COST 526

“Automatic Process Optimization in Materials Technology”
(APOMAT)

Half-Yearly Report

To be sent to **V.Tesch@access.rwth-aachen.de** until **August 31, 2002**

1. Reporting Period	**1.1.2002 – 30.6.2002**
Project title:	Numerical Optimization of the Bridgman Casting Process for Stationary Gas Turbine Blades
Project leader:	Dr. G. Laschet
Organization:	ACCESS e.V. Intzestrasse 5, D-52072 Aachen, Germany
Main collaborators involved:	Dipl.-Inf M. Emmerich, ICD, Dortmund, Germany Cand. Math. M. Makowski, ACCESS e.V.

2. Funding Situation

Amount of money received specifically for COST	0 kEuros
Other resources partially used for the project	50 kEuros

3. International Collaboration

Participation in the Working Group Meeting in Saint-Dié des Vosges + project progress report have been achieved

4. Industry participation

Alstom Power (Switzerland) Ltd, Segelhof 1, CH-5405 Baden-Dättwil

A more physical model to predict freckles formation during the solidification process of single crystal turbine blades has been developed in collaboration with Alstom Power. This model evaluates the blade surface taking into account size and processing effects. Two separate Rayleigh numbers for flow perpendicular and parallel to the dendrites in the mushy region are introduced to describe the processing effects.
This new freckle criterion will be introduced during the next reporting period in the developed optimization procedure either as objective or constraint.

5. Meetings, visits, exchange of scientists, short-term scientific missions	**Location, date**
Participation at ACOMEN 2002 Conference about Numerical Methods applied to Engeneering Problems (this conference has several sessions about optimization algorithms and their applications)	Liège, Belgium, 28th-31th May 2002

6. Progress within the reporting period

1. Introduction

Turbine blades of modern aircraft and power plants are made of Ni-base superalloy and commonly produced by directional solidification (DS) in a Bridgman furnace. Its apparently simple principle of generating a directional heat flow by withdrawing the shell mould out of the heating zone into a cooling zone constitutes in fact a complex optimization for real blade geometries [1]. Technically relevant casting parameters, such as heater's temperature and withdrawal velocity, are currently determined by series of expensive experiments. Therefore, based on the validated casting simulation tool CASTS [2], a first optimization strategy has been developed during this reporting period which is able to optimize the casting quality with respect to achieving low process time and costs. This report describes briefly the developed strategy and presents first optimization results for an industrial application: Bridgman casting of a cluster of 3 SX blades.

2. Material Quality of DS/SX Blade

At first, the relevant process parameters of the Bridgman process have been identified: the withdrawal velocity profile, the heater's temperature or more precisely the applied electrical power and the geometrical configuration: geometry of blade cluster, baffle and heaters.

At next, to produce a high quality DS/ SX turbine blade, the following features have been identified to be relevant in order to have an acceptable grain structure without defects like freckles and stray grains:

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

3. Definition of a Specific Objective Function

In order to formulate an optimization problem following global objective function, defined over the whole solidification time, is introduced by using the selected material quality requirements as constraint terms:

$$Y(w(z)) = \int_V \left[\alpha_1 \left[\frac{G/v|\mathrm{crit}}{G_z/v_z} \right]^n + \alpha_2 \left[\arccos\left(\frac{\vec{G}.\vec{n}}{|\vec{G}|} \right) \right]^m + \alpha_3 \left[\frac{t_{proc}}{t^*_{proc}} \right]^m \right] dV \quad m = 1.5 \text{ and } n = 1.8 \tag{1}$$

where - V denotes the volume of the superalloy
- w(z) : withdrawal velocity profile along the blade axis z
- α_i's are weighing factors which depend on the solidification process (e.g. DS or SX)

This global objective function is a highly nonlinear and implicit function of the withdrawal velocity w and can not be written in a closed or analytical form, suitable for a semi-analytic sensitivity analysis.

4. Optimization Procedures

At next, an optimization procedure based on the transient thermal FE program CASTS is developed. To realize this procedure, interfaces between the simulator CASTS and two selected optimization environments, the commercial software Boss-Quattro [3] and OASIS [4] from the partner institute ICD, have been written and successfully tested. In order to reduce the computational effort, similar input and results files as for Boss-Quattro are exchanged with OASIS.

Two different formulations of the optimization problem have been adopted here:

- OASIS: an unconstrained, mono-objective formulation based on the global quality expression (1);
- Boss-Quattro: a constrained, multi-objective formulation is defined. This formulation uses mean local qualities defined by:

$$Y_k(w(z)) = \int_{z_{k-1}}^{z_k} \int_S \left[\alpha_1 \left[\frac{G/v|\mathrm{crit}}{G_z/v_z} \right]^n + \alpha_2 \left[\arccos\left(\frac{\vec{G}.\vec{n}}{|\vec{G}|} \right) \right]^m + \alpha_3 \left[\frac{t_{\mathrm{proc}}}{t^*_{\mathrm{proc}}} \right]^m \right] dSdz \qquad (2)$$

where $[z_k, z_{k-1}]$ is a selected subdomain of the cast part along the blade axis.

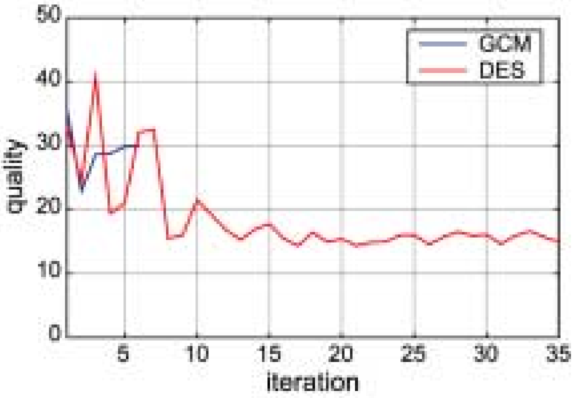
After specifying a target value, t_g, these local qualities are shared in two groups: $Y_k \le t_g$ become constraints and $Y_k > t_g$ are objective functions. This separation allows us to formulate following constrained min-max problem:

min-max Y_q $q=1,n_{obj}$ with $Y_k \le t_g$ $k=1,n_{cst}$ and $0.5 \le w(z_i) \le 25$ mm/min (3)

In this 1st phase, only the withdrawal velocity w(z), described by a polyline of N parameters, is adopted as design variable. This velocity is restricted technologically by the last term of (3).

Then, to apply these formulations following suitable optimization algorithms have been selected:

- Boss-Quattro: the global convergent version of the moving asymptotes method, named GCM [5], is chosen;
- OASIS: as for industrial applications (e.g. cluster of 3 SX blades) the corresponding FE models are large (98,000 nodes; 357,000 tetrahedron elements) and lead to time consuming function evaluation (from 16h to 32h on a SGI workstation (Origin, R12000, 400 Mhz)). Therefore, a classical evolution algorithm (EA), realizing in means more than thousand fitness evaluations, cannot be adopted here. For such applications, a specific low cost EA is adopted here: the derandomized algorithm DES (1 + 4) [6]. This algorithm does an accelerated online estimation of the covariance matrix for the n-dimensional normal distribution which is used to generate the new offsprings within the mutation procedure.



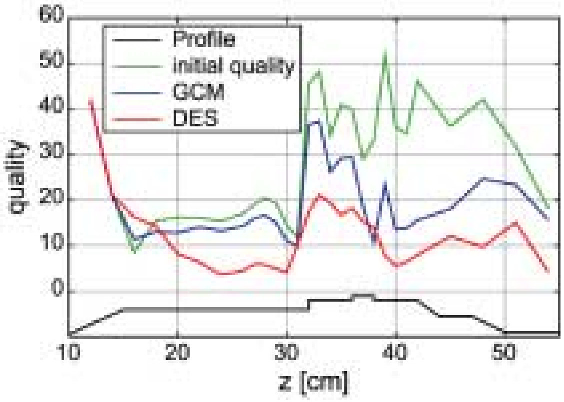


Figure1: Comparison of the variation of the global quality during the optimization runs for the GCM and DES algorithms

Figure 2: Variation of the main local qualities along the blade axis for the initial and optimized configurations. The black curve is the blade profile

5. Application: Optimization of the Bridgman Casting of a Cluster of 3 SX Blades

Both developed optimization strategies have been applied to the optimization of the withdrawal velocity profile for the SX casting process of a cluster of 3 blades of a power gas turbine. The optimization starts with a constant withdrawal velocity profile: w_i = 7 mm/min i=1,10. Only the 8 first positions define design variables and all weighting factors α_i i=1,3 are set to one in expressions (1-2). The quality analysis of the initial configuration shows that 8 local qualities are above the target value 35 and become objective functions. The other 20 local qualities and the global one become constraints in the min-max formulation (3).

At figure 1, the variation of the global quality during the optimization process is reported for both algorithms: GCM and DES. GCM converges directly (iter. 2) to an interesting profile but then cannot improve this profile. DES due to its more randomly generated offsprings does present this difficulty and converge to a “better” global quality: 14.4 (18th iter.) against 22.9 for GCM. In order to explain GCM’s convergence difficulties, the variation of the main local qualities along the blade axis as well as its profile are drawn on figure 2 for the initial and optimized configurations.

At the 1st iteration the local quality lqua21 at z=39 cm is the maximum value and will be minimized. The quality is there very sensitive, thus GCM reduces significantly the global quality. But, then lqua1 (z=10 cm) becomes the maximum. As illustrated at figure 2, the quality is there quasi-insensitive and defines a local plateau, which is difficult to optimize with a gradient algorithm. Therefore, less sensitive local qualities must be defined as constraint and not as objective function even if they are larger than the target value.

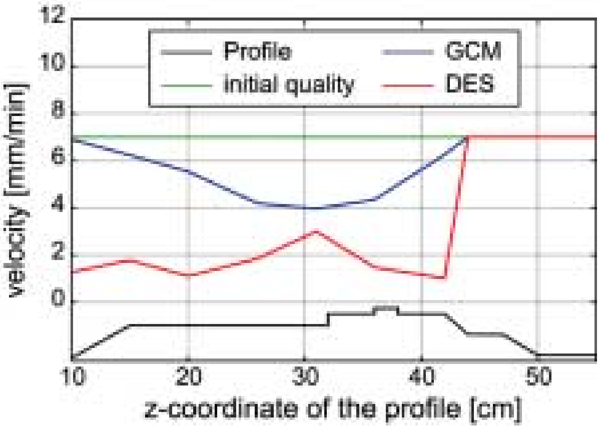


Figure 3: Initial and optimized velocity profiles along the blade axis

Finally, at figure 3 the initial and optimized velocity profiles along the blade axis are reported. The “optimal” DES solution corresponds to a low mean velocity profile (below 2 mm/min). Therefore, the process time increases significantly up to 18,595 sec instead of 5,325 sec for the initial profile. This increase happens although the process time is included as constraint in the objective functions (1-2). Indeed, its value (1.10) is masked by the other two constraints (curvature, G/v)!

6. Conclusion and Outlook

This first investigation on a real industrial casting process shows clearly the weakness of the definition of the actual objective functions (1-2). In a further step, only one quality requirement is adopted as objective function. Thus, the weighting factors disappear. The planarity of the solidification front is adopted as unique objective function, evaluated for several blade segments as follow:

$$Y_k(w(z)) = \int_{z_{k-1}}^{z_k} \int_S \left[\arccos\left(\frac{\vec{G}.\vec{n}}{|G|} \right) \right]^m dSdz \qquad m=1.5 \quad \text{in order to be sensitive} \qquad (4)$$

This choice is justified by the fact that it is the largest constraint which does not depend on a material or user parameter and acts not locally but on the whole blade geometry. The other quality requirements become individual constraints for each blade segment ($\dot{t} > \dot{t}_{crit}$; $G_z / v_z > G / v|_{crit}$) or for the whole process ($t_{proc} > t_{proc*}$). The problem formulation will be for both optimizer a multi-objective min-max one with several inequality constraints. This new quality function implies an extension of the

QUALTY program, rewritten in Fortran 90 and a constraint formulation must be connected to the evolution algorithm DES ($\lambda + \mu$) in OASIS.

7. 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] K. Svanberg: “A globally convergent version of MMA without linesearch”, Proc. of WCSO-1, Goslar, 1995, Ed. Olhoff, pp 9-17.
[6] N. Hansen & A. Ostermeier : “Complementary derandomized self-adaptation in evolution strategies”, Evolutionary Computation, Vol. 9, n. 2, pp 159-195, 2001.

7. List of publications

No specific publications have been realized during this 1st report phase.