Rare Metal Materials and Engineering
Volume 53, Issue 2, February 2024
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Gao Yushe, Xue Xiangyi, Liu Xianghong, et al. Effect of Heat Treatment Process on Microstructure and Mechanical Property of Ti555211 Titanium Alloy[J]. Rare Metal Materials and Engineering, 2024, 53(02): 371-376. DOI: 10.12442/j.issn.1002-185X.20230450.

ARTICLE

Effect of Heat Treatment Process on Microstructure and Mechanical Property of Ti555211 Titanium Alloy

Gao Yushe [1,2], **Xue Xiangyi**[1], **Liu Xianghong**[2], **Gao Huixian**[1,2], **Wang Jianguo**[2], **Du Yuxuan**[2]

[1] Northwestern Polytechnical University , Xi'an 710072, China; [2] Western Superconducting Technologies Co., Ltd, Xi'an 710018, China

Abstract: A new type of near-β titanium alloy (Ti555211) was investigated. This alloy has excellent plasticity, high specific strength, and excellent comprehensive properties, which is widely used in the aerospace and chemistry industries. Through the 3×3 orthogonal experiments, the influences of different stages of two-step annealing treatment (solution temperature, aging temperature, aging time) on the mechanical properties and microstructures of Ti555211 titanium alloy were investigated. Results show that with increasing the solution temperature and decreasing the aging temperature, the alloy strength is increased. The elongation is increased with decreasing the solution temperature and increasing the aging temperature. After treatment of 820 °C/2 h/air cooling and 580 °C/12 h/air cooling, the alloy has better plasticity, and its tensile strength reaches 1333 MPa, which is higher than the strength index (1080 MPa) of similar alloys by 20%. The elongation of the Ti555211 titanium alloy is 12%, which is higher than the plasticity index (5%) of similar alloys by 140%.

Key words: titanium alloy; orthogonal experiment; heat treatment; microstructure; mechanical property; EBSD

Titanium alloys are widely used in the aerospace, ocean, and petrochemistry fields, because they have excellent high-temperature properties, outstanding fatigue property, superb corrosion resistance, low density, and high specific strength[1–5].

The commonly used titanium alloys include metastable-β type Ti-15-3[6], β type-21S[7], near-β type Ti1023[8], Ti5553[9], Ti55531[10], BT22[11], and TB17[12] alloys. Orthogonal test method is commonly used to study the process parameters of near-α titanium alloys with tri-modal structure[13]. The properties[14], deformation behavior[15], and heat treatment effects[16] of titanium alloys have also been extensively researched.

Titanium alloys are the main structural material for the aircraft and engine application, which show important application value and broad application prospects in the aerospace industry. The traditional high strength and high toughness titanium alloys are mainly represented by the Ti-1023 (US) and BT22 (Russian) titanium alloys. With the development of aerospace industry, a new type of high strength and high toughness titanium alloy has been proposed and rapidly applied: Timetal556 alloy (US) and VST55531 alloy (US and Russia). These nouvelle alloys are less sensitive to the segregation and have good hardenability, high strength, and high fracture toughness, which are particularly suitable for the manufacture of structural part, landing gear, wing, and engine pylons of the connections between devices under large stresses.

Ti555211 titanium alloy, as one of the new near-β titanium alloys, has been applied to manufacture key components of main landing gears of aircraft[17]. However, the microstructure evolution and mechanical properties of near-β titanium alloys are very sensitive to the heat treatment temperature. In order to study the performance of Ti555211 titanium alloy to satisfy the requirements of aviation industry, orthogonal tests were conducted to investigate the effects of different heat treatments on the microstructure and mechanical properties of Ti555211 titanium alloy.

1 Experiment

In this research, Ti555211 titanium alloy (Western Superconducting Technologies Co., Ltd) was used as research object. The element composition of Ti555211 titanium alloy is listed in Table 1. The size of Ti555211 titanium alloy bar was Φ350 mm, and the $(\alpha+\beta)/\beta$ transition temperature was 875 – 880 °C. Solution temperature, aging temperature, and

Received date: July 20, 2023
Corresponding author: Liu Xianghong, Ph. D., Professor, Western Superconducting Technologies Co., Ltd, Xi'an 710018, P. R. China, Tel: 0086-29-86514509, E-mail: xhliu@c-wst.com

aging time are the key factors affecting the alloy performance. The solution temperature was 780, 800, and 820 °C. The aging temperature was 580, 600, and 620 °C. The aging time was 6, 9, and 12 h. The solid solution temperature, aging temperature, and aging time were selected according to the remelting temperature of Ti555211 titanium alloy, the standard requirements of project agreement, and the reference product standard (Q/1S M1004-2023). The mechanical properties of the specimens were tested after heat treatment. The metallographic specimens were prepared for observation by scanning electron microscope (SEM). To analyze the microstructure evolution of Ti555211 titanium alloy, the specimens were characterized by electron back-scattered diffraction (EBSD). Before EBSD, the specimens were subjected to electrolytic polishing, and the electrolyte was composed of 10wt% perchloric acid and 90wt% absolute alcohol. The polishing temperature and polishing time were 20 °C and 60 s, respectively.

2 Results and Analysis

Orthogonal tests were conducted to investigate the relationship between the mechanical properties and influence factors. Table 2 shows the tensile strength results of range analysis. Table 3 shows the elongation results of range analysis. In Table 3, the range R is the difference between the largest and smallest results ($R=X_{max}-X_{min}$, where X indicates the related factor).

According to the principle of orthogonal experiment, the influence degree of the factor on the experimental result is represented by the range. As shown in Table 3, the influence factors from the most important to the least important are solution temperature, aging temperature, and aging time.

Fig. 1 shows the variation of tensile strength under the interaction of three factors, except the unreliable results. It can be seen that the tensile strength is increased with increasing the solution temperature (Fig. 1a). However, the tensile strength is decreased with increasing the aging temperature (Fig. 1b). The effect of aging time on the strength is slight (Fig. 1c). Three levels of aging temperature and aging time appear simultaneously. It can be concluded that the aging temperature and aging time do not affect the average effect of the three factors. The tensile strength is only affected by the solution temperature. Similarly, the extreme difference in aging temperature and aging time is only caused by the changes of their levels.

Additionally, the optimal treatment can be obtained: treatment at 820 °C for 2 h with air cooling (AC) and 580 °C for 12 h with AC. Ductility is another key performance. As shown in Fig. 2, with decreasing the solution temperature or increasing the aging temperature, the elongation can be enhanced. In brief, after treatment of 820 °C/2 h/AC and 580 °C/12 h/AC, the alloy has better plasticity, and its tensile strength reaches 1333 MPa, which is higher than the strength index (1080 MPa) of similar alloys by 20%. The elongation of Ti555211 titanium alloy is 12%, which is higher than the plasticity index (5%) of similar alloys by 140%.

Table 1 Element composition of Ti555211 titanium alloy (wt%)

Al	Mo	V	Nb	Fe	Zr	Ti
5.8	4.5	5.3	1.9	1.0	0.9	Bal.

3 Microstructure and Properties of Ti555211 Titanium Alloy

3.1 Solution temperature

As shown in Fig. 3, with increasing the solution temperature, the number of equiaxed primary α particles is decreased. This phenomenon can be explained by the fact that with increasing the solution temperature, the thermodynamic stability of α phase is decreased, which results in the gradual dissolution of original α phase particles during the forging process. With increasing the solution temperature, the tensile strength is increased, whereas the elongation is decreased.

3.2 Aging temperature

Fig.4 shows the microstructures of Ti555211 titanium alloy after treatments at different aging temperatures. It can be seen that with increasing the aging temperature, the size of the secondary α phase embedded in the substrate β sheet is increased, whereas its content is gradually reduced. The secondary α phase changes from the closed state to loosely-arranged state.

Tensile strength is increased with decreasing the aging temperature, because the content of the secondary α phase is

Table 2 Orthogonal test factors and three levels of results

Specimen	Solution temperature/°C	Aging temperature/°C	Aging time/h	Tensile strength/MPa	Elongation/%
1#	780	580	6	1223	16.5
2#	780	600	9	1176	17
3#	780	620	12	1147	18
4#	800	580	9	1271	14
5#	800	600	12	1224	16
6#	800	620	6	1188	18.5
7#	820	580	12	1333	12
8#	820	600	6	1313	12.5
9#	820	620	9	1253	14.5

Table 3 Range analysis of strength and elongation

Range	Solution temperature/°C	Aging temperature/°C	Aging time/h	Error
Tensile strength/MPa	117.667	79.667	8.000	11.334
Elongation/%	4.167	2.833	0.666	1.000

reduced. Because the interface area between α and β phases reduces, the secondary phase strengthening weakens, which degrades the tensile strength. Because the shape of secondary phase changes from small grains to fine equiaxed grains, the dislocation can easily bypass the equiaxed α phase, resulting in the winding path which increases the deformation ability of alloy. Therefore, the elongation improves.

3.3 Fracture morphologies

Fig. 5 shows the room temperature tensile fracture morphologies of Ti555211 titanium alloy bars after treatments at different solution temperatures. It can be seen that the specimens show obvious diameter shrinkage in the fracture process at solution temperatures of 780 – 820 °C, and the central area of the section is basically composed of gray coarse fiber area, which presents the obvious ductile fracture characteristics. With increasing the solution temperature, the coarse fiber area is decreased.

The spherical or short rod-shaped primary α phase hinders the growth of β phase in the Ti555211 titanium alloy and improves the synergetic deformation ability of the

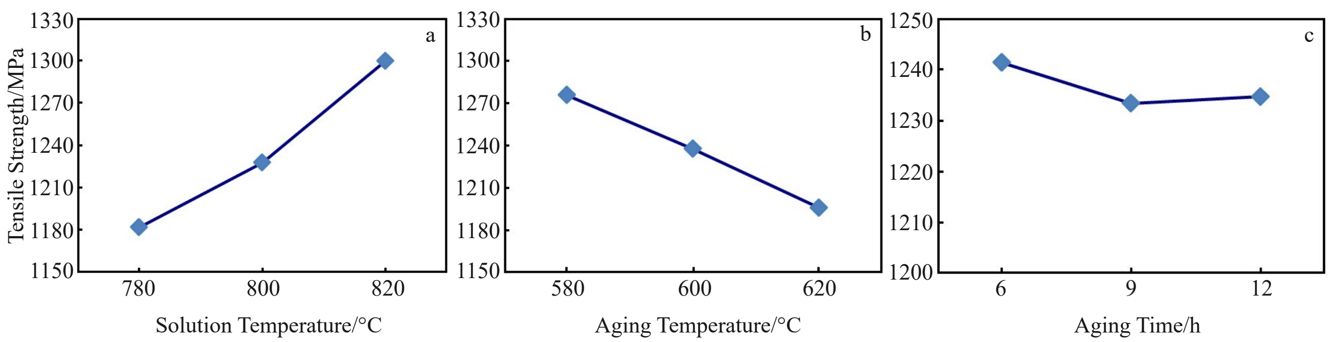

Fig.1 Relationships of tensile strength with solution temperature (a), aging temperature (b), and aging time (c)

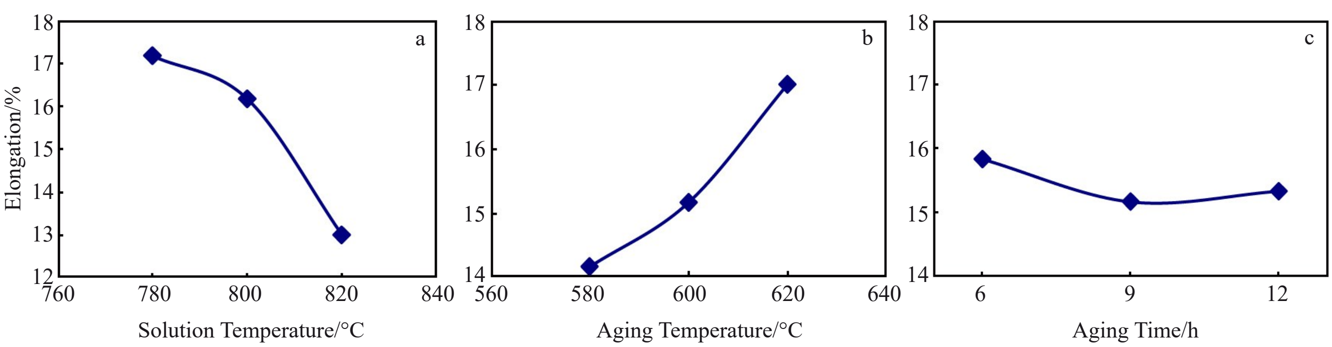

Fig.2 Relationships of elongation with solution temperature (a), aging temperature (b), and aging time (c)

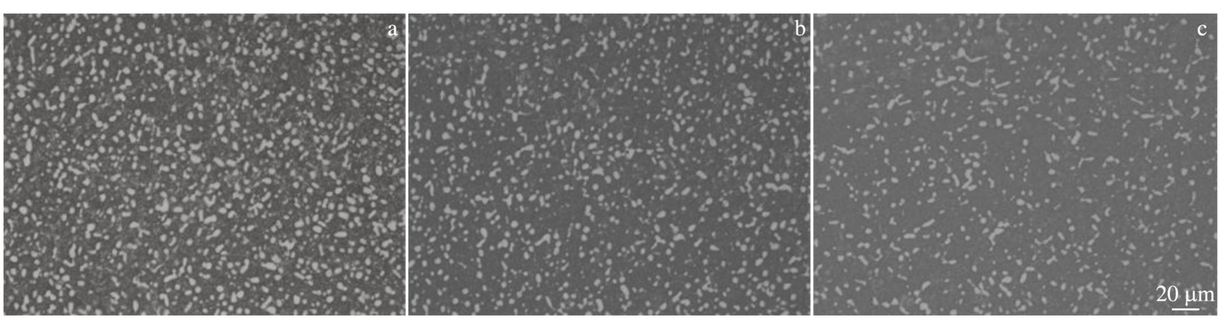

Fig.3 Microstructures of Ti555211 titanium alloy after treatments at different solution temperatures: (a) 780 °C/2 h/AC+600 °C/9 h/AC; (b) 800 °C/2 h/AC+600 °C/12 h/AC; (c) 820 °C/2 h/AC+600 °C/6 h/AC

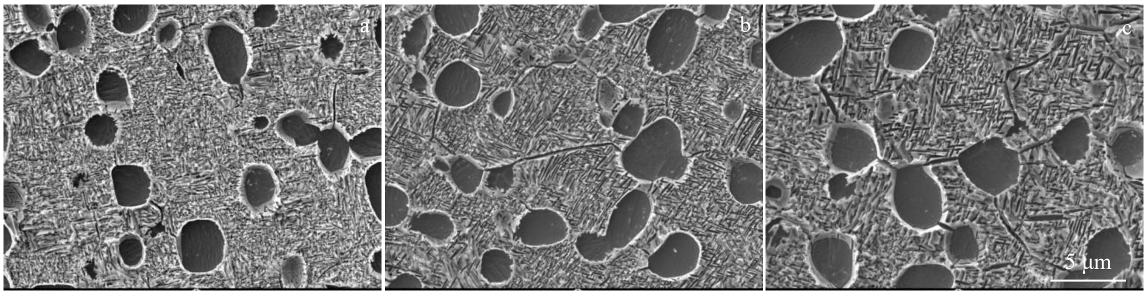

Fig.4 Microstructures of Ti555211 titanium alloy after treatments at different aging temperatures: (a) 820 °C/2 h/AC+580 °C/6 h/AC; (b) 820 °C/2 h/AC+600 °C/9 h/AC; (c) 820 °C/2 h/AC+620 °C/12 h/AC

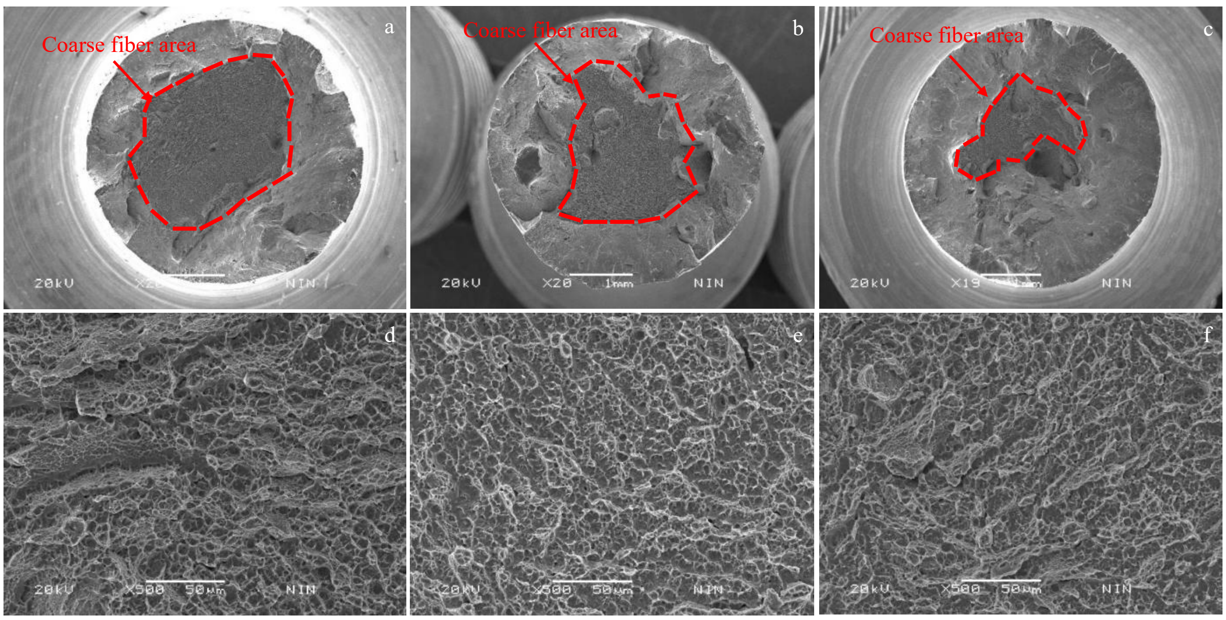

Fig.5 Room temperature tensile fracture morphologies of Ti555211 titanium alloy bars after treatments at different solution temperatures: (a, d) 780 °C/2 h/AC+600 °C/9 h/AC; (b, e) 800 °C/2 h/AC+600 °C/12 h/AC; (c, f) 820 °C/2 h/AC+600 °C/6 h/AC

microstructure. At the initial stage of deformation, β matrix cannot be deformed due to the precipitation of needle-shaped or strip-shaped secondary α phase in β Matrix, and the primary α phase bears the main plastic deformation of the alloy. The plastic deformation of spherical or short rod-shaped primary α phase results in work hardening. More external stress is required to continue the deformation, and the β matrix deforms accompanied with the precipitation of the secondary α phase. With the deformation further proceeding, the necking phenomenon occurs, indicating that micropores exist in the alloy structure.

3.4 EBSD analysis

EBSD can be used to analyze the orientation distribution, grain size, and phase content of specimens. Fig. 6 shows the phase distributions of Ti555211 titanium alloy after different treatments. As shown in Fig. 6 and Fig. 7, it can be seen that the content of α phase is decreased from 50.2% to 40.2% with increasing the solution temperature. These results all prove that the increase in solution temperature leads to the redissolution of equiaxed α phase and the formation of β phase.

Fig. 7 shows the inverse pole figures (IPFs) of orientations of Ti555211 titanium alloy after treatments at different solution temperatures. Fig. 8 shows the internal orientations of α phase in Ti555211 titanium alloy. Fig. 9 shows the pole figure (PF) results of Ti555211 titanium alloy. It can be seen that the orientation of equiaxed α phase can be obtained in all three states. As shown in Fig. 8 and Fig. 9, the internal orientation of equiaxed α phase still has small angle orientation difference. According to Fig. 9, Burgers orientation relation (BOR) exists between the green grain boundary of α phase and the β matrix.

In the $\{0001\}_\alpha$ and $\{110\}_\beta$ PFs as well as the $\{11\bar{2}0\}_\alpha$ and $\{111\}_\beta$ PFs, α_{GB} (the grain boundary of α phase) and α_{p_2} phases have corresponding poles with the β matrix. Besides, there is no corresponding pole between the equiaxed α_{p_1} phase and β matrix, which indicates that the BOR relationship between α phase and β matrix is partially destroyed during hot working.

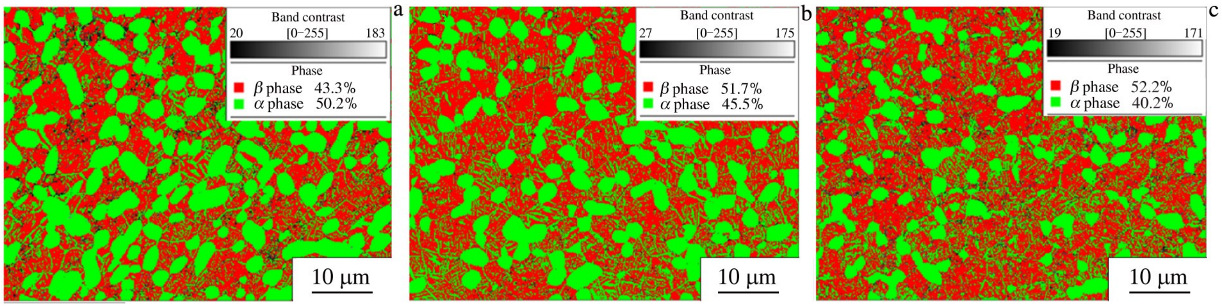

Fig.6 Phase distributions of Ti555211 titanium alloys after different treatments: (a) 780 °C/2 h/AC+620 °C/12 h/AC; (b) 800 °C/2 h/AC+600 °C/12 h/AC; (c) 820 °C/2 h/AC+580 °C/12 h/AC

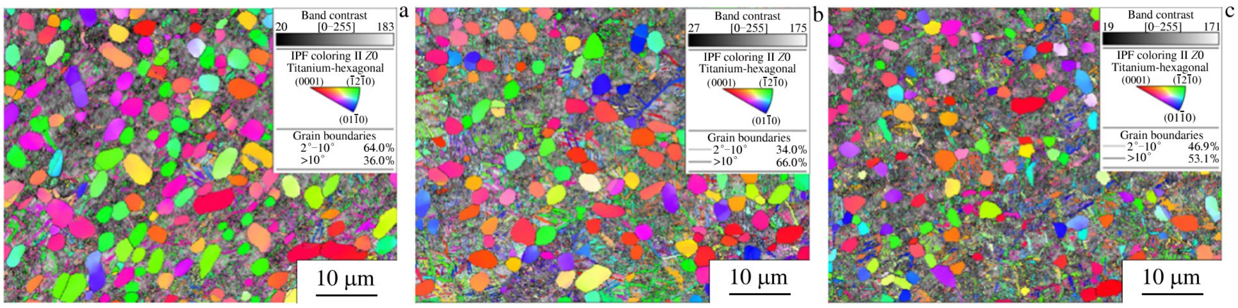

Fig.7 IPF orientations of Ti555211 titanium alloys after different treatments: (a) 780 °C/2 h/AC+620 °C/12 h/AC; (b) 800 °C/2 h/AC+600 °C/12 h/AC; (c) 820 °C/2 h/AC+580 °C/12 h/AC

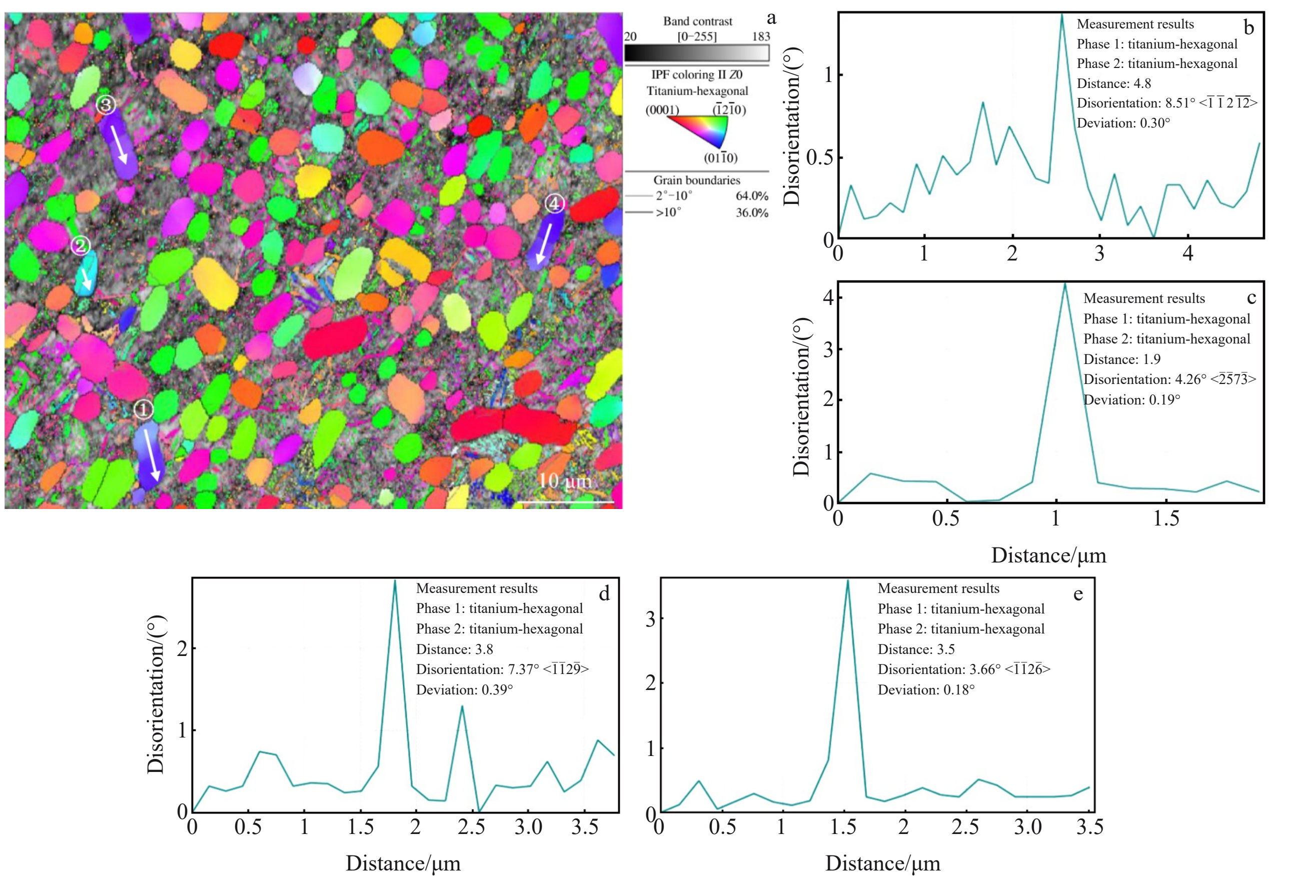

Fig.8 IPF orientation of α phase in Ti555211 titanium alloy (a); internal orientations of α phase along arrow 1 (b), arrow 2 (c), arrow 3 (d), and arrow 4 (e) in Fig.8a

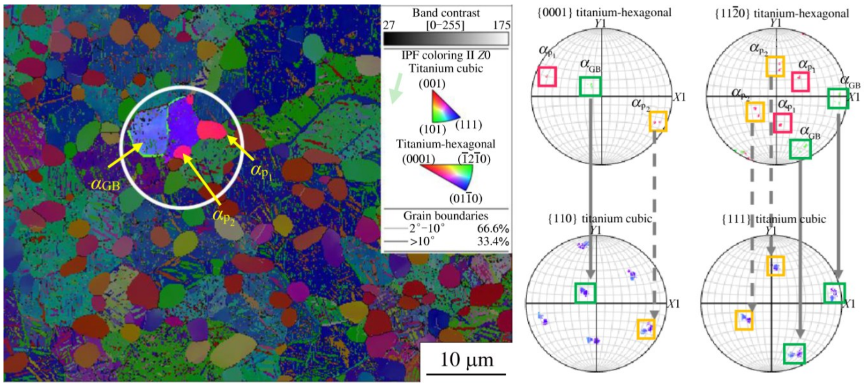

Fig.9 PF results of Ti555211 titanium alloy

4 Conclusions

1) The optimal heat process parameters of Ti555211 alloy should be 820 °C and 2 h with air cooling as well as 580 °C and 12 h with air cooling.

2) The solution temperature affects the number of primary *α* phase. With increasing the solution temperature, the number of primary *α* phase is decreased. The aging temperature affects the size of the secondary *α* phase. With increasing the aging temperature, the size of the secondary *α* phase is gradually increased, and its content is gradually reduced.

3) Burgers orientation relation exists between the grain boundary of *α* phase and the *β* matrix: $\{0001\}_\alpha//\{110\}_\beta$ and $\{11\bar{2}0\}_\alpha//\{111\}_\beta$.

References

1 Zang M C, Niu H Z, Yu J S *et al*. *Materials Science and Engineering A*[J], 2022, 840: 142952
2 Zhang C J, Jiang X, Lü Z D *et al*. *Transactions of Nonferrous Metals Society of China*[J], 2022, 32(4): 1159
3 Kaur M, Singh K. *Materials Science and Engineering C*[J], 2019, 102: 844
4 Huang S S, Zhang J H, Ma Y J *et al*. *Journal of Alloys and Compounds*[J], 2019, 791: 575
5 Li J Q, Lin X, Guo P F *et al*. *Corrosion Science*[J], 2018, 142: 161
6 Xie L F, Zhou W L, Zou S W. *Journal of Materials Research and Technology*[J], 2021, 14: 2865
7 Lavisse L, Kanjer A, Berger P *et al*. *Surface and Coatings Technology*[J], 2020, 403: 126368
8 Chen W, Zhang J Y, Cao S *et al*. *Acta Materialia*[J], 2016, 117: 68
9 Zhu W G, Li P, Sun X *et al*. *Transactions of Nonferrous Metals Society of China*[J], 2019, 29(6): 1242
10 Guo H J, Liu P, Qin X P *et al*. *Materials & Design*[J], 2021, 212: 110286
11 Zhao Q Y, Sun Q Y, Xin S W *et al*. *Materials Science and Engineering A*[J], 2022, 845: 143260
12 Ouyang Delai, Xie Youmei, Hu Shengwei *et al*. *Rare Metal Materials and Engineering*[J], 2023, 52(2): 710 (in Chinese)
13 Yin Z K, Wang C, Su Z C *et al*. *Rare Metal Materials and Engineering*[J], 2022, 51(7): 2409
14 Keist J S, Nayir S, Palmer T A. *Materials Science and Engineering A*[J], 2020, 787: 139454
15 Lu T, Dan Z H, Li T J *et al*. *Journal of Materials Research and Technology*[J], 2022, 19: 2257
16 Zhang Fengshou, Lai Yunjin, Wang Kaixuan *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(6): 1507 (in Chinese)
17 An Zhen, Feng Yong, Li Jinshan *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(8): 1902 (in Chinese)

热处理制度对Ti555211合金组织和性能的影响

高玉社[1,2]，薛祥义[1]，刘向宏[2]，高慧贤[1,2]，王建国[2]，杜予晅[2]

(1. 西北工业大学，陕西 西安 710072)

(2. 西部超导材料科技股份有限公司，陕西 西安 710018)

摘　要：研究了一种新型近*β*钛合金（Ti555211），该合金具有优异的塑性加工能力、高比强度以及优良的综合性能，在航天航空及化工领域上有广泛的应用。通过3×3正交试验，研究了两阶段不同处理（固溶温度、失效温服、时效时间）对Ti555211钛合金力学性能和显微组织的影响。结果表明，随着固溶温度的升高和时效温度的降低，合金强度提高。延伸率随着固溶温度的降低和时效温度的升高而增大。经820 ℃/2 h空冷和580 ℃/12 h空冷处理后，合金具有较好的强塑性，抗拉伸强度达到1333 MPa，较同类合金强度指标（1080 MPa）高出20%；延伸率为12%，较同类合金塑性指标（5%）高出140%。

关键词：钛合金；正交实验；热处理；微观组织；力学性能；EBSD

作者简介：高玉社，男，1981年生，博士生，正高级工程师，西部超导材料科技股份有限公司，陕西 西安 710018，电话：029-86514509，E-mail：gaoyushe@163.com