Thermal deformation behavior and processing maps of nickel-free high nitrogen austenitic Cr18Mn16Mo2.5N0.83Nb0.15 stainless steel

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Abstract
The nickel-free high nitrogen austenitic Cr18Mn16Mo2.5N0.83Nb0.15 stainless steel was fabricated by electroslag remelting technology. The high-temperature thermal deformation behavior of as-fabricated steel was investigated using Gleeble-1500D type thermal-mechanical simulation testing machine under the condition of the temperature range from 950 °C to 1100 °C and the strain-rate range from 0.01 s⁻¹ to 1.0 s⁻¹. The constitutive equation containing polynomial of as-fabricated steel was built to describe stress function containing the variable of deformation temperature and strain-rate based on Arrhenius equation. The Q value is 448.915 kJ mol⁻¹ by computing using the experimental data obtained from the thermal deformation tests. The thermal forging temperature should be higher than 1050 °C and the strain-rate below 1 s⁻¹ based on the thermal processing maps.

1. Introduction

The high nitrogen austenitic stainless steel, having good mechanical properties and excellent corrosion resistance and non-magnetism and bio-compatibility, has been widely applied in high-tech industry and medical materials in recent years. Nitrogen is beneficial to enlarging austenite region, raising austenitic stability, enhancing ultimate tensile strength and yield strength without loss of toughness and ductility, and increasing corrosion resistance and oxidation resistance, so, nitrogen as a beneficial element plays a very important role in stainless steel. Nitrogen can also be used to substitution nickel (an austenitic stabilizer and limited resource and allergic reactions to human organs) in part or in whole to decrease the production costs. The literature shows that the action of nitrogen can be significantly enhanced when the content of nitrogen is more than 0.4%. These are all beneficial to enhancing the solubility of nitrogen in steel that higher manganese, higher chromium, lower carbon, lower silicon, lower nickel. The solubility of nitrogen can also be improved by increasing atmospheric pressure and filling with nitrogen during the smelting process of steel. The main methods of smelting high nitrogen austenitic stainless steel include hot isostatic pressing smelting and pressurized induction furnace smelting and pressurized electroslag remelting. Although the high nitrogen steel can be smelted using the above methods, there are many problems including complex smelting equipment and production process being dangerous and the high cost of smelting. The nitrides is easy to form in steel in the hot isostatic pressing smelting process. The molten metal needs to contact nitrogen in a large area for a long time under pressure in pressurized induction furnace smelting process. In pressurized electroslag remelting smelting process, the molten metal is easy to boil resulting in the overflow of nitrogen in the alloy due to the constant addition of high nitrogen alloys, silicon is introduced into the ingot due to using silicon nitride as a nitrogen source. So, it is urgent to develop a new smelting method under atmospheric pressure.
pressure. At present, the method of fabricating high nitrogen steel at normal pressure has acquired a great breakthrough and it has been adopted [22, 23].

The thermal deformation behavior of metal materials has a theoretical guiding value for design materials molding processes because thermal deformation is a kind major processing method of various pares forming. The constitutive model has been used to depict the plastic molding processes because thermal deformation is a kind major processing method of various pares forming. The constitutive model has been used to depict the plastic fluid characteristic and to predict the relationships between thermal deformation parameters (including temperature and strain and strain-rate). The parameters can dominate the fluid behavior and the evolution of microstructural. The models include mainly physically-based models [24–26], artificial neural networks [27, 28], and phenomenological models [29–32]. The Arrhenius constitutive equation of metal materials can be obtained through analysis and derivation of the data acquired from thermal deformation experiment. This equation has been widely used to evaluate the deformation behavior of metal materials, especially at elevated temperatures [33–38]. The literature shows that the data derived from constitutive equation can properly match the data from thermal compression experiment. It has been more and more people’s attention that using the thermal working diagram to analyze and predict material instability or to determine thermal parameter stability zones in the hot working process. The thermal working diagram is also helpful for optimizing deformation parameters, improving processability of materials, controlling microstructure formed, and analyzing deformation mechanism and microstructure evolution process and the causes of plastic instability. The dynamic materials model (DMM), proposed by Prasad et al [39] based on the continuum mechanics and physical model of materials and thermodynamics, has been applied to build the various bulk materials processing maps [40–45]. Based on DMM, a workpiece subjected to thermal deformation is considered a nonlinear dissipater of power. The processing map consisting of stability and instability domains is a superimposition of a power dissipation map and an instability map at different deformation conditions. The Prasad instability criterion is applied to determine the instability zone.

In this paper, the nickel-free high nitrogen austenitic Cr18Mn16Mo2.5N0.83-Nb0.15 stainless steel was fabricated using the method of electroslag remelting. The thermal compression deformation behavior of as-fabricated steel was studied at different experimental parameters. Arrhenius constitutive equation of as-fabricated steel, which was built based on the thermal deformation experiment data, was used to characterize the intrinsic relations among stress, strain-rate, and the deformation temperature. The thermal processing maps were used to analyze the instability region and optimize the process parameters.

2. Experimental procedures

2.1. Sample preparation of as-fabricated steel

Firstly, the powders as raw materials, consisting of micro carbon pure iron and manganese-iron alloy and ferrochrome nitride alloy, were smelted adequately in a medium frequency induction furnace. Secondly, the raw materials in a molten state were poured into a steel mould to form an ingot at 1550 °C. Finally, the ingot cooled into normal temperature state was remelted in an electroslag remelting furnace at 1650 °C. The composition (wt%) of the as-fabricated steel is C0.13-Cr18.8-Mn16.5-Mo2.5-N0.83-Nb0.15 stainless steel was fabricated using the method of electroslag remelting. The thermal compression deformation behavior of as-fabricated steel was studied at different experimental parameters. The surfaces of cylindrical samples were electro-polished in a supersaturated oxalic acid solution after the surfaces were mechanically polished. The size of the sample is 6 mm in diameters and 12 mm in heights.

2.2. Morphology and structure of as-fabricated specimen

The surfaces morphologies, including specimens of as-cast and as-remelted and as-compressed, were observed using optical microscopy (OM) (EPIPHOT 300, Nikon, Japan) and scanning electron microscopy (SEM) (JEOL-5600LV, JEOL, Japan), respectively. The crystalline structure of the as-remelted specimen was analyzed using x-ray diffraction (XRD) (D/max 2500PC, Rigaku, Japan) with Cu/Kα (λ = 0.154056 nm) within the scope of 30°<2θ<100°.

2.3. High-temperature thermal compression tests of as-fabricated specimen

The as-fabricated specimen was heated to 1200 °C at a rate of 15 °C/s and kept for 3 min to eliminate the temperature gradient. Then, decreasing this temperature to a given deformation temperature at a rate of 10 °C/s and holding isothermal for 30s to obtain the heat balance. The specimen suffered from an isothermal compression test at a given temperature and strain-rate. The sketch of the hot compression test was included as Supplementary appendix 1 (available online at stacks.iop.org/MRX/9/096504/mmedia).

After the compression, the compression specimen was at once quenched to keep the microstructure, and water was used as the quenching liquid. The thermal compression tests were processed using a Gleeble-1500D type thermal-mechanical simulation testing machine at various temperatures (950 °C, 1000 °C, 1050 °C, and 1100 °C) and various strain-rates (0.01 s⁻¹, 0.1 s⁻¹, 0.5 s⁻¹ and 1.0 s⁻¹). Tantalum tablets were used on the
contact surface between the head and sample at both ends to decrease the effect of end friction on experimental results during the test process.

3. Results and discussion

3.1. Structure and morphology of as-fabricated specimen

Figure 1 displays that the as-remelted specimen presents a single-phase structure of austenite through the XRD pattern. The morphology as shown in figure 2(a) displays that the grain size of the as-cast specimen is coarse and the second precipitations exist on the grain boundaries. The morphology of the as-remelted specimen shows that the grains are relatively coarse equiaxed in figure 2(b), and the tissue is more uniform due to the second phase whole dissolving in the matrix after electro-slag remelting.

3.2. Thermal compression deformation behavior and microstructure evolution

During the thermal compression tests, the data of stress and strain at different deformation temperature can be obtained through data transformation of load and displacement data from the data system. Figure 3 is the true stress-strain curves of the as-fabricated specimen. At the initial stage of strain, the stress sharply increases as the strain increases for all given experimental temperatures and strain rates. The above results are due to the effect of work-hardening (WH) being higher than that of dynamic softening (DS). WH and DS are the results of dislocation movement. The proliferation and accumulation and interaction of dislocation generate WH. The climbing and cross slip and rearrangement and annihilation of dislocation cause DS. So, WH dominates at the
initial stage of thermal compression deformation. The WH rate starts decreasing due to the effect of DS gradually enhancing with the strain increasing. Figure 3(a) shows that the stress value decreases gradually with the strain further increasing after the stress value reaches the maximum, which means that DS dominates. However, figures 3(b) and (c) show that the stress tends to stabilize except for the stress curves at 950 °C deformation conditions in figure 3(c), which means that the effect of WH and DS tends to equilibrium. The curves in figures 3(d) and (c) at 950 °C show that the stress gradually enhances, but the growth tendency decreases and tends to stabilize with the strain increasing, which hints that the effect of DS is higher than WH.

The microstructure evolution was characterized by SEM during thermal compression deformation. Figure 4 shows the thermal compression deformation zone microstructure of as-fabricated specimen at different deformation temperatures with strain-rates 0.01s⁻¹. Figures 4(a) and (b) showed that the original grain tissue was severely elongated resulting in the microstructure being fibrous, and the dynamic recrystallization (DRX) wasn’t almost taken place. Figure 4(c) showed that a few equiaxed crystals and twins appeared on the specimen surface at 1050 °C, which indicated that the dynamic crystallization mechanism had started. The number of equiaxed crystals in the deformation zone increased significantly over 1050 °C in figures 4(d) and (e).

3.3. Constitutive model of as-fabricated specimen
The famous Arrhenius equation [46] has been used to describe the relationship between the strain-rate, stress, and temperature, especially at high temperatures.

The Arrhenius equation as follow:

\[
\dot{\varepsilon} = A f(\sigma) \exp\left(-\frac{Q}{RT}\right)
\]  

The Arrhenius equation has three basic equation based on various stress levels, namely exponential law (equation (2)), powder law (equation (3)) and hyperbolic law (equation (4)).
\[
\dot{\varepsilon}_s = -A Q \exp \left( \frac{-Q}{RT} \right) \\
\dot{\varepsilon} = A_2 \exp (\beta \sigma) \exp \left( -\frac{Q}{RT} \right) \\
\dot{\varepsilon} = A [\sinh (\alpha \sigma)]^n \exp \left( -\frac{Q}{RT} \right)
\]

Where \( \dot{\varepsilon} \) is strain-rate (s\(^{-1}\)), \( \sigma \) is stress (MPa) for a given strain, \( Q \) is activation energy of thermal deformation (KJ mol\(^{-1}\)), \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), \( T \) is the absolute temperature (K), \( A, A_1, A_2, \alpha \) and \( \beta \) are the material constant, \( n \) and \( n_1 \) are WH constants, \( \alpha = \beta / n_1 \).

Set up

\[ B = A_1 \exp \left( -\frac{Q}{RT} \right) \text{ and } C = A_2 \exp \left( -\frac{Q}{RT} \right) \]

The equation (2) and equation (3) can be transformed into equation (5) and equation (6).

\[ \dot{\varepsilon} = B \sigma^{n_1} \quad \quad (5) \]
Taking the strain of 0.1 as an example to explain the solution procedures of the material constant. The stress values are provided in Table 1.

By substituting the values of the stress and corresponding strain-rate at the strain of 0.1 into equation (7) and equation (8), The relationship curves between the stress and strain-rate can be obtained in figure 5. The $n_1$ is the mean slope value of the straight line obtained by the linear fitting method at various temperatures in figure 5(a). Also, the $\beta$ is the mean slope value of the straight line in figure 5(b). The $n_1$ and $\beta$ are 11.54 and 0.042175, respectively.

Taking the logarithm on both sides of equation (4) obtains equation (9).

Taking the partial derivative for strain-rate on both sides of equation (9) obtains equation (10) at a given 1/T conditions.

Taking the partial derivative for 1/T on both sides of equation (9) obtains equation (11) at a given strain rate conditions.

Set up $b = \frac{\partial \ln [\sinh (\alpha \sigma)]}{\partial(1/T)}$

Equation (11) can be transform into equation (12).

The relationship curves between the stress, temperature, and strain-rate can be obtained using the experimental values at the strain of 0.1 in figure 6. The $n$ is the mean slope value of the straight line obtained by

\[ \dot{\varepsilon} = C \exp (\beta \sigma) \] (6)

\[ \ln \dot{\varepsilon} = n_1 \ln \sigma + \ln B \] (7)

\[ \ln \dot{\varepsilon} = \beta \sigma + \ln C \] (8)

Table 1. Stress values at strain 0.1.

| Strain rate(s⁻¹) | 950°C | 1000°C | 1050°C |
|------------------|-------|--------|--------|
| 0.01             | 273.17| 238.8  | 229.17 |
| 0.1              | 336.77| 279.34 | 262.78 |
| 0.5              | 383.96| 358.51 | 314.59 |
| 1                | 417.34| 389.04 | 338.79 |

\[ \dot{\varepsilon} = Rn \frac{\partial \ln [\sinh (\alpha \sigma)]}{\partial(1/T)} \] (10)

\[ Q = Rnb \] (12)
the linear fitting method at various temperatures in figure 6(a). Also, the \( b \) is the mean slope value of the straight line at various strain-rate in figure 6(b). The \( n \) and \( b \) are 8.6648 and 6.231, respectively. So, \( Q = Rnb = 448.915 \) kJ mol\(^{-1}\).

The Zener-Hollomon parameter shown in equation (13) [29] can synthetically represent the effect of deformation temperature and strain-rate on the stress.

\[
Z = \dot{\varepsilon} \exp \left( -\frac{Q}{RT} \right) \tag{13}
\]

Equation (4) substitutes into equation (13), giving equation (14)

\[
Z = A \left[ \sinh (\alpha \sigma) \right]^n \tag{14}
\]

Where \( A, \, n, \alpha \) and \( Q \) are material constants at a given strain.

Taking the logarithm on both sides of equation (14) obtains equation (15).

\[
\ln Z = \ln A + n \ln \left[ \sinh (\alpha \sigma) \right] \tag{15}
\]

Figure 7 shows the relationship curve between \( \ln Z \) and \( \ln \left[ \sinh (\alpha \sigma) \right] \). The intercept of the straight line fitted is \( \ln A \), and it is 37.74.

The above calculation method for material constants with strain 0.1 was adopted to calculate and fit the corresponding material constant within the range of 0.1–0.7 strain with the interval of 0.05. Figure 8 shows the
relationship curves between $\ln A$, $n$, $Q$, $\alpha$, and strain, and the all curves are fitted by a 6-order polynomial using the compensation of strain method. The correlation coefficient of the fitted curves is higher than 0.928, which hints the fitting effect can reflect the variation trend of material constant. The fitting coefficients are shown in table 2.

The equation (16) can be obtained by combining equation (4) and equation (14).

$$
\sigma = \frac{1}{\alpha} \ln \left( \frac{\beta}{A} \exp \left( \frac{Q}{RT} \right) \right)^{\frac{1}{\alpha}} + \left[ \left( \frac{\beta}{A} \exp \left( \frac{Q}{RT} \right) \right)^{\frac{1}{\alpha} - 1} \right]^{1/\alpha} \quad (16)
$$

The constitutive relationship of as-fabricated specimen can be obtained by substituting the material parameters fitted into equation (16). The material parameters are as follows after the 6-degree polynomial fitting.

$$
\ln A = 43.13 - 102.85\varepsilon + 796.79\varepsilon^2 - 3632.58\varepsilon^3 + 7721.81\varepsilon^4 - 7696.56\varepsilon^5 + 2905.13\varepsilon^6
$$

$$
n = 8.50 + 21.54\varepsilon - 301.69\varepsilon^2 + 1255.10\varepsilon^3 - 2589.24\varepsilon^4 + 2658.24\varepsilon^5 - 1081.74\varepsilon^6
$$

$$
Q = 530.65 - 1523.0\varepsilon + 11019.10\varepsilon^2 - 46594.95\varepsilon^3 + 94830.59\varepsilon^4 - 91561.01\varepsilon^5 + 33642.93\varepsilon^6
$$

$$
\alpha = 0.00465 - 0.01688\varepsilon + 0.08916\varepsilon^2 - 0.21776\varepsilon^3 + 0.23153\varepsilon^4 - 0.06624\varepsilon^5 - 0.02573\varepsilon^6
$$

Figure 8. Relationship between material constant and true strain by polynomial fit of as-fabricated steel (a) $\ln A-\varepsilon$, (b) $n-\varepsilon$, (c) $Q-\varepsilon$ and (d) $\alpha-\varepsilon$. 

![Figure 8](image-url)
3.4. Evaluation of the constitutive model of as-fabricated specimen

The predicted values of the Arrhenius constitutive model were compared with the experimental values as seen in the figure 9, which indicates that the constitutive model built of as-fabricated steel can accurately predict the thermal deformation behavior of as-fabricated steel in the strain range. So, the constitutive model built can be used to analyze problems in as-fabricated steel forming processes.

3.5. Hot processing maps

Equivalent line diagrams of dissipation efficiency coefficient can be drawn using the stress values and Matlab software on the plane of strain-rate and temperature. The thermal working instability zone in the thermal processing maps can be determined using Prasad’s instability criterion [41, 42, 44]. Corresponding strain rates 0.5 and 0.7 of as-fabricated steel, the stress values at various strain-rates and temperatures are presented in table 3, and the thermal processing maps are seen in figure 10. The red lattice, which represents the coefficient of energy dissipation efficiency, is the instability zone as shown in the figure 10. The instability zone is mainly concentrated in the low temperature and high strain-rate region in the upper left corner, while there is no instability zone in the lower right corner under high temperature and low strain rate. The energy dissipation

Table 2. Polynomial coefficients after fitting.

| Material constant | Coefficient          |
|-------------------|----------------------|
| lnA               | 43.13                |
| n                 | 8.5                  |
| Q                 | 530.65               |
| a                 | 0.00465              |
| I                 | ε                    |
| 1                | −102.85              |
| ε^2              | 796.79               |
| ε^3              | −3632.58             |
| ε^4              | 7721.81              |
| ε^5              | −7696.55             |
| ε^6              | 2905.13              |
| I                 | n                    |
| 1                | 21.54                |
| ε^2              | −301.69              |
| ε^3              | 1255.1               |
| ε^4              | −2589.24             |
| ε^5              | 2658.24              |
| ε^6              | −1081.74             |
| I                 | Q                    |
| 1                | 11019.1              |
| ε^2              | −46594.95            |
| ε^3              | 94830.59             |
| ε^4              | −91561.01            |
| ε^5              | 33642.93             |
| ε^6              | −0.01688             |
| I                 | a                    |
| 1                | 0.08916              |
| ε^2              | −0.21776             |
| ε^3              | 0.23153              |
| ε^4              | −0.06624             |
| ε^5              | −0.02573             |

Figure 9. Comparisons between predicted values of Arrhenius constitutive model and experimental values at strain rates of (a) 0.01 s^{-1}, (b) 0.1 s^{-1}, (c) 0.5 s^{-1} and (d) 1 s^{-1}.
Coefficient increases gradually with the thermal deformation temperature increasing, and the energy dissipation coefficient expands gradually to high temperature with the strain-rate increasing. When the thermal deformation temperature reaches 1050 °C, the instability zone disappears basically. So, the strain-rate of as-fabricated steel should be strictly controlled during thermal deformation at low and medium temperatures in order to avoid material in the instability zone. The strain-rate of as-fabricated steel can be appropriately increased to increase efficiency due to material having good high temperature plasticity in high temperature zone. The hot forging temperature and strain-rate of as-fabricated steel should be higher than 1050 °C and less than 1s⁻¹, respectively.

**Table 3.** Stress values at different strain rates and temperatures with a strain of 0.5 and 0.7.

| Strain | Strain rate (s⁻¹) | Temperature (°C) |
|--------|------------------|-----------------|
|        |                  | 950  | 1000  | 1050  | 1100  |
| 0.5    | 0.01             | 269.48| 222.02| 196.59| 158.31|
|        | 0.1              | 344.58| 275.91| 258.74| 224.54|
|        | 0.5              | 443.70| 369.17| 327.06| 246.21|
|        | 1                | 497.51| 452.80| 403.20| 329.39|
| 0.7    | 0.01             | 221.06| 207.96| 185.41| 148.21|
|        | 0.1              | 347.72| 285.34| 265.65| 228.93|
|        | 0.5              | 464.10| 385.29| 325.89| 257.34|
|        | 1                | 528.06| 485.34| 436.52| 368.85|

**Figure 10.** Thermal processing maps of as-fabricated specimen at strain (a) 0.5 and (b) 0.7.
4. Conclusion

In the present work, the thermal deformation behavior of nickel-free high nitrogen austenitic Cr18Mn16Mo2.5N0.83Nb0.15 stainless steel fabricated using electroslag remelting technology was investigated and the following conclusions can be drawn:

(1) The stress-strain curves present obvious curve characteristic of dynamic recrystallization type at the strain rate of 0.1s\(^{-1}\), and dynamic recovery type (except for the curve at 950 °C) at the strain rate of 0.5s\(^{-1}\), and work-hardening type at the strain rate of 1s\(^{-1}\).

(2) The value of activation energy is 448.915 kJ mol\(^{-1}\).

(3) The flow stress of the constitutive equation built can be expressed as

\[
\sigma = \frac{1}{\alpha} \ln \left\{ \left( \frac{\delta}{A} \exp \left( \frac{Q}{RT} \right) \right)^{1/\alpha} + \left( \frac{\delta}{A} \exp \left( \frac{Q}{RT} \right) \right)^{\frac{1}{\alpha}} + 1 \right\}^{1/\alpha}
\]

\[
\ln A = 43.13 - 102.85\varepsilon + 796.79\varepsilon^2
- 3632.578\varepsilon^3 + 7721.81\varepsilon^4 - 7696.56\varepsilon^5 + 2905.13\varepsilon^6
\]

\[
n = 8.50 + 21.54\varepsilon - 301.69\varepsilon^2 + 1255.10\varepsilon^3
- 2589.24\varepsilon^4 + 2658.24\varepsilon^5 - 1081.74\varepsilon^6
\]

\[
Q = 530.65 - 1523.0\varepsilon + 11019.10\varepsilon^2
- 46594.95\varepsilon^3 + 94830.59\varepsilon^4 - 91561.01\varepsilon^5 + 33642.93\varepsilon^6
\]

\[
\alpha = 0.00465 - 0.01688\varepsilon + 0.08916\varepsilon^2
- 0.21776\varepsilon^3 + 0.23153\varepsilon^4 - 0.06624\varepsilon^5 - 0.02573\varepsilon^6
\]

(4) According to the analysis of the processing maps established, the hot forging temperature and strain rate should be higher than 1050 °C and less than 1s\(^{-1}\), respectively.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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