**COST 526 – Project *D4***

Final Report

*Numerical Optimization of the Bridgman Casting Process for Stationary Gas Turbine Blades*

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## 1. Introduction

Turbine blades of modern aircraft and power plants are made of Ni-base superalloys and commonly produced by directional solidification (DS) in a Bridgman furnace (see Fig. 1). The apparently simple principle of generating a directional heat flow by withdrawing the shell mould out of the heating zone into a cooling zone actually constitutes a complex optimization for real blade geometries [1]. Technically relevant casting parameters, such as heater temperature and withdrawal velocity, are currently determined by a series of expensive experiments. This scenario is ideal for numerical optimization, since the optimization of time dependent parameters such as withdrawal speed and heater temperature is easily achieved by this method. Furthermore, blade casting is the most expensive process step in turbine manufacture, which makes reducing manufacturing costs via optimization very attractive for the industry.

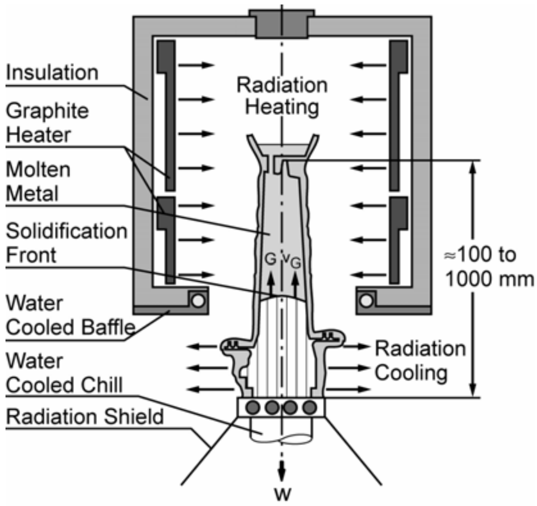


Fig. 1: Principle of turbine blade casting in a Bridgman furnace.

## 2. Goal of the project

While the casting of gas turbine blades in a Bridgman process is a promising application for numerical optimization, such techniques are not used today. Therefore, the possibilities and limitations of numerical optimization for the Bridgman casting process should be investigated in this project. Process parameters, which can be changed by the numerical optimization in order to achieve an improved process, should be identified, different mathematical definitions of the optimization goal should be tested and suitable optimisation strategies developed. Finally the application to an industrial problem should demonstrate the usefulness of numerical optimization for complex manufacturing processes as turbine blade casting in a Bridgman furnace.

## 3. Simulator, calibration, quality function and optimization algorithms, including assessment with respect to alternatives

### 3.1. Simulator and calibration

The hybrid FE/CV program CASTS (Computer Aided Solidification TechnologieS) [2], under development at ACCESS e.V. since the late eighties, is used for numerical prediction of transient temperature response during the Bridgman casting process. CASTS calculates transient temperature distributions in mold, core and alloy, taking into account both latent heat release as a function of fraction solid, and heat transfer resistance at material interfaces. A specialty of CASTS is the calculation of heat exchange by view factor radiation. Since the casting of superalloys is only possible under vacuum, heat exchange by radiation is the dominant cooling mechanism in turbine blade casting processes. Another important feature is the possibility of modeling the withdrawal of the mold and casting from the hot zone of the furnace to the cooling area below (see Fig. 1). The main output of the simulation is the temperature and heat flux field. Based on this data, temperature gradients and isotherm velocities and phenomenological criteria for a defect prediction can be calculated for each set of input process parameters, which provide the basis for the evaluation of the turbine blade. The simulator CASTS was evaluated by numerous comparisons with experimental findings and has been successfully applied in many industrial applications.

### 3.2. Main process parameter

The Bridgman process parameters of relevance are withdrawal velocity profile, heater temperature, or, more precisely, the electrical power, and the geometrical configuration applied: geometry of blade cluster, baffle and heaters. Any change in the geometry necessitates that the geometry is remeshed. This is very time-consuming and currently cannot be done automatically. For this reason, optimization focused exclusively on withdrawal profile and heater control.

### 3.3. Quality function

The main goal of the optimization is to cast a high quality turbine blade in the shortest possible process time. The quality of the turbine blade was evaluated according to 3 criteria:

1. The probability of local freckle formation, which is governed, in a first approximation, by the cooling rate at the liquidus isotherm.
2. The degree of curvature of the solidification front.
3. The ratio G/v (temperature gradient vs. solidification speed) must be greater than a critical value, describing the transition from columnar dendritic growth to an equiaxed grain structure.

Combining the three quality criteria requires the development of a new formulation: post-simulation, the three criteria are evaluated for each node of the finite element mesh used in the simulation. The quality of the blade can now be calculated simply by counting the number of nodes with freckle probability, the curvature of the solidification front, or the G/v ratio above or below a defined threshold. The individual criteria can be merged into a single plot by assigning different colors to nodes with freckle tendency, nodes with too high a curvature and nodes whose G/v ratio is too low (fig. 2). As well as being useful in numerical optimization, merged visualizations of various casting

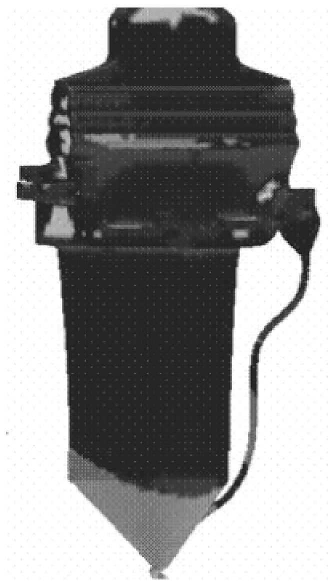

Fig2: Merging 3 quality criteria. Nodes showing freckle tendency are shown white, nodes of too high a curvature are shown light gray, and nodes of too low a G/v ratio are shown dark gray. In contrast, all “good” nodes remain black.

quality criteria can be generally helpful in evaluating casting outcomes.

In a second step, merging the three criteria (freckles, G/v and curvature) was enhanced by weighting. Nodes not meeting the above- mentioned criteria, rather than being simply counted as previously, were weighted according to modal volume contribution, which is expressed in the CASTS control volume approach. To reflect that a few nodes with freckles are equally bad as several nodes of too high G/v value and a large number of nodes of incorrect curvature, an additional factor was introduced.
This new quality measure, achieved by counting “bad nodes” weighted according to their corresponding control volume and the criteria weight was successfully used in three industrial applications.

### 3.4. Optimization algorithms

For the optimization of the Bridgman process a metamodel-assisted optimization strategies (MA-DES) showed a stable and fast convergence and outperformed other strategies. Evolution Strategies are often used for parameter optimization in industrial applications, because they are robust and simple to implement. A disadvantage of this type of optimization strategy is the high number of function evaluations needed to find an optimum. The evaluation of one parameter set means a complete simulation of the Bridgman process, which is computationally expensive. Consequently, the number of function evaluations necessary needs to be kept to a minimum. To reduce the number of evaluations, the number of possible parameter combinations was reduced by a derandomization strategy.
To further reduce the number of simulations necessary, a fast approximation model to the objective function (metamodel) was applied. The metamodel is consulted to reduce the number of exact function evaluations. In each iteration of the optimization 20 variations are generated by adding normally distributed perturbations to each vector position. The algorithm then selects from the 20 variants, the 4 most promising variants via a preselection criterion based on the approximation of the response by the metamodel. Only 4 input vectors with the highest ranking in the metamodel are then evaluated by the computationally expensive evaluation tool and the archive for the metamodel is updated with the new results.

The MA-DES was compared with the standard downhill simplex algorithm [5], a derandomised evolution strategy (DES) [6] and iterative Kriging [7]. For this comparison a simplified blade was used. The results showed that the metamodel-assisted evolution strategy MA-DES outperforms classical methods with respect to the results obtained with the same number of precise evaluations (see Fig. 3).

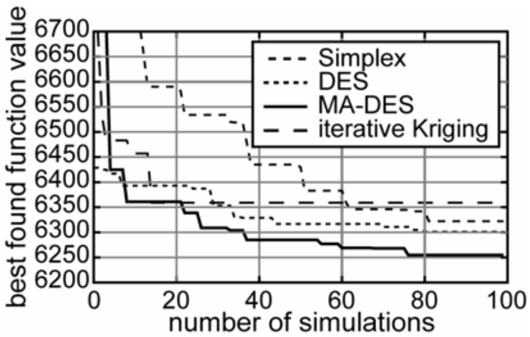

Fig. 3: A comparison of various conventional and metamodel-assisted optimization strategies for optimization of the Bridgman casting process

## 4. Main scientific outcome

- **Optimization of complex manufacturing processes is possible**
  The results of this project demonstrates the even complex processes like Bridgman casting, which can only be simulated using computational expensive programs, can be successfully optimised by numerical methods. The number of optimisation parameters should not exceed the range of 10-20 and parallel computation must be used to get a significant improvement within a few days.

- **MA-DES is a stable and fast optimization strategy**
  The Metamodel Assisted Derandomized Evolution Strategy (MA-DES) was found to be a stable optimization algorithm for optimising the Bridgman casting process. It was used for calibration of material and process parameters as well as different quality functions and showed a stable and fast convergence in all applications. Here, fast convergence means the identification of a good solution or a significant improvement within a small number of necessary function evaluations.

- **Objective function definition**
  Great effort was invested to achieve an appropriate definition of the objective function. While different quality criteria could be successfully integrated into one objective by a newly developed approach (see above) the combination of short process time and good blade quality into one objective was found to be difficult. By dividing the objective function into three parts, a useful approach could be developed which could be used to improve the withdrawal profile of the Bridgman process towards a better quality produced in a shorter process time. But the results indicate that the use of a multi-objective strategy may be more promising when contradictory objectives should be optimised simultaneously.

## 5. Main technical outcome

- **Parameter calibration**
  The MA-DES was successfully used to calibrate different material and process parameters for an industrial Bridgman process for gas turbine blade production. One main outcome of the calibration was that the simulation model underestimated the heat capacity of the Bridgman furnace, because several parts of the furnace were neglected in the model, since they should not directly influence the heat distribution. But the calibration showed that they, nevertheless, have a significant influence on the heat capacity.
  In summary this industrial application of parameter calibration demonstrates that a calibration is mandatory for a quantitative simulation of complex processes and numerical optimization can be used very efficiently for parameter calibration.

- **Turbine blade quality and process time optimization**
  The likelihood of casting defects in a directionally solidified gas turbine blade could be reduced to almost zero by optimising the time dependent temperatures of the heaters in the Bridgman furnace. A reduction of the heater temperature shortly after the start of the withdrawal leads to a significantly improved temperature distribution on the blade during solidification (Fig. 4).

The results of the optimisation are currently applied by our industrial partners to the real casting process.

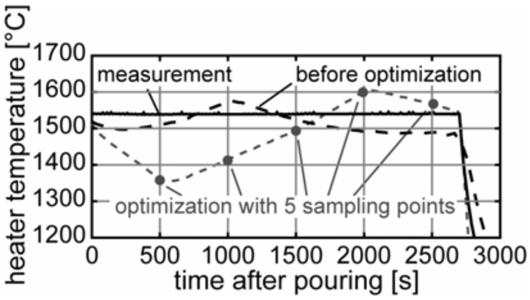


Fig. 4: Optimized heater temperature profile in comparison with the measured constant profile and the profile obtained by the first simulation.

In a second application a withdrawal profile was determined which simultaneously improved the turbine blade quality asset by 3 quality measures and reduced the process time. Within less than 50 function evaluations the MA-DES found the improved withdrawal profile which outperformed the best withdrawal profile optimized by try and error. But the blade quality did still not fulfil all quality requirements.

## 6. Collaboration within COST 526

The development of the quality function as well as the optimisation strategy was greatly inspired by the discussion with the other groups in COST 526. The different quality criteria were discussed intensively with M. Balliel (Ch2). The use of a quality weighting was suggested by N. Hofmann (CH4). C. Knopf-Lenoir (F3) suggested the use of design of experiment methods to investigate the dependencies between the different optimisation parameter. In collaboration with the FH-Aargau (CH4) a user interface for numerical optimization was developed, which may become a part of the CASTS software package.

## 7. Cooperation with industry

From the beginning the choice of the optimization parameter, the design of the objective function and the relevance of the results were discussed with our industrial partner from Alstom Power Ltd. In the summer 2004 ALD Vacuum Technologies GmbH showed interest in numerical optimization. One of their Bridgman processes could be successfully optimized using the methodology developed in this project.

## 8. References

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