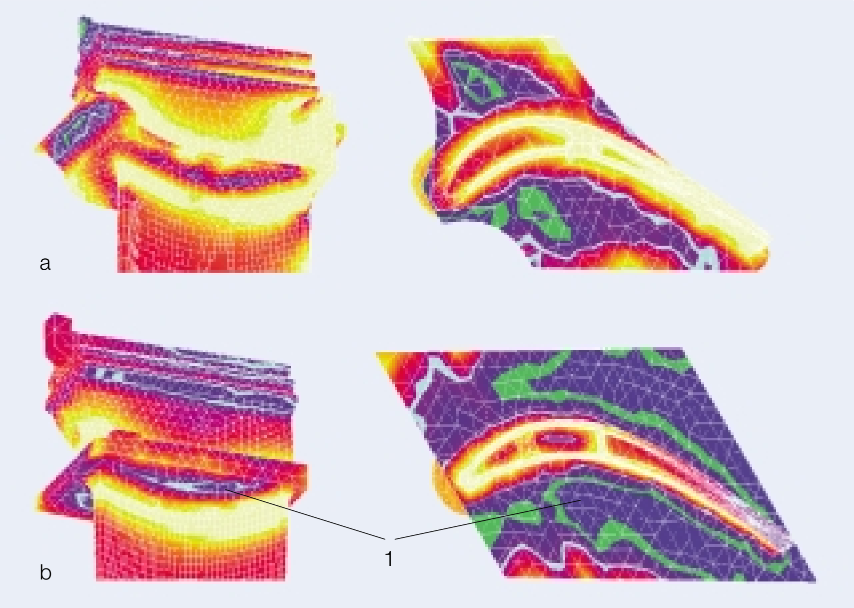
I. First input for design changes
+ tool manufacture
+ mould and core manufacture
+ casting of blade
= 26 weeks

II. First input for design changes
+ enmeshment of blade, core and mould
+ simulation
= 3–4 weeks

Modelling business impact during design phase. The greatest impact of casting modelling is realized as soon as a three dimensional concept is available. Design changes are easy to implement at this stage; later changes require an increasing investment of time and money.

6





Design optimization with respect to castability of inner and outer platform for a directionally solidified blade **7**

a	*Improved design: greatly enhanced castability*	Green	*Medium risk*
b	*Initial design: poor castability*	Light-blue	*Slight risk*

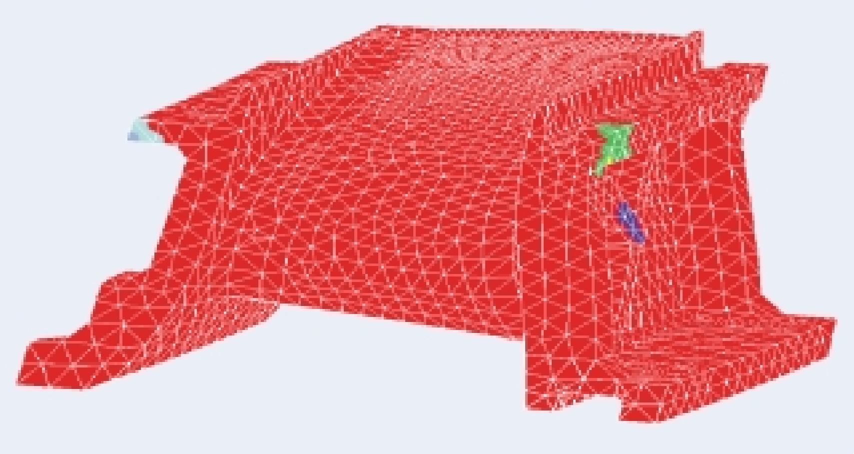
1 *Risk of grain structure breakdown in platform and shroud*

Synergy effects

An essential part of the simulation of a cooled, complex component is the FE enmeshment. Similar enmeshments are required by the mechanical integrity team to establish the predicted lifetime of the components. Although the net parameter requirements differ for casting simulation and lifetime prediction, there is common work on the so-called 'solid model' which represents the three-dimensional geometry of the part as a volume. As a consequence about 35 % of the cost can be saved, compared with the cost of two separate enmeshments.

Intermediate design stage of a single-crystal vane: stray grain prediction led to a better castable design modification. **8**

Red *Single crystal* Other colours *Stray grains*



Ongoing R&D

The casting simulation tool was developed at ABB Corporate Research in a collaboration lasting several years with ACCESS e.V. and the Foundry Institute of Aachen Institute of Technology (RWTH), Germany. Further cooperations have been established with Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, and the University of British Columbia in Vancouver, Canada.

Outlook

After several years of development work on the CASTS software with a number of strategic partners, the software has been accepted and adopted by ABB gas turbine designers as a useful tool for reducing costs and speeding up the time to market. This creates a competitive advantage for ABB in the industrial gas turbine market. However, the tool still represents a stand-alone application, and it will require major additional effort to fully incorporate it into an integrated design methodology for cast components. Such an integrated design tool – a vision of ABB researchers and designers – will incorporate all the different aspects of design, aerodynamics, mechanical integrity, costs, and castability, the latter being just one of the various modules of a larger system.

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