COST 526

**"Automatic Process Optimization in Materials Technology"**

(APOMAT)

## Half-Yearly Report

| **1. Reporting Period** | **1.7.2003 – 12.31.2003** |
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| Project title | Numerical Optimization of the Bridgman Casting Process for Stationary Gas Turbine Blades |
| Project leader | Dr. J. Jakumeit |
| Organization | ACCESS e.V.<br>Intzestrasse 5, D-52072 Aachen, Germany |
| Main collaborators involved | Dipl.-Inf M. Emmerich, ICD, Dortmund, Germany<br>Dr. G. Laschet, ACCESS e.V. |

| **2. Funding Situation** | |
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| Amount of money received specifically for COST | 80 kEuros |
| Other resources partially used for the project | 40 kEuros |

**3. International Collaboration**

(mention group and type of work done in collaboration during the reporting period)

Participation in the Working Group Meeting in Krakau + project progress report

X YES

❐ No

**4. Industry participation**

(mention name of companies and work done in collaboration during the whole project)

Alstom Power Ltd, Segelhof 1, CH-5405 Baden-Dättwil, Schwitzerland

Together with our industrial partners we defined one real gas turbine blade and one simplified blade for the application of the optimization strategies. We have the permission to publish results obtained with these test cases.

| **5. Meetings, visits, exchange of scientists, short-term scientific missions** | **Location, date** |
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## 6. Progress within the reporting period

(Not exceeding 3 pages, including tables and figures)

1. Introduction

The highest gas turbine efficiency is achieved today with single-crystal (SX) or directionally solidified (DS) blading material, commonly produced in a Bridgman furnace. The Bridgman process is controlled by time dependent parameters (withdrawal speed, heater temperatures), which are ideal for the application of numerical optimization [1]. In addition the blade casting is the most expensive process during the manufacturing of a turbine making a reduction of the fabrication costs by optimization very interesting for the industry.

In the first year a preliminary optimization loop has been developed based on the validated casting simulation tool CASTS [2]. Goal of the optimization was an improved withdrawal profile for the Bridgman process of a cluster of 3 SX blades. The simulation results were evaluated by 4 criteria:

- the probability of local freckle formation;
- the degree of curvature of the solidification front;
- the ratio G/v (temperature gradient over solidification speed) must be greater than a critical value (~600 K/s), describing the transition from columnar dendritic growth to an equiaxed grain structure;
- the process time.

These criteria where combined to one objective function by a weighted sum of the normalized individual values, integrated over the whole structure. As optimization strategies the Global Convergent Method (GCM) [3] of BOSS Quattro and a Derandomized Evolution Strategy (DES) [4] developed at the Informatic Center Dortmund were used. First results showed, that both GCM and DES lead to improved withdrawal profile in respect to the used optimization criteria. But the best withdrawal profile found by the DES lead to a long process time and a freckle tendency. Thus the objective function did not lead to improvement in respect to all criteria.

In order to achieve a better definition of the optimization goal, a new formulation has been developed for the first three optimization criteria, the freckle probability, the curvature of the solidification front and the G/v ratio. In the new formulation these criteria are evaluated by counting the number of "bad" nodes, i.e. nodes with freckle probability, the curvature of the solidification front is above 20° or the G/v ratio is below 600 K/s. The criteria can be tuned by changing the limits (20°,600 K/s).

2. New metamodel-assisted optimization strategy

Another problem with Evolution Strategies for the optimization of process parameter is the high number of solutions needed to find an optimum. Until now the derandomization was used to reduce this number to a practical size below 100. For a further reduction a metamodel-assisted optimization strategy was developed in the first half of 2003. The metamodel based strategies are compared with the standard downhill simplex algorithm [5] and the derandomised evolution strategy (DES) used so far [6]. For this comparison a simplified blade was used, which can be simulated with in one hour. 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.

3. Application of the MA-DES to a industrial turbine blade

In this period we applied the MA-DES to the optimization of an industrial turbine blade, the cluster of 3 SX blades mentioned above. For this optimization the way, in which the three criteria freckles, G/v and curvature are combined, was improved. Nodes, which don't fulfill the criteria mentioned above, where not simply counted as before but weighted by the volume, which can be assigned to the node by the CASTS control volume approach. An additional factor was introduced to reflect that a few nodes with freckles are equally bad as several nodes with a too high G/v value and many nodes with a wrong curvature.  Figure 1 shows the old criteria, where nodes are just marked, and the new weighted criteria.

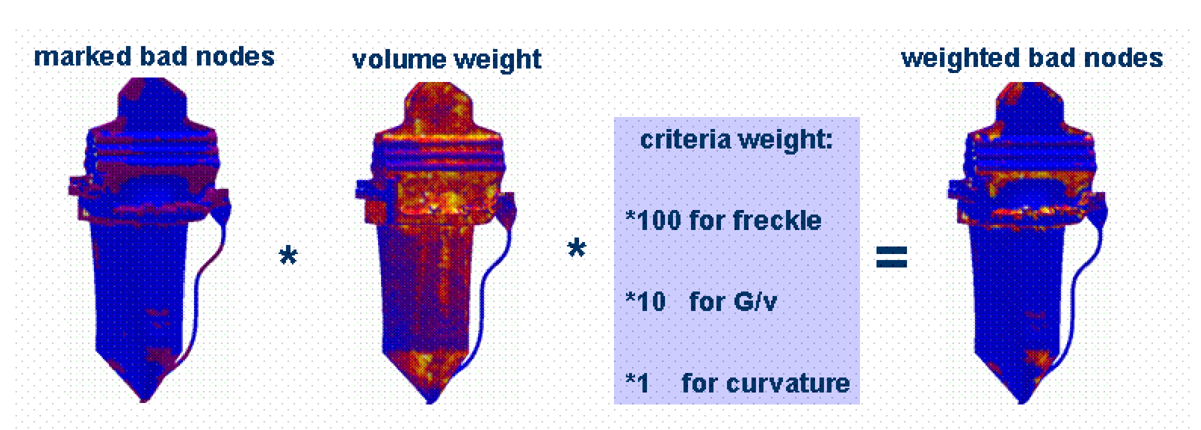


Figure 1: Improved optimization criteria by a weighting of nodes by the assigned control volume and an additional criteria weighting factor.

The objective function was defined as follows (see also figure 2):
As long as the process time is above 10000 s and bad nodes exist, the weighted sum of the freckle, G/v and curvature criteria are added to the process time to give the objective value. If the process time is below 10000 s the weighted sum plus a fix value of 10000 is used as objective function. A process time of 10000 s is assumed to be acceptable and the optimization focuses on the improvement of the blade quality by reducing the number of bad nods. If a high quality blade with no bad nodes is achieved the optimization can again try to reduce the process time. There for the process time in seconds becomes the objective function, when all bad nodes are removed.

**Definition of objective function z:**

$$z = \begin{cases} \text{Weight of bad nodes + process time [in s]} & \text{if weight>0 and time>10000 s} \\ \text{Weight of bad nodes + 10000} & \text{if weight>0 and time<10000 s} \\ \text{Process time [in s]} & \text{if weight=0} \end{cases}$$

Figure 2: Objective function definition

Figure 3 summarizes the result of the optimization of cluster of SX blades. The withdrawal profile was discretized using 6 velocity values at the withdrawal positions: 6 cm, 20 cm, 28 cm, 36 cm, 44 cm and 60 cm. The left upper plot shows the convergence of the MA-DES. The dotted red line gives the result of each simulation, while the full red line shows the objective value of the best solution so far. After a significant improvement within the first 12 simulations the optimization could not yield further improvements after 40 simulations and the process was stopped. A withdrawal profile which yields no bad nodes could not be obtained within 45 simulations. For the main improvements found, the blades with the marked bad nodes are plotted below the convergence plot (the color of the frame of the plots gives the position on the convergence curve). The improvements found in the objective function can obviously not be visualized by simply marking the bad nodes on the surface of the blade.
For comparison the turbine blade was also optimized by a downhill simplex (DS) algorithm. The DS starts with a rather good solution but finds no further improvements.

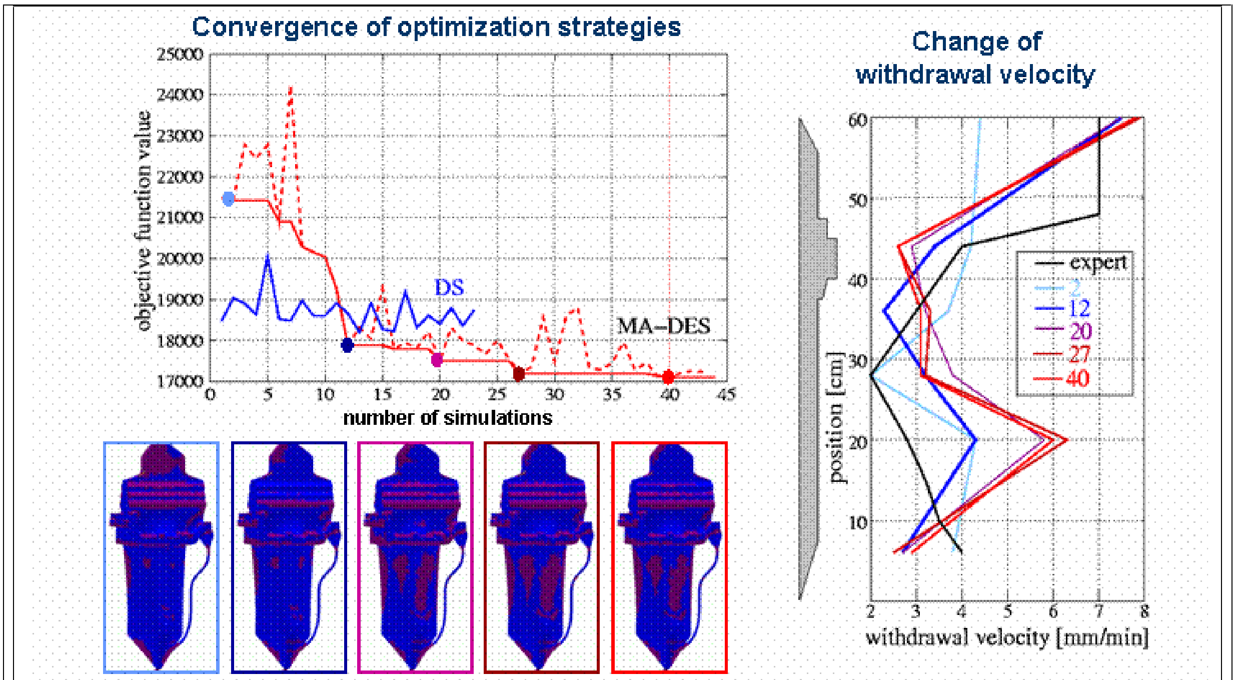


Figure 3: Result of the optimization of an industrial turbine blade.

The right plot of figure 3 shows the resulting withdrawal profiles. Starting from an initial guess the MA-DES finds the main form of the withdrawal profile with 20 simulations. The withdrawal velocity should be small around 3 mm/min at the beginning of the process. The velocity can be increased to 6 mm/min in the range of the blade itself. For the solidification of the thick basis of the blade slow velocities around 3 mm/min are again necessary. For the last centimeter of the process the velocity can by high to reduce the total process time. Compared to a withdrawal profile designed by a casting engineer the numerical optimized withdrawal profile leads to a higher quality of the blade within a shorter process time.

4. Conclusion

The MA-DES was successfully used to optimize the withdrawal profile of the Bridgman process for casting industrial turbine blades. The result of the optimization is a withdrawal profile which leads to a higher quality of the turbine blade and a shorter process time compared to a withdrawal profile designed by hand. For the future the objective function definition has to be further adjusted to the needs of the casting engineers and a discretization of the withdrawal profile with more than 6 velocities would be desirable.

5.References

[1] G. Laschet, M. Schallmo & N. Hofmann: "Optimization tools for Bridgman casting process", Proc. 7th Conf, on Casting, Welding and advanced Solidification, Ed. B. Thomas & C. Beckermann, TMS editions, San Diego, pp 1095-1102, 1998.
[2] G. Laschet, J. Neises and I. Steinbach: « Micro- Macrosimulation of casting processes", 4ième école d'été de "Modélisation numérique en thermique", C8 1-42, Porquerolles, 1998.
[3] BOSS QUATTRO, version 4.2, Samtech S.A., Liège, 2002.
[4] OASIS, optimization toolbox, ICD Dortmund, 2001.
[5] H.-P. Schwefel, *Evolution and Optimum Seeking*, Wiley, NY, 1995
[6] T. Bäck. *An overview of parameter control methods by self-adaptation in evolutionary algorithms*, Fundamenta informaticae 35 (1998), pp. 51-66, IOS Press

## 7. List of publications

a) Published

R. Laqua, T. Ivas, J. Scheele, J. Jakumeit, M. Braun and M. Pelzer, *Mold Filling and Solidification Simulations of Investment Casting Processes using CASTS-FLUENT,* Proceedings of ERUOTHERM Seminar 69, Ljubljana, 2003

M. Emmerich,ICD and J. Jakumeit, *Metamodel-Assisted optimisation with constraints: A case study in material process design,* Procceedings of EUROGEN 2003, Barcelona

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| b) Submitted for publications |
| J. Jakumeit, M. Herdy and M. Nitsche<br>*Parameter optimization of the sheet metal forming process using an iterative parallel Kriging algorithm*<br>Submitted to Structural and Multidisciplinary Optimization |
| c) In preparation |
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