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TECHNOLOGICAL ASPECTS OF OBTAINING HIGH-QUALITY AND ECONOMICAL CASTINGS FROM HEAT-RESISTANT NICKEL ALLOYS FOR GAS TURBINE UNITS

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Nickel-based superalloys are the primary materials for the manufacture of critical components of gas turbine units (GTUs), such as turbine blades and disks, due to their unique ability to maintain high mechanical properties and corrosion resistance under extreme thermal and mechanical loads. The modern trend towards increasing the efficiency of gas turbine engines by raising operating temperatures (up to and above 1000 °C) constantly complicates the technological challenges faced by metallurgists and foundry workers. On the one hand, there is a need to obtain castings with a perfect microstructure (single-crystal structure, regular morphology of the γ'-phase), which requires complex and expensive technologies (directional solidification). On the other hand, there is an acute issue of economic efficiency, both in the production of the castings themselves and in ensuring their long service life to reduce operating costs. We have three key technological aspects for obtaining high-quality, cost-effective castings: metallurgical features of alloy design [1], optimization of hot deformation parameters [2], and analysis of failure causes to prevent them [3].

Technological aspects of production and operation:

1. Metallurgical approaches to improving the quality of castings.

Modern, highly efficient gas turbines require single-crystal blades to eliminate grain-boundary weakening. According to the review by Gudivada and Pandey [1], the development of such alloys is moving towards increasing refractoriness by adding refractory metals. However, a key technological nuance is controlling the strains induced by these elements: they induce non-isotropic strains that can be detrimental or used for controlled rafting (directional coarsening) of the γ'-phase to enhance properties [1]. The casting quality is also significantly influenced by the oxygen partial pressure during operation, which dictates the alloy's susceptibility to oxidation. From a production standpoint, an important technological aspect is the management of topologically close-packed (TCP) phases. The review notes that their effects are not always negative, allowing for a more flexible approach to alloy composition and potentially reducing cost by using a wider range of alloying elements without strictly prohibiting the formation of these phases [1]. Additionally, the introduction of rare earth elements is becoming an integral part of the technology for controlling the solidification and micromechanics of the alloy [1].

2. Technological plasticity and optimization of processing modes.

Obtaining a high-quality semi-finished product or casting not only involves casting but also subsequent thermomechanical processing. The study by Yu et al. on the SJTU-1 nickel superalloy, intended for operation at 815°C, demonstrates the critical importance of selecting hot deformation parameters [2]. The authors constructed a processing map that identifies the material's instability zones. Technological recommendations have been established to produce a high-quality microstructure: the optimal hot deformation range is a temperature of 1000-1075°C and a strain rate of 0.005-0.1 s^{-1} [2]. At the beginning of deformation, it is crucial to control the strain rate, as the flow stress rapidly reaches a peak value, and its further dynamics directly determine the final grain structure [2]. This approach allows selecting economical pressing or stamping conditions that minimize reject rates due to cracking or uneven microstructure, thereby reducing the overall cost of producing the final part.

3. Technological reasons for failure and the economic aspect of quality.

The quality of a casting is ultimately assessed by its service life. The failure analysis of a first-stage gas turbine blade by Kolagar et al. clearly shows how violations of technological regimes (or unforeseen operating conditions) negate all efforts to create a high-quality initial casting [3]. The study of a blade that failed after 6500 hours showed that the initial microstructure of the blade root corresponded to the norm. However, analysis of the airfoil revealed clear signs of overheating: dissolution of the strengthening γ'-phase (Ni_3Al) and matrix carbides, followed by their redeposition upon cooling, as well as traces of local melting at

the leading edge [3]. From a technological and economic perspective, this case demonstrates that "quality" is not only the ideal initial structure obtained through expensive directional solidification methods but also the casting's resistance to operational overloads. Ensuring a margin of safety at the casting design stage or introducing protective coatings becomes a necessary measure to prevent catastrophic failures, the cost of which is incomparably higher than the cost of manufacturing a single high-quality blade.

The analysis of the technological aspects of producing castings from heat-resistant nickel alloys indicates that achieving a balance between high quality and economic efficiency requires an integrated approach.

1. At the smelting and casting stage, it is necessary to precisely control the content of refractory and rare earth elements, as they determine not only the high-temperature strength (through the rafting mechanism) but also the technological plasticity of the alloy [1].

2. To produce high-quality semi-finished products, it is essential to rely on hot processing maps, which make it possible to select the optimal temperature-deformation rate conditions (e.g., 1000-1075°C and 0.005-0.1 s^{-1}), minimizing microstructure defects and material reject rates [2].

3. Ensuring the cost-effectiveness of the product lifecycle is impossible without analyzing operational failures. The experience of blade overheating shows that even a technologically advanced casting is susceptible to degradation (γ'-phase dissolution, local melting) under extreme conditions [3]. Consequently, improving the quality of castings should aim not only at achieving initial perfection but also at increasing the alloy's robustness to unforeseen temperature spikes, which, in the long run, is the most economically viable strategy.

REFERENCES

1. Gudivada G., Pandey A. K. Recent developments in nickel-based superalloys for gas turbine applications : Review. *Journal of Alloys and Compounds*. 2023. Vol. 963. 171128. https://doi.org/10.1016/j.jallcom.2023.171128/

2. Yu J. High temperature behaviors of a casting nickel-based superalloy used for 815°C. *Materials*. 2021. №14(4). P. 716. https://doi.org/10.3390/ma14040716/

3. Kolagar A. M., Tabrizi N., Cheraghzadeh M., Shahriari M. S. Failure analysis of gas turbine first stage blade made of nickel-based superalloy. *Case Studies in Engineering Failure Analysis*. 2017. Vol. 8. P. 61-68. https://doi.org/10.1016/j.csefa.2017.04.002/