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ARTICLE

Effect of Solid Solution Treatment on Mechanical Properties of Aero-Engine Turbine Cases

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Abstract: Waspaloy alloy is widely used in aerospace applications, particularly in gas turbines operating under extreme service conditions. The effects of solid solution duration and temperature on the microstructure and mechanical properties of a Waspaloy low-pressure turbine (LPT) case in in-service aero-engines were investigated via on-site metallographic replication techniques and laboratory verification tests. The results show that excessive solid solution treatment (1010 °C/11 h) has no adverse impact on the microstructure or grain size of the LPT cases. The alloy exhibits low sensitivity to solid solution duration. As the solid solution duration is prolonged from 4 h to 20 h, the grain size remains unchanged, and the grain morphology remains essentially consistent. Only a gradual decrease in the number of twins in the microstructure and a gradual increase in proportion of fine strengthening phases are observed. In contrast, the alloy is highly sensitive to solid solution temperature. When the solid solution temperature increases from 1010 °C to 1040 and 1070 °C, the grain size increases from Grade 7.5 to Grade 6.5 and to grade 3.0, respectively. Simultaneously, the primary strengthening phases within austenite grains are fully replaced by secondary ones. Additionally, $M_{23}C_6$ carbides at γ phase grain boundaries transition from isolated island-like morphologies (at low temperature) to elongated strip-like morphologies (at high temperature). Simultaneously, both the quantity and size of the intragranular MC carbides significantly increase. The microhardness and mechanical properties of the alloy are predominantly governed by the scale of strengthening phases and grain size. With the prolongation of solid solution duration, the microhardness, tensile strength, and yield strength progressively increase. However, as the solid solution temperature rises, these properties increase first and then decrease.

Key words: Waspaloy alloy; LPT cases; grain size; microhardness; mechanical properties

1 Introduction

Waspaloy alloy (namely GH738) is a nickel-based austenitic-precipitation-hardening superalloy. Due to the addition of solid-solution-strengthening elements (molybdenum, cobalt, and chromium), aging-strengthening elements (aluminum and titanium), and trace elements (boron and zirconium), this alloy has high yield strength and fatigue resistance at 760−870 °C. It also possesses excellent oxidation and corrosion resistance, good machinability and plasticity, and stable microstructure and properties below 870 °C[1–4]. Currently, Waspaloy alloys have been widely used in aerospace, particularly for gas turbines in harsh service environments, and are suitable for the production of turbine disks, working blades, high-temperature screws, flame tubes, shafts, turbine cases, and other components[5–6].

In order to achieve and maintain the excellent high-temperature endurance strength of components, Waspaloy alloy requires an appropriate heat treatment in vacuum or inert atmosphere, which mainly includes two stages: solid solution and aging[7]. Solid solution treatment refers to heating the alloy to a specific temperature related to the high-temperature single-phase region and keeping it at a constant temperature for a certain period of time. On the one hand, solid solution treatment dissolves the carbide, γ' phase, and other phases into the substrate to form a uniform supersaturated solid solution.

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This facilitates the precipitation of fine and uniformly distributed strengthening phases such as carbides and γ' during subsequent aging. Meanwhile, it eliminates residual stresses introduced by thermomechanical and cold processing and promotes recrystallization of the alloy. On the other hand, the solid solution treatment can obtain the appropriate grain size to ensure the high-temperature creep resistance of the alloy.

The effect of solid solution treatment process on the properties of Waspaloy alloy is one of the hot topics in the field of superalloys. Andersson et al[8] conducted 4 h-solid-solution treatment in the range of 996−1080 °C. Gleeble test with heating and cooling cycles was also conducted to study the effect of different solid solution treatments on the Waspaloy superalloy. The results showed that although the macroscopic hardness is similar under different heat treatment conditions, the differences in the grain size and distribution of γ' and $M_{23}C_6$ phases significantly affect the thermoplasticity of the alloy in the low-temperature test region. Liu et al[9] investigated the dissolution and roughening characteristics of the γ' precipitated phases in Waspaloy superalloys in the temperature range of 1000−1045 °C. The results showed that the roughening of the γ' precipitated phase is mainly controlled by the substrate diffusion of the γ' -forming elements. At 1030 °C, abnormal grain growth is formed due to the relatively low pinning force of a small amount of γ' phase. Zeng et al[10] studied the microstructure and properties of GH738 alloy under different solid solution treatment regimes. The results showed that with the increase in solid solution temperature, the grain size of the alloy increases, the γ' phase undissolved in the substrate gradually reduces, and the newly precipitated γ' phases gradually grow. The room-temperature tensile strength, yield strength, and Rockwell hardness of GH738 alloy decrease with the increase in secondary solid solution temperature. Wei et al[11] studied the effect of solid solution temperature on the properties of GH738 alloy ring forgings with the unqualified room-temperature and yield strength by heat treatment. The results showed that within 1000–1040 °C, with the increase in solid solution temperature, the room-temperature yield strength of GH738 ring forgings gradually increases. By contrast, the tensile strength, elongation, and reduction in area remain largely unchanged. And increasing the solid solution temperature has slight effect on the grain size of GH738 alloy ring forgings. Rong et al[12] studied the effect of different solid-solution cooling media (oil, air, and refractory wool) and subsequent aging treatment on the microstructure and mechanical properties of high-quality GH738 alloy. The results showed that the cooling medium has no effect on the grain size of the alloy, but mainly affects the dissolution and precipitation behavior of the primary and secondary γ' phases, which in turn affects the properties of the alloy. In the solid solution stage, with the increase in cooling rate (oil quenching>air cooling>refractory wool cooling), the number and size of secondary γ' phase in the alloy decrease, and the tensile strength of the alloy after solid solution decreases.

The aforementioned researches have primarily used Waspaloy alloy specimens as research subjects, investigating the effects of solid solution temperature, cooling rate, and other parameters on the microstructure (precipitated phases and grain size) and mechanical properties (plasticity, tensile strength, and yield strength) of alloy. These studies have achieved significant theoretical and experimental results. In the field of civil aviation maintenance, for in-service Waspaloy alloy components in aero-engines, re-heat treatment is typically required during engine overhauls to prevent degradation of mechanical properties under prolonged high-temperature service conditions. Among these processes, solid solution treatment is one of the critical steps for restoring the high-temperature mechanical properties of Waspaloy alloy components. This study focuses on in-service aero-engine turbine cases made of Waspaloy alloy. The effects of solid solution duration and temperature on the microstructure and mechanical properties of low-pressure turbine (LPT) cases were investigated through on-site metallographic replication techniques and laboratory validation experiments. The results are expected to provide a theoretical basis and experimental data to support the establishment or revision of solid solution treatment process specifications during the repair of such components.

2 Experiment

The verification test specimens used in this study were provided by the original manufacturer of LPT cases. These specimens were made of the same Waspaloy alloy, with the main chemical composition listed in Table 1. Additionally, the alloy contains a trace quantity of elements, such as Mn, Si, P, S, and Cu.

Metallographic replication, also known as on-site metallographic testing, does not involve direct observation of the material itself. Instead, it uses a relief surface imprint of the material produced by an intermediate medium. By examining this relief imprint, the microstructure of the material can be indirectly analyzed[13–14], as shown in Fig. 1. The area subjected to on-site grinding and polishing is typically controlled to a very small scale, which is far below the wall thickness of the component. This ensures that the structural integrity and mechanical strength of the component remain virtually unaffected. As a result, metallographic replication is widely employed as a non-destructive testing technique for in-service inspection of critical equipment operating under extreme conditions. Given the high value of aero-engine components, this study adopted metallographic

Table 1 Chemical composition of Waspaloy alloy (wt%)

Cr	Mo	Co	Al	Ti	B	C	Zr	Fe	Ni
18.000–21.000	3.500–5.000	12.000–15.000	18.000–21.000	2.750–3.250	0.003–0.010	0.030–0.100	0.020–0.080	≥2.000	Bal.

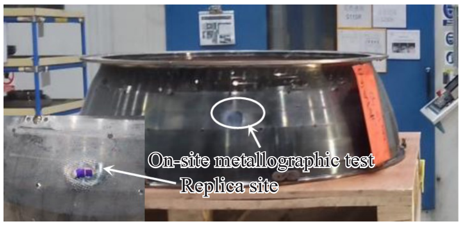

Fig.1 Image of metallographic replication of LPT case

replication to examine the effects of solid solution treatment on the microstructure of LPT cases, ensuring no damage to its original microstructure or strength.

According to the aero-engine maintenance manual, the standard solid solution process for LPT case made of Waspaloy alloy involves the treatment at 1010 °C for 4 h, followed by cooling to room temperature in an argon atmosphere. Based on the metallographic replica analysis and microstructural characterization conducted on LPT component, this study was designed to evaluate the effect of solid solution duration on the mechanical properties of the component, and to further elucidate the influence of both solid solution temperature and duration on the microstructure and mechanical properties of Waspaloy alloy. Accordingly, the validation test matrix for Waspaloy alloy specimens was established, as presented in Table 2.

The Waspaloy alloy specimens subjected to different solid solution treatments and standard aging treatments were prepared for metallographic examination through sectioning, mounting, grinding, polishing, and etching. Microhardness measurements were conducted using an HVS-1000Z microhardness tester. Five measurements were taken for each specimen group, and the results were averaged. The test parameters included a load of 0.2 kg and a dwell time of 10 s.

Microstructural characterization was conducted using an optical microscope (OM, Axio Imager. A2m) and a scanning electron microscope (SEM). Grain size analysis was performed according to ASTM E112-13, employing the planimetric method. For each metallographic image, a rectangular area of 5000 mm^2 was selected for analysis. The number of grains completely within this area (N_1) and that of grains intersecting the boundary (N_2) were recorded. The grain number per square millimeter (N_A) was then calculated using Eq. (1), as follows:

$$N_A = f\,(N_1 + N_2/2) \tag{1}$$

where f represents the Jeffries multiplier with f=2.0 at 100× magnification and f=8.0 at 200× magnification. Measurements were taken from three randomly selected fields of view and averaged.

Table 2 Verification test matrix of Waspaloy alloy specimens

Specimen	Solid solution temperature/°C	Solid solution duration/h
1010-04	1010	4
1010-11	1010	11
1010-20	1010	20
1040-04	1040	4
1070-04	1070	4

The grain size number (G) was calculated using Eq. (2), as follows:

$$G = 3.321928\,\lg \bar{N}_A - 2.954 \tag{2}$$

Tensile test was conducted using an INSTRON 5982 universal testing machine to determine mechanical properties, including elastic modulus, tensile strength, and yield strength. For each treatment condition, three specimens were tested and the results were averaged. The schematic diagrams of specimen for tensile test are shown in Fig.2.

3 Results and Discussion

3.1 Metallographic replica microstructure of LPT cases

Fig. 3 shows the metallographic replica microstructures of LPT case components after solid solution treatment at 1010 °C for 4 and 11 h, and Table 3 shows the carbide sizes of each microstructure.

After different solid solution durations, LPT components exhibit uniform and equiaxed grain structures. The microstructures primarily consist of γ matrix phase and a small number of carbides precipitated during cooling, with the carbides mainly distributed along grain boundaries. And the average size of carbides in 1010-04 and 1010-11 specimens is 1.28 and 1.32 μm, respectively. No significant changes of these carbides in either the morphology (all granular) or size are observed.

The grain sizes of LPT components subjected to solid solution treatment at 1010 °C for 4 and 11 h were calculated using Eq.(1–2). Three random fields of view were selected for each metallographic replica, with the calculation results presented in Table 4. The grain sizes of components following different solid solution durations remain consistent at Grade 4.0. These results demonstrate that prolonging the solution treatment duration from 4 h to 11 h has no effect on the metallographic structure of LPT cases.

3.2 Microstructure of Waspaloy alloy

Fig. 4 shows the metallographic microstructures of Waspaloy alloy specimens under different solid solution treatment conditions. The 1010-04 specimen mainly consists of equiaxed austenite grains with a certain number of twin crystals[15], while fine carbides are dispersed at grain boundaries ($M_{23}C_6$) and within grains (MC)[10]. When the solid

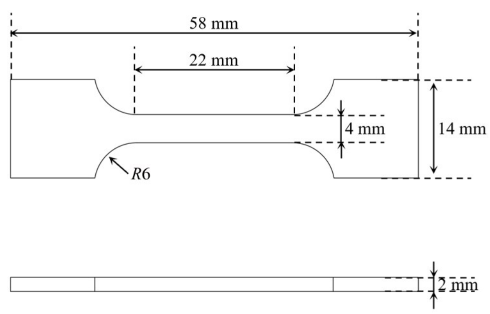

Fig.2 Schematic diagrams of specimen for tensile test

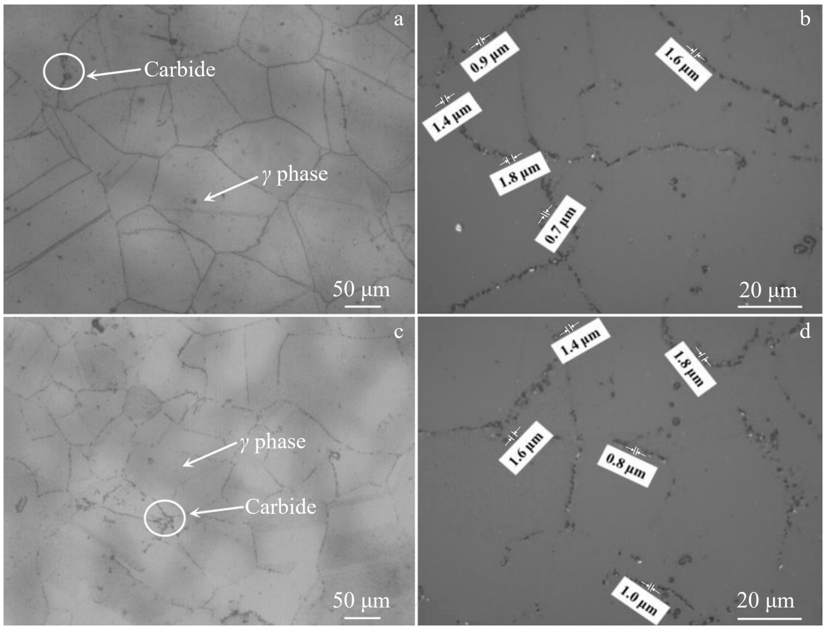

Fig.3 Metallographic replica microstructures at low (a, c) and high (b, d) magnifications of different specimens : (a–b) 1010-04; (c–d) 1010-11

Table 3 Carbide size of each microstructure in Fig.3 (μm)

Specimen	Carbide size	Average
1010-04	0.9, 1.4, 1.6, 1.8, 0.7	1.28
1010-11	1.4, 1.6, 1.8, 0.8, 1.0	1.32

Table 4 Calculated results of grain size number of different specimens

Specimen	Field of view	Calculated value	Grain size number, *G*
1010-04	1	3.988 51	4.0
	2	4.112 15	4.0
	3	4.036 63	4.0
1010-11	1	4.011 78	4.0
	2	4.051 42	4.0
	3	4.002 68	4.0

solution duration is prolonged from 4 h to 11 h at constant solid solution temperature, as shown in Fig. 4a – 4b, the microstructure, grain size, and carbide size of Waspaloy alloy specimens remain almost unchanged. However, when the duration is further prolonged to 20 h, the excessively long duration may lead to excessive dissolution of the strengthening phase and alteration in carbide morphology[16]. This leads to moderate degradation of the pinning effect, which in turn facilitates a slight coarsening of the equiaxed grains. Concurrently, partial twin crystals are engulfed and eliminated due to the prolonged duration, as shown in Fig.4c. When the solid solution duration is fixed at 4 h, as shown in Fig. 4a, 4d, and 4e, the microstructure of Waspaloy alloy specimens changes significantly with the increase in solid solution temperature. When the temperature increases from 1010 °C to 1040 °C, the grain size of Waspaloy alloy specimens increases slightly, and the carbide sizes of both $M_{23}C_6$ and *M*C exhibit a considerable increase, while the austenite grains remain mainly equiaxed. When the solid solution temperature increases to 1070 °C, the sizes of grains and carbides increase significantly, and the austenite grains change from an equiaxed morphology to an irregular blocky one.

Table 5 shows the grain size measurement results of Waspaloy alloy specimens under different solid solution treatment conditions. Under standard heat treatment conditions, the 1010-04 specimen has a grain size of Grade 7.5.

When the solid solution temperature remains unchanged, prolonging the solid solution duration from 4 h to 11 h and 20 h does not change the grain size of the three groups of specimens, all remaining at Grade 7.5. When the solid solution duration remains unchanged, the grain size of specimens decreases from Grade 7.5 under standard heat treatment conditions to Grade 6.5 at sould solution temperature of 1040 °C, and rapidly decreases to Grade 3.0 when the solid solution temperature reaches 1070 °C.

Fig. 5 shows SEM images of Waspaloy alloy specimens under different solid solution treatment conditions, and Table 6 shows the γ' phase sizes of these specimens. Under standard heat treatment conditions, as shown in Fig. 5a, the Waspaloy alloy specimen consists predominantly of large-scale strengthening phases, along with a minimal amount of fine strengthening phase. The size range of the large-scale strengthening phases is 325.5–357.5 nm, with $M_{23}C_6$ carbides primarily dispersed along grain boundaries. When the solid solution temperature remains constant, the size ranges of the primary strengthening phases in the Waspaloy alloy after solid solution treatments for 4, 11, and 20 h are 325.5–357.5, 368.4–379.6, and 315.2–340.1 nm, respectively. The size of the large-scale strengthening phases shows little variation with the prolongation of duration and remains essentially consistent. Similarly, the size of $M_{23}C_6$ carbides in the microstructure of

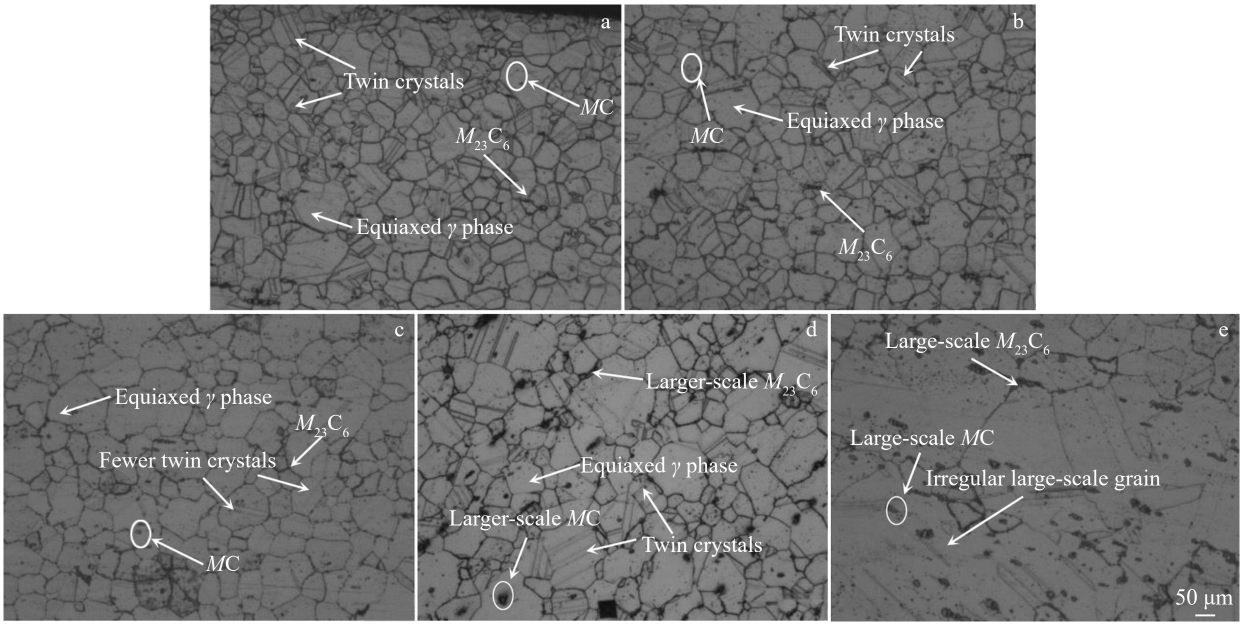

Fig.4 OM images of different Waspaloy alloy specimens: (a) 1010-04; (b) 1010-11; (c) 1010-20; (d) 1040-04; (e) 1070-04

Table 5 Calculated results of grain size number of different specimens

Specimen	Calculated value	Grain size number, G
1010-04	7.624 71	7.5
1010-11	7.545 85	7.5
1010-20	7.706 00	7.5
1010-04	7.624 71	7.5
1040-04	6.625 32	6.5
1070-04	2.853 35	3.0

the three specimens exhibits negligible change with the prolongation of duration, which are predominantly distributed along grain boundaries. The principal distinction is the significant variation observed in the content of fine strengthening phases. Compared to that in the alloy subjected to solid solution treatment for 4 h, the proportion of fine strengthening phases increases slightly in the specimen treated for 11 h, while a significant increase is observed in the specimen treated for 20 h.

When solid solution duration is 4 h, significant changes in the morphology of strengthening phases and carbides in the Waspaloy alloy specimens are observed, as shown in Fig. 5a, 5d, and 5e. Firstly, the large-scale strengthening phases disappear, leaving only dispersed fine strengthening phases. No large-scale strengthening phases exceeding 300 nm are observed in the alloy treated at 1040 and 1070 °C, and the size ranges of the fine strengthening phases are 79.0 – 105.9 and 100.5–116.6 nm, respectively. Secondly, the M_{23}C$_6$ carbides at grain boundaries are gradually aggregated and coarsened, transitioning from dispersed isolated island-like structures to continuously distributed and elongated strip-like structures. Thirdly, a significant number of MC carbides appear within the austenite grains, and the size of these intragranular carbides gradually increase with the increase in solid solution temperature.

3.3 Microstructure evolution mechanism

Based on the above analysis, the microstructure of Waspaloy alloy primarily consists of γ matrix and γ' strengthening phases distributed within the matrix (large-scale γ' phases as primary strengthening phases and fine γ' phases as secondary strengthening phases), complemented by M_{23}C$_6$ and MC carbides distributed along grain boundaries and within grains, respectively. During solid solution treatment at 1010 °C, the γ' phases gradually dissolve into the matrix. With the prolongation of solid solution duration, the dissolution becomes more complete, but the dissolution rate remains relatively slow. As a result, although the content of primary γ' phases gradually decreases, some large-scale primary γ' phases are still retained in the austenitic matrix even after solid solution treatment for 20 h (Fig. 5c). Additionally, at the solution temperature of 1010 °C, the morphology of M_{23}C$_6$ carbides at grain boundaries shows negligible changes with the prolongation of solid solution duration (Fig. 5a – 5c). Consequently, the pinning effect of these secondary phase particles does not undergo significant weakening as the solid solution duration is prolonged[16]. This results in a restricted growth tendency of γ grains .

When the solid solution temperature is increased, on the one hand, the dissolution rate of primary γ' phases in the austenitic matrix rapidly rises with the increase in temperature. As a result, when the temperature exceeds 1040 °C, the primary γ' phases in the Waspaloy alloy microstructure completely dissolve. Subsequently, during the aging treatment, uniformly dispersed fine secondary γ' phases begin to precipitate within the austenite grains (Fig. 5d – 5e), which is consistent with findings reported in Ref. [17]. On the other hand, as the temperature increases, the morphology of

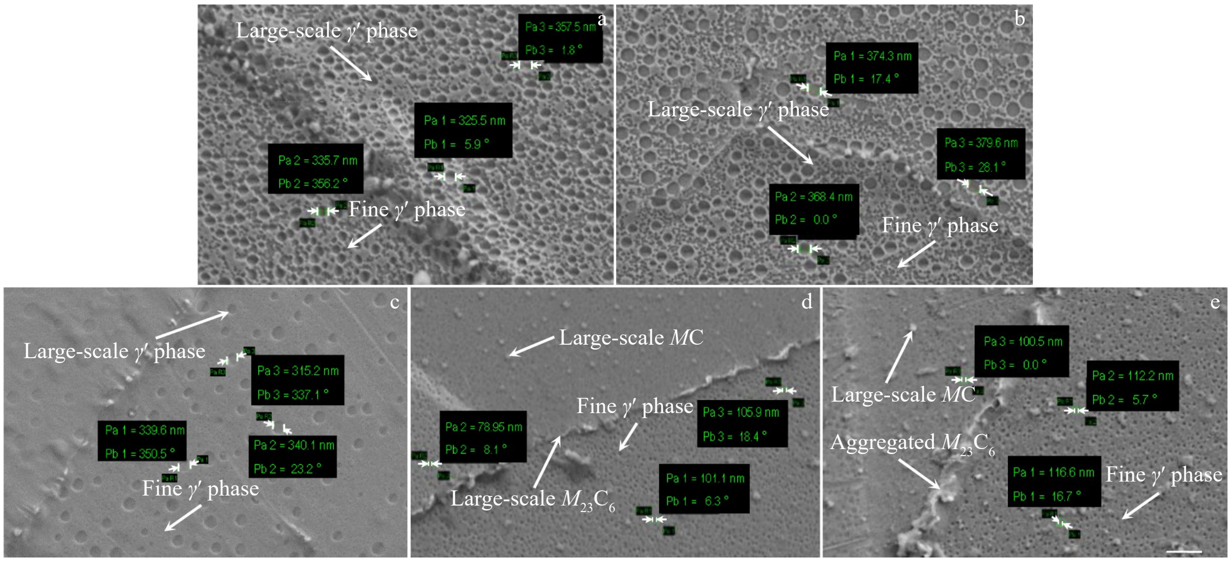

Fig.5 SEM images of strengthening phases in different Waspaloy alloy specimens: (a) 1010-04; (b) 1010-11; (c) 1010-20; (d) 1040-04; (e) 1070-04

Table 6 γ′ phase sizes of different Waspaloy alloy specimens in Fig.5 (nm)

Specimen	γ′ phase size	Average
1010-04	325.5, 335.7, 357.5	339.6
1010-11	374.3, 368.4, 315.2	352.6
1010-20	339.6, 340.1, 315.2	331.6
1040-04	101.1, 79.0, 105.9	95.3
1070-04	116.6, 112.2, 100.5	109.8

carbides at grain boundary gradually transitions from isolated island-like to elongated strip-like structures. This change in carbide morphology weakens their pinning effect on grain boundaries, leading to gradual grain coarsening of austenite with the increase in temperature. Notably, when the temperature reaches 1070 °C, abnormal grain growth occurs in austenite, transforming the originally equiaxed grains into irregular large-scale ones (Fig.5e).

3.4 Mechanical properties of Waspaloy alloy

3.4.1 Microhardness

Table 7 presents the microhardness measurement results of Waspaloy alloy specimens under different solid solution conditions, while Fig. 6 shows the microhardness scatter plot of these specimens.

Table 7 Microhardness of different Waspaloy alloy specimens ($HV_{0.2}$)

Specimen	Microhardness	Average value
1010-04	392.4, 391.6, 383.0, 373.9, 400.4	388.3
1010-11	393.1, 394.3, 383.3, 405.4, 397.6	394.7
1010-20	403.4, 413.1, 383.3, 373.1, 405.4	395.7
1040-04	391.2, 420.0, 395.1, 402.9, 428.5	407.5
1070-04	386.8, 419.6, 409.6, 389.6, 399.2	401.0

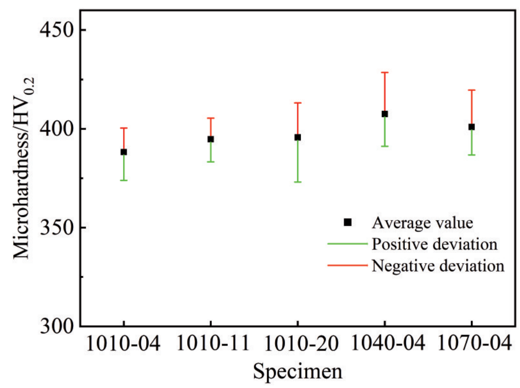

Fig.6 Scatter plot of microhardness of different Waspaloy alloy specimens

The 1010-04 specimen (standard heat treatment process) exhibits a microhardness of 388.3 $HV_{0.2}$. Compared to the 1010-04 specimen, the microhardness of the 1010-11 and 1010-20 specimens increases by 1.65% and 1.91%, respectively. The microhardness of the three specimens solid-solution treated at 1010 °C is essentially at the same level. However, compared to the 1010-04 specimen, the 1010-11 specimen shows a smaller range of positive and negative deviation, while the 1010-20 specimen exhibits a larger range of deviation. When the solid solution duration is constant and the solid solution temperature is increased, compared to the 1010-04 specimen, the microhardness of the 1040-04 and 1070-04 specimens is increased by 4.94% and 3.27%, respectively, and the error bars for both specimens are longer. The length of the error bars represents the uncertainty range of the microhardness values. Shorter error bars indicate higher stability of the microhardness values, which reflects better microstructure uniformity of the specimen. These results demonstrate that prolonging the solid solution duration to 11 h has no adverse effect on microhardness or microstructure uniformity of Waspaloy alloy. However, prolonging the solid solution duration to 20 h or increasing the solution temperature enhances microhardness but simultaneously reduces microstructural homogeneity to varying degrees. The most significant microhardness improvement is observed at 1040 °C, but this is accompanied by increased microhardness variability, suggesting a trade-off between microhardness enhancement and microstructure uniformity.

3.4.2 Tensile properties

Fig. 7 and Fig. 8 present the tensile strength-displacement curves and stress-strain curves of Waspaloy alloy specimens under different solid solution treatment conditions, respectively, with the corresponding tensile strength, yield strength, and elastic modulus calculated from these tests summarized in Table 8. The 1010-04 specimen processed under standard heat treatment conditions exhibits the tensile strength of 1 347.77 MPa, the yield strength of 863.61 MPa, and the elastic modulus of 10 724.70 MPa. When the solid solution temperature is 1010 °C and the duration is prolonged from 4 h to 11 h, the 1010-11 specimen exhibits moderate improvements of 2.19% in tensile strength, 4.65% in yield strength, and 1.53% in elastic modulus. Further prolonging the duration to 20 h results in slightly tensile and yield strength enhancements by 2.69% and 5.87%, respectively, but causes a 44.64% reduction in elastic modulus. Under the condition of constant solid solution duration, when the solid solution temperature is increased from 1010 °C to 1040 °C, the tensile strength and yield strength of the 1040-04 specimen are increased by 5.18% and 10.67%, respectively, while the

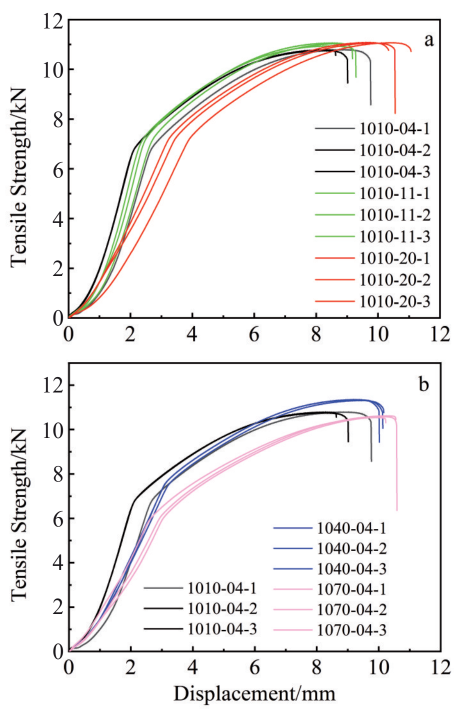

Fig.7 Tensile strength-displacement curves of Waspaloy alloy specimens under different solid solution treatment conditions: (a) treated at 1010 °C for different durations; (b) treated at different temperatures for 4 h

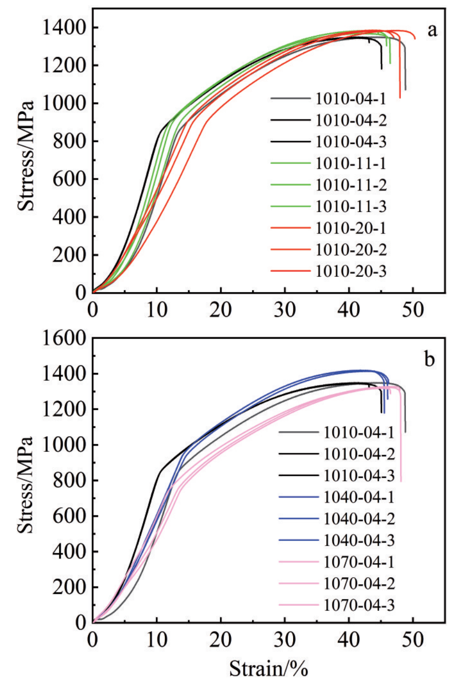

Fig.8 Stress-strain curves of Waspaloy alloy specimens under different solid solution treatment conditions: (a) treated at 1010 °C for different durations; (b) treated at different temperatures for 4 h

Table 8 Mechanical properties of different Waspaloy alloy specimens

Specimen	Tensile strength/ MPa	Yield strength/ MPa	Elastic modulus/MPa
1010-04	1 347.77	863.61	10 724.70
1010-11	1 377.23	903.73	10 888.28
1010-20	1 384.03	914.32	5 937.36
1040-04	1 417.54	955.76	8 260.05
1070-04	1 323.01	766.64	5 753.22

elastic modulus is decreased by 22.98%. When the solution temperature is further increased to 1070 °C, the tensile strength, yield strength, and elastic modulus of the 1070-04 specimen are decreased by 1.84%, 11.23%, and 46.36%, respectively.

The fitted curves of mechanical properties of Waspaloy alloy specimens evolving with solid solution duration and solid solution temperature are shown in Fig. 9 and Fig. 10, respectively. The tensile strength, yield strength, and elastic modulus are set as the dependent variables of σ_b, σ_s, and E, respectively, and the solid solution duration and solid solution temperature are set as the independent variables of t and T, respectively.

The variation rules of the mechanical properties of the material with solid solution duration and temperature obtained by fitting curves are shown in Eq. (3–8), as follows:

$$\sigma_b = -0.22t^2 + 7.45t + 1321.44 \tag{3}$$

$$\sigma_s = -0.28t^2 + 10.00t + 828.16 \tag{4}$$

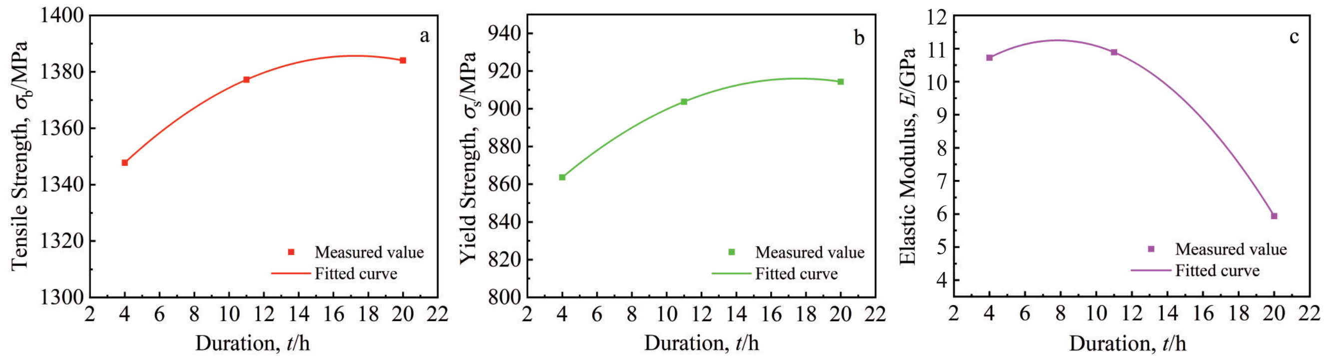

Fig.9 Evolution of tensile strength (a), yield strength (b), and elastic modulus (c) of Waspaloy specimens after solid-solution treatment at 1010 °C for various durations

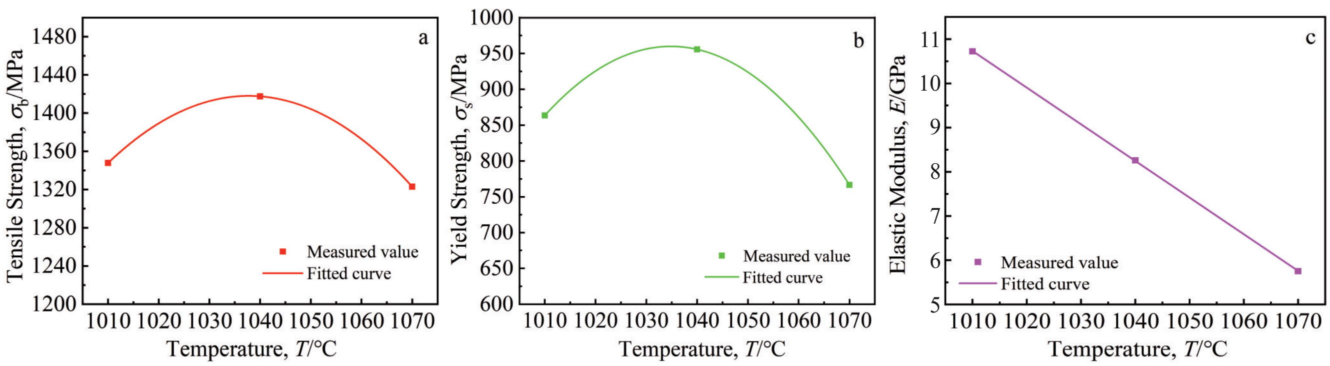

Fig.10 Evolution of tensile strength (a), yield strength (b), and elastic modulus (c) of Waspaloy specimens after 4 h solid-solution treatment at various temperatures

$$E = -35.84t^2 + 561.00t + 9054.18 \quad (5)$$

$$\sigma_b = -0.09128T^2 + 189.45T - 96879.33 \quad (6)$$

$$\sigma_s = -0.1563T^2 + 323.41T - 166375.44 \quad (7)$$

$$E = -82.86T + 94418.31 \quad (8)$$

When the solid solution temperature is constant at 1010 °C, the tensile strength and yield strength of Waspaloy alloy exhibit a gradual increasing trend with the prolongation of solid solution duration, and their specific evolution patterns are described by Eq. (3) and Eq. (4), respectively. The coordinates of the maximum points for Eq. (3) and Eq. (4) are (16.93, 1384.51) and (17.86, 917.45), respectively. In both cases, the independent variable values at these maxima exceed 11 h, indicating that the solid solution duration of 11 h falls within the increasing intervals of both Eq. (3) and Eq. (4). Conversely, the elastic modulus displays an initial slow increase followed by a rapid decrease, as characterized by Eq. (5). The maximum point for Eq. (5) occurs at coordinates (7.83, 11 249.50), with the independent variable value being less than 11 h. This result demonstrates that the solid solution duration of 11 h lies within the decreasing interval of Eq. (5).

With a constant solid solution duration of 4 h, the tensile strength and yield strength of Waspaloy alloy initially increase and then decrease as the temperature increases from 1010 °C to 1040 and 1070 ° C. These trends are quantitatively described by Eq. (6) and Eq. (7). The maximum points for Eq. (6) and Eq. (7) occur at coordinates (1037.74, 1420.69) and (1034.58, 921.47), with both optimal temperatures being below 1040 °C. This indicates that both the 1040 and 1070 °C lie within the descending intervals of these equations. In contrast, the elastic modulus exhibits a linear decreasing trend, as precisely characterized by Eq. (8). This demonstrates that when the solid solution temperature exceeds 1010 °C, the elastic modulus decreases monotonically following the mathematical relationship defined in Eq. (8).

3.4.3 Evolution mechanism of mechanical properties

The evolution of mechanical properties in Waspaloy alloy under different solid solution conditions is fundamentally governed by corresponding microstructure evolution. When the solid solution duration is prolonged while the temperature maintains constant, the microhardness of alloy exhibits a gradual upward trend, reaching merely a 1.90% enhancement after treatment for 20 h compared to that treated by standard processing. This moderate improvement stems from the dual dependence of microhardness on strengthening phase size and grain size characteristics, where finer γ' precipitates typically enhance strengthening effect, while coarser grains diminish strengthening effect[9]. Throughout the 4–20 h of treatment duration, the stable grain structure combined with the gradually increasing fraction of refined γ' phases collectively contributes to the observed increase in microhardness. The influence of solid solution duration on the tensile strength and yield strength of the alloy is similar to that on the microhardness. Since the grain size remains unchanged, the tensile strength and yield strength are governed primarily by the size of the strengthening phase and gradually increase with the increased content of refined γ' phases.

As the solid solution temperature increases while the solid solution duration maintains constant, the microhardness of the alloy first increases and then decreases. This phenomenon occurs due to the strengthening phase within the austenite grains transitioning from large-scale γ' precipitates to a fine and dispersed ones at 1040 °C, while the austenite grains exhibit no significant growth. Consequently, the microhardness of alloy treated at 1040 °C increases by 4.94% compared to that treated by the standard process. At the higher solid solution temperature of 1070 °C, the strengthening phase composed of fine γ' particles; however, the austenite grains undergo noticeable coarsening, leading to a reduction in microhardness. Nevertheless, owing to the dominant influence of the fine γ' phase, the microhardness still shows an increase of 3.27% relative to that treated by the standard process. Similarly, the influence of solid solution temperature on the tensile properties follows a trend comparable to that observed in microhardness. The presence of fine γ' particles contributes to the enhanced tensile strength and yield strength, whereas grain coarsening tends to degrade these properties. As a combined result of these two competing factors, both the tensile strength and yield strength initially increase and subsequently decrease with the increase in solid solution temperature.

The elastic modulus, defined as the ratio of stress to strain within the elastic deformation stage, reflects the stiffness of a material and is primarily influenced by interatomic bonding forces. Moreover, as a structurally insensitive property, it exhibits restricted responsiveness to variations in microstructure[18–19]. In general, the elastic modulus of Waspaloy alloy is mainly determined by the properties of the γ matrix phase. As the solid solution duration is prolonged, the volume fraction of fine γ' precipitates within the γ matrix gradually increases. Particularly, when the solid solution duration reaches 20 h, the proportion of fine γ' phases increases significantly, leading to progressive changes in the physical and chemical properties of the γ matrix. As a result, the elastic modulus of the alloy first increases slowly and then decreases rapidly with the prolongation of solid solution duration. With the increase in solution temperature, the large-scale strengthening phases within the γ matrix are completely dissolved, followed by the precipitation of the dispersed fine strengthening particles. Additionally, carbides at the γ grain boundaries transition from isolated island-like morphology to elongated strip-shaped structures, which also alters the properties of the matrix phase. Ultimately, these changes cause the elastic modulus to decrease linearly with the increase in solid solution temperature.

In this research, quantitative models correlating mechanical properties with solid solution parameters were established for the studied operational conditions. The metallographic replication technique was used in failure analysis of LPT case. The findings provided crucial theoretical foundation and experimental data for revising heat treatment specifications of critical high-temperature components in aeroengines.

4 Conclusions

1) After solid solution treatment at 1010 °C for 4 and 11 h, LPT components consistently exhibit homogeneous equiaxed grain structures. The microstructure primarily consists of γ matrix phase with minor carbides precipitated during cooling. These carbides are predominantly distributed along grain boundaries, with no significant variation observed in either their morphology or size.

2) When the solid solution temperature is maintained constant at 1010 °C, Waspaloy alloy exhibits low sensitivity to solid solution duration. Prolonging the duration from 4 h to 20 h has slightly effect on the grain size, but results in a gradual increase in volume fraction of fine strengthening phases. The microhardness and mechanical properties of the alloy, governed by both strengthening phase characteristics and grain size, demonstrate a consistent increasing trend with the prolongation of duration.

3) Under the condition of a constant duration of 4 h, the microstructure of Waspaloy alloy exhibits high sensitivity to solid solution temperature. As the temperature increases from 1010 °C to 1040 and 1070 °C, the grain of the specimens progressively coarsens, from Grade 7.5 to Grade 6.5 and further to Grade 3.0. Meanwhile, the large-scale intragranular strengthening phases within the γ matrix are gradually transformed into finely dispersed precipitates, while both grain boundary and intragranular carbides coarsen continuously with the increase in temperature. The microhardness, tensile strength, and yield strength of the alloy all demonstrate an initial increase followed by a subsequent decrease.

4) Under the condition of 1010 °C/11 h, LPT case exhibits no significant changes in either microstructure or grain size. Meanwhile, the mechanical properties of the Waspaloy alloy, including microhardness, tensile strength, yield strength, and elastic modulus, show slight improvements. Notably, the solid solution duration of 11 h falls within the increasing interval of the independent variable in functional relationships of both the tensile strength versus solid solution duration and yield strength versus solid solution duration. Therefore, the solid solution treatment process of 1010 °C for 11 h is considered acceptable.

References

1 Sazerat M, Nait-Alo A, Cervellon A *et al*. *Journal of Alloys and Compounds*[J], 2023, 966: 171626

2 Li Chao, Zhang Haoqiang. *Mechanical Engineering & Automation*[J], 2021(1): 68 (in Chinese)

3 Xie Xishan. *Materials for Mechanical Engineering*[J], 2004(1): 2 (in Chinese)

4 Hong Chengmiao, Yao Zhihao, Zhang Maicang *et al*. *Chinese Journal of Engineering*[J], 2008, 30(9):1018 (in Chinese)

5 Wang Miaoquan, Tian Chenggang, Nan Yang *et al*. *Materials Reports*[J], 2017, 31(19): 72 (in Chinese)

6 Lou Jin, Chen Kanghua, Liu Li *et al*. *Hot Working Technology*[J], 2017, 46(4): 58 (in Chinese)

7 Xu Luopeng, Hao Mengquan, Xiong Lei *et al*. *Science Technology and Engineering*[J], 2024, 24(17): 7406 (in Chinese)

8 Andersson J, Sjöberg G P, Viskari L *et al*. *Materials Science and Technology*[J], 2013, 29(1): 43

9 Liu H L, Zhao X, Liu X *et al*. *Journal of Alloys and Compounds*[J], 2023, 946: 169461

10 Zeng Weihu, Zhou Xiaoming, Fang Bo *et al*. *Foundry Technology*[J], 2019, 40(5): 500 (in Chinese)

11 Wei Zhijian, Xu Wenshuai, Yuan Hui *et al*. *Die & Mould Industry*[J], 2017, 43(9):63 (in Chinese)

12 Rong Yi, Cheng Lei, Tang Chao *et al*. *Journal of Iron and Steel Research*[J], 2016, 28(11): 74 (in Chinese)

13 Xiao Dongfei, Wang Xuan, Wei Zhongxuan *et al*. *Physical Testing and Chemical Analysis* (*Part A: Physical Testing*)[J], 2021, 57(1): 19 (in Chinese)

14 Sun H T. *Nuclear Power Engineering*[J], 2011, 32(S1): 162

15 Qian M, Lippold J C. *Acta Materialia*[J], 2003, 51(12): 3351

16 Han Yichun, Cui Zhifeng, Jiang Jinyu *et al*. *Physical Testing and Chemical Analysis* (*Part A: Physical Testing*)[J], 2010, 46(9): 547 (in Chinese)

17 Wu Baoping, Li Linhan, Wu Jiantao *et al*. *Transactions of Materials and Heat Treatment*[J], 2014, 35(S1): 146 (in Chinese)

18 Li Zhengguang, Xu Kejun, Qin Haiqin *et al*. *Rare Metal Materials and Engineering*[J], 2023, 52(7): 2511 (in Chinese)

19 Ye D Y. *International Journal of Fatigue*[J], 2005, 27(9): 1102

固溶处理对航空发动机涡轮机匣力学性能的影响

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摘 要： Waspaloy合金广泛应用于航空航天领域，特别是服役环境恶劣的燃气涡轮机。以在役航空发动机涡轮机匣为研究对象，通过现场金相复型技术和实验室验证试验，研究固溶时间和固溶温度对Waspaloy合金低压涡轮（LPT）机匣显微组织和力学性能的影响规律。结果表明，超时固溶（1010 ℃/11 h）对于LPT机匣的显微组织和晶粒度无不利影响。合金对于固溶时间的敏感度较低，随着固溶时间延长（4~20 h），晶粒度未发生变化，晶粒形态基本保持不变，显微组织中孪晶数量逐渐减少，小尺度强化相的占比逐渐增加。合金对于固溶温度的敏感度较高，随着固溶温度由1010 ℃分别升高至1040和1070 ℃，试片的晶粒度级别从7.5级分别降低至6.5级和3.0级，同时奥氏体晶内的强化相由一次强化相全部转化为二次强化相；另外，γ相晶界处$M_{23}C_6$碳化物由低温固溶条件下的孤岛状转变为高温固溶条件下的长条状，晶内$M_{23}C_6$碳化物的数量和尺度也明显增加。合金显微硬度和力学性能主要由合金显微组织中的强化相尺度和晶粒尺度2个因素决定。随着固溶时间延长，显微硬度、抗拉伸强度及屈服强度呈现出逐渐增大的趋势。随着固溶温度升高，合金的显微硬度、抗拉伸强度和屈服强度均呈现出先增加后降低的变化规律。

关键词： Waspaloy合金；LPT机匣；晶粒度；显微硬度；力学性能

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