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Development of advanced P/M Ni-base superalloys for turbine disks

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Abstract. In the process of evolution of powder metallurgy in Russia the task permanently formulated was the following: to improve strength properties of P/M superalloys without application of additional complex HIPed blanks deformation operation. On the other hand development of a turbine disk material structure to ensure an improvement in aircraft engine performance requires the use of special HIP and heat treatment conditions. To ensure maximum strength properties of disk materials it is necessary to form a structure which would have optimum size of solid solution grains, γ'-phases and carbides. Along with that heating of the material up to a temperature determined by solvus of an alloy ensures a stable and reproducible level of mechanical properties of the disks. The above-said can be illustrated by successful mastering of new complex-alloyed VVP-class superalloys with the use of powder size $-100\,\mu$m. Application of special HIP and heat treatment conditions for these superalloys to obtain the desired grain size and the strengthening γ'-phase precipitates allowed a noticeable improvement in ultimate tensile strength and yield strength up to $\geq$1600 MPa and $\geq$1200 MPa respectively. 100 hrs rupture strength at 650 °C and 750 °C was improved up to 1140 MPa and 750 MPa respectively. P/M VVP nickel-base superalloys offer higher characteristics in comparison with many superalloys designed for the same purposes. HIPed disc compacts manufactured from PREP-powder have a homogeneous micro- and macrostructure, a stable level of mechanical properties.

Advanced disk materials are the base for creation of fifth generation aircraft engines and also form scientific anticipative reserve for development of high technologies in the field of military and civil aircraft. The use of new high-strength high-temperature materials in gas-turbine engines allows one to improve power and service life of the engines and thereby to improve efficiency and reliability of aircraft.

From the very outset of the development of the powder metallurgy in Russia the purpose was to produce as-HIP large-size P/M Ni-base superalloy disk blanks (Fig. 1) without subsequent plastic working of the blanks [1].

Although originally the blanks were intended for military aircraft engines [2,3], already in 1986, for the first time in world practice, as-HIP P/M EP741NP superalloy disks produced without subsequent plastic working were used in the fourth generation PS 90A aircraft engine designed at JSC Aviadvigatel (Perm-town) and intended for civil and transport aircraft. At present, total operating time of such disks in the PS 90A engine family is above 16 500 000 hrs [4]. Studies are being carried out and a technology is being developed to produce turbine and compressor disks of advanced P/M VV751P superalloy for a new PD 14 civil aircraft engine designed at JSC Aviadvigatel.

Avoidance of the plastic working of the disk blanks requires very high quality of as-HIP material. Macro- and

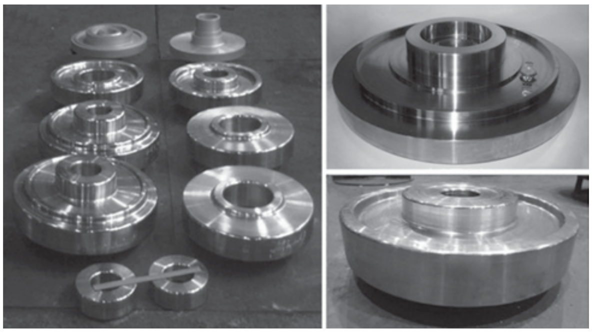

Figure 1. Large-size P/M Ni-base superalloy HIPed disk blanks up to 850 mm in diameter and up to 300 kg in weight.

microstructures of the disk material should be homogeneous at most to ensure attainment of the desired properties after heat treatment. Elimination of such P/M material defect as prior particle boundaries (PPB) without application of plastic working of compacts can be achieved due to observance of several conditions. The most obvious one is purity of powder particle surface, i.e. minimization of surface oxidation and gas adsorption. Powder particles should have no contact with free air, dust, moisture, etc. All process from atomization of cast rods up to filling of cans should be carried out in "all-inert" atmosphere. Besides, it is necessary also to ensure absence of any phases including filmy carbides, which prevent realization of the

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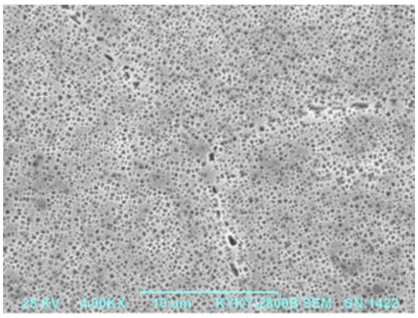

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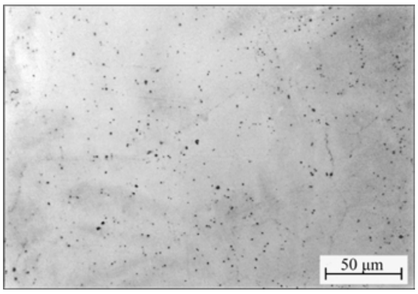

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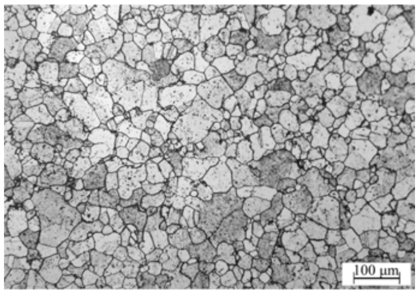
Figure 2. Microstructures of the HIPed disk material: a) γ' phase, SEM, ×4000; b) carbide phases, ×300.



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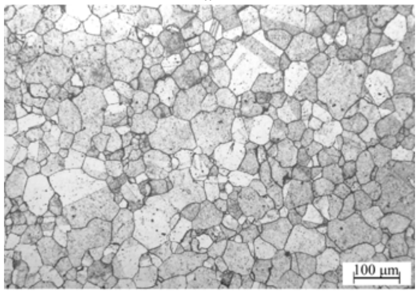

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Figure 3. Typical grain structures of the HIPed blanks after various solution heat treatment conditions, ×100: a) from the two-phase field; b) from the single-phase field.

recrystallization process, on powder particle surfaces due to rational alloying of metal.

The plasma rotating electrode process (PREP) technique used for powder production reduced intraparticle gas porosity in final powder down to practically zero values. As a result, compaction can be carried out at higher temperatures (above the γ' phase solvus) in comparison with material made of gas-atomized powder without the risk of thermally induced porosity exhibition [5].

Combination of these conditions forms an equiaxial recrystallized structure in the HIPed disk material, which enables the desired combination of properties (Fig. 2). Avoidance of the blank plastic working operation reduces the price of the final product. In addition, subsequent appropriate heat treatment enables development of a microstructure in the as-HIP material; it should be noted that it is very difficult to obtain such microstructure via the use of another production technology.

It has been told above already that minimization of the intraparticle argon porosity and absence of the risk of thermally induced porosity exhibition at subsequent stages of the processing enable implementation of HIPing and solution heat treatment at temperatures above the γ' phase solvus. Recrystallization of the as-HIP material during heating for solution heat treatment proceeds slower in comparison with a compact material subjected to extrusion, forging, etc. Degree of microdeformation after HIPing is less than 10% [6], that is much lower than in the case of conventional plastic working which includes several stages with intermediate annealing, used for production of turbine disks.

For example, NASA Glenn Research Center's specialists studied powder material manufactured by argon atomization, subsequent compaction and extrusion. Solution heat treatment from a temperature below the solvus by 25 °C and above it by 10 °C resulted in formation of a mean grain size of 8 μm and 32 μm respectively [7]. Grain growth in the as-HIP material proceeds slower. This fact is corroborated by experiments with respect to solution heat treatment of P/M VV751P superalloy from the two-phase field: grain size was 30 μm, while in the case of solution heat treatment above the solvus the size was 35 μm (Fig. 3).

In spite of slight grain growth which resulted in some reduction of strength properties, solution heat treatment from the single-phase field allows one to obtain smaller γ' phase precipitates in comparison with solution heat treatment from the two-phase field. The cause of this is that in the case of heating above the solvus, the primary coarse incoherent γ' phase (Fig. 4a) formed at the previous process stages such as melting or remelting or plastic working dissolves completely.

This regularity is corroborated not only theoretically, but experimentally as well. For example, Rolls-Royce Corporation's scientists found difference in microstructures of P/M Udimet 720L alloy solution heat treated at temperatures both below and above the γ' phase solvus [8]. Size of the largest primary γ' phase particles in the case of solution heat treatment from the two-phase field exceeds size of the secondary γ' phase in the material heat treated in the single-phase field by a factor of several tens.

Absence of the coarse γ' phase in a structure (the phase is incoherent with alloy matrix and does not participate practically in material strengthening) governs a high level of mechanical characteristics of the material after solution heat treatment above the solvus. Although solution heat treatment from the two-phase field can enable smaller grain size, but the fact that the less amount of the γ' phase in the form of fine coherent particles (Fig. 4b) participates in strengthening of the alloy results in a reduction in yield

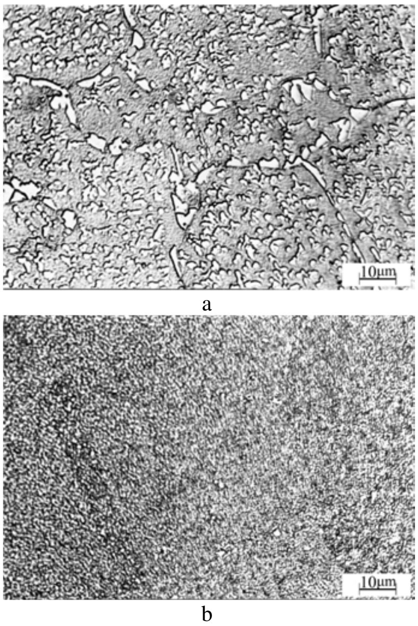

Figure 4. Microstructures of the disk material after different solution heat treatment conditions, ×800: a) from the two-phase field; b) from the single-phase field.

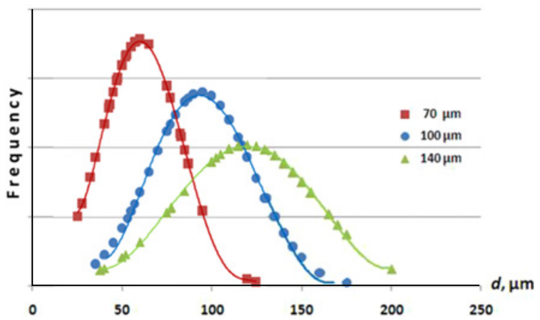

Figure 5. A reduction in size of nonmetallic inclusions in the HIPed disk material, resulted from transfer to the use of finer powder.

strength, LCF resistance and rupture life at 650 °C.

One of the most important characteristics of disk material reliability is low-cycle fatigue resistance which depends directly on size of possible metallurgical defects. As there are almost no microporosity and prior particle boundaries in our material, main type of defects which can cause premature failure in the case of LCF is nonmetallic (slag or ceramics) inclusions trapped from cast rods used for powder production by the PREP technique. As a reduction in powder size results automatically in a reduction in size of possible inclusions (Fig. 5), this way is considered as one of the main ways for an improvement in reliability characteristics of the turbine disk material.

A reduction in size of the powder used not only increases purity of the disk material, but reduces grain size as well (Fig. 6). The latter in its turn improves strength properties of the material at intermediate temperatures.

The use of fine powder allows one to produce not only fine-grained homogeneous material, but, if it is desired for special purposes, to develop coarser grains by varying HIPing and heat treatment conditions. Transition to fine powders widens noticeably possibilities of grain size control in the compact material and, hence, opens possibilities to obtain any desired combination of mechanical properties in P/M superalloys. Size of recrystallized grains can be changed in a wide range from 15 μm up to 70 μm.

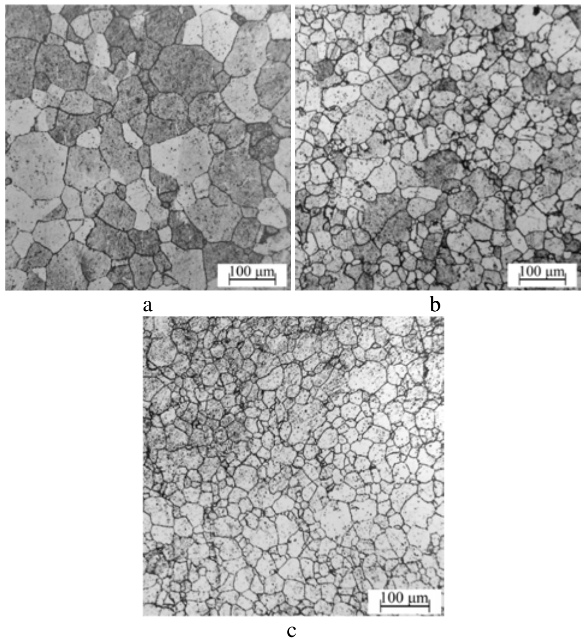

Figure 6. Grain structures of the disk material made of different powder size: a) 140 μm; b) 100 μm; c) 70 μm.

There is no doubt that the powder metallurgy technology has wide potentialities for further improvement in mechanical properties of the disk material due to production of homogeneous material, a reduction in powder size and comprehensive alloying. There are two trends in the matter of further improvement and development of P/M Ni-base superalloys at JSC VILS. The trends bound up with requirements imposed by designers of gas-turbine engines are as follows: 1) creation of high-strength VV751P [9] and VV752P-type alloys [10] (UTS > 1640 MPa and 0.2%YS > 1220 MPa) with an operating temperature up to 650 °C and 2) creation of ultra high-temperature VV750P [11] and VV753P-type alloys [12] (100 hrs stress-rupture strength at 750 °C = 750 – 800 MPa) for operating temperatures of 750 °C and more.

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