Effects of C and La on the Tensile Property and Hot Working Characteristics of CoCrFeMnNi High-Entropy Alloy

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Abstract. CoCrFeMnNi high-entropy alloy series were cast by magnetic suspension vacuum melting furnace. They were forged at 1160°C and annealed at different temperatures. Gleeble3800 thermal deformation simulation testing machine was used to conduct thermal compression simulation to research the hot workability of the alloy. The results show that the microstructures of these alloys are made up of solid solution with face-centered-cubic structure and white granular precipitate \( \text{M}_2\text{C}_6 \). The addition of C and La increases the elongation of CoCrFeMnNi high-entropy alloy forged without annealing by 1.32 times. Annealing deteriorates the tensile properties of these alloys. The constitutive equation and thermal processing diagram of the alloy are established according to the results of thermal simulation. The addition of C and La reduces the flow stress of CoCrFeMnNi high-entropy alloy, but significantly reduces the instability region of thermoplastic deformation. The optimized thermal process parameters are as following: ①CoCrFeMnNi, when the range of the deformation temperature and the strain rate are respectively 900~1040°C and 0.01~0.025s\(^{-1}\), the optimum deformation temperature is 1040~1100°C, and the strain rate is in the range of 0.013~0.033s\(^{-1}\); ②CoCrFeMnNi\(_{C=0.007}\)\(_{La=0.004}\), when the range of the deformation temperature and the strain rate are respectively 1000~1080°C and 0.31~1s\(^{-1}\), the optimum deformation temperature is 1080~1100°C, and the strain rate is 0.01~0.025s\(^{-1}\).

1. Introduction

The traditional alloys, such as steel, aluminium alloy and copper alloy, is made of one or two elements, and by adding a trace number of other elements to achieve the goal of optimizing performance. In 2004, at the first time,Yeh et al.[1] made the point of high-entropy alloys produced by five or more elements simultaneously as the main elements. Stable solid solution phase is formed in high-entropy alloys, and it is not easy to form intermetallic compounds. High-entropy alloy has excellent performance with high hardness, high work hardening, high temperature softening resistance, high temperature oxidation resistance, corrosion resistance and high electrical resistance[1~6]. The microstructure is a high-entropy alloy containing Co, Cr, Fe, Ni, Mn principal elements composed of a single face-centered cubic solid solution phase, which has attracted the attention of scholars[7-11]. While the CoCrFeMnNi high-entropy alloy with equimolar atomic ratio is a typical representative. Because CoCrFeMnNi high-entropy alloy has a single solid solution, and its hardness and strength are lower, moreover, it has better toughness; its strengthening method, processing, the mechanical properties[12], phase formation characteristics[13] and phase stability[13~20] have been widely studied by scholars. F. Otto et al.[20] found that after the CoCrFeMnNi high-entropy alloy is annealed for a long time above 800 °C, the alloy can still maintain a single face-centered cubic (FCC) solid solution phase, while below 800 °C, a second phase precipitation would occur. The authors
believe that the high entropy of the alloy can increase the stability of the solid solution at high temperatures, while at lower temperatures, the change in the enthalpy of the alloy causes the second phase to precipitate. At present, the research on the cold working of CoCrFeMnNi high-entropy alloy has achieved certain results [21~24], but the study on its thermal processing is less. In this paper, the characteristics of hot forging microstructure and tensile properties of CoCrFeMnNi high-entropy alloy with a small amount of solid solution element C and refined grain element La are studied. The hot compression simulation has been carried out by Gleeble 3800 thermal deformation simulation test machine. According to the experimental results, the constitutive equations and thermal processing maps have been established, and the optimized thermal processing technology has been obtained, which provides experimental and theory basis for the thermal processing of CoCrFeMnNi alloy.

2. Experiment Procedure
The experiment materials are pure Co, Cr, Fe, Ni, Mn, La, their purity is 99.9%. The CoCrFeMnNi series high-entropy alloys were cast by magnetic suspension vacuum induction furnace. The element of the CoCrFeMnNi alloy is an equimolar ratio, and the atomic ratio of the elements of the CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄ is 1:1:1:1:1:0.₀₀₇:0.₀₀₀₄. C element was added in the form of a Fe-C intermediate alloy, and the La element was added in the form of a single substance. The melting temperature of the alloy is 1350°C, and the melting time is 10 min. Air cooling treatment was used after melting, and the temperature decreased by 3 to 5°C every two seconds. The ingot was forged at 1160°C, which was naturally cooled in air after forging.

The forged alloys were processed into a heat-treated sample with the size of φ10 mm×9 mm, and heated at a heating rate of 5°C/min to 200°C, 600°C, 700°C, 800°C, 900°C, and 1000°C, and the holding time was 2 h, and cooling with the furnace.

The alloy samples were polished to obtain metallographic samples by aqua regia. The metallographic structures were analyzed by Hitachi S-3400N scanning electron microscope (with energy spectrometer EDAX PV8200) and a 300 KV emission transmission electron microscope (FEI TECNAI G2 F30), and the phases composition of the alloys were analyzed by a ray diffractometer (D/Max 2500V). The tensile test was carried out with an Instron 8801 electronic universal testing machine. The total length of the tensile sample was 50 mm and the gauge length was 18 mm; the gauge length was 2mm wide and 1mm thick, and the tensile speed was 1mm/min. The thermal compression simulation was performed by Gleeble3800 thermal deformation simulation tester. The compressed sample size was Φ8×12mm. During the compression process, the samples were heated to the experimental deformation temperature at a heating rate of 10°C/min and the compression test was performed after the deformation temperature was maintained for 3 minutes. After the compression, the sample was cooled to room temperature with distilled water to maintain the high-temperature deformed structure.

3. Results and Discussion

3.1 Microstructures
Figure.1 is the metallographic microstructures of CoCrFeMnNi, CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄ high-entropy alloy forged at 1160°C(such as (a),(b)) and annealed after forging at 600°C,800°C(such as (c),(d)). There are many twins (such as (a), (b), (c), (d)), dislocation lines (such as (e), (f)) in these forged alloys. Many white particles precipitate at the grain boundary of CoCrFeMnNi alloy, moreover, the number and the size of them are more than those of CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄, which implies that La can decrease the generation of white particles. The results of the energy spectrum analysis of CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄ are shown as Figure.2. For CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄ alloy, C and La are mainly distributed in the grain boundary, and Co, Cr, Fe, Mn, Ni are uniformly distributed in the alloy. After annealing, white particles are also precipitated. The results of line scanning energy spectrum analysis of the samples show that the white particles are rich in C and Cr (such as Figure.2(B)).

Figure.3 shows the results of XRD analysis of CoCrFeMnNi and CoCrFeMnNiC₀.₀₀₇La₀.₀₀₀₄ high-entropy alloys. It can be seen from the Figure3 that the microstructure of these alloys are made up of solid solution with a face-centered cubic structure, M23C6 and a small amount of unknown
phase. According to the result of the spectrum analysis, the white particles are confirmed to be Cr-rich M23C6 type carbides. Since the raw material of Fe has a trace amount of carbon, a small amount of M23C6 is also formed in the CoCrFeMnNi alloy.

Figure 1. Microstructures of CoCrFeMnNi series high-entropy alloys after high temperature forging

Figure 2. Results of the energy spectrum analysis of CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} forged (A) unannealed (B) annealed at 700°C

Figure 3. XRD analysis results of CoCrFeMnNi and CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004}

Figure 4. Room temperature tensile curves of CoCrFeMnNi and CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} high-entropy alloys

3.2 Tensile Property
Through the tensile test, the normal temperature tensile curves of CoCrFeMnNi and CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} high-entropy alloys at different annealing temperatures can be obtained as
shown in Figure. 4, and the tensile data are shown in Table.1.

According to the data of normal temperature stretching, compared to CoCrFeMnNi, the addition of C and La increases the elongation of CoCrFeMnNi high-entropy alloy by 1.32 times, while the tensile strength decreases slightly (about 1.06 %). Annealing after forging deteriorates the tensile properties of these alloys. The tensile strength and the elongation of the CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> high-entropy alloy annealed appear different degrees of decline. When the alloy added C and La is annealed at 600 ~ 900 ℃, with the increase of temperature, tensile strength of the alloy is lower, but the elongation increases, and the higher annealing temperature (1000 ℃) does not strongly reduce the tensile strength of the alloy, but the elongation decrease significantly; however, at low annealed temperature such as 200 ℃, the mechanical property of the alloy is close to that of one annealed at 800 ℃. All in all, the comprehensive mechanical properties of the alloys annealed are inferior to that un-annealed alloys. According to the analysis of the microstructures of the alloy, because of adding trace amount of carbon and carbon dissolves in the FCC solid solution, which has the effect of solid solution strengthening, and the tensile strength increases, but the plasticity drops to a certain extent. However, because the addition of rare earth element La makes the alloy carbide smaller and reduces the number of carbides which distributes at the grain boundary, and reduces the extend of grain boundary weakening, therefore plasticity of the alloy increases. According to Figure.1, there are a large number of dislocation lines, twins in CoCrFeMnNi and CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub>, so the deformation mechanism of these high-entropy alloys is dislocation slip and twinning.

| Alloy                      | Annealing temperature/℃ | Tensile strength σb/MPa | Elongation δ/% | Elastic Modulus E/10<sup>3</sup>MPa | Product of strength and elongation /MPa |
|----------------------------|--------------------------|-------------------------|----------------|-------------------------------------|---------------------------------------|
| CoCrFeMnNi                 |                          | 772.3                   | 22.06          | 70.27                               | 170.36                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> |                          | 764.1                   | 51.23          | 66.65                               | 391.44                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 200                      | 761.9                   | 37.03          | 106.93                              | 282.13                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 600                      | 739.8                   | 44.50          | 118.21                              | 329.21                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 700                      | 776.7                   | 34.70          | 100.96                              | 269.51                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 800                      | 739.0                   | 41.64          | 130.73                              | 307.71                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 900                      | 714.0                   | 44.39          | 110.36                              | 316.94                                |
| CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> | 1000                     | 702.8                   | 48.92          | 66.79                               | 343.80                                |

3.3 Flow stress curve
Plastic deformation consists of three parts: work hardening, dynamic recovery, and dynamic recrystallization. Figure.5 shows the true stress-strain curves of CoCrFeMnNi and CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> high-entropy alloys at different deformation temperatures and strain rates. All the curves show an approximation trend, it means that the peak of the flow stress increases as the deformation temperature decreases and the strain rate increases. It can be seen from the curve that the slope value of the curve tangent is exceptionally large in the initial stage of thermal deformation. Because in the initial stage of plastic deformation, work hardening is produced due to the fracture of crystal grains and the drastic increase in dislocation density. The high dislocation density caused by thermal deformation is the main reason leading to work hardening. It can be seen from Figure.5 that the peak value of the flow stress of the CoCrFeMnNi high-entropy alloy is generally higher than that of the CoCrFeMnNiC<sub>0.007</sub>La<sub>0.0004</sub> high-entropy alloy.
Figure 5. Relationship of different deformation rate, temperature and rheological stress of CoCrFeMnNi and CoCrFeMnNiC0.007La0.0004 high-entropy alloys
(a) Strain rate:0.01%; (b) Strain rate:0.1%; (c) Strain rate:1%; (d) Three-dimensional diagram

3.4 Constitutive Equation
The constitutive equation is a form of mathematical equations that expresses the relationship of the flow stress value, different deformation temperature and strain rate during hot working deformation. Constructing accurate constitutive equations can not only describe the relationship of flow stress value, deformation temperature and strain rate, but also guide the thermal processing of materials.

This paper analyzes the true stress-strain curves obtained under different experimental parameters and fits the constitutive equations of the materials obtained by the relevant parameters. The flow stress reflected by the true stress-strain curve is determined by the deformation temperature and the strain rate. The mathematical expression of the constitutive equation reflecting the mathematical relationship between the flow stress, the deformation rate and the deformation temperature can be expressed as [25]:

\[ \dot{\varepsilon} = \alpha F(\sigma) \exp\left( -\frac{Q}{RT} \right) \] \hfill (1)

\[ F(\sigma) = \begin{cases} \sigma^n & , \quad \alpha \sigma < 0.8 \\ \exp(\beta \sigma) & , \quad \alpha \sigma > 1.2 \\ \sinh(a \sigma)^n & , \quad a \sigma \\ 
\end{cases} \]

The equation is the Arrhenius hyperbolic sinusoid model proposed by Sellars and Tegart[26], which is widely used to reflect the relationship of the three variables. Where \( \dot{\varepsilon} \) represents the strain rate, \( \sigma \) represents the peak flow stress, \( Q \) represents the thermal deformation activation energy, \( A \) (\( A_1, A_2, A_3 \)) is the structural factor (material-dependent constant), \( \alpha \) is the stress level parameter; \( \beta, n_1, n \) represents the stress index, and \( R \) is the gas constant. Take the logarithm of equation (1):

\[ \ln \dot{\varepsilon} = n_1 \ln \sigma + \ln A_1 - \frac{Q}{RT} \] \hfill (2)
\[
\ln \dot{\varepsilon} = \beta \sigma + \ln A \cdot \frac{Q}{RT} 
\]

\[
\ln \dot{\varepsilon} = n \ln \left[ \sinh (\alpha \sigma) \right] + \ln A \cdot \frac{Q}{RT} 
\]  

(3) \hspace{1cm} (4)

Furthermore, the flow stress value can be expressed as a function of the Zener-Hollomon parameter with a temperature compensated strain rate factor, the expression is as follows:

\[
Z = \dot{\varepsilon} \exp \left[ \frac{Q}{RT} \right] 
\]

(5)

The thermal deformation activation energy is expressed as following equation (6):

\[
Q = R \left[ \frac{\partial \left( \ln \dot{\varepsilon} \right)}{\partial \ln \left[ \sinh (\alpha \sigma) \right]} \right]_T \left[ \frac{\partial \ln \left[ \sin (\alpha \sigma) \right]}{\partial \left( 1/T \right)} \right]_T 
\]

(6)

From the \((\ln Z-1000/T)\) function relationship shown in Figure. 6, \(S\) is defined as the slope of the \((\ln Z-1000/T)\) function curve.

The logarithm of equation (5) as equation (7):

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

(7)

According to the fitting results of Figure. 6(a), \(\ln Z\) has an approximately linear relationship with \(\ln[\sinh(\alpha \sigma)]\).

After calculation, the calculation results of each parameter (A, S, \(\alpha\), n, Q) are shown in the Table.2.

The thermal activation energy of CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy is 231.2KJ/mol, and the thermal activation energy of CoCrFeMnNi high-entropy alloy is 278.9KJ/mol. The thermal activation energy of CoCrFeMnNi high-entropy alloy is 20.6% higher than that of CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy.

**Table.2** Calculation of constitutive equation parameters of CoCrFeMnNi and CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloys.

| Alloy                  | Parameter | A   | Q       | \(\alpha\) | n   | S       |
|------------------------|-----------|-----|---------|-------------|-----|---------|
| CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) | exp(24.724) | 231.2 | 0.0068  | 4.566      | 6.0903 |
| CoCrFeMnNi           | exp(29.959) | 278.9 | 0.0068  | 4.845      | 6.9238 |

Thus, the constitutive equation of the CoCrFeMnNi high-entropy alloy is:

\[
\dot{\varepsilon} = e^{29.959} \left[ \sinh (0.0068 \sigma) \right]^{4.845} \exp \left( -\frac{278.97}{RT} \right) 
\]

(8)

The constitutive equation of the CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy is:

\[
\dot{\varepsilon} = e^{24.724} \left[ \sinh (0.0068 \sigma) \right]^{4.566} \exp \left( -\frac{231.161}{RT} \right) 
\]

(9)

In order to test the accuracy of the constitutive equations for the prediction results, the experimental values will be compared with the predicted values. The correlation coefficient value \(R\) is quoted to test the linear correlation between the predicted value and the experimental value.
Figure 6. Correlation analysis between experimental and predicted values of two high-entropy alloys
(a) ln $Z$ and ln[$\sinh(\alpha \zeta)$]; (b) ln $\dot{\varepsilon}$ and ln[$\sinh(\alpha \zeta)$]; (c) ln $\dot{\varepsilon}$ and ln $\sigma$; (d) ln[$\sinh(\alpha \zeta)$] and T-1/10-3; (e) ln $\dot{\varepsilon}$ and $\sigma$; (f) Correlation Analysis of Constitutive Equation of CoCrFeMnNi high-entropy alloy; (g) Correlation analysis of constitutive equations of CoCrFeMnNiC$_{0.007}$La$_{0.0004}$ high-entropy alloy.

Equation (10) can be used to examine the reliability of the measured data and prediction data come from the constitutive equation of the flow stress of the CoCrFeMnNi high-entropy alloy and the CoCrFeMnNiC$_{0.007}$La$_{0.0004}$ high-entropy alloy. The Figure.6 (f) and (g) show the correlation between experimental values and predicted values. The correlation coefficient of CoCrFeMnNi high-entropy alloy is $R=0.99064$ and the correlation coefficient of CoCrFeMnNiC$_{0.007}$La$_{0.0004}$ high-entropy alloy is $R=0.97837$, which reflects the constitutive equation constructed predictability in this paper is more accurate.

$$R = \frac{\sum_{i=1}^{N} (E_i - E_0)(P_i - P_0)}{\sqrt{\sum_{i=1}^{N} (E_i - E_0)^2 (P_i - P_0)^2}}, \quad (10)$$

3.5 Thermal Processing Figure
On the basis of the thermodynamic and physical system models of materials during large plastic deformation, Gegel and Prased et al. [26] proposed a thermal processing map based on dynamic materials. In order to determine the optimal thermal processing conditions of the sample, a thermal processing map of the two kinds of alloys was established based on this dynamic material model. In the hot working process, the energy required for the thermoplastic deformation of a unit volume of the alloy sample is generally composed of two parts, which are expressed by the formula as following:
\[ P = \sigma \varepsilon = G + J = \int_{0}^{\varepsilon} \sigma d \varepsilon + \int_{0}^{\varepsilon} \varepsilon d \sigma \]  \hspace{1cm} (11)

\( G \) refers to the part of the energy that the metal material needs to consume during the thermoplastic deformation process. Most of the energy is dissipated as the viscoplastic heat, and \( J \) represents the energy dissipation caused by the evolution of the microstructure (such as dynamic recovery, recrystallization, etc.) of the material.

In this paper, the strain rate sensitive parameter \( m \) is defined, which can be expressed as:

\[ m = \frac{dJ}{dG} = \frac{\varepsilon d \sigma}{\sigma d \varepsilon} = \frac{\partial (lg \sigma)}{\partial (lg \varepsilon)} \bigg|_{\varepsilon,T} \]  \hspace{1cm} (12)

Prasad, Gegel et al. believe that \( G \) is associated with the generation of dislocations; \( J \) is associated with the consumption of dislocations. Therefore, when \( m=1 \), it means that the generation of dislocations is balanced with the consumption. Currently, the J value reaches the maximum value: \( J_{\text{max}} = \sigma \varepsilon / 2 \). The definition of \( \eta \) represents the power dissipation efficiency factor, which is defined as:

\[ h = \frac{J}{J_{\text{max}}} = \frac{P - G}{\sigma \varepsilon / 2} = 2(1 - \frac{\int_{0}^{\varepsilon} \sigma d \varepsilon}{\sigma \varepsilon}) \]  \hspace{1cm} (13)

According to the definition of \( \eta \), it can be seen that \( \eta \) reflects the ratio of the energy consumed by the change of microstructure during the thermal deformation of the material to the total energy consumed. Therefore, the value of \( \eta \) can reflect the process ability of the material to some extent. Prased et al. based on the maximum entropy production rate theory, according to the Murty instability criterion, the material instability expression is:

\[ \xi(\varepsilon) = \frac{\partial lg (\frac{m+1}{m})}{\partial lg (\varepsilon)} + m < 0 \]  \hspace{1cm} (14)

The spline interpolation method in the Orgin 8.0 software is used to plot the contour map of the dissipative efficiency factor (\( \eta \)) on the plane of the T and \( lg \varepsilon \), that is, the dissipative map. The heat dissipation map is obtained by superimposing the dissipation map and the instability map. The hot working diagrams of CoCrFeMnNi and CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy are shown in Figure.7. The gray area is represented as a destabilized area. It can be seen from the Figure.7 that the instability zone of CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy is mainly concentrated in the low temperature region, and the instability zone of CoCrFeMnNi high-entropy alloy is mainly concentrated in the high strain rate region. And the instability zone of CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\) high-entropy alloy is obviously smaller than the instability zone of CoCrFeMnNi high-entropy alloy.

The region of CoCrFeMnNi high entropy alloys with high dissipation values include two areas, one is the area with the temperature of 900–1040°C and the strain rate of 0.01–0.025s\(^{-1}\), the other is the area with the temperature of 1040–1100°C and the strain rate of 0.013–0.033s\(^{-1}\); And for CoCrFeMnNiC\(_{0.007}\)La\(_{0.0004}\), two areas are: 1000–1080°C, 0.31s\(^{-1}\)–1s\(^{-1}\) and 1080–1100°C, 0.01–0.025s\(^{-1}\). The region with high dissipation value of high entropy alloy is suitable for high-temperature processing of materials, while the instability zone is located in the oblique region in the Figure.7.
4. Conclusion

A series of CoCrFeMnNi high-entropy alloys were cast by magnetic suspension vacuum melting furnace. They were forged at 1160 °C and annealed at different temperatures. The effect of C and La elements and annealing process on the microstructures and the tensile properties of these alloys were studied. Thermal compression simulation was proceed by the Gleeble 3800 thermal deformation simulation test machine to research the hot workability of the alloys. The results show as following:

1. The microstructures of CoCrFeMnNi high-entropy alloys forged at high-temperature are made up of solid solution with face-centered-cubic (FCC) structure and white granular precipitate M23C6. The addition of C and La increases the elongation of CoCrFeMnNi high-entropy alloy by 1.32 times, while the tensile strength decreases little (about 1.06 %). Annealing after forging deteriorates the tensile properties of these alloys.

2. The peak values of the flow stress of the two high-entropy alloys increase with the decrease of the deformation temperature and the increase of the strain rate.

3. The constitutive equations of CoCrFeMnNi high-entropy alloy and CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} high-entropy alloy are obtained by parameter fitting as following:

\[ \dot{\varepsilon} = e^{29.959} \left[ \sinh(0.0068\sigma) \right]^{1.845} \exp \left( \frac{-278.97}{RT} \right) \]

\[ \dot{\varepsilon} = e^{24.724} \left[ \sinh(0.0068\sigma) \right]^{4.566} \exp \left( \frac{-231.161}{RT} \right) \]

In order to verify the accuracy of the constitutive equation prediction, the regression equations of experimental data and prediction data are obtained respectively. For the CoCrFeMnNi high-entropy alloy, the correlation coefficient is R=0.991; for the CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} high-entropy alloy, the correlation coefficient is R=0.978. The predicted value of the constructed constitutive equation is dependable.

4. According to the dynamic material model, the thermal processing diagrams of CoCrFeMnNi and CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004} high-entropy alloys are established. Optimum thermal processing parameters for two alloys based on thermal processing are as following: ①CoCrFeMnNi, when the range of the deformation temperature and the strain rate are respectively 900~1040°C and 0.01~0.025s\textsuperscript{-1}, the optimum deformation temperature is 1040~1100°C, and the strain rate is in the range of 0.013~0.033s\textsuperscript{-1}; ②CoCrFeMnNiC\textsubscript{0.007}La\textsubscript{0.0004}, when the range of the deformation temperature and the strain rate are respectively 1000~1080°C and 0.31~1s\textsuperscript{-1}, the optimum deformation temperature is 1080~1100°C, and the strain rate is 0.01~0.025s\textsuperscript{-1}; Moreover, the addition of C and the rare earth element La reduces the high temperature rheological instability region of the CoCrFeMnNi high-entropy alloy.
5. Acknowledgements
The authors gratefully acknowledge the financial support for this research by the Project Sponsored by National University Student Innovation and Entrepreneurship Program (Grant No.201810593054).

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