Microstructure and mechanical properties of a novel high Co+W polycrystalline nickel-based blade superalloy

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Abstract. A novel polycrystalline nickel-based superalloy SLZhS-1R, heavily alloyed with Co+W and intended as a structural material for turbine blades in gas turbine engines, has been studied. The initial cast superalloy was prepared by vacuum induction melting in the form of an ingot with a size of Ø 100×180 mm. Compression and tensile tests were performed for the cast condition. Before compression testing, the superalloy was subjected to homogenization and heterogenization annealing, which led to an improvement of chemical homogeneity and coagulation of $\gamma'$ precipitates. As a result, the flow stresses during compression at elevated temperatures were reduced as compared to those obtained for the as-cast condition. Before the tensile testing, the superalloy was subjected to homogenization annealing (solution treatment) followed by air cooling and ageing. This improved the chemical homogeneity and led to the formation of fine $\gamma'$ precipitates with a size in the range of 0.1-0.2 μm. The obtained mechanical properties in tension were compared with those of the typical cast superalloy ZhS6U.

1. Introduction

To increase the efficiency of the gas turbine engine (GTE), novel materials and processes are required that would meet the growing operational requirements due to the increase in temperature and loading of components [1]. To meet these requirements, novel nickel-based superalloys are designed to achieve tailored mechanical properties, such as higher creep resistance along with higher strength, fatigue strength and other service properties. Particularly, in respect to polycrystalline nickel-based superalloys, intended for blade manufacturing, alloying with inexpensive elements, which provide efficient solid-solution strengthening, is of interest. Note that the use of rare-earth alloying elements for solid-solution strengthening and the single crystal technology widely applied for blade manufacturing in modern high performance GTEs, are very expensive and therefore efficient alloying of polycrystalline superalloys with common refractory elements is of a great practical significance [1-4]. In this regard, there is a risk of formation of topologically close packed (TCP) phases during long-term high temperature exposures that can deteriorate the mechanical properties of a superalloy. Thus, the alloying additions should be precisely chosen to avoid the formation of undesirable phases.

The present work is a preliminary study of the microstructure and mechanical properties of a new polycrystalline blade superalloy highly alloyed with Co and W and prepared by casting. The obtained tensile properties were compared with those of the typical Russian blade superalloy ZhS6U.
2. Experimental

The nickel-based superalloy Ni-47(Al, Cr, Co, Ta, W, Hf)-0.2(C, B) (in wt. %) named SLZhS-1R was taken as the starting material. The superalloy ingot with a size of Ø 100×180 mm was manufactured by vacuum induction melting. The γ′ solvus temperature was determined by differential scanning calorimetry and quenching experiments and found to be equal to \( T_s = 1185 \pm 5 \, ^\circ\text{C} \). Before compression testing, the cast material was homogenized at temperatures below and slightly above the γ′ solvus temperature for 8 hours and then subjected to slow furnace cooling with a rate of 25 °C/h. Before tensile testing, the cast material was subjected to homogenization and solution annealing at the same regimes followed by air cooling and ageing at \( T = 1000 \, ^\circ\text{C} \) (2 h) and \( T = 850 \, ^\circ\text{C} \) (8 h). The as-cast and heat treated materials were used for preparation of specimens for compression and tensile tests. All specimens for mechanical testing were prepared by electrospark cutting followed by fine grinding of work surfaces. Compression tests were carried out at \( T = 1100-1200 \, ^\circ\text{C} \) with an initial strain rate of \( \dot{\varepsilon} \approx 10^{-3} \, \text{s}^{-1} \). Tensile tests were carried out at \( T = 20 \) and 650-850 °C with an initial strain rate of \( \dot{\varepsilon} \approx 7 \times 10^{-4} \, \text{s}^{-1} \). Two samples per point were tested. The microstructure examination was carried out using scanning electron microscopy (SEM) in backscattering electron (BSE) mode.

3. Results and discussion

3.1. Initial cast materials

A typical coarse grained microstructure was observed in the as-cast condition (not presented here). Nonequilibrium eutectic colonies resulted from dendritic segregation were sometimes distinguished. The γ′ phase precipitates had a size mostly in the range of 0.1-0.2 µm and predominantly near cuboidal morphology. White particles identified as carbides are observed and have a size of 0.5-5 µm. The volume fraction of the γ′ phase can be visually estimated to be about 60%.

Figure 1 represents the BSE images of SLZhS-1R in the cast and heat treated conditions. One can see that homogenization and heterogenization annealing led to the disappearance of the dendritic structure and coagulation of the γ′ phase precipitates. Their size increased up to 0.5-2 µm. Near cuboidal morphology was often retained (figure 1a, b).

After heat treatment including air cooling and ageing, fine nearly round γ′ precipitates with a size of 0.1-0.2 µm were obtained (figure 1c, d). The obtained microstructural conditions were used for preparation of samples for subsequent compression and tensile tests.

3.2. Compression properties

Figure 2 shows the true stress-strain curves obtained as a result of compression tests of the superalloy at elevated temperatures. All the deformed samples had cracks on their lateral surfaces, but the depth of the cracks was smaller in the samples, subjected to heat treatment. This suggests that homogenization and heterogenization annealing improved the hot workability of the superalloy. As the test temperature increased, the flow stresses decreased that is associated with the dissolution of γ′ precipitates. One can see that the samples in the annealed condition showed lower flow stresses during compression at \( T = 1100 \) and 1150°C than the samples in the as-cast condition. This is explained by the fact that coarse coagulated γ′ precipitates exerted a smaller strengthening impact than fine γ′ precipitates in the as-cast condition. The compression at \( T = 1200 \, ^\circ\text{C} \) showed the same flow stresses in the as-cast and annealed conditions. That is explained by the complete dissolution of the γ′ precipitates and indirectly confirms that the γ′ solvus temperature was below 1200 °C.

3.3. Tensile properties

Table 1 represents the tensile properties obtained for the superalloy at room and elevated temperatures. The strength and ductility decreased with increasing test temperature. Note that the obtained strength characteristics and rather low ductility are typical of cast nickel-based superalloys. For comparison, the tensile properties of the typical Russian blade superalloy ZhS6U in the cast condition are also...
represented. The SLZhS-1R superalloy showed higher strength and similar ductility at room temperature as compared to the ZhS6U alloy. At elevated temperatures, the rather low strength and ductility of the SLZhS-1R superalloy can be associated with the formation of undefined plate-like phase(s), which arose after heat treatment.

**Figure 1.** BSE images obtained for the superalloy SLZhS-1R in the cast condition subjected to heat treatments: (a, b) after homogenization and heterogenization annealing, (c, d) after homogenization annealing followed by air cooling and ageing. Arrows show plate-like precipitates of unknown phases. White particles are carbides.

**Figure 2.** True stress-strain curves obtained for the superalloy SLZhS-1R as a result of compression tests of samples at elevated temperatures (HHA – homogenization and heterogenization annealing).
Table 1. Tensile mechanical properties of the superalloy SLZhS-1R in comparison with those of the Russian nickel base superalloy ZhS6U.

| Superalloy    | σ_{UTS}, MPa / δ, % |
|--------------|---------------------|
|              | 20 °C   | 650 °C | 750 °C | 850 °C |
| SLZhS-1R     | 1015 / 4.5 | 885 / 1.1 | 679 / 0.5 | 604 / 0.3 |
| ZhS6U [5, 6] | 920-970 / 3-6 | -     | -     | -     |
|              | 830 / 3   | -     | -     | -     |

Note that the obtained properties can be improved via more precise alloying with Co and W. On the other hand, the new superalloy should not be considered as a casting superalloy, and an efficient working process can help in attaining enhanced mechanical properties.

4. Conclusions

A preliminary study of the microstructure and mechanical properties has been performed for the newly developed nickel-based superalloy SLZhS-1R heavily alloyed with Co and W. It was shown that the chemical homogeneity can be improved, and coarse coagulated or fine γ' precipitates can be obtained using simple heat treatments. The compression and tensile mechanical properties of the new superalloy were evaluated. It showed higher strength properties at room temperature that can be ascribed to the efficient solid solution strengthening caused by high alloying with Co and W. Further efforts are to be directed to the development of efficient hot working, which would promote the formation of a finer grained microstructure and properly balanced mechanical properties.

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