COST 526

Automatic Process Optimization in Materials Technology
(APOMAT)

Title:

Numerical Optimization of the Brigdman Casting Process for Stationary Gas Turbine Blades

Keywords: Bridgman Process; Gas Turbine Blades; Finite Element soldification Simulation

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1. Duration / run time of the project

3 years, from Sep 2001 to Aug 2004

2. Overall cost

approx. 450 kEURO

3. Funding situation

- Partly funded by ALSTOM Ltd, Switzerland
- National funding to be applied for

4. Project partners indicated to participate

- ALSTOM Ltd, Baden, Switzerland (investment casting of blade trials)
- Informatik Centrum Dortmund (ICD), Dortmund, Germany (development of optimisation algorithms)
- SAMTECH, Liège, Belgium (supplier of Boss Quattro: optimisation task managment)

5. Project partners to be found

- Casting vendor (not yet determined)

6. Short description of the material process to be optimized

An increasing worldwide demand for directionally solidified single crystal turbine blades of lengths up to 500 mm for stationary gas turbines demands that both turbine manufacturers and casting vendors improve their casting process with respect to quality and efficiency. These blades are made of Ni-base superalloys and produced by the directional solidification process in a Bridgman casting furnace. The apparently simple principle of generating a directional heat flow by withdrawing the shell mould out of a heating zone into a cooling zone in fact constitutes a complex optimization problem for real blade geometries [1]. Technically relevant casting parameters, such as heater temperature and withdrawal velocity, still have to determined by series of expensive experiments.

7. Material(s) involved

Superalloys, Ceramic shell mould and core materials

8. Optimization potential of the process or process step

Along the production chain of cast turbine blades up to 50 % of the costs result from the vacuum casting and solidification step.

a) Reducing casting defects - based on the component specification - leads to an improved yield rate, saving expensive alloy, shell and core costs and cutting delivery time.
b) Casting simulation is of greatest impact on robust process development time for each new blade design when applied during an early concept phase.

9. Specified material properties to be achieved

- to meet grain structure specifications (e.g. to prevent stray grains)
- to prevent freckle formation
- to minimize residual stress in specified critical areas
- to minimize porosity

10. Process parameters to be optimized

- The withdrawal velocity profile (equivalent to 10 up to 30 parameters) for the cast blade as a function of the withdrawal unit position
- The temperature evolution of a multizone heating system (equivalent to 5 up to 15 parameters)

11. Material laws including material dependent coefficients

In order to compute some material qualities for the directional solidification process of turbine blades, the following material laws and criteria have been coupled with CASTS:

a) Criterion for dendritic growth: columnar-equiaxed transition (CET) [2]:

$$G/V < (G/V)_{c-e}$$

where: G: local temperature gradient at the solidification front
V: local velocity of the solidification front
$(G/V)_{c-e}$: critical (G/V) value for CET

b) Criterion for tendency of freckles formation [2]:

$$I_F = \frac{D_{eq}}{D_0}\frac{Ra}{Ra*}$$

where: D_{eq}: local equivalent diameter of the component
D_0: critical diameter for freckles formation
Ra: Rayleigh number as function of G and V
Ra*: critical Rayleigh number determined experimentally

c) Laws for dendritic growth:

$\lambda_1 = C_1 G^{-1/2} V^{-1/4}$ primary dendrite spacing [4]:
$\lambda_2 = C_2 (G^* V)^{-1/3}$ secondary dendrite spacing [4]:

d) Hot tearing criterion for directional solidification [5]:

$$\varepsilon' = \varepsilon'_{p,\max} = \left(\frac{\lambda_2^2}{180} \frac{G}{(1+\beta)\mu} \Delta P_c - V_T \frac{\beta}{1+\beta} H \right) / F_2(T)$$

ε': strain rate
$\varepsilon'_{p,max}$: maximum plastic strain rate sustained by the mushy
μ: viscosity
ΔP_c: gravitation depression
β: shrinkage factor

The material laws in thermomechanical analysis are thermoelasto-(visco)-plastic models with isotropic hardening for the superalloy and the ceramic mould, as well as frictionless contact laws.

Objective function design will be based on these above mentioned laws and criteria. The simulator CASTS provides input data to evaluate the objective function.

12. Simulator

The finite element simulation program CASTS will be applied to constitute a virtual model of the real-world Bridgman casting sequences [6,7]. The technical advantages of this tool are its fast and accurate viewing factor-based radiation model, coupled calculation of the transient temperature and stress distribution (in the component, mould and core) and the handling of large finite element models thanks to a high-speed computational methodology. Additionally, an automatic shell mould finite element mesh generator is part of the CASTS program. Over the last few years this simulator has proved itself by enabling many practical task solutions, in particular for Bridgman casting. Additionally, the model has been validated by comparison between predictions and the physical output from casting trials.

The hot tearing criterion mentioned in § 11 needs to be implemented into the thermomechanical module of CASTS.

13. Optimizer

Because of the high-grade non-linear optimization problem, which provides a sensitivity analysis, and the fact that the impact on quality of current process parameter settings involves time delay, it is appropriate to couple various optimization algorithms. The development of a robust, efficient hybrid approach is only achievable by a step-by-step application and subsequent coupling of various techniques.

As optimization algorithm or technique, the following methods are currently under investigation as to their properties and usefulness as a hybrid approach:

- **SIMPLEX method** [8]

  Linear optimization technique currently widely used and highly stable. Application to non-linear problems is possible, but requires adaptation of the technique.

  Advantage: high speed, relative stability

  Drawback: not always converging to the optimum
- **Gradient algorithms**

  Examples of this method are described as CDM (Conjugate Direction Methods) and apply a gradient to identify a minimum (or maximum) of a function. This technique requires to define derivation of a objective function, which, in most actual industrial optimization problems is not actually possible because this function is not available in an explicit form. Application to the process under discussion requires special gradient techniques, such as SQP, CONLIN [9] and GCM (Global Convergent Moving Symptote Method) [10].

  Advantage: robust, relatively fast, converges to a local optimum

  Drawback: program halts at local optima, i.e. the search for global optima largely depends on the starting point of the optimization calculation
- **Evolution strategies**

  A distinction is made between ES (Evolutionary Strategies) and GA (Genetic Algorithm), both of which method according to the same principle. These techniques apply a random-supported search in the optimization field, in which the search is controlled by the application of special methods. Without these methods, the search would be a random one, as in the Monte Carlo methods. The DES algorithm (derandomized evolution strategy) [11], for example, has shown itself to be a particularly interesting model for generating a new generation by means of previous evaluations. The great advantage of this technique is the option of ignoring local optimas in order to find better ones.

  Advantage: very stable, omission of local optima

  Drawback: a very great number of evaluations required

Both commercial and self-developed programs (Simplex) are available for each of the techniques outlined above.

A hybrid technique, in which the advantages of the gradient and evolution strategies are combined is to be developed within the scope of this project. Coupling of ES with the commercial program BOSS Quattro (supplier: SAMTECH), and also the ICD library can be applied.

14. Competence / activities of proposer

In 1980, the original purpose of the software development of CASTS was to model the BRIDGMAN casting process. Since the very beginning, these activities have been linked to extensive casting experiments in a Bridgman casting furnace of industrial scale (operated by both the Foundry Institute and ACCESS at Aachen). Since 1992, close technical cooperation between ABB Power (now: ALSTOM Power) and ACCESS has ensured ongoing improvement of the CASTS software. First steps towards an automatic optimization procedure for the Bridgman casting process have been already undertaken in collaboration with ALSTOM Power [1,12,13].

15. International state-of-the-art and references

Several software packages for solidification modelling are available on the market today. Only two programs (Procasts and CASTS) are dedicated to simulate the Bridgman process. Several publications [14,15,16] are available dealing with basic approaches towards numerical optimization of solidification processes. However, only recent papers of ACCESS describe the optimization of the Bridgman investment casting process. [1,12,13].

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