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Effects of Hot Compression on Grain Boundary Evolution and Twin Boundary Characteristics on the Material Properties of Inconel 617 Alloy

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Abstract

The evolution of grain size and special grain boundary in Inconel 617 alloy was analyzed by electron backscatter diffraction (EBSD). It was found that during hot compression, dynamic recrystallization (DRX) occurs, the grain size changes, and a twinning structure is generated, which then affects grain growth. In this paper, the high-angle grain boundaries (HAGBs) and low-angle grain boundaries (LAGBs) under different conditions were studied, and the formation mechanism of special twin boundaries and the proportion of these grain boundaries under different conditions were analyzed. In addition, it was found that the variation in twin boundaries is complex at different temperatures and strain rates, and the formation mechanism of special twin boundaries $\Sigma 3$, $\Sigma 9$, and $\Sigma 27$ is also closely related to temperature and strain rate. Through electrochemical corrosion testing, it was further found that there is a positive relationship between the content of $\Sigma 3$ and the corrosion resistance of the material. This paper provides theoretical guidance for the microstructural study of Inconel 617 alloy during plastic deformation.

Keywords: Inconel 617; EBSD; corrosion; DRX



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1. Introduction

Inconel 617, a solid solution-strengthened alloy, shows good mechanical properties. It maintains good strength, plasticity, and corrosion resistance at high temperatures, and has good high-temperature stability and high creep resistance. The Cr and Al concentrations in Inconel 617 alloy are high, so it also has good circulation oxidation resistance. These two elements form a critical ratio, where, under high temperature, thin oxide particles form in a subcutaneous layer, and the chrome oxide layer provides good diffusion conditions and protects the metal surface. Inconel 617 alloy is widely used in many important fields, such as in combustion chambers, flame stabilizer nozzles, and the brackets of aircraft engines [1–8].

Twin deformation is the key mechanism of high-temperature plastic deformation of metal materials. It reduces local stress concentration by changing the unfavorable crystallographic orientation of the twins and slip and promotes the interaction between

twins and slip during the deformation process, thereby improving the plasticity of the material [9–14]. In the thermoplastic deformation process of nickel-based superalloys, twinning deformation is a very important deformation mechanism. When crystals are deformed in a twinning manner, the twin planes and twinning directions are related to the type of crystal structure [15–20]. As a typical face-centered cubic structure of Inconel 617 alloy, the twin plane is (111) and the twinning direction is $\langle 11\bar{2} \rangle$. By themselves, because the twin itself is only a kind of orientation relationship between grains, it has little effect on the plastic deformation of the crystal, but its formation in the process of thermoplastic deformation affects the dynamic recrystallization (DRX) behavior of the metal material. For example, the subgrains can continuously annex the deformation twins during the deformation process and grow up, finally evolving into new DRX grains. Moreover, the twins can also promote the ‘bowing’ of the grain boundary, which greatly promotes the continuous dynamic recrystallization (CDRX) nucleation process, and the DRX will further affect the mechanical properties and microstructure of the material. In nickel-based superalloys, annealing twins, along the twin interface, the two parts of the twin, are completely closed, the nearest neighbor relationship does not change, and only the second-nearest neighbor relationship changes. The atomic misalignment caused by the twin is very small, so the twin interface energy is very low, greatly affecting the grain size of the material during thermal deformation, grain boundary evolution, and the DRX process [21]. The multi-lattice is also called the coincidence lattice or the coincidence site lattice (CSL). The multi-lattice was originally created by Kronberg and Wilson, who proposed in the study of secondary recrystallization, the texture of copper [22]. The heavy lattice is composed of two infinitely extended grains with the same lattice structure. One of the grains rotates at a special angle relative to the other grain around a low-index crystal axis, and some positions in the two grain lattices are regularly overlapped. If there is such a relationship between the grains on both sides of the grain boundary, it can be called the CSL grain boundary. The term Σn CSL grain boundary is commonly used to denote a lattice-coincident grain boundary, where n denotes that $1/n$ lattice positions coincide within the superlattice formed by the lattices of two adjacent grains. Clearly, the Σ value represents the degree of overlap at the CSL position. The smaller the n value, the greater the number of atomic positions that overlap in the lattice, meaning more atoms are shared between the two grains. Consequently, the grain boundary structure becomes more ordered, the grain boundary energy is relatively lower, and the grain boundary exhibits superior performance. CSL grain boundaries can be determined by the electron backscatter diffraction (EBSD) method. Low Σ CSL grain boundaries can change the structure and performance of the grain boundary and enhance the performance of the material. For face-centered cubic metals, the twinning plane (111) on the $\Sigma 3$ grain boundary shows lower energy than any other, which has been shown to improve material performance [23–28]. Studying the special grain boundary can help to improve material performance, and, at present, studies of these special grain boundaries are relatively rare, especially for Inconel 617.

In this study on Inconel 617, compression deformation was 60% under different temperatures and strain rates, and the evolution of these special grain boundaries was analyzed. After that, several samples were selected for electrochemical corrosion testing to verify the improved corrosion resistance of $\Sigma 3$ materials.

2. Experimental

Inconel 617 alloy is a nickel-based high-temperature alloy with high Cr and Al content. The specific contents are shown in Table 1. The sample size used in the thermal compression experiment is $\Phi 8 \times 12$ mm and was polished before the experiment. The entire experiment was carried out on a Gleeble-3500 machine. In order to ensure that the test temperature

is above the DRX temperature and below the melting point, the experiment uses four temperatures between 900 °C and 1200 °C and then combines the parameters of the test machine to determine five strain rates in the range of 0.001–10 s^{−1}. According to the research objectives, the reduction was, finally, determined to be 60%. The compressed sample was then cut in half, polished with sandpapers of different grit, and etched in aqua regia for 35 s. The microstructure was then observed with an optical microscope (OM), and then samples were selected for EBSD testing. Finally, microstructural evolution was observed at different temperatures under the same strain rate.

Table 1. The constituent elements of the Inconel 617 alloy.

Element	Ni	Cr	Mo	Co	Fe	Al	C	Si	Ti
ω (%)	Bal	20.8	9.12	13.1	0.8	1.28	0.07	0.11	0.22

A group of samples was selected for the electrochemical corrosion test, and the relationship between corrosion resistance and $\Sigma 3$ was studied. The electrode working area was 0.686 cm², with the non-working area coated with epoxy resin. The working electrode was polished with 5000-grit SiC sandpaper, wiped with alcohol, and dried with a hair dryer. Prior to polarization testing, the sample was immersed in the corrosion liquid for 30 min. The corrosion medium was a 3.5% NaCl solution. A three-electrode system was employed: the working electrode, a 1 cm² platinum plate as the counter electrode, and a saturated calomel electrode as the reference electrode. After immersing the working electrode in the test medium, the potential polarization test was conducted once the open-circuit potential stabilized for 1800 s. The polarization curve was scanned at a rate of 0.001 V/s, with experiments performed at room temperature. Then, two samples were selected for transmission electron microscopy (TEM) analysis.

Figure 1 is a schematic diagram of the hot compression process of Inconel 617 alloy samples. The Inconel 617 alloy cylindrical specimen with an initial size of $\Phi 8$ mm $\times$ 12 mm was selected for hot compression. After 60% high-temperature compression deformation, the sample shows a typical drum shape, the size in the diameter direction becomes larger, and the longitudinal size becomes smaller. However, due to the non-uniformity of deformation, the actual size in the diameter direction is relatively irregular, which is caused by the friction between the sample and the indenter and the uneven flow of the metal during the deformation process. Subsequently, wire cutting was performed along the longitudinal section of the compression shaft to observe and analyze the evolution of its microstructure. Figure 2 shows the original microstructure of the Inconel 617 alloy. It can be seen that the original microstructure of the material is basically equiaxed grains of different sizes before compression.

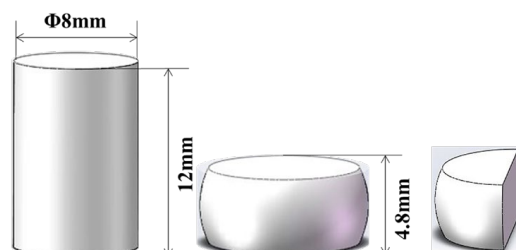


Figure 1. Original sample.

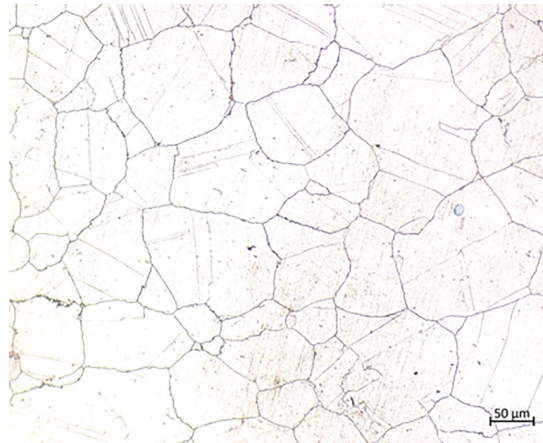


Figure 2. Original morphology.

3. Results

3.1. Grain Boundary Behavior Analysis

It can be seen from Figure 3a–c that the grain orientation begins at 1000 °C and develops towards {111}. With increasing temperature, the grain orientation gradually begins to develop towards {101}. DRX and grain growth occur at both high temperature and low strain rates. In addition, many twins have been found in DRX grains. At 1000 °C, many necklace structures can be seen in Figure 3a. At 1100 °C and 1200 °C, these phenomena were not observed, indicating that the grains began to grow and DRX became gradually sufficient. However, when the strain rate was 0.1 s^{-1} , the necklace structure was hardly observed at 1000 °C, as shown in Figure 3d, indicating that DRX occurred, some grains grew abnormally due to the preferred orientation, and then DRX grew at 1200 °C. It is the occurrence of DRX that changes the grain size, resulting in many changes to the grain boundary. With increasing strain rate, the growth trend of DRX slows.

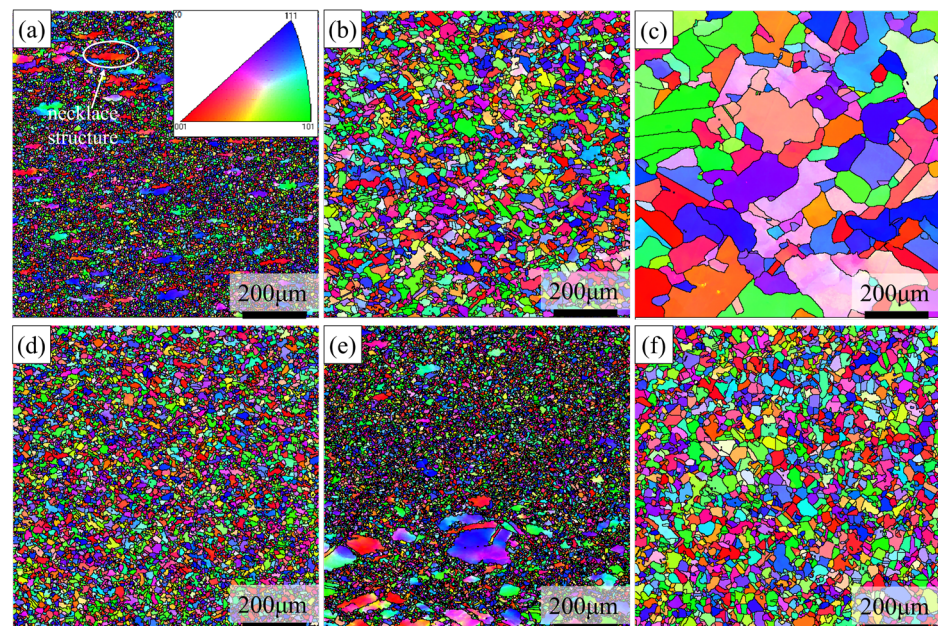


Figure 3. Inversed pole figure (IPF) map of strain rates of 0.001 s^{-1} and 0.1 s^{-1} at different temperatures: (a) 1000 °C- 0.001 s^{-1} , (b) 1100 °C- 0.001 s^{-1} , (c) 1200 °C- 0.001 s^{-1} , (d) 1000 °C- 0.1 s^{-1} , (e) 1100 °C- 0.1 s^{-1} , and (f) 1200 °C- 0.1 s^{-1} .

Figure 4 shows the grain boundary distribution and grain orientation angle at different temperatures. Black represents high-angle grain boundaries (HAGB $> 15^\circ$), gray represents low-angle grain boundaries (LAGB $< 15^\circ$), red is $\Sigma 3$, blue is $\Sigma 9$, and green is $\Sigma 27$. $\Sigma 3$ describes the orientation relationship of two grains rotating 60° around a common $\langle 111 \rangle$ axis. It is the most important and common special grain boundary. The grain boundary energy is very low, and the structure is highly ordered. When two $\Sigma 3$ grain boundaries meet, they can react to form a $\Sigma 9$ grain boundary. The grain boundary energy is higher than $\Sigma 3$, but it is still much lower than the random HAGB. A $\Sigma 3$ grain boundary and a $\Sigma 9$ grain boundary meet, which can further react to form a $\Sigma 27$ grain boundary. The grain boundary energy is higher than $\Sigma 9$, but it still belongs to the category of “special grain boundary”, and its performance is between $\Sigma 9$ and random HAGB. The higher the order degree of the structure is, the lower the grain boundary energy is. It can be seen from Figure 4 that the grain boundaries are relatively sensitive to temperature at a low strain rate of 60% deformation. As the temperature increases, the HAGBs first decrease and then increase, while the LAGBs increase and then decrease. It can be seen from Figure 4d–f that the grain boundary frequency distribution diagram gradually moves toward a bimodal distribution, which indicates that as the temperature increases, some LAGBs gradually transform into HAGBs, as shown in Figure 5, which promotes the occurrence of the DRX process. The generally accepted explanation is that the DRX processes depend on the migration of the HAGB to eliminate the deformed structures. This promotes the DRX at high temperatures, and the interfacial energy of the HAGB was higher.

Figure 6 shows the grain size distribution at different temperatures under low strain rates. Blue represents the proportion of DRX, yellow represents the substructure, and red represents the deformed grain. It can be seen from the figure that at low strain rates, with increasing temperature, the recrystallization degree decreases relatively, and the deformed grain greatly decreases. When it reaches 1200°C , there is hardly any deformed grain, only a few tenths of a percent, while the proportion of the substructure continuously increases. This indicates that temperature has no promotion effect on the recrystallization process at low strain rates but has a great promotion effect on the substructure formation. At 1000°C , the proportion of recrystallization grain ratio and deformation are the largest, and DRX occurs. With increasing temperature, the deformation grain percentage gradually decreases and the DRX grain grows up. At 1100°C , isometric crystal grains grow, but under conditions of the recrystallization grain boundary, serious arching occurs into the neighboring grain. This is associated with the rapid migration of the twin, and due to the low deformation rate, deformation and high temperature play a major role in the process. At 1200°C , it is even more obvious. The remaining grains continue to undergo DRX, and the increase in the substructure indicates that CDRX occurs in this process. The subgrain boundary makes the difference in orientation continuously increase through continuous torsion, so as to produce new grains.

The variation in a particular twin boundary with temperature and strain rate is shown in Figure 7. It can be seen from Figure 7a–c that the evolution trend of the $\Delta\Sigma 3^n$ ($n = 1, 2, 3$) twin boundary is complex at different temperatures and strain rates. When the strain rate is 0.001 s^{-1} , $\Sigma 3$ increases first and then decreases with increasing temperature, while when the strain rate increases to 0.01 s^{-1} , $\Sigma 3$ decreases first and then increases. When the strain rate increases to 1 s^{-1} , $\Sigma 3$ increases, and $\Sigma 9$ is more complex. As seen from Figure 7b, with decreasing strain rate, the trend of $\Sigma 9$ is roughly in the shape of an “N”, where the proportion of $\Sigma 9$ first decreases, then increases, and then decreases. When the strain rate is low, $\Sigma 27$ increases first and then decreases. When the strain rate is 0.01 s^{-1} , $\Sigma 27$ decreases first and then increases. When the strain rate is 0.1 s^{-1} , it de-

creases, and when the strain rate is 1 s^{-1} , it increases first and then decreases again. These results are due to DRX and grain growth during hot compression. The results show that temperature has different effects on the grain boundary at low- and high-speed deformation. In addition, $\Sigma 3^n$ ($n = 1, 2, 3$) boundary interactions can be observed in some grains. Generally, among these three special grain boundaries, the following are the rules of constraints:

$$\Sigma 3 + \Sigma 3 \rightarrow \Sigma 9; \Sigma 3 + \Sigma 9 \rightarrow \Sigma 27; \Sigma 9 + \Sigma 3 \rightarrow \Sigma 3 \quad (1)$$

According to Formula (1), when two $\Sigma 3$ twins meet, a $\Sigma 9$ twin boundary will be generated. When two $\Sigma 3$ twins and $\Sigma 9$ twins meet at the trigeminal boundary, a $\Sigma 3$ twin boundary or a $\Sigma 27$ twin boundary will be generated. During thermal deformation, a new $\Sigma 3$ twin boundary can be formed by grain boundary migration through interactions of the $\Sigma 3$ twin boundary that already existed before. The other is related to the “growth accident,” which results in the formation of a coherent annealing twin boundary at the grain boundary migration due to the stacking fault during DRX.

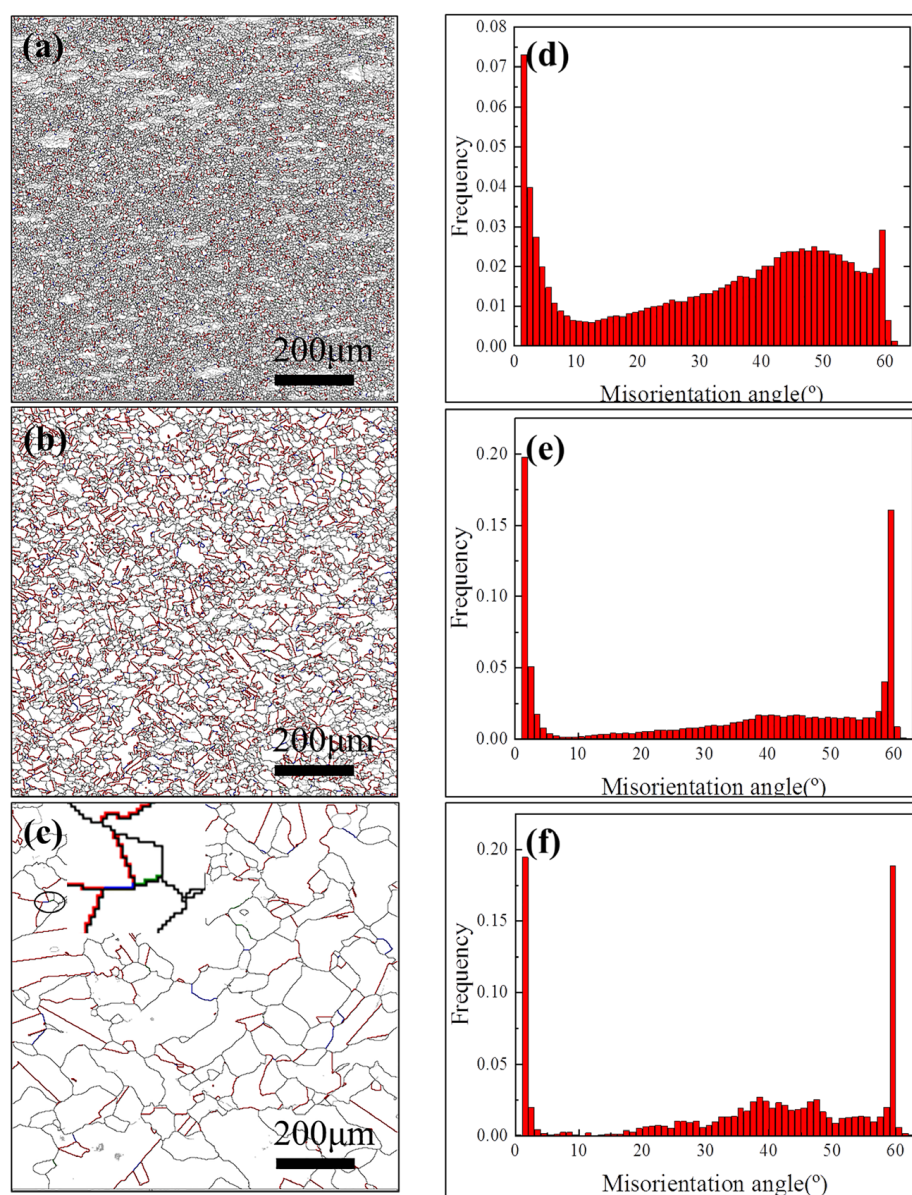


Figure 4. Grain boundary and grain boundary local orientation diagram: (a,d) 1000 °C, (b,e) 1100 °C, and (c,f) 1200 °C.

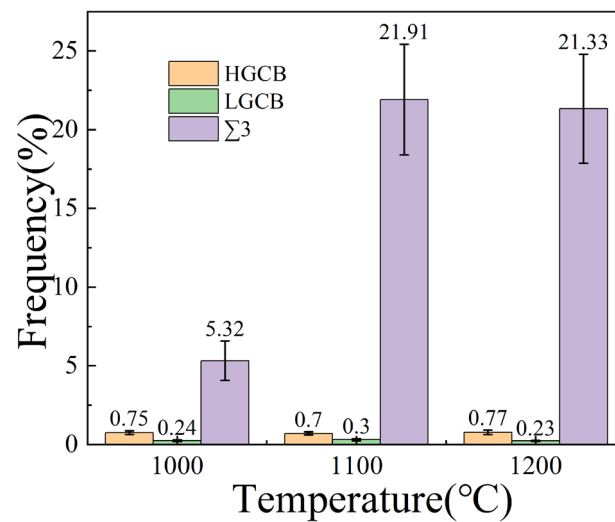


Figure 5. The influence of temperature on grain boundary types.

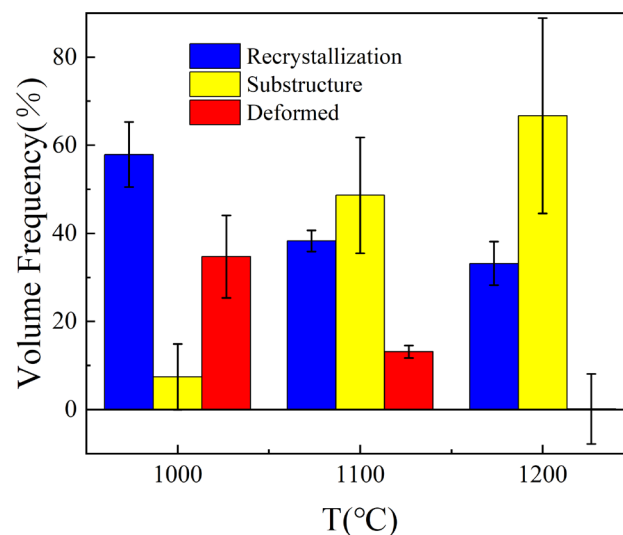


Figure 6. Grain distribution at low strain rates.

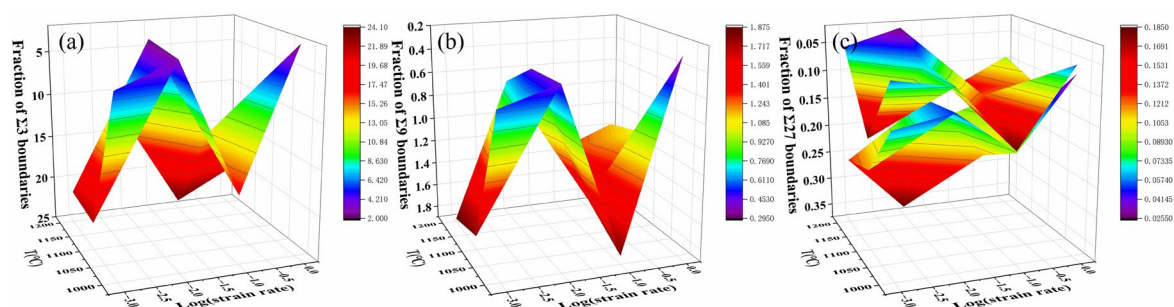


Figure 7. Special grain boundary evolution of Inconel 617 alloy at different temperatures and strain rates: (a) $\Sigma 3$, (b) $\Sigma 9$, and (c) $\Sigma 27$.

In general, the decrease in $\Sigma 3^n$ ($n = 1, 2, 3$) at low strain rates may be due to the fact that there is enough time for DRX, and the grains have enough time to grow up. However, the adiabatic temperature rise effect is obvious at high strain rates, which promotes the occurrence of DRX. However, the decrease in $\Sigma 3^n$ at high strain rates is primarily caused by the depletion of the twin boundary due to the rapid grain growth.

Figure 8a shows the effect of temperature on the ratio of $\Sigma 3$ grain boundaries at a strain rate of 0.001 s^{-1} . With increasing temperature, the total Σ CSL proportion rose sharply at first and leveled off at 1100°C . The peak value was at 1100°C , and the trend was the same as that of $\Sigma 3$. However, the variation range of $\Sigma 9$ and $\Sigma 27$ is small, and $\Sigma 9$ generally shows a trend of increasing first and then stabilizing. When the strain rate was 0.01 s^{-1} , the total Σ CSL grain boundary proportion was opposite that of 0.001 s^{-1} , showing a slow decline and then a sharp rise. When the peak value appeared at 1200°C , the change range of $\Sigma 9$ and $\Sigma 27$ was even smaller. When the strain rate was 0.1 s^{-1} , the general trend was the same as that of 0.01 s^{-1} , but the range decreased to a certain extent. When the peak value was still at 1200°C , $\Sigma 9$ showed a downward trend. When strain rates ranged from 0.001 s^{-1} to 0.1 s^{-1} , the total Σ CSL showed a downward trend, which was because the DRX had enough time to grow up at low strain rates, while the increase was due to the adiabatic temperature rise effect. When the strain rate was 1 s^{-1} , the total Σ CSL and $\Sigma 3$ showed a completely different trend from the previous one, an upward trend, while $\Sigma 9$ and $\Sigma 27$ showed little change. This indicates that at high strain rates, with increasing temperature, the formation of special grain boundaries is favorable, which is also the effect of DRX.

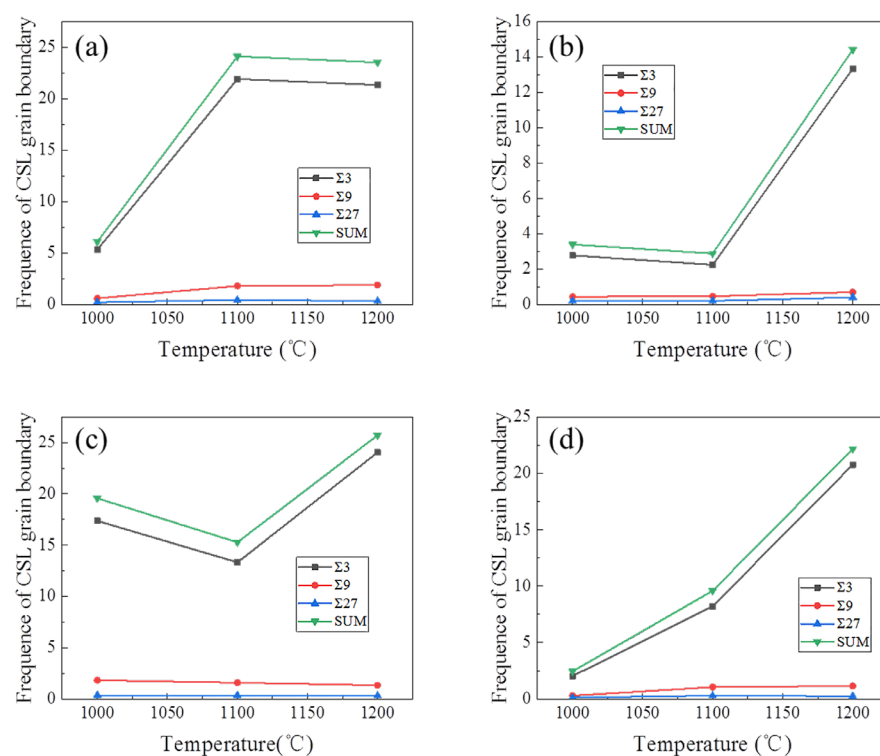


Figure 8. Special grain boundary changes with respect to temperature: (a) 0.001 s^{-1} , (b) 0.01 s^{-1} , (c) 0.1 s^{-1} , and (d) 1 s^{-1} .

Figure 9 shows the proportion of new twin boundaries generated at different temperatures and strain rates. $\Sigma (9 + 27)/\Sigma 3$ represent $\Sigma 3$'s ability to derive $\Sigma 9$ and $\Sigma 27$. As you can see, at 1000°C , with an increasing strain rate, $\Sigma (9 + 27)/\Sigma 3$ shows a sharp increase in the ratio at first, and then decreases, and then tardily increases again. At 1100°C , the trend is roughly the same, while at 1200°C , only the decline does not increase, and the whole curve always presents a slow downward trend. Overall, the $\Sigma (9 + 27)/\Sigma 3$ ratio of highs and lows in strain rate is 0.01 s^{-1} , and at this time, under the strain rate of deformation, it is prone to instability. At low temperatures ($\leq 1100^\circ\text{C}$), with increasing strain rate, the deformation is dominated by DRX, and with sufficient time, DRX promotes the formation of a twin boundary, so there is an upward trend; in the process of large grain boundary migration,

some special grain boundaries are absorbed and eliminated, so it decreases. When the strain rate increases to 0.01 s^{-1} , the discontinuous dynamic recrystallization (DDRX) caused by LAGB migration gradually transforms to the CDRX caused by LAGB by subgrain rotation, resulting in a decrease in the twin boundary ratio. At higher deformation temperature, the twin boundary migrates significantly and deviates from the specific twinning orientation, causing the original twin boundary to disappear. Compared with DRX behavior, the grain boundary migrates at a lower rate, which prevents the formation of new twin boundaries at 1200°C ; this is why the ratio decreases.

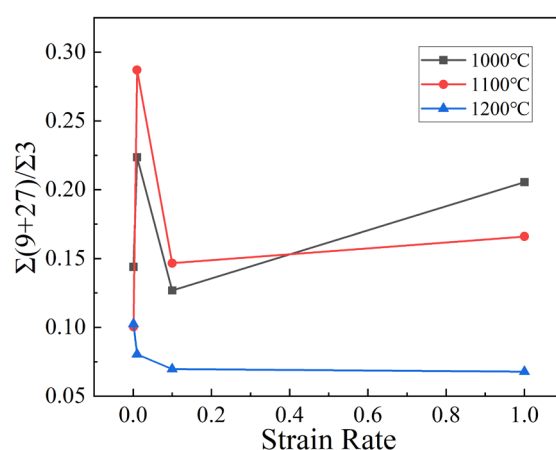


Figure 9. Evolution of $\Sigma(9 + 27)/\Sigma3$ at different temperatures and strain rates.

Furthermore, combined with the statistics of the proportion of special twin boundaries, it can be seen that when the proportion of special twin boundaries is high, the microstructure distribution is relatively uniform. Although the average grain size is the smallest in Figure 3a, the microstructure is very uneven. There are large coarse original grains and fine recrystallized cores around the coarse original grains. Followed by Figure 3e, there are some coarse grains in the local area, and the microstructure distribution of the other samples is uniform. Although the grain size of Figure 3c is large, it is almost all newly generated grains, indicating that the content of special twin boundaries, especially $\Sigma3$, has a great influence on the microstructure uniformity of the material. It is also shown in Figure 3 that DRX is basically formed along HAGBs, and the formation of special twin boundaries will reduce the Gibbs free energy, and then the degree of DRX will decrease, making the deformation more stable. The effects of temperature and strain rate on DRX are generally attributed to this.

3.2. Corrosion Behavior Analysis

Scanning and observing the microstructure of 617 alloy after electrochemical corrosion, as shown in Figure 10, it can be found that some white particles of different sizes are generated on the surface of each sample, and it can be seen that the sample surface is relatively flat and has the least corrosion trace at $1100^\circ\text{C}-0.001 \text{ s}^{-1}$. At $1000^\circ\text{C}-0.001 \text{ s}^{-1}$, it can be seen that there are a lot of corrosion spots and a large number of bumps at the grain boundaries, while at $1100^\circ\text{C}-0.1 \text{ s}^{-1}$, although there are fewer small spots, there are large local corrosion spots. EDS analysis of white spots at $1100^\circ\text{C}-0.001 \text{ s}^{-1}$ showed that they were mainly precipitated phases containing Cr and Mo elements, and Cr and Mo elements had a great influence on the corrosion resistance of the material, so the corrosion resistance of the material was further analyzed.

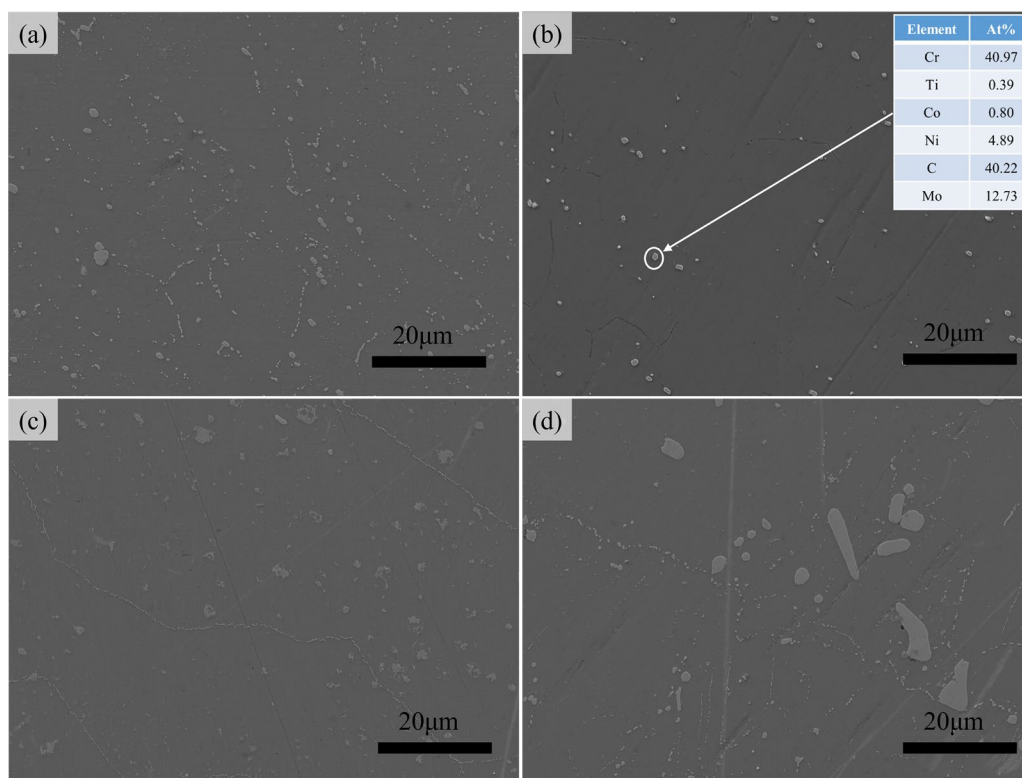


Figure 10. SEM micrograph and EDS element mapping results: (a) 0.001 s^{-1} 1000°C , (b) 0.001 s^{-1} , 1100°C , (c) 0.001 s^{-1} , 1200°C , and (d) 0.1 s^{-1} , 1100°C .

The Bode diagrams and polarization curves under different conditions are shown in Figure 11. It can be seen that the curves are basically the same, except at 1000°C - 0.001 s^{-1} and 1200°C - 0.001 s^{-1} ; when the frequency is between 0.01 Hz and 0.1 Hz , there is a big difference in Z . This indicates that the passivation films on the surface of these two samples are more likely to allow charge transfer than those on the other two samples. The general trend of the polarization curve is consistent with that described in the literature. The current density at some positions on the anode curve decreases with the increase in the potential, indicating that passivation occurs and a dense oxide film is generated, which blocks the ion diffusion and leads to the decrease in the corrosion current density. By analyzing along the X axis, it can be found that the self-corrosion current density first decreases and then increases with the increase in temperature. By analyzing along the Y axis, the self-corrosion potential increases with the increase in temperature. At the same temperature, the self-etching current density increases with the increase in strain rate.

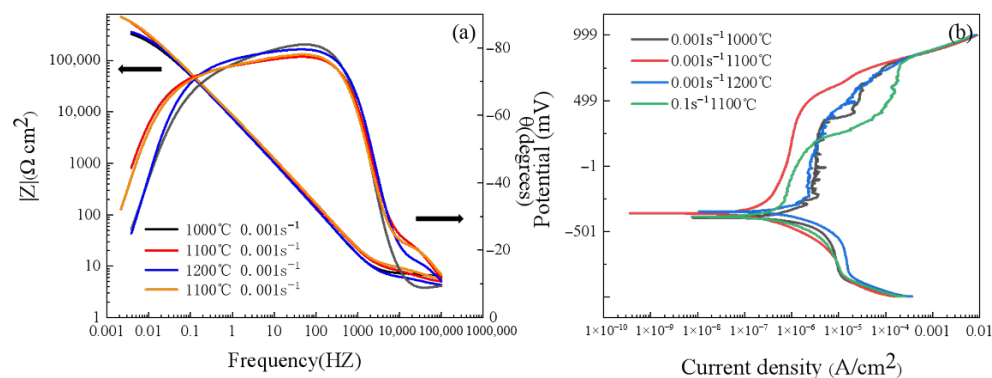


Figure 11. (a) Bode diagrams corresponding to the EIS measurements of the Inconel 617 superalloy. (b) Polarization curves of the Inconel 617 superalloy at different conditions.

Figure 12 shows the impedance spectrum diagram and equivalent circuit diagram fitted by Zview. An effective circuit of Inconel 617 alloy in 3.5%NaCl solution was obtained through fitting, where R_1 was the solution resistance, CPE was the phase angle element, R_2 was the equivalent polarization resistance corresponding to the reactance arc, C was the capacitor, and R_3 was the charge transfer resistance. Characterized by the open circuit capacitance half arc curve, it is similar to the samples under the conditions of corrosion mechanism, but the radius is different; this is directly related to the polarization resistance and material, representing the change characteristic of passive film, and the polarization resistance is associated with the charge of transmission through the passivation membrane, and there are more electrons and ions in the passivation film because electrical conductivity is strong, so the corrosion rate is faster. It can be seen that the larger the radius is, the better the corrosion resistance tends to be. To quantitatively characterize the corrosion rate, the corrosion rates of different samples were calculated.

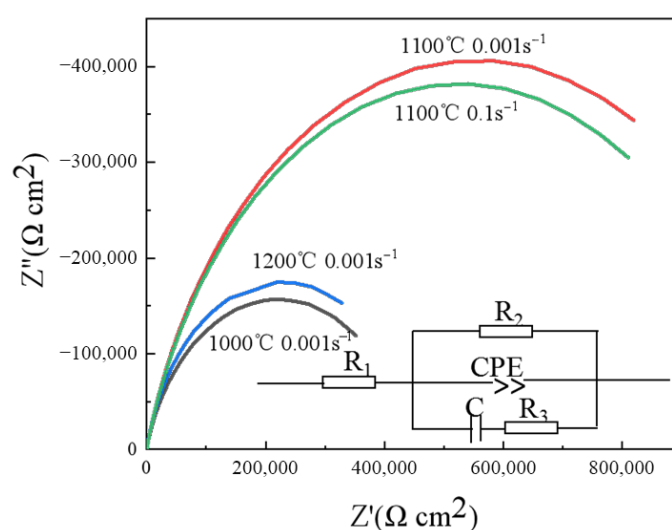


Figure 12. Electrochemical impedance spectra of Inconel 617 alloy under different conditions.

The calculation of the corrosion rate for the sample is calculated, and the average penetration rate is as follows: $CR = K_1 (i_{\text{corr}}/\rho) E_w$, and the quality loss rate is as follows: $MR = K_2 i_{\text{corr}} E_w$, for which k_1 is the Faraday constant, $3.27 \times 10^{-3} \text{ mm} \cdot \text{g}/\mu\text{A} \cdot \text{cm} \cdot \text{a}$. k_2 is $8.954 \times 10^{-3} \text{ g} \cdot \text{cm}^2/\mu\text{A} \cdot \text{cm}^2 \cdot \text{d}$. i_{corr} is the corrosion current density. ρ is the density of the alloy ($\rho = 8.36 \text{ g/cm}^3$); E_w is the equivalent weight, using the lower formula: $E_w = 1/\Sigma(n_i f_i/W_i)$. The specific values are shown in Table 2.

Table 2. Corrosion parameters of Inconel 617 alloy.

Sample	E_{corr} (V)	I_{corr} (A)	R_p (Ω)	CR (mm/a)	MR ($\text{g/m}^2 \cdot \text{d}$)
1000 °C 0.001 s ^{−1}	−0.378	7.62×10^{-7}	65,388	0.011	0.253
1100 °C 0.001 s ^{−1}	−0.377	1.08×10^{-7}	340,270	0.001	0.036
1200 °C 0.001 s ^{−1}	−0.351	7.05×10^{-7}	54,210	0.010	0.233
1100 °C 0.1 s ^{−1}	−0.368	3.70×10^{-7}	119,833	0.005	0.123

In these, f_i is the mass fraction of the i -th element in the alloy, n_i is the price of the i -th element in the alloy, and W_i is the atomic weight of the i -th element in the alloy.

It can be seen from the above table that the corrosion rate is closely related to the impedance and the grain boundary. In general, the higher the proportion of special twin boundary $\Sigma 3$ is, the more the material performance improves. This is also confirmed by the experimental results at the strain rates of 0.001 s^{-1} and 0.1 s^{-1} . Although the proportion of the $\Sigma 3$ grain boundary is lower than that at 1200°C - 0.001 s^{-1} , the corrosion resistance at 1100°C - 0.1 s^{-1} is abnormally better due to the influence of other factors. Furthermore, the TEM analysis of samples at 1100°C - 0.001 s^{-1} and 1100°C - 0.1 s^{-1} is as follows.

Figure 13 presents the TEM images of Inconel 617 alloy at 1100°C - 0.001 s^{-1} . Both conditions exhibit significant twinning and dislocation entanglement, which can promote the occurrence of dynamic recrystallization (DRX). The diffracted spots in (a) and (e) are matrix-diffracted spots. At a strain rate of 0.001 s^{-1} , numerous micro-twins are observed. As a specific defect in metallic materials, micro-twins can effectively impede dislocation movement, thereby strengthening the material. Consequently, numerous dislocation walls and areas of dislocation entanglement are evident in the figure. Figure 14 shows that a high density of dislocation entanglement and twins is also observed at a strain rate of 0.1 s^{-1} . As illustrated in Figure 14, a significant density of dislocation tangles and twins is also evident at a strain rate of 0.1 s^{-1} , with comparable quantities. However, at 0.1 s^{-1} , the twin volume is relatively larger, thereby exhibiting the aforementioned difference in corrosion resistance.

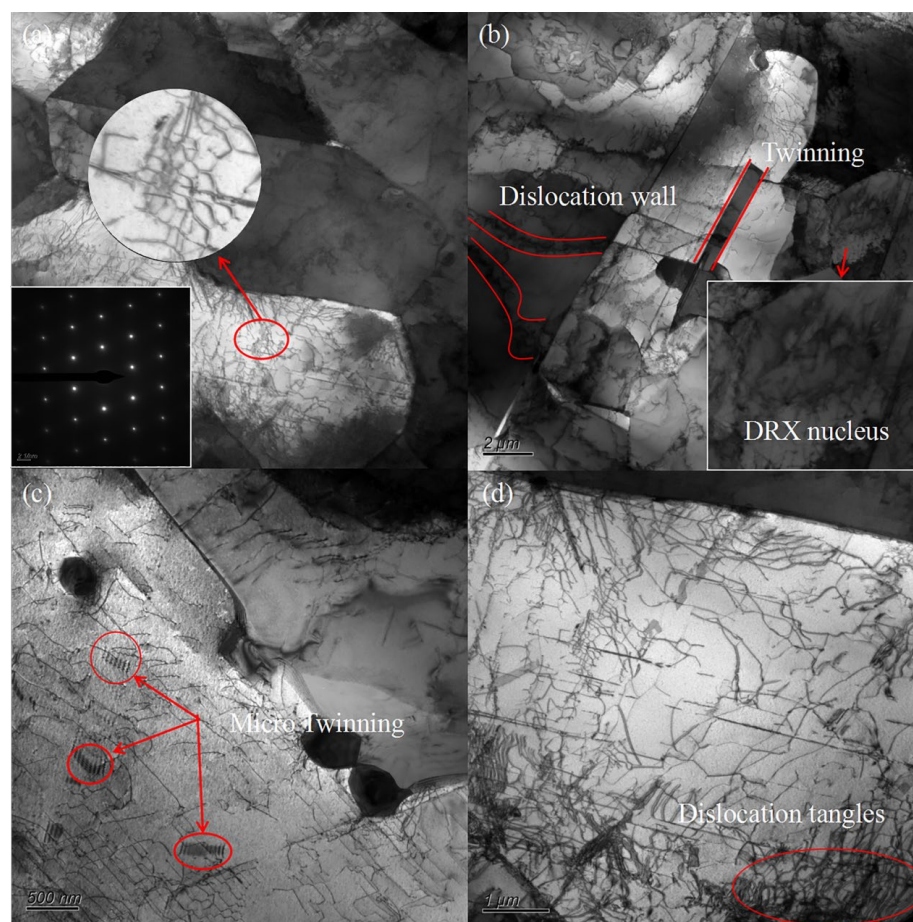


Figure 13. TEM bright field images of Inconel 617 alloy at 1100°C 0.001 s^{-1} : (a) Matrix diffraction spot, (b) twins and dynamic recrystallization nucleation, (c) micro-twin, and (d) dislocation tangles.

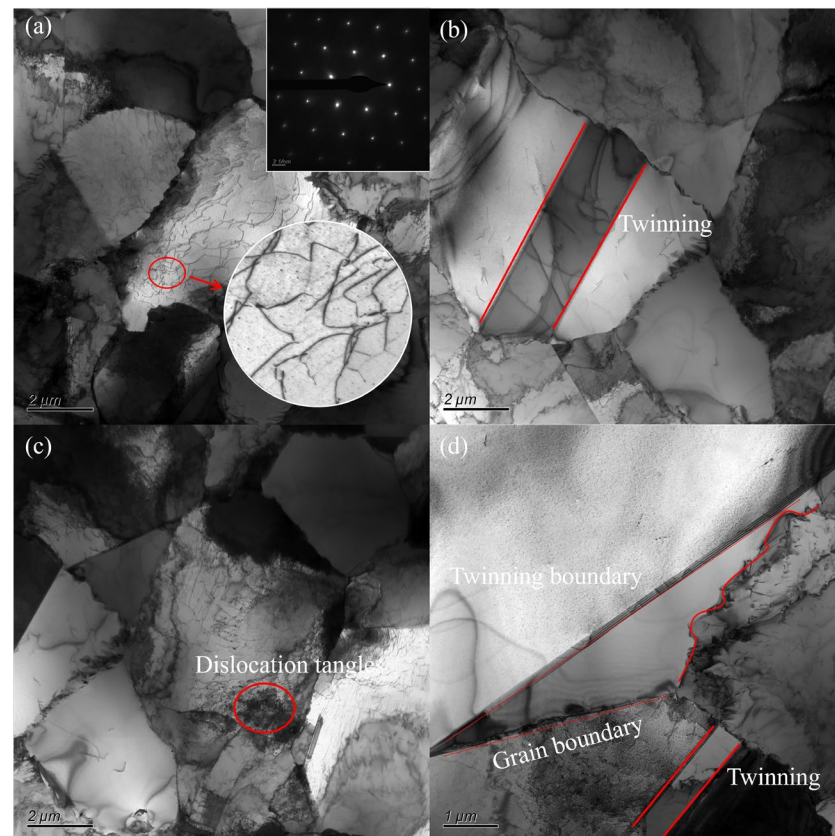


Figure 14. TEM bright field images of Inconel 617 alloy at 1100 °C 0.1 s^{−1}: (a) Matrix diffraction spot, (b) twinning, (c) dislocation tangles, and (d) grain boundary and twinning boundary.

4. Conclusions

1. This study clarifies that at low strain rates, increasing temperature activates significant DRX and annealing twins. The statistical analysis of grain boundaries shows that the transformation from LAGBs to HAGBs is the dominant mechanism of continuous dynamic recrystallization. At the same time, the interaction between special grain boundaries and their complex evolution with thermodynamic parameters is observed. However, current analysis based on static organization has difficulty in capturing the instantaneous dynamics of these processes. Therefore, direct observation using high-temperature in situ EBSD technology is crucial for thoroughly elucidating these microscopic mechanisms in the future.
2. By introducing the $\Sigma (9 + 27)/\Sigma 3$ ratio as a novel evaluation index, we find that the ratio reaches the extreme value at the strain rate of 0.01 s^{−1}, which is highly consistent with the macroscopic deformation instability behavior, revealing the decisive influence of the dynamic evolution of the grain boundary network on the processing sensitivity. This finding provides a microscopic basis for predicting the process window, but the universality of the correlation still needs to be verified in different alloy systems. Subsequent research can be devoted to the establishment of a physical constitutive model based on the grain boundary stability index to achieve accurate simulation and optimization of the thermal processing process.
3. The analysis results established a positive correlation between the density of the $\Sigma 3$ grain boundaries and the corrosion resistance of the material, and confirmed the role of coherent twin boundaries as an effective barrier for corrosion propagation. This provides a clear direction for optimizing the service performance of materials through grain boundary engineering. The current research is mainly based on statistical corre-

lations. In the future, it is necessary to combine carefully regulated grain boundary networks with customized micro-area electrochemical tests to quantitatively analyze the passivation behavior and failure mechanism of different special grain boundaries in specific corrosion environments.

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