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AUTONOMOUS DIRECTIONAL SOLIDIFICATION FOR SINGLE CRYSTAL TURBINE BLADES

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1. INTRODUCTION

The Bridgman technique is normally used for directional or monocrystalline solidification of gas turbine blades and requires a highly complex vacuum casting plant and, hence, substantial investments. To achieve optimized microstructures time and energy intensive processing is necessary. A key topic of research work in the field of directional soldification of single crystals (DS/SC) at the Foundry-Institute of the Rhine-Westfalien Institute of Technology (Gießerei-Institut der RWTH Aachen) is to investigate the potential of alternative processes, particularly the so-called autonomous directional solidification (ADS) process. In this technique, the melt is highly undercooled before solidification occurs and, thus, crystal growth takes place very rapidly into the undercooled melt.

Autonomous directional solidification offers the following advantages as compared to conventional technology:

- simplification of the complex equipment required (e.g., the withdrawal device and baffle construction can be omitted),
- shorter process time due to the rapid solidifcation,
- finer microstructure and reduced microsegregations as a result of the high solidification rate.

This paper describes studies performed to investigate the capability of autonomous directional solidification for producing single crystalline superalloy turbine blades. Experiments have been carried out using nickel-based SRR99 and CMSX-6 superalloys.

The studies entail the following key activities:

- Determination of the undercoolability of nickel-based superalloys and microstructure characterization of the solidified specimens,
- monocrystalline solidification from the undercooled melt,
- computer simulations to estimate the process limits.

2. THE PROCESS OF AUTONOMOUS DIRECTIONAL SOLIDIFICATION

The difference between the conventional and the autonomous directional solidification processes is schematically shown in Fig. 1. In the Bridgman type DS process, the shell mold is placed within a controllable heater device on a water cooled lowerable chillplate. The so-called baffle isolates the heating and cooling zone which results in a constant temperature gradient within the baffle area. By moving the double-sided open shell mold that passes this gradient, a directional solidification takes place. The thermal conductivity of the solidifying metal and the heat radiation from the shell mold limits the maximum withdrawal speed. In order to obtain single crystals, a high temperature gradient and a low solidification must be applied.

In contrast to this technique, the autonomous directional solidification process uses bottom closed shell molds which are fixed within the heater device. The shell molds are made of SiO_2-free ceramics covered inside with a nucleation inhibiting amorphous layer. After casting the melt into the shell mold, the heater device is switched off. The temperature of the melt decreases and due to the amorphous front layer the nucleation is delayed, leading to a substantial undercooling. The isolated water cooled chillplate at the bottom of the shell mold ensures a small longitudinal temperature gradient within the melt and thus the nucleation to appear at the coldest position within the foot of the turbine blade. Table 1 gives a comparison of the important features of the DS and ADS processes. Figure 2 shows a typical cooling curve measured during the autonomous directional solidification of CMSX-6.

On the basis of their investigations B. Lux et al. (1981) developed a solidification sequence for the autonomous directional solidification process (fig. 3). After free cooling of the melt within the heater device, the nucleation starts at the maximum undercoolling temperature. During the recalescence period a fine dendritic network spreads out into the undercooled melt with a high velocity, whereby the imposed temperature gradient determines the orientation of the network. This network predefines the microstructure and its orientation in the whole casting.

After recalescence, the interdendritic melt solidifies under equilibrium conditions, and coarsening and ripening processes (Ostwald-ripening) result in the final microstructure. Due to the small temperature gradients within this post recalescence phase the solidification rate is comparable with that of conventional cast processes. Because of internal friction to melt flow the porous dendritic network hampers the feeding of the casting leading to shrinkage porosity.

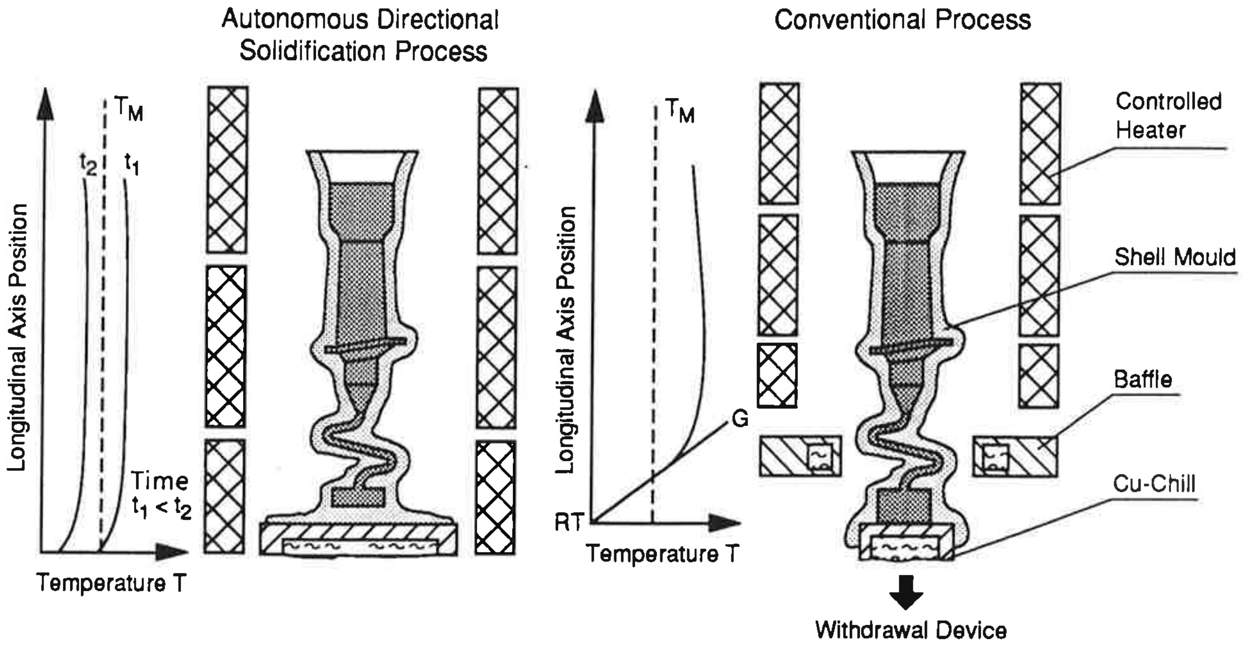

Fig. 1: Comparison of the ADS and the conventional DS/SC processes and their typical temperature distributions.

Process Parameter	Autonomous	Conventional
Casting Mold Temperature	Similar	
Withdrawal Speed	0	3-8 mm/min
Baffle Configuration	Needless	Control Solidification Front
Gating Risering	Control Macroporosity and Crystal Orientation	
Shell Mold	Treated to Prevent Nucleation	Inert
Cast Alloy	High Undercoolable	No Limitations

Table. 1: Comparison of the important process features of the DS/SC and the ADS technology.

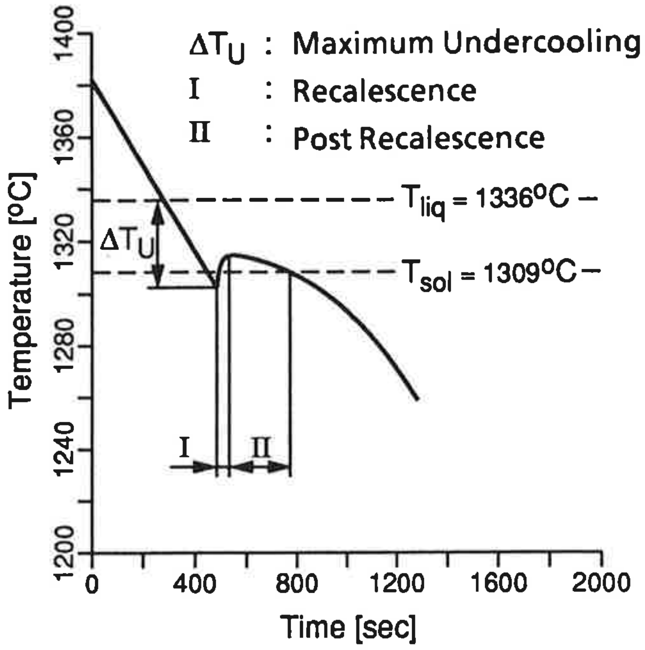

Fig. 2: Typical cooling curve measured during the autonomous directional solidification of CMSX-6.

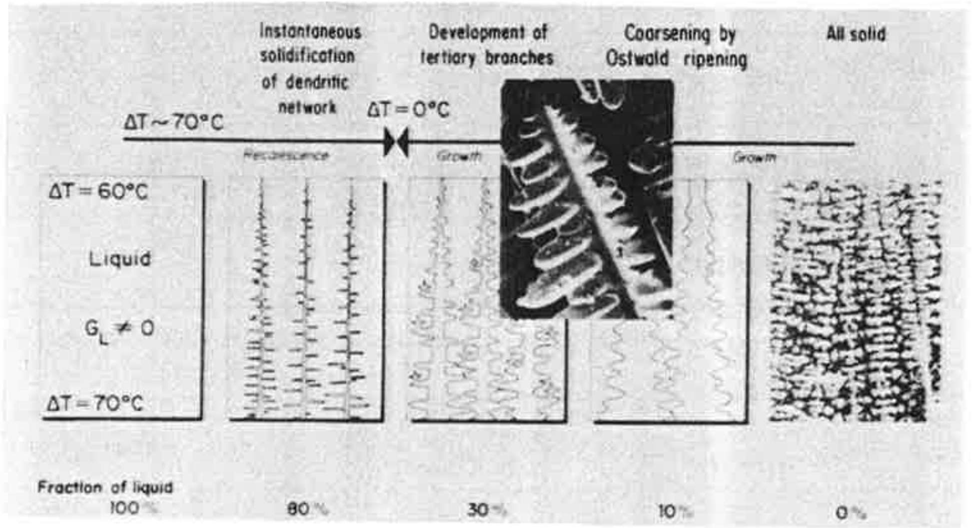

Fig. 3: Solidification sequence of the directional solidification from an undercooled melt, B. Lux et al. (1981).

3. DETERMINATION OF THE UNDERCOOLABILITY OF NICKEL-BASED SUPERALLOYS AND MICROSTRUCTURE CHARACTERIZATION OF THE SOLIDIFIED SPECIMENS.

After performing undercooling experiments with nickel and binary nickel alloys with the flux technique, where bulk undercoolings of about 270 K could be achieved (W. Axmann, 1986), small samples (4-6g) of the technically relevant superalloys SRR99 and CMSX-6 were levitated under a He/Ar atmosphere. The chemical composition of these alloys is given in Table 2. Both single crystal alloys are nearly free of carbon and the grain boundary stabilizing elements Hf and Zr. This leads to an increased melting temperature and an improved high temperature creep rupture strength. A further advantage of the CMSX-6 alloy is the relatively low density of 7,93 g $\cdot$cm^{-3}. Each sample has undergone a few melting, undercooling and solidification cycles. During the experiments the temperature was measured using a pyrometer. The results are summarized in Fig. 4 where the dark dotted areas represent the most frequently achieved undercooling temperatures.

The undercoolability of bulk samples with a mass of about 50-60g was investigated in crucibles with different nucleation-hampering front layers using a tamman furnace under Argon atmosphere and, for comparison, an induction furnace under a vacuum of about 10^{-4} mbar (J. Stanescu, P. R. Sahm, 1990). It was found, that the furnace type as well as the surrounding atmosphere have a negligible influence on the maximum undercooling. On the other hand, it is shown in Fig. 4 that the front layer material at the crucible wall (oxides, borides or carbides) is extremely important. An investigation of the chemical concentrations at the interface between the metal and the front layer enabled an optimization of the coated shell molds. Thus, the undercooling of bulk superalloy melts could be increased to about 50 K.

Figure 5 shows various cross-sections of a single crystal turbine blade which was undercooled to about 50 K before nucleation. Primary dendrite arm spacings of autonomous solidified samples, measured as a function of different cooling rates in the post-recalescence phase, are smaller compared to those in the DS process (Fig. 6). The secondary dendrite arm spacings are also less in the investigated sample. The average pore size and the proportional pore area for the two processes are compared in Fig. 6, where the light dotted bars represent measured values for the ADS bulk samples (50-60g) and for comparable DS specimens. Measurements at single crystal turbine blades solidified by ADS show considerable lower porosity (dard-dotted areas). The influence of the metallostatic pressure on the porosity of ADS processed cast parts is shown in Fig. 7. An insufficient metallostatic pressure and, thus, a hindered feeding leads to large shrinkage porosities within the cast parts.

	SRR99 mass %	CMSX-6 mass %
Cr	8,5	10,0
Co	5,0	5,0
W	9,5	-
Mo	-	3,0
Ti	2,2	4,75
Al	5,5	4,85
Ta	2,8	2,0
C	0,01	0,02
Hf	-	0,01
N	-	10 ppm
O	-	9 ppm
Ni	bal	bal

Table 2: Chemical Composition of the investigated alloys SRR99 and CMSX-6, from M. McLean, 1983.

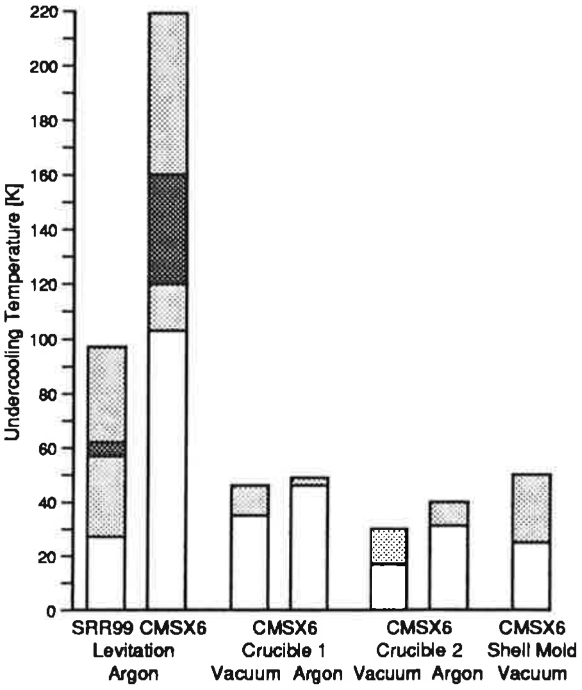

Fig. 4: Undercooling temperature influenced by different parameters.

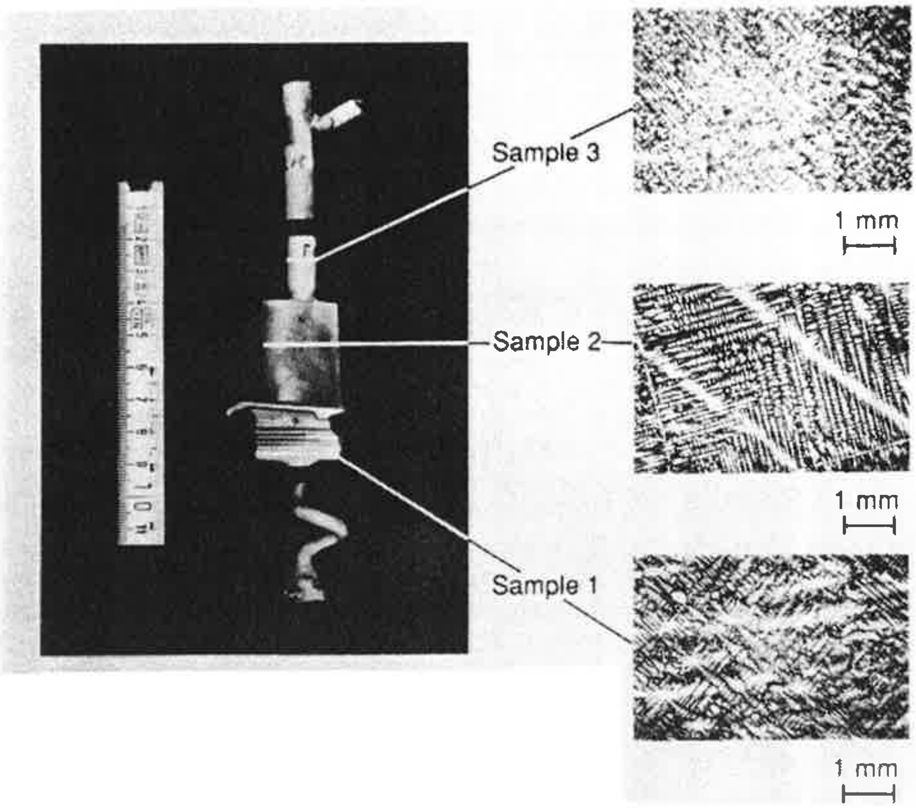

Fig. 5: Cross sections of an ADS single crystal turbine blade.

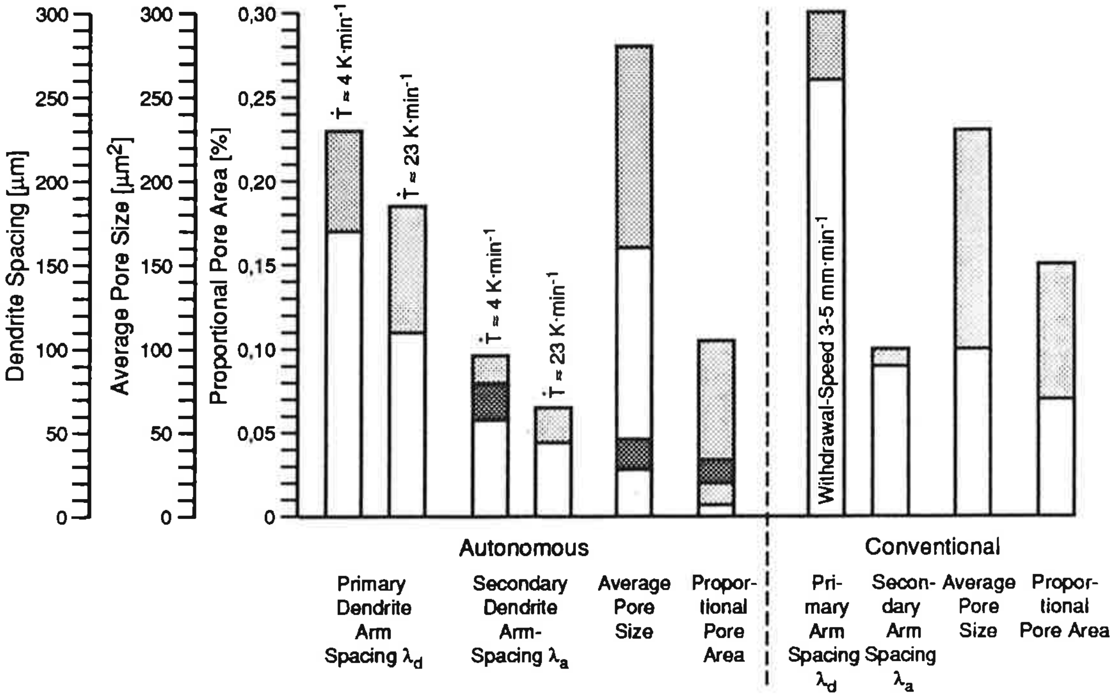

Fig. 6: Comparison of primary and secondary dendrite arm spacing, average pore size and proportional pore areas of samples solidified with conventional DS/SC and the ADS process.

4. MONOCRYSTALLINE SOLIDIFICATION FROM THE SUPERCOOLED MELT

At the beginning of the investigations most samples revealed that the microstructure was made of only a few large grains. Thus, great efforts have been undertaken to control the process in such a way that single crystal soldification occurs. Under special conditions, it was possible to produce single crystal cast parts by autonomous directional solidification. Up to now the longest single crystal turbine blade produced by ADS is 15 cm (Fig. 8). The helicoidal crystal selector improves the yield of single crystals and guarantees a good reproducibility.

In Fig. 9, the result of a Υ-diffraction analysis is given. The single crystal has a good quality with small half-width values and low distortions along the specimen axis. The second peak in some of the rocking curves belongs to dendrite areas which deviate from the main crystal orientation. The maximum deviation is about 5° and, thus, in the range of technical single crystals. The orientation of many single crrystals determined by the Laue back-scattering-method shows a small accumulation in the region of the <001>-direction (Fig. 10). In order to control the orientation of the cast part, more fundamental research is necessary.

5. COMPUTER SIMULATION FOR ESTIMATING THE PROCESS LIMITS

A further important activity in establishing ADS is to improve the process and to estimate the process limits with the help of computer simulations. During the last decade the finite element simulation program CASTS has been developed at the Foundry-Institute. Figure 11 illustrates the capabilities of the computer program for simulating casting and solidification processes.

Figure 12 shows the temperature distribution in a partly undercooled superalloy melt within a shell mold of turbine blade geometry. Such simulations are necessary to estimate areas with insufficient undercooling and locations where undesired nucleation will appear due to a very high undercooling.

To estimate the process limits, such as the maximum possible size of a single crystal turbine blade, simulation of the autonomous directional solidification process is essential.

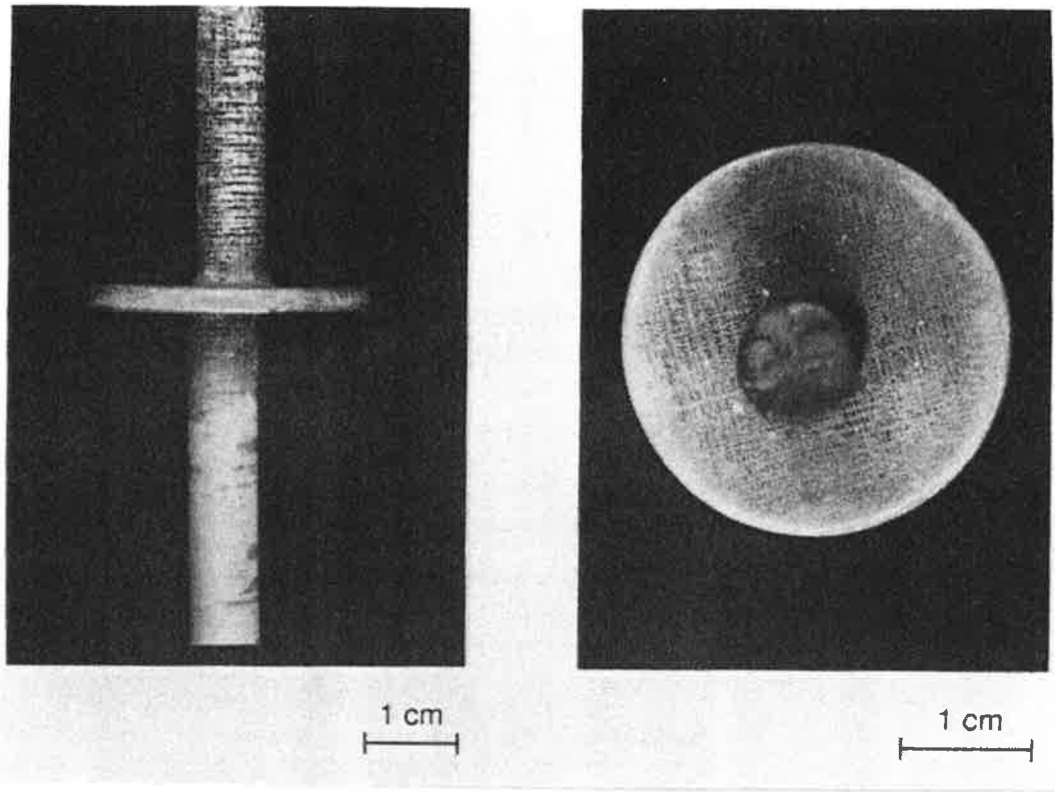

Fig. 7: Open porosity of a special test specimen.

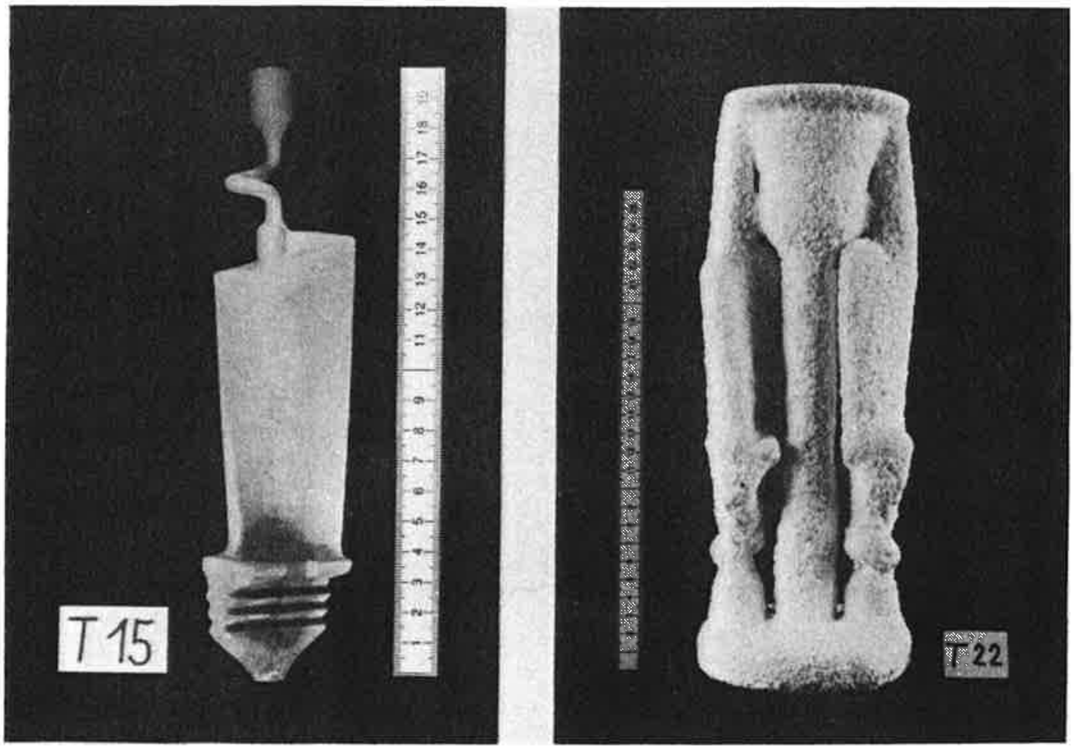

Fig. 8: Single crystal turbine blade produced by the autonomous directional solidification process and corresponding shell mold.

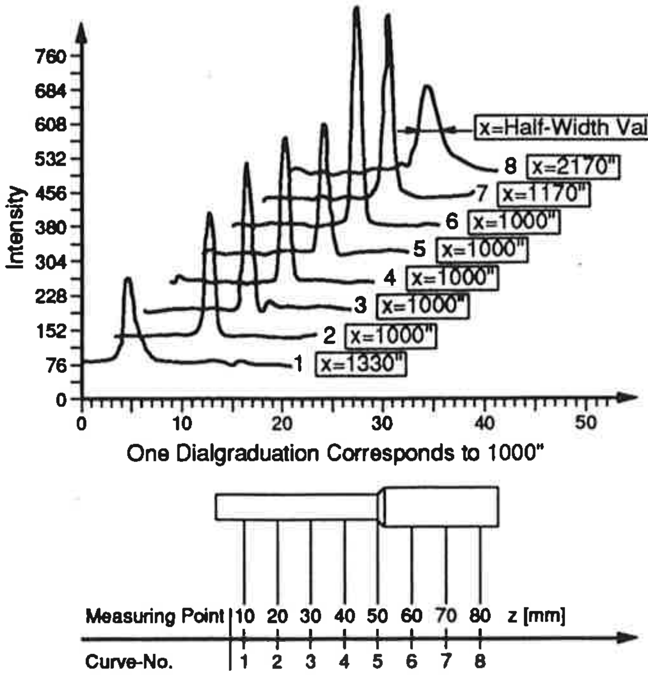

Fig. 9: Results of γ-diffraction analysis.

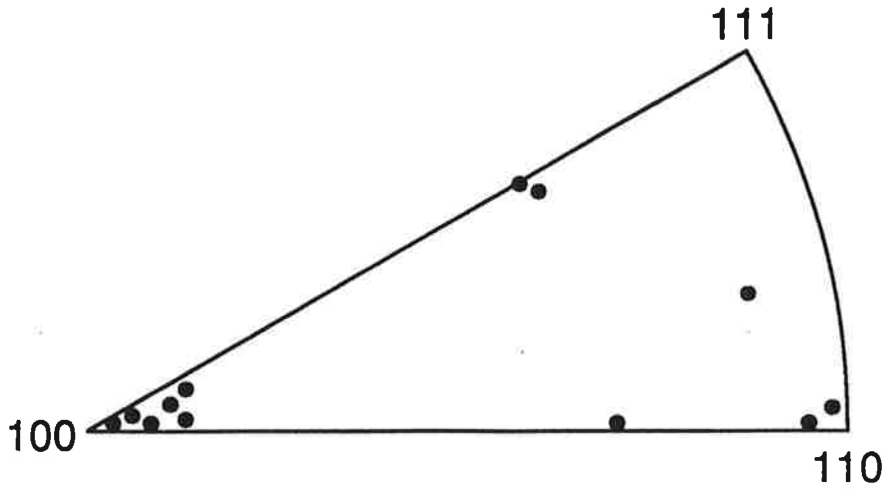

Fig. 10: The crystal orientation of several cast parts.

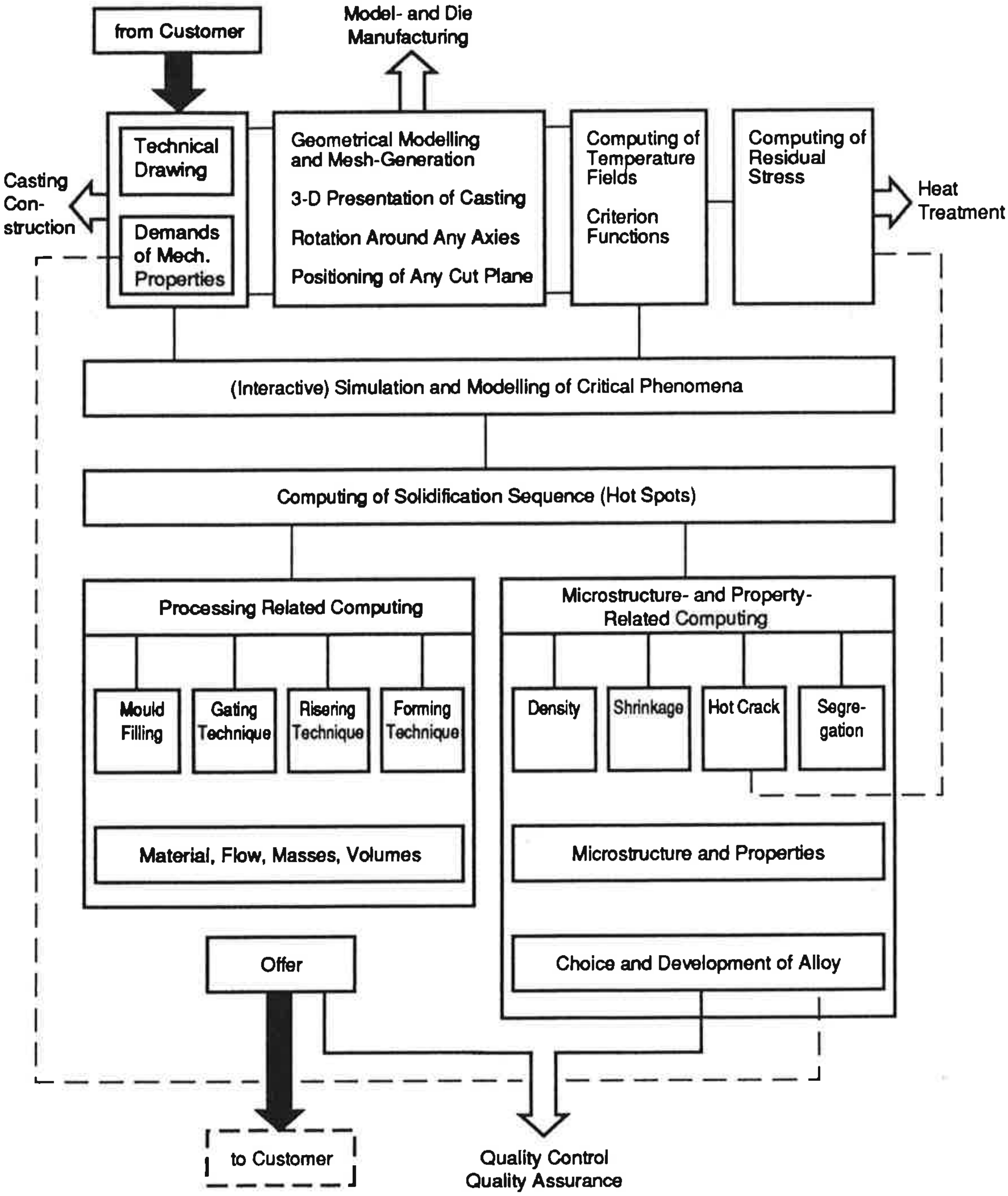

Fig. 11: Schematic scetch of the simulation program CASTS, developed at the Foundry-Institute.

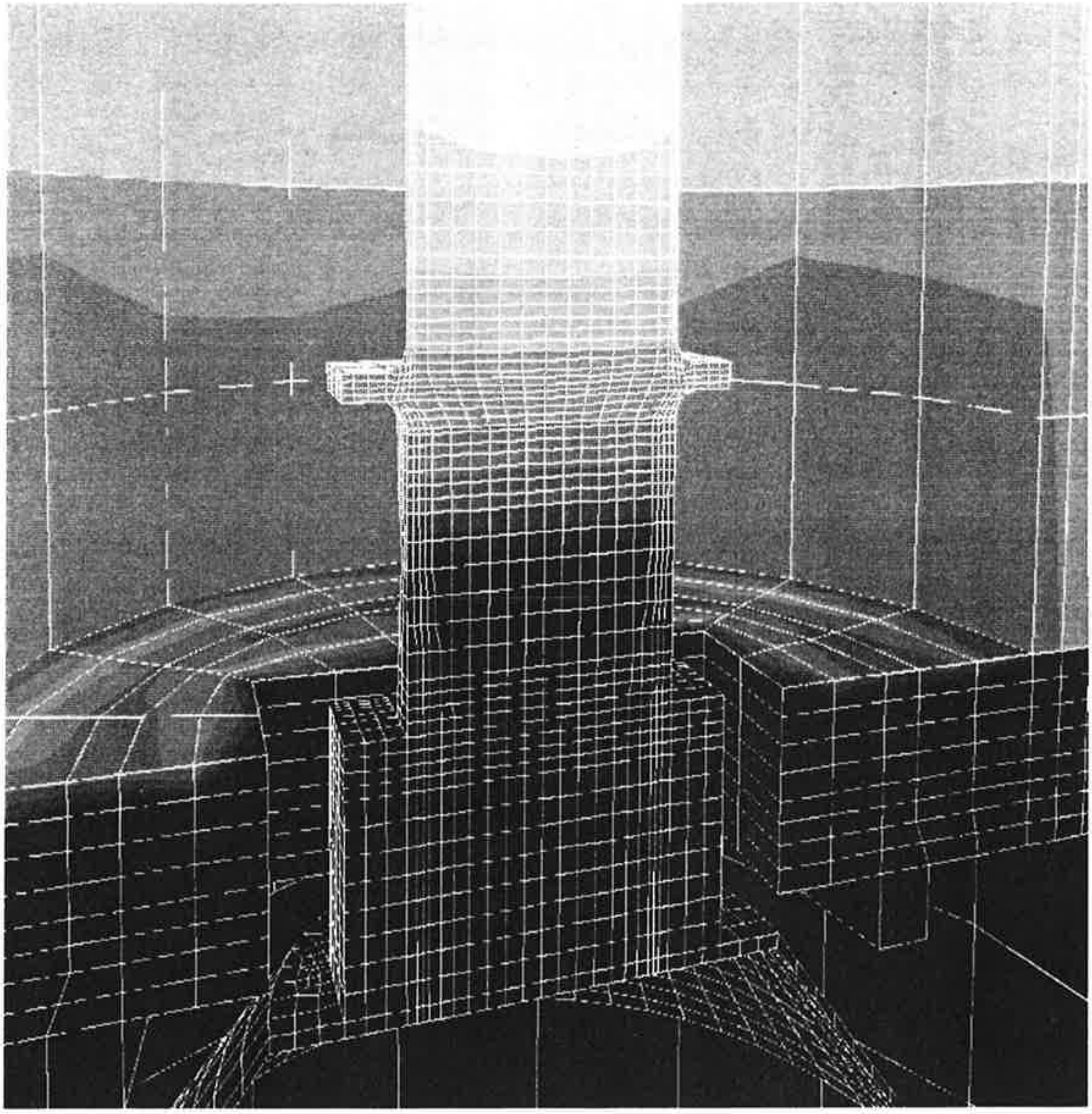

Fig. 12: Numerical simulated temperature distribution during the cooling of a dummy blade.

CONCLUSIONS

Autonomous directional soldification (ADS) is an interesting alternative to the conventional directional solidification techniques. It offers several advantages which can be used to improve the final cast parts and to decrease the production costs.

At the Foundry-Institute of the Rhine-Westfalian Institute of Technology single crystal turbine blades have been produced for the first time by this new technology. These turbine blades exhibit finer microstructures and lower porosities as compared to conventionally produced single crystal.

Computer simulation has been applied to estimate the process limits, such as the maximum possible size of the single crystal cast parts. The knowledge of the temperature distribution within the furnace, the shell mold, and the melt gives the opportunity for optimizing the process and to use this new technology to its full advantage.

ACKNOWLEDGMENTS

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