

Hot deformation behavior of 2707 hyper duplex stainless steel

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Abstract: The hot deformation behavior of 2707 hyper duplex stainless steel (HDSS) was investigated through a hot compression test at 950 °C to 1,250 °C at strain rates of 0.01 s⁻¹ to 10 s⁻¹. Observations from the flow stress curves reveal a balance between work hardening and dynamic recovery at the beginning of the deformation and subsequently demonstrate various softening mechanisms with the increase of strain. At high strain rates, dynamic recovery is the prevailing mechanism, whereas, at medium and low strain rates, dynamic recrystallization becomes dominant. The constitutive equation was constructed, and the deformation activation energy was calculated to be 645.46 kJ·mol⁻¹. The hot processing map was drawn based on the dynamic material model at a strain of 0.8. The results indicate that the hot workability of 2707 HDSS decreases due to its high alloying content. The microstructure evolution of 2707 HDSS at 1,050 °C was identified by means of electron backscatter diffraction and transmission electron microscopy. The results demonstrate that the ferrite completes dynamic recrystallization at the strain rate of 1 s⁻¹. The softening process of austenite is influenced by ferrite and mainly experiences dynamic recovery. The austenite located at the α/γ phase boundaries tends to undergo dynamic recrystallization.

Keywords: hyper duplex stainless steel; hot deformation; constitutive equation; softening mechanism

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1 Introduction

Hyper duplex stainless steel (HDSS) 2707 contains two main phases, austenite (γ) and ferrite (α), which have different hot deformation behaviors due to different softening mechanisms^[1]. As a new steel, 2707 HDSS contains higher content of Cr than 2507 and 2205 super duplex stainless steels (SDSS). Thus, the 2707 HDSS has better corrosion resistance and higher strength than 2507 and 2205 SDSS^[2]. Due to the excellent mechanical properties of 2707 HDSS, it can serve as a cost-effective substitute for super austenitic stainless steel in extremely corrosive environments^[3-5].

Deformation temperature and strain rates are the

main factors influencing the hot deformation of duplex stainless steel^[6]. In the temperature range of hot deformation, the γ and α phases have different softening mechanisms^[7]. Kang et al.^[6] studied the hot deformation behavior of S32760 SDSS by combining thermal simulation tests with model verification. Results show that phase fraction is an important factor affecting the hot deformation behavior of the materials. Besides, it is commonly considered that ferrite would undergo dynamic recovery due to the high stacking fault energy^[8], while austenite owning low stacking fault energy would undergo dynamic recrystallization^[9]. A study on the thermal processing of 2205 DSS at low strain rates was conducted by Momeni et al.^[10]. Experimental results showed that at high deformation temperatures, ferrite underwent dynamic recovery and transformed into continuous dynamic recrystallization, while the dynamic recrystallization of austenite was delayed due to the influence of phase boundaries. Kingklang et al.^[11] investigated the hot working behavior of 2507 SDSS and found that the optimum process window was at a temperature range of 1,000–1,100 °C

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and a strain rate of $0.1\text{--}1\text{ s}^{-1}$. Moreover, they found that the primary softening mechanism at high temperature of $1,200\text{ }^{\circ}\text{C}$ was the dynamic recrystallization in the austenite. Chen et al.^[12] investigated the hot processing characteristics of 2205 DSS and determined that the optimal processing window of the tested steel was $1,373\text{--}1,473\text{ K}$ and 0.01 s^{-1} .

Liu et al.^[13] investigated the microstructure evolution of LDX 2101 DSS by electron backscatter diffraction (EBSD) and explained the reason for the softening phenomenon of the “yield-like platform”. Haghdadi et al.^[14] used the specially designed 23Cr-6Ni-3Mo DSS to study the softening mechanism of ferrites and reached a conclusion contrary to current popular belief. Cizek et al.^[15] explained in detail the dynamic recrystallization softening mechanism of austenite in 21Cr-10Ni-3Mo DSS and discussed its effect on the flow curve. They found that a significant portion of austenite dynamic softening was attributed to the coalescence of large-scale sub-grain, resulting in decreased flow stress. Evidently, there is still controversy in the study of the softening mechanism of DSS. Therefore, it is essential to investigate the microstructural evolution and softening mechanisms in DSS to address these controversies.

In this study, 2707 HDSS was selected as the research subject. Hot compression experiments were conducted using a Gleeble simulator at temperatures ranging from $950\text{ }^{\circ}\text{C}$ to $1,250\text{ }^{\circ}\text{C}$ at strain rates between 0.01 and 10 s^{-1} . The present work aims to examine the microstructural evolution during hot deformation, clarify the deformation mechanism, and, by integrating the results, provide a theoretical basis for the deformation process of the high-alloy 2707 HDSS.

2 Experimental procedures

The chemical composition of the 2707 HDSS was as follows (in wt.%): C 0.03, Cr 26.82, Ni 7.03, Mo 4.52, Mn 1.01, N 0.39, Co 0.92, S 0.005, and Fe (balance). The steel was melted using a vacuum melting furnace (ZG-100 type, Suzhou Zhenwu Electric Furnace Co., Ltd., Suzhou, China). When heated to a pouring temperature of $1,490\text{ }^{\circ}\text{C}$, the molten steel was poured into a cylindrical cast iron mold with a diameter of 170 mm and a height of 350 mm . The resulting ingot was then machined via wire cutting into cylindrical specimens measuring $\Phi 8\text{ mm}\times 13\text{ mm}$. The samples were heated to $1,250\text{ }^{\circ}\text{C}$ at a rate of $20\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$ on the Gleeble 1500D thermal simulation test machine and held for 180 s to ensure uniform temperature distribution. The samples were then cooled to the desired deformation temperature at a rate of $5\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$. Once the target temperature was achieved, the samples were held for an additional 60 s to stabilize before initiating the hot compression experiment. After hot deformation, the samples were immediately put into water and quenched to room temperature to retain the high-temperature deformation microstructure. The deformation temperatures ranged from 950 to $1,250\text{ }^{\circ}\text{C}$, and the strain rates ranged from 0.01 to 10 s^{-1} . The samples were compressed until the true strain was 0.8 . The deformation samples were cut along the axial direction with

a wire cutting machine and embedded with a Mosaic thermal machine. The samples were then ground, mechanically polished, and corroded. The hot compression test procedure employed for 2707 HDSS is shown in Fig. 1.

The microstructures of samples were observed by means of optical microscopy (Zeiss, Vert.A1 OM), scanning electron microscopy (JSM-7800F SEM), and field emission scanning electron microscopy (JSM-5610LV FE-SEM). The samples underwent electrical etching using a solution composed of FeCl_3 (5 g), HNO_3 (10 mL), and HCl (30 mL). The central area of hot deformed samples was electro-chemically polished by electrolytic polishing with $10\%\text{ HClO}_4+90\%\text{ glacial acetic acid}$ solution. The deformed microstructure of the samples was examined using an EBSD device with a step size of $1\text{ }\mu\text{m}$. The measurement of crystal orientations was conducted using the OIM Data Collection Version 7.0 software. The specimens of $\Phi 3\text{ mm}$ were cut for transmission electron microscopy (TEM, JEM 2100) examination. The disks were thinned to 0.07 mm by SiC papers and then twin-jet electropolished by $6\%\text{ HClO}_4+94\%\text{ absolute ethanol}$ at $-20\text{ }^{\circ}\text{C}$.

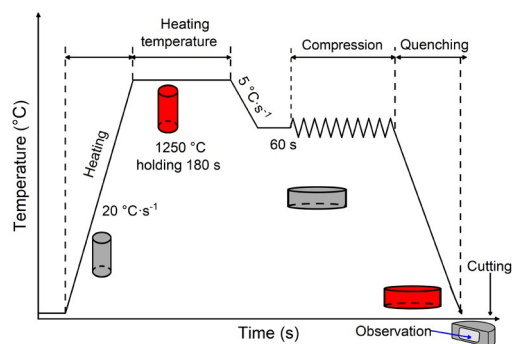


Fig. 1: Hot compression test procedure

3 Results and discussion

3.1 As-cast microstructure

Figure 2 shows the as-cast microstructure of the 2707 HDSS, revealing a distribution of light-etched austenite (γ) phase within a matrix of dark-etched ferrite (α) and light-etched σ phase. During solidification, the molten alloy first forms primary ferrite dendrites. As solidification progresses, elements such as nickel and nitrogen segregate into the remaining liquid, finally, austenite forms during the final stages of solidification.

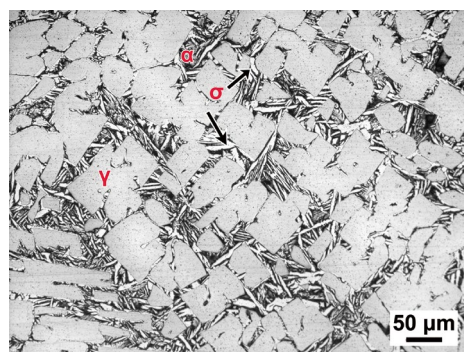


Fig. 2: Optical microstructure of as-cast specimen

3.2 True stress-strain curves

True stress-strain curves of 2707 HDSS, obtained from the hot compression tests at different parameters, are presented in Fig. 3. Under all conditions, the peak stress decreases as the strain rate ($\dot{\epsilon}$) decreases or the deformation temperature increases. The stress sharply increases at the initial stage of the hot deformation, resulting from work hardening^[16]. As shown in Figs. 3(a–c), after reaching a peak, the deformation resistance decreases with increasing strain at low strain rates, indicating the occurrence of dynamic recovery or initiation of

cracks within the alloy^[17]. However, as shown in Fig. 3(d), the deformation resistance at higher strain rates remains nearly unchanged with increasing strain after reaching the peak, indicating a certain degree of balance between work hardening and dynamic softening^[18]. When the steel deforms at a lower strain rate, such as 0.01 s^{-1} , the steel's internal microstructure has more time to undergo heat treatment and evolution^[19]. Hence, at the same deformed temperature, the deformation resistance at lower strain rates is lower than that at higher strain rates.

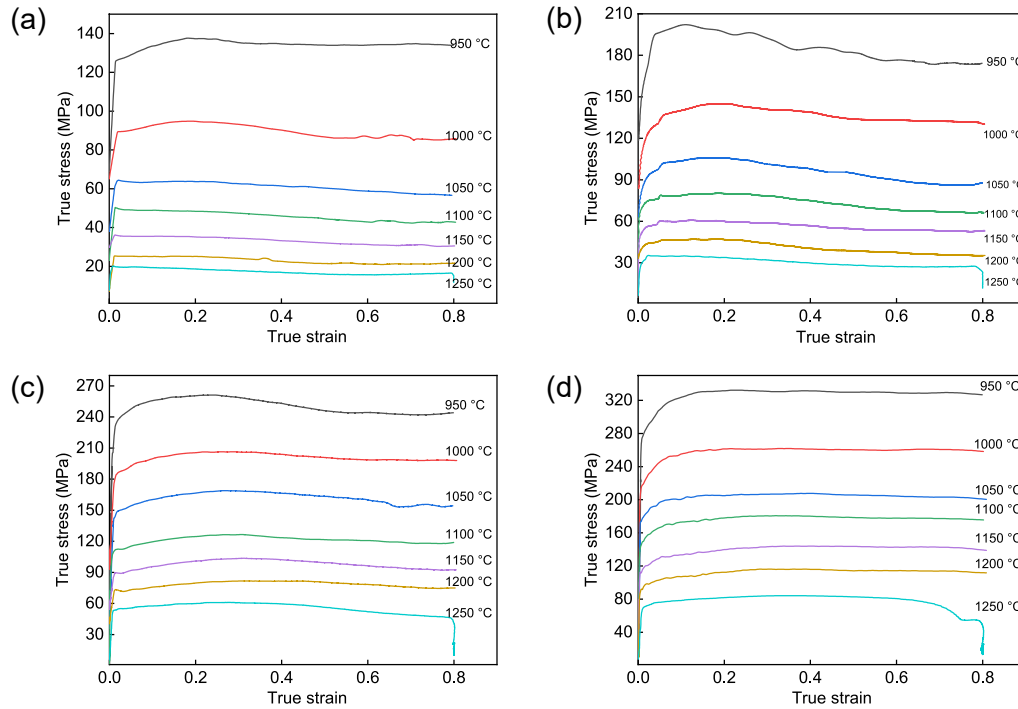


Fig. 3: High-temperature true stress versus true strain curves for 2707 HDSS deformed under different strain rates: (a) $\dot{\epsilon}=0.01 \text{ s}^{-1}$; (b) $\dot{\epsilon}=0.1 \text{ s}^{-1}$; (c) $\dot{\epsilon}=1 \text{ s}^{-1}$; (d) $\dot{\epsilon}=10 \text{ s}^{-1}$

3.3 Constitutive equation and processing maps

The constitutive equation is a mathematical relation describing the mechanical properties of materials. The hot deformation activation energy (Q) can reflect the deformation resistance of the plastic deformation of materials at high temperatures. The higher the activation energy, the more difficult the softening of the microstructure^[20]. The hot deformation behavior of materials can be analyzed using the modified Arrhenius equation proposed by Sellars and Tegart in 1966^[20]:

$$\dot{\epsilon} = A [\sinh(\alpha \sigma_p)]^n \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where A and α are the material constants which need to be concluded by hot deformation compression experiment, σ_p is the peak stress, R is the gas constant, and T is the deformation temperature. By plotting $\ln \sigma - \ln \dot{\epsilon}$ and $\sigma - \ln \dot{\epsilon}$ curves and performing a linear fit, as shown in Figs. 4(a, b), α is calculated to be 0.0095 MPa^{-1} . To obtain the Q of the materials, the following equation can be obtained from Eq. (1):

$$Q = R \left\{ \frac{\partial \ln \dot{\epsilon}}{\partial \ln [\sinh(\alpha \sigma_p)]} \right\}_T \left\{ \frac{\partial \ln [\sinh(\alpha \sigma_p)]}{\partial \left(\frac{1}{T}\right)} \right\}_{\dot{\epsilon}} \quad (2)$$

The first term in Eq. (2) is the n value in Eq. (1), which can reflect the relationship between $\ln[\sinh(\alpha \sigma_p)]$ and $\ln \dot{\epsilon}$, i.e., the relationship between the peak stress and strain rate at constant strain temperature, as shown in Fig. 4(c). Similarly, the last term of Eq. (2) can reflect the relationship between peak stress and deformed temperature at a constant strain rate, as shown in Fig. 4(d). According to the fitting curves, n is calculated to be 4.462 and the Q is calculated to be $645.46 \text{ kJ} \cdot \text{mol}^{-1}$. The obtained Q value is higher than that of the 2507 and 2205 SDSS^[7, 21], indicating an increase in deformation resistance. The Q value is related to the content of alloying elements in the material^[22]. The 2707 HDSS contains a higher content of Cr, Mo, and N elements than those of traditional DSS. Nitrogen (N) atoms can reduce the effective diffusion rate of atoms, and their blocking effect on dislocations is more significant^[23]. Besides, Li et al.^[16] investigated the constitutive modeling of 2707 HDSS and concluded the Q

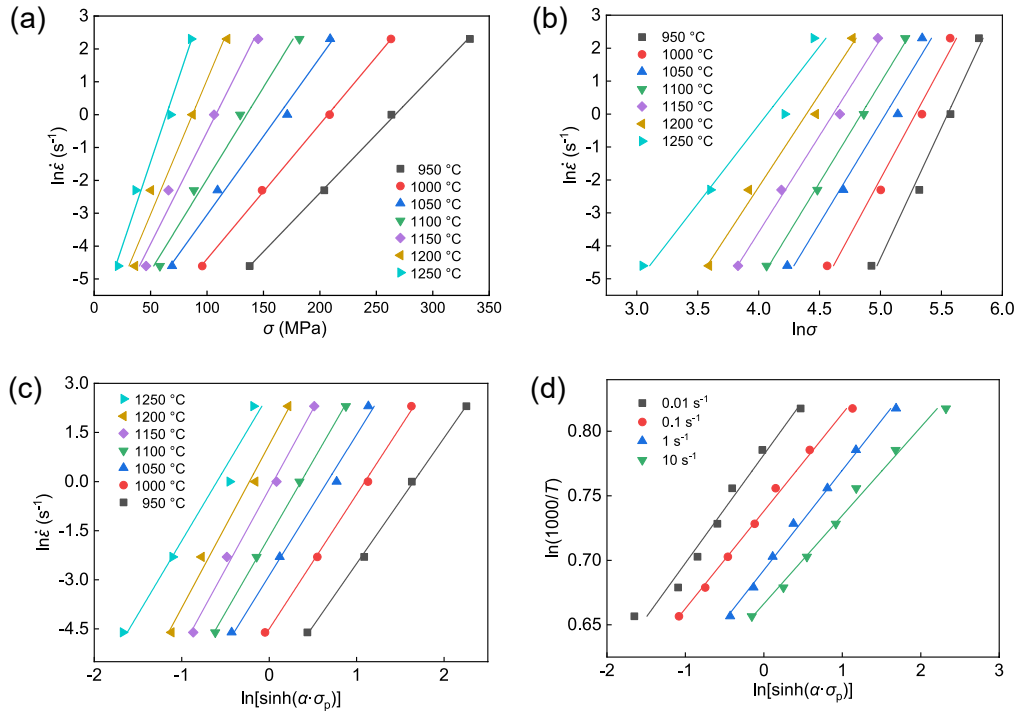


Fig. 4: Relationship of (a) σ - $\ln\dot{\epsilon}$; (b) $\ln\sigma$ - $\ln\dot{\epsilon}$; (c) $\ln\dot{\epsilon}$ - $\ln[\sinh(\alpha\sigma_p)]$; (d) $\ln[\sinh(\alpha\sigma_p)]$ - $1000/T$ for 2707 HDSS at different deformation parameters (symbols show the experimental data and solid lines represent the linear fit)

value is $569.279 \text{ kJ}\cdot\text{mol}^{-1}$. The difference of two Q values is attributed to the different microstructures before compression. The Zener-Hollomon parameter (Z parameter) is usually used to express the relationship between deformation temperature and strain rate, as presented in Eq. (3)^[24]:

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) \quad (3)$$

Combining Eqs. (1) and (3), Z can be expressed as Eq. (4):

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A [\sinh(\alpha\sigma_p)]^n \quad (4)$$

By substituting Q and $\dot{\epsilon}$ at different deformation temperatures into Eq. (4), the Z parameter at different temperatures and strain rates can be obtained. The value of A was calculated to be 6.31×10^{23} by the slope of $\ln Z$ - $\ln[\sinh(\alpha\sigma_p)]$, as shown in Fig. 5. Substituting all the obtained values into Eqs. (1) and (4), the Z parameter and the strain rate of 2707 HDSS are obtained as follows:

$$Z = 6.31 \times 10^{23} [\sinh(0.00954\sigma_p)]^{4.462} \quad (5)$$

$$\dot{\epsilon} = 6.31 \times 10^{23} [\sinh(0.00954\sigma_p)]^{4.462} \exp\left(-\frac{645460}{RT}\right) \quad (6)$$

According to the dynamic model proposed by Prasad et al.^[25], the hot processing diagram was constructed, which can represent the response of the material to different strain rates at a certain temperature. In the process of hot deformation, the instantaneous absorbed power (P) per unit volume of material is the product of flow stress and strain rate. It is considered as the sum of the energy consumed in the process of plastic deformation (G) and the energy consumed by dynamic

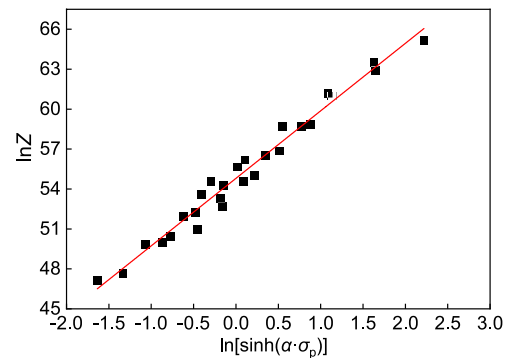


Fig. 5: Relationship between $\ln Z$ and $\ln[\sinh(\alpha\sigma_p)]$

microstructure evolution (J), as presented in Eq. (7)^[26]:

$$P = \sigma \dot{\epsilon} = \int_0^{\dot{\epsilon}} \sigma d\dot{\epsilon} + \int_0^{\sigma} \dot{\epsilon} d\sigma = G + J \quad (7)$$

The sensitivity coefficient of strain rate (m) is defined as Eq. (8)^[12]:

$$m = \frac{\partial J}{\partial G} = \frac{\partial \log \sigma}{\partial \log \dot{\epsilon}} \quad (8)$$

The degree of power dissipation caused by the microstructure evolution can be expressed by the efficiency of energy dissipation (η), as expressed in Eq. (9)^[27]:

$$\eta = \frac{2m}{m+1} \quad (9)$$

Based on dynamic material model theory, Ziegler combined the maximum principle of irreversible thermodynamics with large-strain plastic flow, and proposed the rheological instability criterion under certain deformation conditions^[28]:

$$\zeta(\dot{\epsilon}) = \frac{\partial \ln\left(\frac{m}{m+1}\right)}{\partial \ln \dot{\epsilon}} + m < 0 \quad (10)$$

The thermal processing map is obtained by superimposing the maps of energy dissipation efficiency and instability. The processing map of 2707 HDSS at a strain of 0.8 is shown in Fig. 6. The gray area denotes the instability area, while the white area denotes the stable region. The number marked in the figure represents the η value. Zones of flow instability are observed at the temperatures of 1,150 °C and 1,250 °C with strain rate ranges of 0.01–1 s⁻¹. Moreover, within the temperature range of 950–1,100 °C or at 1,200 °C, the flow instability zones also can be found with strain rates of 1–10 s⁻¹. The processing map shows three distinct domains with the peak energy dissipation efficiency of 44%. The high η means that the changes in the microstructure of the material would dissipate more energy, which is beneficial for hot deformation^[29]. Based on this, it can be concluded that the optimal range for hot deformation of 2707HDSS falls within a temperature range of 1,050–1,100 °C or at 1,200 °C with a strain rate of 0.01–0.1 s⁻¹. In comparison to 2205 SDSS and 2507 SDSS^[30, 31], the processing map of

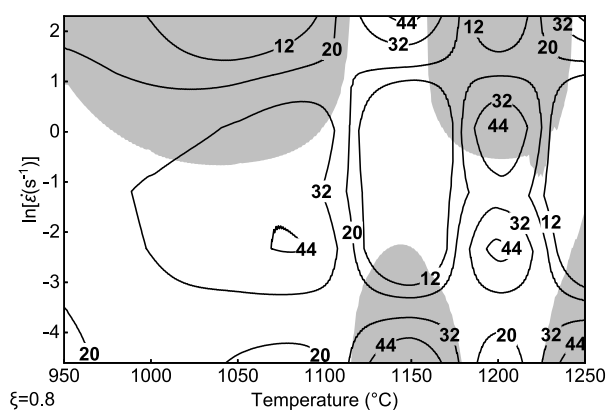


Fig. 6: Processing maps of 2707 HDSS at a strain of 0.8

2707 HDSS exhibits a narrower stable region, indicating reduced hot workability due to its higher content of alloying elements. According to the hot processing map, the microstructure in different deformation regions at 1,050 °C was analyzed. It can be observed from Fig. 7 that the samples located in the unstable area exhibit both surface and internal cracks, while no cracks are observed in the microstructure of those in the stable area.

3.4 Microstructural evolution of 2707 HDSS

It is generally believed that dynamic recrystallization can be found obviously in the materials when η is 30%–60%, and in the austenite with low fault energy when η is 35%–45%^[27, 29]. At high values of $\ln Z$, the dynamic recrystallization is the dominant softening mechanism of ferrite steels^[32]. According to the phase diagram of 2707 HDSS^[33], when the heating temperature is over 1,050 °C, the equilibrium microstructure consists of α and γ phases. In the temperatures range of 1,050 °C–1,250 °C, the content of α phase firstly decreases and then increases. When the heating temperature is 1,050 °C, the content of α phase is lower than that of γ phase, while it is higher than that of γ phase after heating at 1,250 °C. However, the sample does not reach the equilibrium state due to the short hold time when hot deformed at 1,050 °C. Therefore, the microstructures from the central region of uniform deformation, obtained at 1,050 °C under different strain rates, were selected for analysis, as shown in Fig. 8, where the white austenite is distributed on a grey ferrite matrix. Compared to the as-cast microstructure in Fig. 1(a), no σ phase precipitation is observed. The coarse as-cast dendritic structure is fragmented, with grains elongated and rearranged along the deformation direction, forming a fibrous structure that leads to microstructural refinement. Grains are elongated and rearranged, forming a fibrous structure, resulting

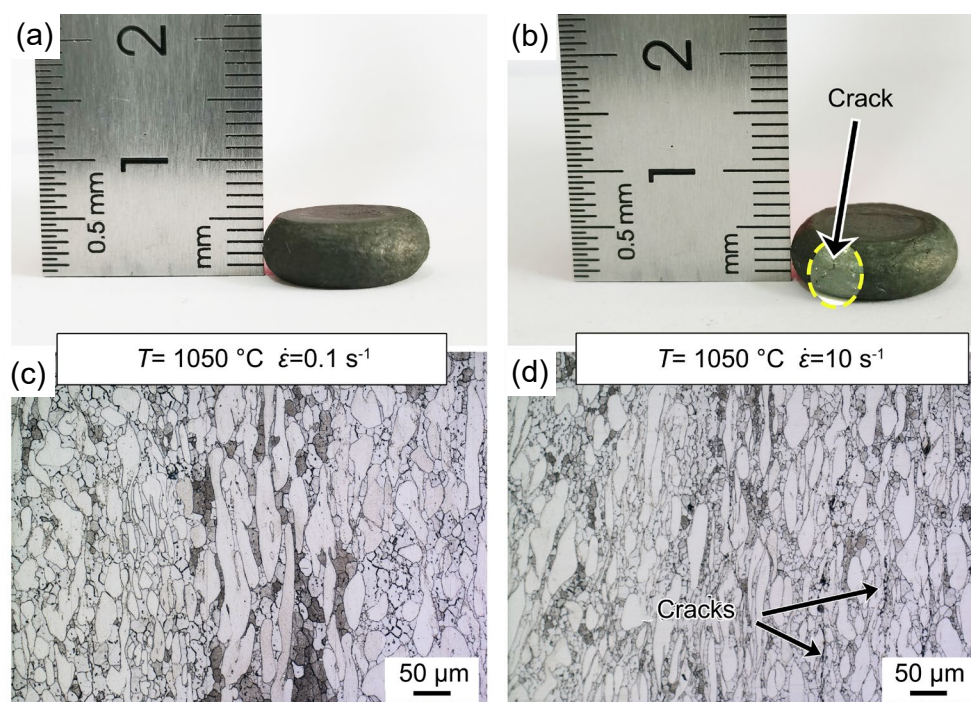


Fig. 7: Macro and micro characteristics verification of samples located at different areas of processing maps: (a, c) stable area; (b, d) unstable area

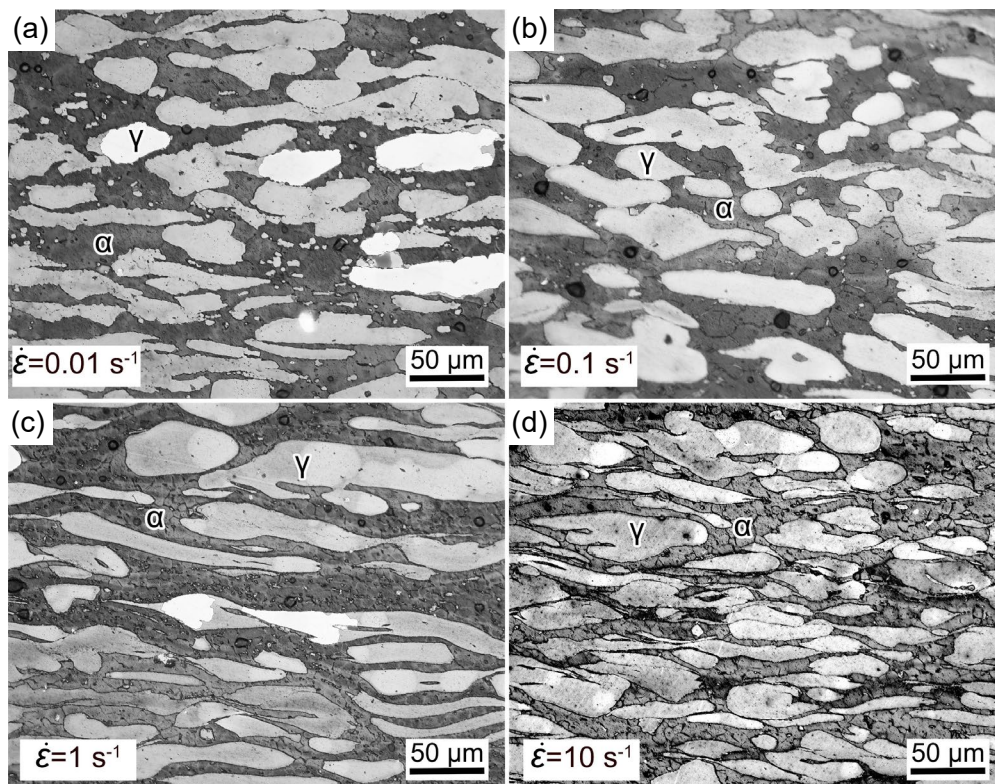


Fig. 8: Optical micrographs of 2707 HDSS at 1,050 °C under different strain rates: (a) $\dot{\epsilon}=0.01 \text{ s}^{-1}$; (b) $\dot{\epsilon}=0.1 \text{ s}^{-1}$; (c) $\dot{\epsilon}=1 \text{ s}^{-1}$; (d) $\dot{\epsilon}=10 \text{ s}^{-1}$

in microstructural refinement. When the strain rates are 0.01 s^{-1} and 0.1 s^{-1} [Figs. 8(a, b)], the austenite phase is precipitated at the ferrite phase boundaries. This is because the deformation time of the samples at low strain rates is longer than that in high strain rates. Therefore, the friction work and plastic work have more time to diffuse. During prolonged deformation, the two-phase microstructure evolves toward a thermodynamic equilibrium state. At high strain rates, the plastic work and frictional work are converted to energy in a short time, leaving insufficient time for the transfer of heat^[34]. Hence, the α phase transforms to γ phase abundantly. As the strain rate increases [Fig. 8(c)], the austenite changes from an island-like phase to a long strip. As the strain rate increases to 10 s^{-1} [Fig. 8(d)], the degree of deformation in the original austenite intensifies, accompanied by a significant reduction in grain size.

The main dynamic softening mechanism of 2707 HDSS during hot deformation can be further confirmed by the results of EBSD and TEM analysis. The EBSD images of 2707 HDSS under different strain rates are shown in Fig. 9. In Fig. 9, the white-colored outlines represent low-angle grain boundaries ($2^\circ \leq \text{LAGBs} \leq 5^\circ$), the blue-colored outlines represent medium-angle grain boundaries ($5^\circ \leq \text{MAGBs} \leq 15^\circ$), and the black-colored outlines represent high-angle grain boundaries ($15^\circ \leq \text{HAGBs} \leq 65^\circ$). The red areas are austenite, and the green areas are ferrite. During the processing of dynamic recovery, the dislocation of deformed grains is constantly multiplied and rearranged. The morphology of the deformed grains evolves, with equiaxed subgrains forming along the peripheries of the original grain boundaries. At low strain rates [Figs. 9(a, b)], the microstructure of the austenite includes

lots of fine grains that are composed of HAGBs, as well as subgrains formed by LAGBs and MAGBs. The number of LAGBs and MAGBs inside the ferrite is low. At the strain rate of 1 s^{-1} [Fig. 9(c)], the microstructure of the ferrite exhibits lots of equiaxed grains composed of HAGBs and subgrains formed by LAGBs and MAGBs. This suggests that some portion of the ferrite has undergone dynamic recrystallization and formed equiaxed grains, while another portion is currently undergoing transformation. At a strain rate of 10 s^{-1} [Fig. 9(d)], the ferrite grains exhibit a predominance of HAGBs that are elongated along the deformation direction, with a minor presence of LAGBs simultaneously. The proportion of LAGBs in the austenite decreases, while that of MAGBs increases, signifying a higher degree of recovery in the austenite compared with that observed at the strain rate of 1 s^{-1} . Based on the above results, fine, newly formed austenite particles are observed at ferrite phase boundaries during deformation. The ferrite phase undergoes dynamic recrystallization followed by partial dynamic recovery.

Diagrams of grain reference orientation deviation (GROD) are superimposed to analyze the softening mechanism of 2707 HDSS, as shown in Fig. 10. GROD is based on the misorientation between a reference point of the grain and the other points^[35]. The distribution of GROD is used to evaluate the degree of localized deformation inside the grains. At low strain rates [Figs. 10(a) and (b)], austenite grains exhibit localized deformation preferentially at their ends oriented perpendicular to the compression direction. As the strain rate increases, the degree of deformation in the austenite grains increases, while the degree of localized deformation decreases

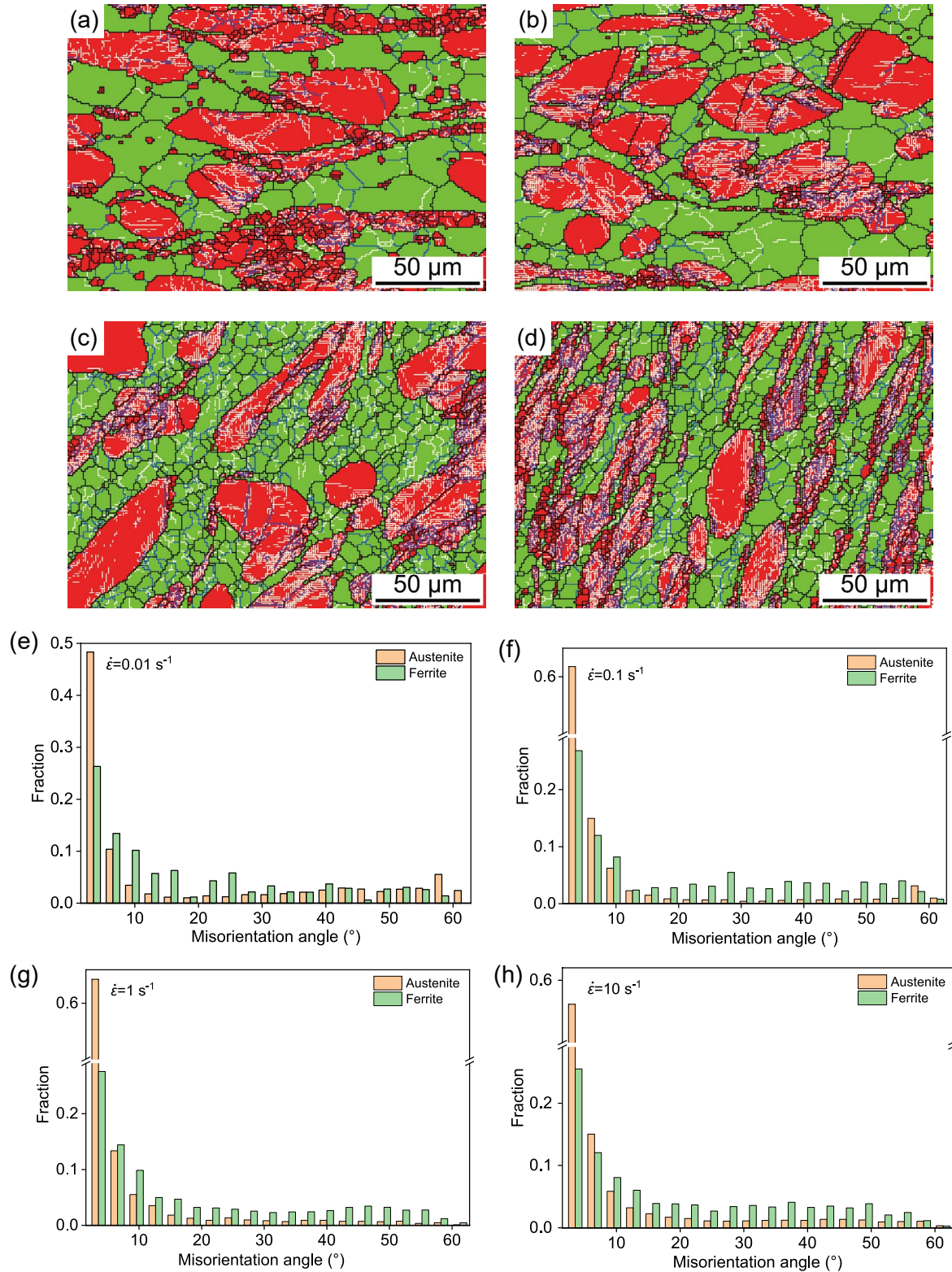


Fig. 9: EBSD results for 2707 HDSS at 1,050 °C with different strain rates: (a, e) $\dot{\epsilon}=0.01 \text{ s}^{-1}$; (b, f) $\dot{\epsilon}=0.1 \text{ s}^{-1}$; (c, g) $\dot{\epsilon}=1 \text{ s}^{-1}$; (d, h) $\dot{\epsilon}=10 \text{ s}^{-1}$

[Fig. 10(c)]. The localization deformation that appears in the austenite is related to the orientation relationship between α and γ phases^[36]. At a strain rate of 10 s^{-1} [Fig. 10(d)], the overall deformation of austenite intensifies, while intragranular localized deformation decreases. Instead, localized deformation becomes more pronounced at ferrite-austenite phase boundaries, with the highest degree of localized deformation occurring at

austenite-austenite grain boundaries.

Figure 11 shows the TEM morphologies of the 2707 HDSS samples deformed at 1,050 °C with various strain rates. As shown in Figs. 11(a) and (b), when the strain rate is 0.01 s^{-1} , a cellular structure, formed by dislocation entanglement, is observed within the ferrite. As the deformation proceeds, the walls of above cells can be flattened, forming subcrystalline, which

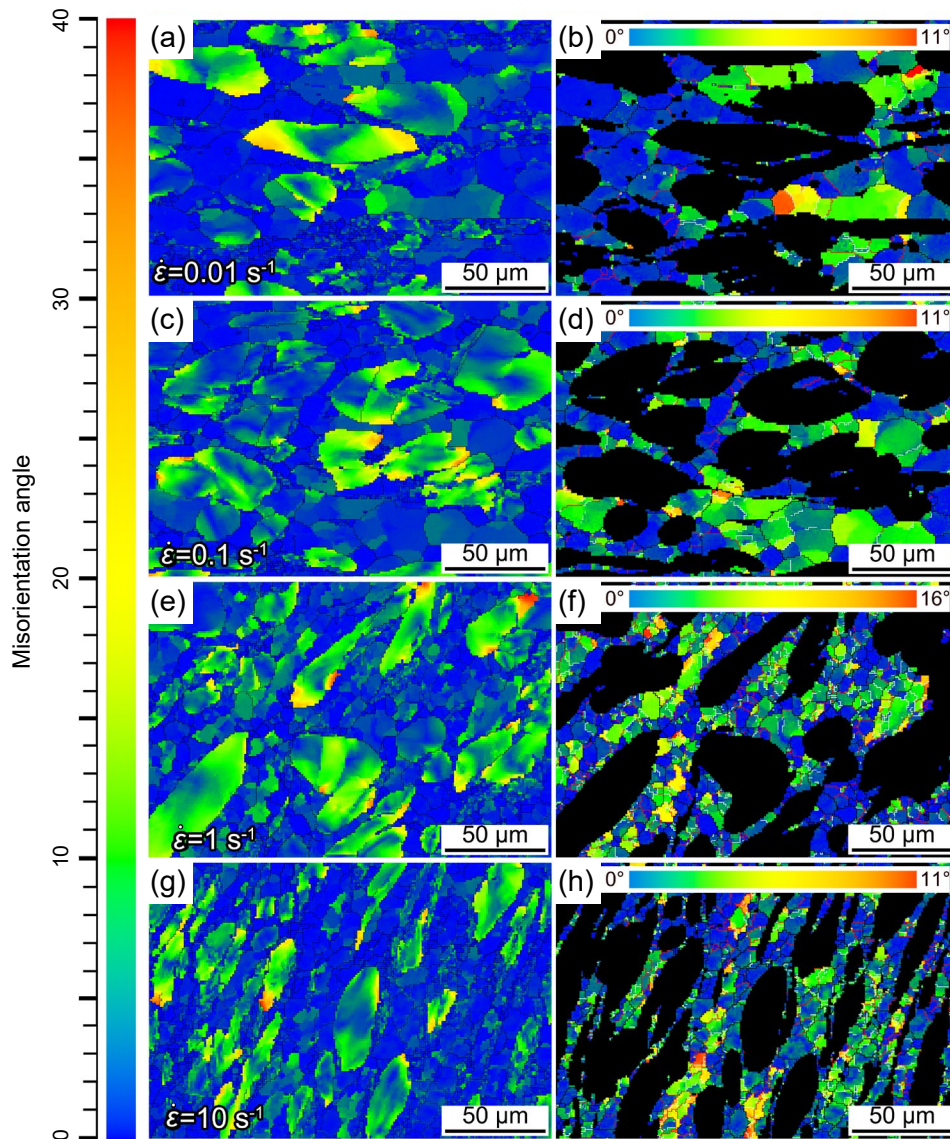


Fig. 10: GROD diagrams of 2707 HDSS (a-d) and α phase (e-h) at deformation temperature of 1,050 °C with different strain rates: (a, e) $\dot{\epsilon}=0.01 \text{ s}^{-1}$; (b, f) $\dot{\epsilon}=0.1 \text{ s}^{-1}$; (c, g) $\dot{\epsilon}=1 \text{ s}^{-1}$; (d, h) $\dot{\epsilon}=10 \text{ s}^{-1}$

becomes the core of dynamic recrystallization. There are also some dislocation cells formed by dislocation entanglement at the γ/γ grain boundaries. When the strain rate is 1 s^{-1} [Figs. 11(c, d)], the grains inside α phase almost complete the dynamic recrystallization process, resulting in the formation of equiaxed grains. Meanwhile, several grains are found undergoing dynamic recrystallization process. Dislocation cell structures are clearly observed within the grains, and the density of the dislocation is very high. The increasing stress within the austenite promotes the formation of microbands, which form transiently prior to dynamic recrystallization and are subsequently reorganized through the migration of dislocation networks during deformation^[37]. When the strain rate reaches 10 s^{-1} [Figs. 11(e, f)], the grains within the ferrite finish dynamic recrystallization and subsequently grow up. However, the recovery process of the austenite is inhibited at the α/γ phase boundaries, resulting in lots of dislocations entanglement. The nucleation and growth of grains at such dislocation entanglement position can be observed in Fig. 10(f).

Such phenomenon of subgrain nucleation and growth is common in metals with low stacking fault energy^[15, 38]. In summary, across varying strain rates, dynamic recrystallization in austenite occurs preferentially at γ/γ grain boundaries, while localized deformation is observed at α/γ phase boundaries, indicating active dynamic recovery in these interfacial regions. These findings suggest that the softening behavior of austenite is influenced by the surrounding ferrite phase. The strong α/γ interaction arises from dislocation pile-up at phase boundaries, driven by mechanical incompatibility between the two phases^[39].

4 Conclusions

(1) The activation energy of 2707 HDSS is calculated to be $645.46 \text{ kJ} \cdot \text{mol}^{-1}$. The constitutive equation for steady-state flow stress at 950–1,250 °C and $0.01\text{--}10 \text{ s}^{-1}$ is:

$$\dot{\epsilon} = 6.31 \times 10^{23} \left[\sinh(0.00954 \sigma_p) \right]^{4.462} \exp \left(-\frac{645460}{RT} \right)$$

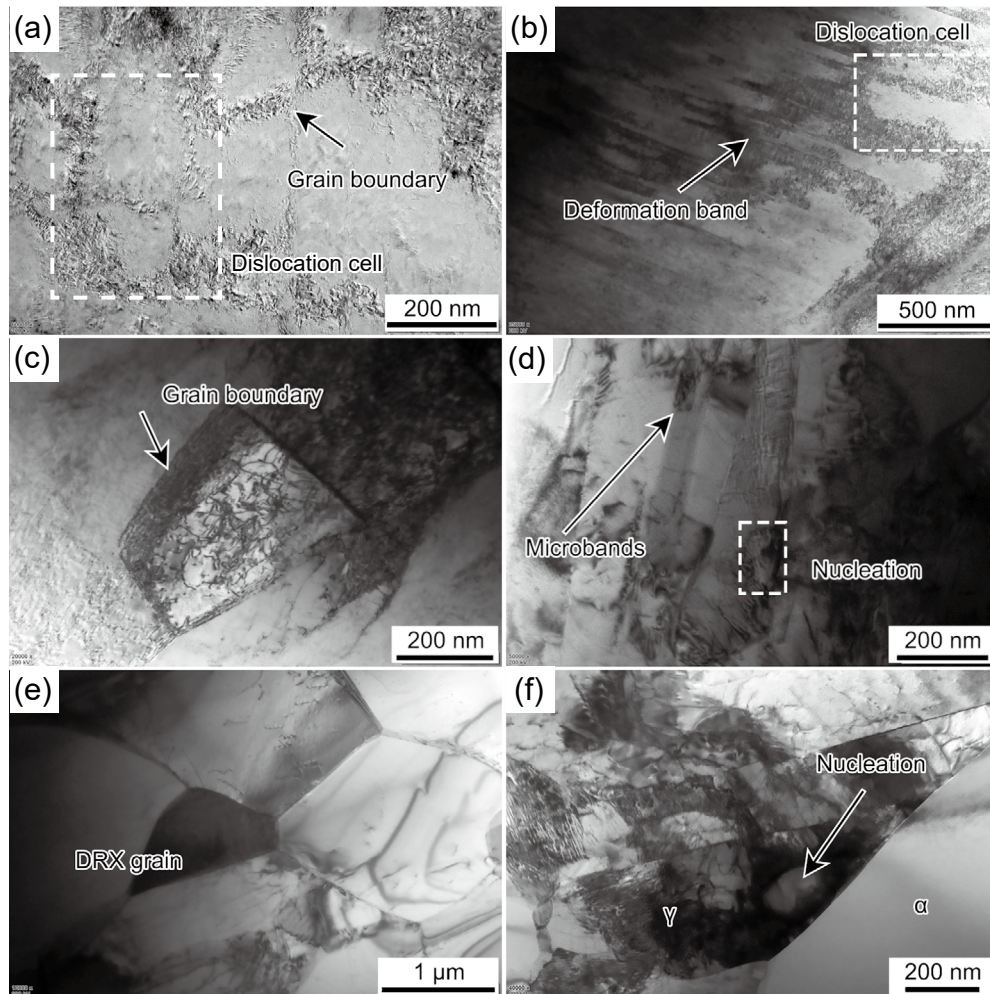


Fig. 11: TEM micrographs of α phase (a, c, e) and γ phase (b, d, f) in 2707 HDSS deformed at 1,050 °C with various strain rates: (a, b) $\dot{\epsilon}=0.01 \text{ s}^{-1}$; (c, d) $\dot{\epsilon}=1 \text{ s}^{-1}$; (e, f) $\dot{\epsilon}=10 \text{ s}^{-1}$

(2) Based on the thermal processing map, the optimal parameters of hot processing for 2707 HDSS is within a temperature range of 1,050–1,100 °C or at 1,200 °C with a strain rate range of 0.01–0.1 s^{-1} .

(3) At low strain rates of 0.01 s^{-1} and 0.1 s^{-1} , cellular structure is formed by dislocation entanglement inside the ferrite, forming subcrystalline. Meanwhile, at high strain rate of 10 s^{-1} , the dynamic recrystallization process is finished inside the ferrite. The dynamic recovery process of the austenite is inhibited at the phase boundaries, resulting in lots of dislocations entanglement.

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Conflict of interest

The authors declare that they have no conflict of interest.

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