Effect of La-Ce Mixed Rare Earth on High Temperature Deformation Behavior of 685 Armor Steel and Its Mathematical Model

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Abstract. A thermal simulation test machine was used to conduct high-temperature compression tests on two sets of 685 test steels with and without rare earths. Through linear fitting analysis and microstructure observation, the effect of rare earths on the high-temperature deformation behavior of 685 armored steel was studied. The results show that when the deformation temperature is 1000°C, La-Ce mixed rare earth can increase the deformation resistance of steel, and the influence varies with the amount of compression deformation, while at 1100°C, the rare earth has no obvious influence on the deformation resistance of steel. After adding rare earth, the recrystallization activation energy of steel is increased by 6.78%. Mixed rare earth (La-Ce) has an inhibitory effect on the recrystallization of steel. Using Origin8.0 software for regression analysis, a mathematical model of armored steel containing rare earths is established. The model has good curve fitting characteristics, and the calculated values are basically in agreement with the experimental values.

1. Introduction
The thermoplastic deformation of steel can improve the size, shape and distribution of inclusions, change the microstructure morphology through dynamic recrystallization, and improve mechanical properties. Most of the steel in my country is hot-rolled section steel and hot-rolled steel plate. Through the hot rolling process, the coarse grains in the steel ingot can be broken and the steel
structure can be compacted. The deformation behavior of the steel in the austenite region is the basis of the control rolling theory. A good rolling process can improve the performance of steel[1-6].

685 armored steel has high strength and hardness, and is the main material for impact protection of armored vehicles such as tanks. Since 685 steel is generally hot-rolled after smelting, strict hot-rolling processes are required to ensure the performance requirements of the steel [7-8]. At present, the domestic and foreign literature on the application research of anti-impact protective steel mainly focuses on the heat treatment process and the anti-elasticity properties[9-11], and there is less research on the hot rolling process of steel.

Rare earths are known as "vitamins in steel" and their functions are mainly to purify molten steel, metamorphic inclusions, microalloying, etc. Adding very small amounts of rare earth elements to steel can significantly improve the structure and performance of steel. At present, researches on the application of rare earths in steel are mainly focused on the structure and mechanical properties at room temperature, but there are few studies on the high temperature mechanical behavior of rare earths on steel[12-14]. For this reason, this article takes 685 armored steel as the research object. By adding traces of mixed rare earth La and Ce to the steel, the effect of rare earth on the high temperature deformation behavior of steel is studied, and the structure after high temperature compression is observed and analyzed. Finally, the establishment of adding rare earth The mathematical model of the back steel provides a reference for the rolling process of rare earth armored steel.

2. Test materials and methods
The experimental materials are two sets of steel ingots after smelting and forging by Hebei Iron and Steel Research Institute, numbered 1#, 2#, 1# steel ingot does not contain rare earth, 2# steel ingot contains rare earth, and the chemical composition is shown in Table 1.

The Gleeble-1500D thermal simulation testing machine of Inner Mongolia University of Science and Technology was used for high temperature compression test. The sample size is Φ8×15 mm. The sample was heated to 1000°C and 1100°C at 10°C/s respectively, and after holding for 3 minutes, a single-pass compression test was carried out at a strain rate of 1s⁻¹. The deformation at each test temperature was 20% and 30%. Then air-cooled to room temperature to obtain stress-strain curves at different temperatures and deformations. The compressed sample is chemically eroded for tissue observation.

| Table 1. Chemical composition of steels after smelting (% mass fraction) |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| No. | C    | Si    | Mn    | P    | O    | S     | Cr    | Ni    | Mo    | V     | Nb    | Ce    | La    |
| 1#  | 0.34 | 0.34  | 1.00  | 0.010| 0.0046| 0.004| 1.05  | 2.03  | 0.43  | 0.19  | 0.033 | -     | -     |
| 2#  | 0.36 | 0.33  | 0.98  | 0.008| 0.0024| 0.002| 1.02  | 2.01  | 0.43  | 0.19  | 0.032 | 0.0059| 0.0043|

3. Results and discussion

3.1. Influence of rare earth on the deformation resistance of steel
Figure 1 shows the true stress-strain curves of the steel samples with and without rare earth. The curves have similar trends for the two steels under different temperature and compression
At fixed deformation temperature and strain rate, the stress increased rapidly with increasing strain ($\varepsilon$) when $\varepsilon \leq 0.05$, showing a strong work hardening characteristic. When $\varepsilon > 0.05$, the stress increase slowed down with increasing strain, and dynamic recovery and recrystallization softening occurred in conjunction with the work hardening, so that the curve tended to be flat. In addition, a comparison of Figures 1(a)–(d) reveals that under the same amount of compression deformation, the deformation resistance significantly decreases when the temperature rises from 1000°C to 1100°C. As the deformation temperature increases, the dislocation slip resistance caused by plastic deformation decreases, and dynamic recovery and recrystallization are more likely to occur, thus reducing the deformation resistance.

It can be seen from Figures 1(a) and (b) that when the compression deformation temperature is 1000°C, the curve of 2# was always above that of 1# without rare earth. However, the curve deviation of the two groups of test steel with 30% compression deformation was less than 20% compression deformation. At 1000°C, the peak stress of 2# was 9.6% and 23.8% higher than that of 1# when the compression deformation was 30% and 20%, respectively. At 1100°C, the true stress-strain curves of 1# and 2# basically agree, as shown in Figures 1(c) and (d). These results indicate that the addition of rare earth increased the deformation resistance of steel at 1000°C, and the degree of compression deformation varied with the amount of compression deformation, while rare earth had little effect on the deformation resistance at 1000°C.

When the steel was compressed and deformed at 1000°C, rare earths can reduce the activity coefficient of carbon and alloying elements in austenite, hinder their diffusion, and de-aggregate at or near the grain boundaries. Thus, the movement of dislocations is hindered and the deformation resistance is increased\(^{[13]}\). When the compression deformation increases, the dislocation density increases. At a higher temperature of compression deformation, more dislocations will participate in the slip, reducing the deformation resistance\(^{[2,3,15]}\). From 1000°C to 1100°C, the effect of rare earth on carbon and alloying elements is weakened due to the increase of deformation temperature. Meanwhile, the enhanced thermal vibration of atoms facilitates the dislocation slip and atomic diffusion. A higher temperature is also conducive to dynamic recovery and recrystallization, thus reducing the deformation resistance\(^{[13]}\).
3.2. The effect of rare earth on the structure of test steel

Figure 2 shows the structure of the test steel after high temperature compression of 20% at different deformation temperatures. It can be seen that the two groups of test steels undergo dynamic recovery and recrystallization at various deformation temperatures. Comparing Figures 2(a)–(b) and Figures 2(c)–(d), it can be seen that when the deformation temperature is 1000 °C, the original austenite grain deformation zone can be clearly seen, the grains are coarse and uneven, and the test steel mainly becomes dynamic recovery with accompanying There is some dynamic recrystallization; when the deformation temperature is 1100°C, the austenite grains are relatively uniform and fine, and a large amount of dynamic recrystallization occurs, which is reflected in the stress-strain curve as an obvious dynamic recrystallization softening behavior, thereby reducing the deformation resistance.

Comparing Figures 2(a) and (c), it can be seen that 2# test steel containing rare earth has larger and uneven grains than 1# test steel without rare earth when compressed at a high temperature of 1000°C. Rare earth compounds appear around the grain boundaries of 2# test steel. It shows that rare earth has an inhibitory effect on dynamic recrystallization during high temperature compression at 1000°C, thereby improving the deformation resistance; while at high temperature compression at 1100°C, the grain sizes of the two groups of test steels are basically the same, as shown in Figures 2(b) and (d). It shows that the temperature rises, the rare earth weakens the inhibitory effect on dynamic recrystallization, and the deformation resistance decreases, so that the two sets of test steel stress-strain curves appear consistent characteristics as shown in Figure 1(c).

3.3. The effect of rare earth on the activation energy of recrystallization

Under the condition of low strain rate $\dot{\varepsilon}$, the relationship between deformation temperature T, recrystallization activation energy Q and flow stress with Zener-Hollomon parameter Z is as follows:
\[ Z = \dot{\varepsilon} \exp(Q/RT) = F(\sigma) \]  

(1)

In the formula: R is the gas constant, generally; T is the deformation temperature, K. The flow stress can be expressed by the Arrhenics equation. In order to facilitate the measurement, this experiment uses the peak stress as the research, namely:

\[ F(\sigma) = A\sigma^n = \dot{\varepsilon} \exp(Q/RT) \]  

(2)

In the formula: A is the structural factor; \( \sigma_p \) is the peak stress; n is the stress index. The logarithm and partial guidelines for Equation (2) are:

\[ n \ln \sigma_p = \partial \ln \dot{\varepsilon} + Q/R \partial(1/T) \]  

(3)

When the temperature T is a fixed value, it can be obtained by Equation (3):

\[ n = \partial \ln \dot{\varepsilon} / \partial \ln \sigma_p \]  

(4)

When the strain rate \( \dot{\varepsilon} \) is a constant value, it can be obtained from Equation (3):

\[ Q = nR \partial \ln \sigma_p / \partial(1/T) \]  

(5)

At a low strain rate, when the strain rate does not change, strain 2 corresponding to peak stress \( \sigma_p \) can be used instead of strain rate 3. Substituting the measured test data into the corresponding relational formula, the recrystallization activation energy of the test steel can be obtained. The specific results are shown in Table 2.

| No. | n     | \( \partial \ln \sigma_p / \partial(1/T) \) | Q (kJmol\(^{-1}\)) |
|-----|-------|------------------------------------------|--------------------|
| 1#  | 11.02 | 5421.91                                  | 496.76             |
| 2#  | 9.67  | 6597.46                                  | 530.41             |

It can be seen from Table 2 that after adding rare earth, the recrystallization activation energy of the test steel increased from 496.76 kJ/mol to 530.41 kJ/mol, an increase of 33.65 kJ/mol, an increase of 6.78%, which shows that the rare earth has the effect of delaying recrystallization.

4. Mathematical Model of Deformation Resistance of Test Steel Containing Rare Earth

4.1. Mathematical model establishment

In order to better study the high temperature deformation behavior of armored steel containing rare earths, according to the principle of establishing the mathematical model of metal deformation resistance, through the analysis of the influence factors of deformation resistance, and the comparison and accuracy analysis of the mathematical model of metal plastic deformation resistance, it is determined that rare earths are contained. The mathematical model of test steel deformation resistance is \[^4\]:
\[ \sigma = \frac{A}{T}e^{b*\varepsilon - (b + c*\varepsilon)} \]

In the formula: \( \sigma \) is the deformation resistance, MPa; \( T \) is the absolute temperature, K; \( \varepsilon \) is the true strain; \( A, a, b, \) and \( c \) are data related to the material. In order to establish a suitable mathematical model, Origin8.0 software is used to perform regression analysis on the obtained test results. After many debugging, a more accurate mathematical model of deformation resistance is obtained as follows:

\[ \sigma = (3.8\times10^5/T)e^{0.5*\varepsilon - (0.003+1.6\varepsilon)} \]

4.2. Comparison of regression value and measured value

In order to verify the accuracy of the deformation resistance, the calculated value of the model and the test value were compared and analyzed. The analysis result is shown in Figure 3. It can be seen from Figure 3 that the experimental value is basically consistent with the calculated value of the prediction model.

![Figure 3](image)

**Figure 3.** Comparison of regression and calculated values

It can be seen from Figures 3(a) and (b) that at a deformation temperature of 1000°C, the compression deformation is 20%, the maximum error between the experimental value and the calculated value is 3.21 MPa, and the compression deformation is 30%, and the maximum error between the experimental value and the calculated value is 5.62 MPa; from Figure 3(c), D It can be seen that at the deformation temperature of 1100°C, the compression deformation is 20%, the maximum error between the test value and the calculated value is 3.54 MPa, the compression deformation is 30%, and the maximum error between the test value and the calculated value is 5.42 MPa. It can be seen that the test value is in good agreement with the calculated value. The mathematical model is suitable for the test plan. When the compression deformation is 20%, the error is smaller. The test result can provide a basis for the formulation of the test plan.
5. Conclusions

(1) When the strain is less than 0.05, as the strain of the test steel increases, the deformation resistance increases significantly, which is characterized by work hardening. When the strain is greater than 0.05, the change in deformation resistance tends to be gentle, which is manifested by work hardening and dynamic recovery and renewal. Comprehensive effect of crystal softening.

(2) When the deformation temperature is 1000°C, rare earth can increase the deformation resistance of armor steel, and the degree of improvement varies with the amount of compression deformation; while at 1100°C, rare earth has no obvious effect on the deformation resistance of the test steel. The deformation temperature rises from 1000°C to 1100°C, and the deformation resistance is significantly reduced;

(3) The mixed rare earths La and Ce have the effect of delaying recrystallization. After adding rare earths, the recrystallization activation energy of 685 armored steel increased from 496.76 kJ/mol to 530.41 kJ/mol, an increase of 6.78%.

(4) Use Origin8.0 software to perform regression analysis on the selected mathematical model, and obtain the mathematical model of deformation resistance of rare earth-containing armor steel: 

\[ \sigma = (3.8 \times 10^7/T)^*e^{0.5}*\exp[-(0.003+1.6e)] \]

this mathematical model is suitable for deformation rate of 1 s\(^{-1}\), deformation temperature of 1000°C, 1100°C, and compression deformation of 20% and 30%.

6. References

[1] Chu Liang, Xie Tan, Zhong Zhiping 2017 High temperature compression deformation behavior experiment of S34Mn V steel Forging Technology 42 155-158

[2] Li Yanfeng 2017 The effect of rare earth Ce on the high temperature deformation behavior of IF steel Henan Metallurgy 25 5-7

[3] SONG Shenhua ,XU Yewei , CHEN Xianmiao,et al 2013 Effect of rare earth cerium and impurity tin on the hot ductility of a Cr-Mo low alloy steel Science Direct 34 1062-1068

[4] Wang Lijun, Yu Wei, Wu Huibin, etc 2010 High temperature deformation behavior and mathematical model of 12MnNiVR steel Heat Treatment of Metals 35 5-8

[5] Huang Shiquan, Yi Youping, Li Pengchuan 2011 High temperature deformation behavior of 23Co13Ni11Cr3Mo ultra-high strength steel Chinese Journal of Materials Research 25 283-288

[6] Cui Zhanquan, Wang Kunlin, Wu Run 2010 Metal Science and Heat Treatment (Beijing: Peking University Press) pp 179-228

[7] I.G. Crouch, S.J. Cimpoeru, H. Li, et al 2017 Armour steels The Science of Armour 2 67-77

[8] Zhang Ziqiang, Zhao Baorong, Zhang Ruisheng, etc 2000 Armor protection technology basis (Beijing: Ordnance Industry Press) pp 29-185

[9] P K Jena, Bidyapati Mishara, M Ramesh Babu,et al 2010 Effect of heat treatment on mechanical and ballistic properties of a high strength armour steel International Journal of Impact Engineering 37 242-249

[10] S Ryan, H Li, M Edgerton, et al 2016 The ballistic performance of an ultra-high hardness armour steel: An experimental investigation International Journal of Impact Engineering 94 60-73
[11] Li Xiaoyuan, Shi Jie, Dong Han 2008 The effect of material factors on the elastic performance of armored steel plates *Journal of Iron and Steel Research* **20** 1-4

[12] 2017 *The 9th China Baotou Rare Earth Industry Forum Rare Earth New Material Industry and Technological Innovation Expert Report Collection* (Baotou: China Baotou Rare Earth Industry Forum Organizing Committee)

[13] Li Chunlong 2013 New progress in the application and research of rare earths in steel[J]. *Rare Earths* **34** 78-83

[14] Wang Chunrong 2014 The effect of rare earth on the structure and properties of steel materials *Hot Working Technology* **43** 13-16

[15] Xu Guangxian 2002 *Rare Earth (Part 2)* (Beijing: Metallurgical Industry Press) pp 418-462