

COST 526 – Project CZ1

Final Report

A numerically based optimization of a near-gamma TiAl precision casting process

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1. Introduction

The up-scaling of production and applications of gamma-TiAl based alloys is still conditional on increasing the reliability and availability of these materials in engineering practice. Limiting factors are not only their low ductility and insufficient forming ability at low and medium temperatures but also unresolved problems in the development and operational applications of financially less demanding technologies for the production of components.

The melting and casting of gamma-TiAl alloys is difficult due to comparatively high pouring temperatures, reactions of the two basic alloy components Ti and Al with the furnace atmosphere, crucibles and ceramic moulds, and due to Al evaporation [1 - 6]. Gamma-TiAl based alloys are usually melted and cast using vacuum induction furnaces equipped with either ceramic crucibles (vacuum induction melting - VIM) [7] or cold crucibles (induction skull melting – ISM) [8, 9]. Apart from conventional gravity casting, the counter-gravity CLV method is also used. A technology that combines the advantages of ISM procedure and CLV casting is referred to as the LEVICAST process [8, 9]. The method of lost-wax-pattern is commonly applied for fabrication of ceramic moulds that yield shapes of turbocharger wheels, blades of low-pressure stages of combustion turbines, and stationary parts of aircraft turbines [9, 10]. The mass production of combustion engine exhaust valves based on the investment casting route has also been considered [11 - 13].

There is a need to reduce costs associated with the production of gamma - TiAl alloy castings. A promising way how to achieve this goal is to use the classical vacuum induction furnace furnished with a refractory crucible. A comparative efficiency of vacuum induction furnaces equipped with either ceramic crucibles (VIM) or cold crucibles (ISM) was investigated [5, 6, 14]. The experimental work done so far suggests that the main drawbacks of the ISM process rest in the very low energy efficiency, the difficulty to achieve the required superheat [5, 6] and the tendency to bubble-forming and misruns during casting under the argon atmosphere [15]. The main advantage of the ISM process (as compared to VIM) is the smaller oxygen pick-up during remelting. However, both processing routes, ISM and VIM, suffer from the problem that castings of complex shapes such as integrally cast turbocharger wheels, exhibit macroscopic cracks resulting from a constrained contraction of the tough ceramic mould and the intermetallic cast [16 – 18]. Thermo-elastic stresses generated in the castings during cooling of the system ceramic mould - TiAl casting to room temperature are the consequence of both, the different thermal expansion coefficients of the intermetallic alloy and the ceramic mould, and different temperatures of the two parts of the system [19]. The cooling path of the system could be divided roughly into two temperature ranges. In the high temperature range, where the creep rate of intermetallic TiAl alloys is sufficiently high, substantial differences in the cooling kinetics do not lead to any fundamental differences in the

stress state inside the casting. The situation, however, dramatically changes in the low-temperature range of the cooling curve, where, by contrast, the undesirable thermo-elastic stresses induced into the casting strongly depend on the cooling kinetics and damage the cast components.

2. Goal of the project

Therefore, the present project focused on the VIM (cheap) processing route and on the issues associated with the macrocracks nucleation and growth during cooling of the cast - mould system down to room temperature. The solution aimed at the minimization of tensile stresses induced into brittle TiAl intermetallic casts on cooling. The influential parameters of the process like the amount of superheat, the mould preheating, thermal expansion coefficient of different moulding materials and the cooling kinetics were considered.

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

In the model of the process, three coupled mechanisms governed the evolution of the thermal strain mismatch and associated stress state in the cast-mould system during the cooling stage. A *heat flow* from the system controlled the actual temperatures at different locations inside the TiAl cast and the ceramic shell mould. The local temperatures, that vary not only with the positions in the system but also with increasing time, influenced both, the amount of *thermal contraction* of the cast and mould and the rate of *creep* in the TiAl cast. The interaction between the cast and mould during cooling thus gave rise to the stress state that might have been partially relaxed by creep in the cast while the model permitted no creep of the ceramic shell mould. We have used a simplified 1D - 1D formulation that was implemented into the numerical code based on the finite differences technique and solved using the Mathematica 5.0 environment. Compiled C++ routines were applied in critical parts of the code to achieve an adequate calculation speed. Besides other process quantities, the temperature-stress history during cooling was the most important result yielded by the individual calculations. Further details on the model and the implementation can be found elsewhere [20].

The calculated temperature-position-time profiles were verified experimentally for dedicated girder-shaped casts that were designed in line with the assumptions of the model [19]. Results of these experiments clearly confirmed the viability of the adopted modelling approach. Since the main modelling effort was directed towards the minimization of tensile stresses induced into casts, values of our objective function were given by stress maxima found on the temperature-stress path on cooling. The maxima were then minimized with respect to influential process parameters. Dimensions of the search space extended up to four since, along with the amount of superheat and mould preheating temperature, two parameters characterizing the cooling kinetics were considered for the optimization. Two procedures were employed in order to minimize the maximum stress attained on the temperature-stress path. The first procedure was based on a sequential optimization in which the objective function was first minimized with respect to one parameter (keeping the other parameters constant). In the next steps, the optimized value of the first parameter was fixed and the new minimum was searched for with the second parameter as a variable. This cycle was repeated a number of times up to the final

dimension of the search space. Since the sequential optimization can only be justified in cases when the objective function exhibits a simple landscape in the parameter space, the results of the sequential optimization were checked up using the random search method. In spite of the considerable simplification adopted in the model, one calculation of the objective function value (maximum stress on the temperature-stress path) required a non-negligible amount of the CPU time. Thus some measures were taken to make the random search routine work efficiently such that the adequate approximation of the minimum could be found with a low number of the objective function evaluations. The random search method was thus modified such that the overall population of random parameter vectors was split into two parts. A part of the population mapped the objective function landscape in the vicinity of the current function minimum and the second part kept searching throughout the rest of the parameter space. Finally it turned out that both optimization strategies (the sequential optimization and the random search) yielded similar results [20].

4. Main scientific outcome

The project activities resulted in the formulation of the 1D-1D model of coupled heat flow, thermal strain (stress) mismatch and creep. This model enabled efficient optimization of process parameters governing the induced mismatch stresses and cast damage. The model predictions were verified experimentally and satisfactory agreement between both sets of data was found. Moreover, a processing window based on the numerically optimized parameters resulted in sound TiAl casts, as it is presented below in Fig.1b.

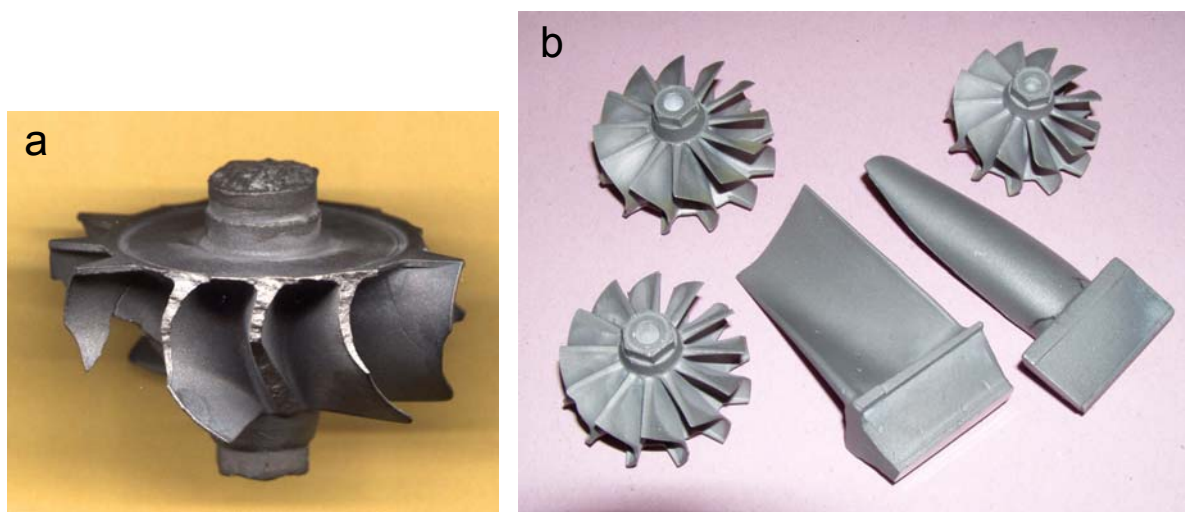


Figure 1: Status of the near-gamma TiAl VIM-based precision casting technology in (a) December 2001 and (b) October 2004.

5. Main technical outcome

Here in Fig. 1 we compare the status of the VIM-based cheap precision casting technology in December 2001 (before the CZ1 project had actually started) - Fig. 1a - and in October 2004 (in an advanced stage of the project solution) - Fig. 1b. It is apparent that the numerical modelling and optimization clearly contributed to the technology progress. The damage of the cast components due to the intensive stress state in the cast-mould system has been completely suppressed and the technology is now ready to yield reproducible cast parts.

6. Collaboration within COST 526

We have regularly attended the technical COST 526 meetings throughout the four-year COST 526 action period. Presentations at these meetings considerably improved our knowledge of the optimization algorithms and they also stimulated fruitful discussions on the melting and casting processes of modern engineering alloys. In this respect we have particularly enjoyed the exchange of ideas with Dr. Bogdan Filipic (project SI 1), Prof. N. Hofmann (project CH 4) and Dr. J. Jakumeit (project D 4).

7. Cooperation with industry

Since the very early beginning of the CZ 1 project, our industrial partner PBS Turbo Limited at Velka Bites supported the fabrication of the ceramic shell moulds for our casting trials. In the later stage of the project solution (early in 2004) we presented the capabilities of the optimized TiAl casting technology to experts from PBS Turbo. Since then we have also been collaborating with the Turbocharger Development Department of PBS Turbo working on the turbocharger wheel performance and high-temperature strength issues. Apparently, next step in the optimization of the TiAl cast parts should address the microstructure and strength topics. The company seems to be interested in further development and prospective future process optimization activities within a framework of a new spin-off COST action.

8. References

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