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ARTICLE

Effect of Heat Treatment on Fracture Characteristics and Serrated Yielding of Inconel 718 Superalloy

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Abstract: Due to the gradually prominent impact of fracture characteristics and serrated yielding in the application of nickel-based superalloys, the hot tensile properties of Inconel 718 superalloy were studied, including fracture behavior, mechanical properties, and plastic behavior. The experiments adopted three heat treatment regimes and two tensile directions. Results show that various heat treatments make grain sizes different. The larger-sized grains make the vertical surface uneven, which also decrease the number of grain boundaries and carbides, restricting the occurrence of dimples and ultimately reducing the material plasticity. The reduced grain boundaries can decrease dislocations, increase the demand for thermal activation energy, and transform the serration mode of serrated yielding. In addition, various heat treatments also make precipitates different. Carbides can promote the formation of dimples. The needle-shaped δ phase precipitates at grain boundaries and twin boundaries, and slightly inclines towards the rolling direction. Therefore, its pinning effect is outstanding along the transverse direction, which can affect the dimple aggregation and the dislocation movement, ultimately exhibiting anisotropy in fracture characteristics, mechanical properties, and serrated yielding.

Key words: superalloy; fracture characteristics; heat treatment; serrated yielding; anisotropy

1 Introduction

Inconel 718 superalloy is an aging precipitation-strengthening nickel-based superalloy. Except for excellent high-temperature mechanical properties, its uniqueness includes good welding performance, corrosion resistance, oxidation resistance, and thermal stability[1–2]. Therefore, Inconel 718 superalloy is widely used in critical safety and high-temperature structural components in advanced manufacturing industries, such as aerospace, nuclear energy, marine, defense, chemistry, petroleum, natural gas, power generation, and vehicles[3–5]. Nowadays, the particular and harsh environment is placing higher demands on the performance of materials as advanced manufacturing industries rapidly and continuously develop.

The crack generation and fracture characteristics are the key factors affecting material properties in the application process of nickel-based superalloys. Numerous scholars have studied the fracture characteristics of metal materials. Liu et al[6] discussed the impact extent of the microstructure and material parameters on the macroscopic fracture toughness and the ductile crack propagation mechanism. Lin et al[7] analyzed the influence of initial microstructure on the fracture characteristics of nickel-based superalloys.

The serrated flow, a plastic instability behavior, is one of the most challenging complexities during high-temperature plastic deformation[8]. The serrated yielding, one kind of dynamic strain aging (DSA) of materials, indicates this plastic instability phenomenon. It is worth noting that DSA has an indispensable impact on performance in practical applications. It may even be a strengthening and toughening process. However, its importance had been largely ignored, particularly in classic textbooks on physical metallurgy, mechanical properties, and dislocation theory. Research on the microstructural cause of serration yielding is numerous in light metals and steel[9–10] but rare in nickel-based superalloys.

Due to the complex loading conditions in practice, the uniaxial tensile experiments were conducted to simplify

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loading. Heat treatment is a general method to alter mechanical properties. Therefore, this work investigated the effect of heat treatment and tensile directions on the hot tensile properties of Inconel 718 superalloy, including fracture behavior, mechanical properties, and plastic behavior. Microstructure analysis can help to explore the causes of the above effect. This research can provide feasible methods for regulating the properties of nickel-based superalloys.

2 Experiment

The hot-rolled Inconel 718 superalloy sheets were used in this experiment, with the chemical composition shown in Table 1. The thickness of hot-rolled sheets was 3 cm. The initial microstructure of the Inconel 718 superalloy, as shown in Fig. 1, consisted of γ matrix, lamellar twin, dispersed block-shaped carbide, boride, γ'' phase, γ' phase, and Laves phase. The average grain sizes were similar on different observation surfaces. In Fig. 1, ND, TD, and RD mean normal direction, transverse direction, and rolling direction, respectively.

This study applied three heat treatment regimes according to the SAE AMS 5383F 2018 standard. Table 2 lists the details. In Fig. 2, the bulk specimens with the size of 11 mm×10 mm prepared by wire cutting were prepared for microstructure observation. The tensile specimens were prepared for tensile property test. The uniaxial tensile experiments were conducted at the deformation temperature of 650 °C and the strain rate of 0.001 s^{-1} on the Gleeble3800 thermal simulator. The tensile directions included TD and RD.

Table 1 Chemical composition of Inconel 718 superalloy (wt%)

C	P	Cr	Ni	Mo	Ti	Nb	B	Al	Fe
0.08	0.003	19.00	52.50	3.01	0.90	5.10	0.003	0.50	Bal.

The optical microscope (OM) was used to observe the microstructure of the bulk specimens and tensile specimens under different circumstances. The scanning electron microscope (SEM) was used to observe the fracture surface of tensile specimens. The Image Pro Plus software was used to calculate the size of grain and dimple.

3 Results and Discussion

3.1 Fracture behavior

γ'' and γ' phases precipitate in the microstructures of Inconel 718 superalloy after HST, ST, and DA, as shown in Fig. 3. The particle-shaped δ phases after DA are less than those after HST and ST, because the precipitation temperature of δ phase ranges from 780 °C to 980 °C. The grain size after HST significantly increases. After tensile test, the fracture surface is at an angle of 45° to load direction (Fig. 3b), which is a characteristic of pure shear fracture. The grains in Fig. 3d–3i are elongated slightly along the load direction. In addition, individual microcrack diffuses or coalesces vertically to load direction around the fracture surface. After HST, the vertical surface is uneven in macro-perspective. The larger-sized grains reduce the grain constraints on the specimen surface[11], resulting in grain rotation, dislocation formation, and surface fluctuation. Numerous apparent intergranular microcracks cover the surface, which are initiated at the triple junction of grain boundaries or precipitates. However, the surfaces are flat in macro-perspective, and the size and coverage area of the microcrack reduce after ST and DA. After ST, some transgranular fracture characteristics originate in cracks inside the grain. The transgranular cracks appear in stress concentration areas, such as near the precipitate coalescence bands (as shown in partial enlargement drawings). Compared with TD tension, the RD tension makes microcracks denser

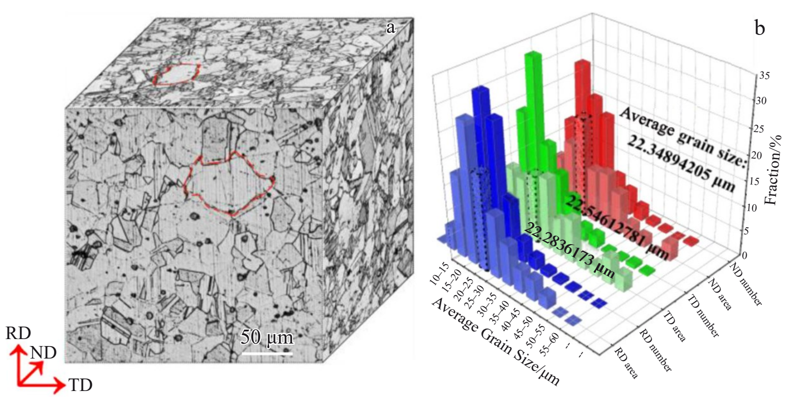

Fig.1 Initial microstructure (a) and average grain size distribution (b) on ND, TD and RD surfaces of Inconel 718 superalloy

Table 2 Details of various heat treatments

Name	Detail
HST	Heating at 5 °C/s to 1100 °C, 1100 °C, 1 h/air cooling (homogenization)+954 °C, 1 h/air cooling (solution treatment)+720 °C, 8 h/furnace cooling at 50 °C/h to 620 °C/620 °C, 8 h/air cooling (double aging)
ST	954 °C, 1 h/air cooling+720 °C, 8 h/furnace cooling at 50 °C/h to 620 °C/620 °C, 8 h/air cooling
DA	720 °C, 8 h/furnace cooling at 50 °C/h to 620 °C/620 °C, 8 h/air cooling

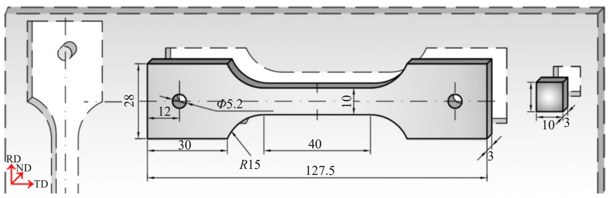

Fig.2 Specimen diagram

and microcrack size smaller. However, the anisotropy is little after DA.

In Fig. 4, the fracture surface includes fibrous region, radiant region, and shear lip according to the macrostructure characteristics. Their relative proportion and distribution depend on the material plasticity. The shear lip does not appear in the fracture cross-section morphology of all specimens. The fracture surfaces after HST consist of fibrous and radiant regions. The radiant edges all converge together, forming two fracture

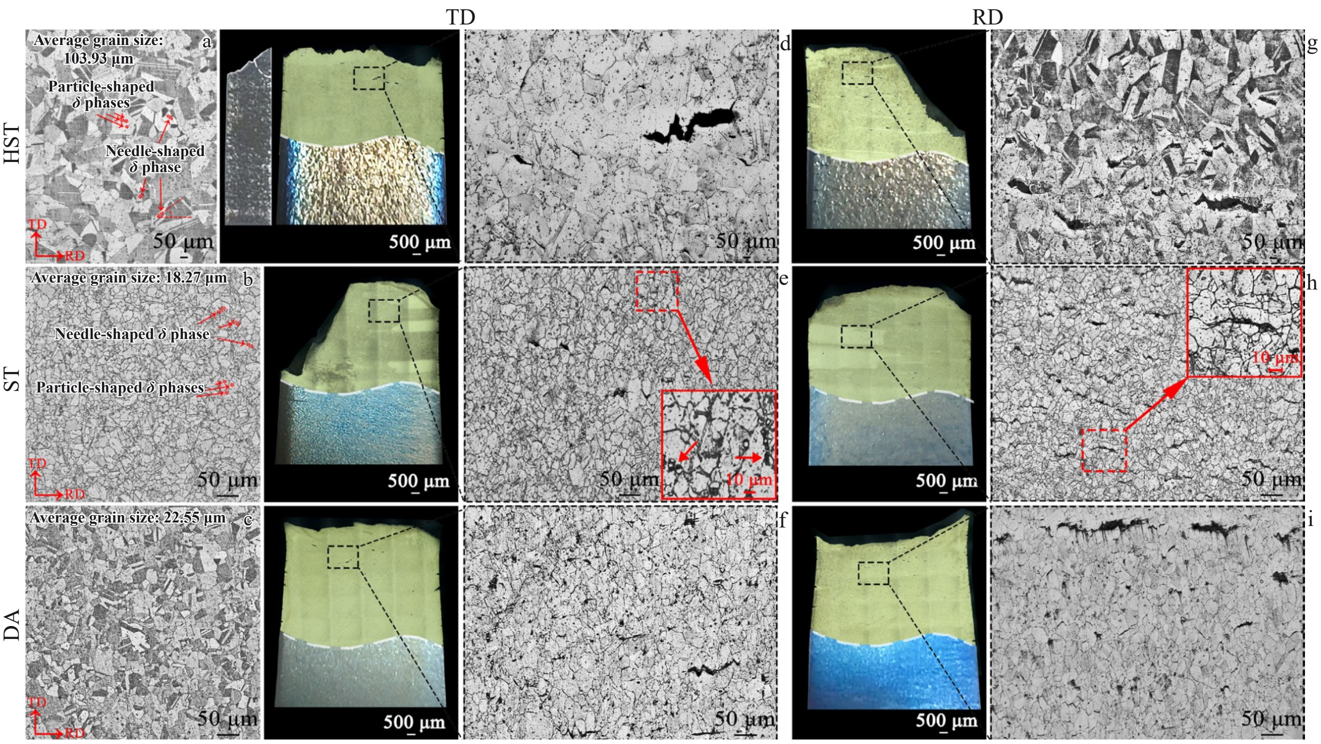

Fig.3 Microstructures (a–c) and macroscopic and microscopic tensile fracture morphologies (d–i) of Inconel 718 superalloy after different heat treatments along TD (d–f) and RD (g–i)

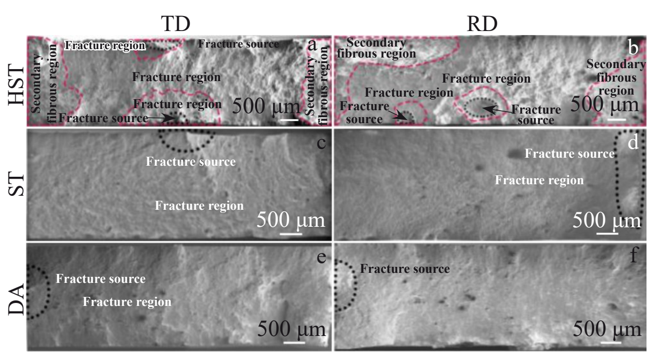

Fig.4 Fracture cross-section morphologies of Inconel 718 superalloy under different conditions

sources. This reason is that numerous large-sized grains makethe mechanical properties uneven in loading areas[12–13], and several slip systems further are activated. The fracture surfaces after ST and DA both have massive fibrous regions. The fracture surfaces are flat and have almost no radiant edge. Therefore, the brittle fracture occurs when larger-sized grains exist.

In Fig.5, all fracture surfaces have dimples, microvoids, and slip bands. Some dimples have typical characteristics, such as serpentine sliding, blade-type edge, and tearing. Carbide fragments may exist at the bottom of dimples. Therefore, dimples are likely to occur at carbides. There are some cleavage characteristics after HST, and some transgranular fracture characteristics after ST and DA. The cleavage characteristics are crack jumping caused by less plasticizing effect[14], characterized by the flat local area. Some minorsized dimples and voids even cover cleavage characteristics. It is generally accepted that void nucleation, growth, and coalescence are the essence of ductile fracture, ultimately manifesting as dimples on the fracture surface[15–16]. With the increase in grain size, the number of grain boundaries, carbides, and dimples decreases, and the dimple depth increases. The fracture-characteristic size of both dimples or cleavage characteristics after TD tension is slightly larger than that after

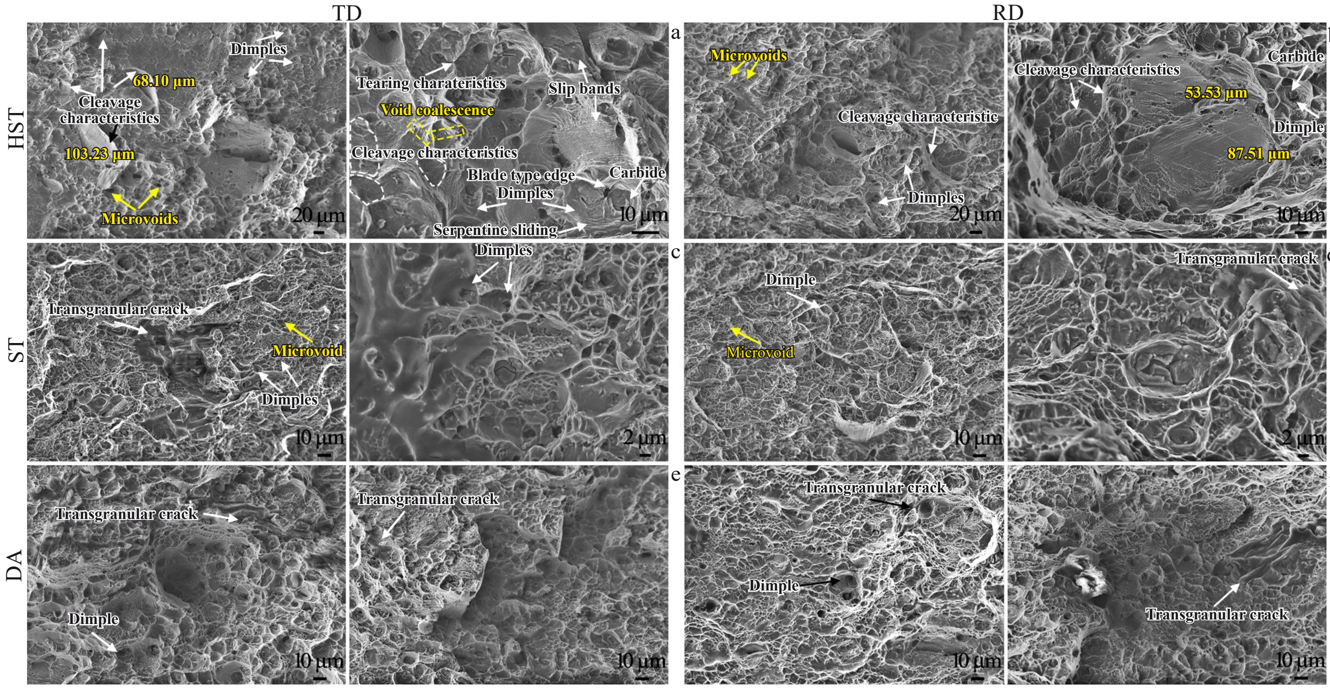

Fig.5 Local morphologies of fracture surfaces of Inconel 718 superalloy under different conditions

RD tension. The fracture cross-section morphology exhibits a ductile-brittle mixed fracture characteristic.

3.2 Mechanical properties

According to the engineering stress-engineering strain curves in Fig. 6, the specimens undergo elastic deformation, yielding, work hardening, necking, softening, and fracture. Among those curves, the softening is most pronounced after DA, followed by ST, and finally HST. Based on the average grain size data in Fig. 3, the yield strength decreases sequentially with the increase in average grain size. The plasticity after DA is better than that after HST or ST, manifesting as great overall and necking-stage strain. In conclusion, the Inconel 718 superalloy reaches and the expected mechanical properties after DA, and has better strength and plasticity along TD.

3.3 Plastic behavior

The serrated yielding phenomena and unique plastic behavior occur under some heat treatment conditions. Fig. 7a shows four types of serration modes[17]. Their differences focus on the frequency and amplitude of stress drops. In Fig. 7b and 7c, the serrated yielding phenomena after hot rolling and HST can be classified as B-type and A-B mixed-type serrations, respectively. The serrated yielding phenomena are almost absent after ST and DA.

Researchers believe that DSA occurred due to the pinning effect caused by the segregation of diffusive solute atoms towards mobile dislocations[18]. Serrated yielding is a resonance phenomenon with the equilibrium state between solute atom migration and dislocation mobility. With the increase in thermal activation energy, the diffusion rate changes, the equilibrium state shifts, and the serration mode may be transformed from A-type to B-type and then to C-type. Finally, the serration disappears. As the grain size increases, the proportion of grain boundaries decreases, the quantity of dislocations decreases, and the demand for thermal activation energy increases. As shown in Fig. 7, the as-received

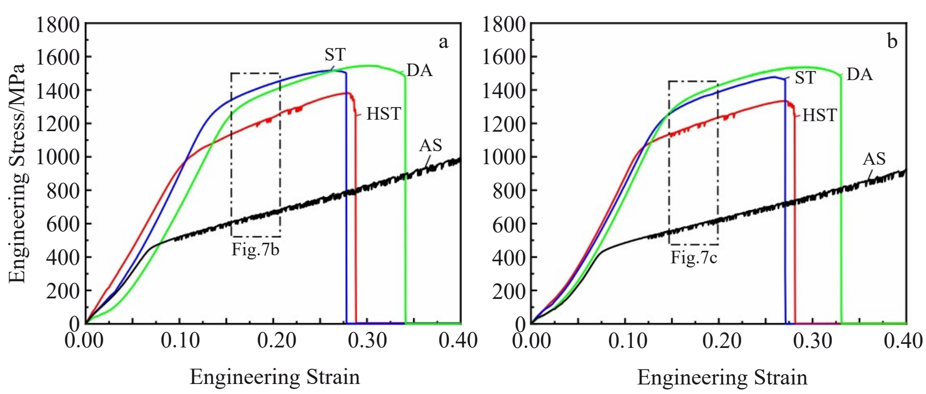

Fig.6 Engineering stress-engineering strain curves of Inconel 718 superalloy under different conditions: (a) TD; (b) RD (AS denotes as-received specimens)

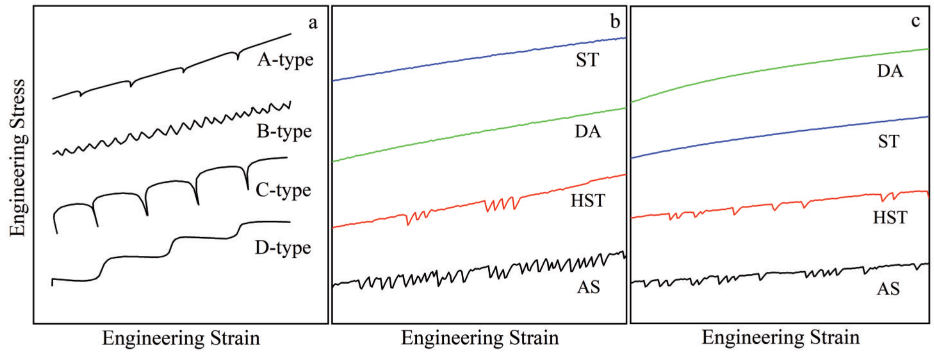

Fig.7 Common serration modes (a)[17]; partial enlargement drawings of engineering stress-engineering strain curves along TD (b) and RD (c) marked in Fig.6a and Fig.6b, respectively

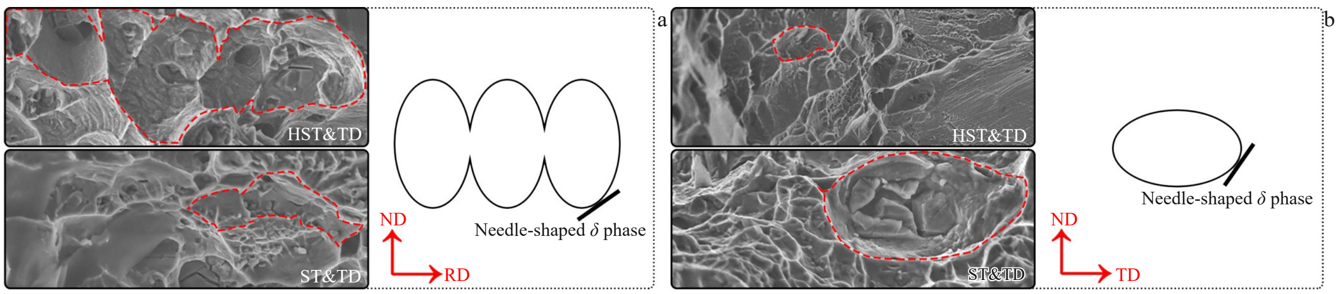

Fig.8 Schematic diagrams of dimples at fracture surfaces along different tensile directions: (a) TD; (b) RD

specimens (denoted as AS) have B-type serrations. After HST, the serration mode transfers to A-B mixed type due to the increased grain size. After ST and DA, the slightly decrease in grain size and the increase in precipitates make the demand for thermal activation energy decrease. The thermal activation energy reaches the equilibrium state effortlessly under the same tension conditions. Ultimately, the serration is absent. In addition, the serration mode along RD is more inclined towards B-type than that along TD.

3.4 Material anisotropy

In most alloys, microvoids form at the secondary-phase particles. Sometimes, secondary-phase particles can be found at the bottom of the dimples[19], such as block-shaped carbides in Fig. 3. Therefore, carbides can promote the formation of dimples. Compared with dimples under various conditions in Fig. 8, some dimples aggregate together along RD after TD tension, while some dimples are elongated along TD after RD tension. This phenomenon corresponds to the microstructure characteristics near the fracture surfaces in Fig.3. Specifically, the main microcrack characteristics are large in size after TD tension and higher in density after RD tension. This phenomenon occurs after HST and ST, but is not significant after DA. After HST and ST (Fig.3a–3b), the composition phases both include the δ phase. The needle-shaped δ phase appears at grain and twin boundaries, while the particle-shaped δ phase appears within grains. The needle-shaped δ phase has an angle of 35° to RD. Since the fracture mode is mainly intergranular fracture, the pinning effect of the needle-shaped δ phase is more evident along TD than RD. It can affect the dimple aggregation and the dislocation movement, ultimately exhibiting anisotropy in fracture characteristics, mechanical properties, and serrated yielding. Due to the less δ phase after DA, the anisotropy is not significant.

Due to the larger-sized microcracks, the fracture characteristic is larger-sized after TD tension, including dimples and cleavage characteristics. In addition, dislocation movement along TD is more restricted than that along RD. The above analysis explains the excellent plasticity after RD tension in Fig. 6. Moreover, the equilibrium state of serrated yielding along TD tension requires a higher thermal activation energy than RD tension. Therefore, the serration mode along RD is more inclined towards B-type serration than that along TD.

4 Conclusions

1) Various heat treatment conditions can make fracture characteristics different for Inconel 718 superalloy. After HST, the larger-sized grains promote unevenness on the vertical surface, reduce the number of grain boundaries and carbides, and hinder the occurrence of dimples. The fracture cross-section morphology exhibits a ductile-brittle mixed fracture characteristic. After ST and DA, the dimples almost cover the fracture surface.

2) The serrated yielding phenomenon is a resonance phenomenon with the equilibrium state between solute atom migration and dislocation mobility. The as-received specimens

have B-type serrations after tensile experiments. After HST, the larger-sized grains lead to the decrease in grain boundaries and dislocations, increasing the demand for thermal activation energy, and ultimately returning the serration mode to the A-B mixed type. After ST and DA, the slight decrease in grain size and the increase in precipitates make the demand for thermal activation energy decrease. The thermal activation energy is sufficient to make serration absence after the same tensile experiments.

3) Block-shaped carbides can promote the formation of dimples. After HST and ST, the needle-shaped δ phase precipitates at grain and twin boundaries. It slightly inclines towards the RD at angle of 35°. Therefore, the pinning effect of the needle-shaped δ phase is more pronounced along TD than RD. It can affect the dimple aggregation and the dislocation movement, ultimately exhibiting anisotropy in fracture characteristics, mechanical properties, and serrated yielding.

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热处理对Inconel 718高温合金断裂特征和锯齿屈服的影响

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摘　要：由于断裂特征和锯齿屈服在镍基高温合金应用中的影响逐渐突出，探讨了Inconel 718高温合金的热拉伸性能，包括断裂行为、力学性能和塑性行为。该实验选用了3种热处理制度和2种拉伸方向。结果表明，不同的热处理方式使得晶粒尺寸有差异。大尺寸晶粒使纵断面不平整，并且减少了晶界和碳化物的数量，限制了韧窝生成，最终降低了材料塑性。晶界的减少会减少位错，增加达到锯齿屈服平衡条件对热活化能的需求，并改变锯齿类型。另外，热处理也会使沉淀物不同。碳化物可以促进韧窝的形成。针状δ相在晶界和孪晶界析出，并略向轧向倾斜。因此，针状δ相沿横向的钉扎效应显著，这会对韧窝聚集和位错运动产生影响，最终在断裂特征、力学性能和锯齿屈服方面表现出各向异性。

关键词：高温合金；断裂特征；热处理；锯齿屈服；各向异性

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