Research on the Effect of Rare Earth on the Structure and Impact Performance of Armor Steel

Mingyi Zhang¹,²*, Ping Gao¹, Guoping Luo², Wenyuan Geng¹ and Xiaobin Jia³

¹Inner Mongolia Institute of Metal Materials, Baotou 014034, China
²School of Materials and Metallurgy, Inner Mongolia University of Science and Technology, Baotou 014010, China
³Inner Mongolia North Heavy Industry Group co. Ltd, Baotou 014034, China

*Corresponding author: 190991544@qq.com

Abstract. In order to study the impact performance of 685 armored steel with different mischmetal content, the impact performance of the steel at room temperature and -40 ℃ was tested, and the impact fracture morphology and microstructure were observed and analyzed. The results show that the addition of mixed rare earth La-Ce to the test steel improves the tempered martensite structure and refines the austenite grains. At the same time, the inclusions in the steel are modified, and the elongated MnS inclusions are modified. It is a spherical composite rare earth inclusion, and the size of the inclusion is reduced from 6μm to 2μm. Compared with the test steel without rare earth, the room temperature impact performance of the mixed rare earth test steel and the -40 ℃ low temperature impact performance are improved. When the La-Ce content is 102×10⁻⁶, the room temperature impact energy of the protective steel increases by 24.5%, and the low temperature impact energy at -40 ℃ increases by 17. 4%. The results of the shooting test showed that the protection level of rare earth-containing armored steel reached NATO Level 2.

1. Introduction

Traditional foreign armored steels include Sweden's Armox series armored steel[1], American MIL series armored steel[2] and Australia's BISALLOY series armored steel[3], etc. The chemical composition and main properties of armored steel are shown in Table 1[1-3].

There are 685, 616 and other series of traditional armored steel in our country. The steel contains more precious alloy elements such as Cr and Ni, which make the steel itself have high strength and hardness. It is the main material for impact protection of armored vehicles such as tanks. However, the traditional armor steel is a quenched martensitic steel, and it is difficult to obtain ultra-high strength while possessing high toughness and plasticity, especially low-temperature impact toughness[4]. In recent years, with the rapid development of industry and technology, the performance requirements of
anti-impact protection steel have become higher and higher. It is required not only to have higher strength and hardness to meet the needs of normal protection, but also to have a certain impact toughness. Ensure that the material does not cause back collapse or brittle fracture during impact protection[5-7].

Rare earth is known as the "vitamin" in steel. Its role in steel is mainly focused on improving the shape of inclusions, refining grains, and powerful microalloying. Adding a very small amount of rare earth elements to steel can significantly improve the organization and performance of steel materials[8]. Many scholars have done research on the impact of rare earth on the impact performance of steel, and have achieved certain results. For example, adding appropriate amount of rare earth to steel such as ship plate steel, pipeline steel, and heat-resistant steel, the impact performance of steel All have different degrees of improvement, and the improvement of low temperature impact performance is particularly obvious [9-10]. Based on the research of others, this paper studies the influence of mixed rare earth La-Ce on the structure and impact performance of 685 armored steel plate, so as to provide reference for the application research of rare earth in armored steel.

| Table 1. Compositions and properties of typical ultra-high strength armor steels[4-6] |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Steel                          | Composition(mass fraction/%) | YS (MPa) | UTS (MPa) | EL (%) | Hardness HB | As(20℃)J |
| Armox 440T                     | 0.21 1.2 0.5 1.0 2.5 0.7 0.005B | 1100 | 1500 | 10 | 420~480 | 45(-40℃) |
| Armox 500T                     | 0.32 1.2 0.27 1.0 1.8 0.7 0.005B | 1250 | 1600 | 8 | 480~540 | 32(-40℃) |
| Armox 600T                     | 0.47 1.0 0.4 1.5 3.0 0.7 0.003B | - | 2000 | 7 | 570~640 | 12(-40℃) |
| MIL-46100                      | 0.28 0.9 0.53 0.3 0.19 0.24 0.003Ti+0.18Cu | 1050 | 1750 | 12 | 480~540 | 25(-40℃) |
| UHT440                         | 0.25 1.4 0.6 1.2 0.5 0.35 0.002B | 1150 | 1450 | 14 | 420~480 | 16(-40℃) |
| HHA500                         | 0.32 0.8 0.5 1.2 0.5 0.3 0.002B | 1350 | 1640 | 14 | 477~534 | 16(-40℃) |

2. Test materials and methods

The experimental material is 685 armored steel plates smelted, forged and rolled by the Central Iron and Steel Research Institute, which are divided into 3 groups, numbered 1#, 2#, and 3#. 1# tests steel does not contain rare earths, 2# tests steel contains mischmetal La and Ce total 59×10⁻⁶, and 3# tests steel contains mischmetal La and Ce total 102×10⁻⁶. The chemical composition is shown in Table 2.

| Table 2. The chemical composition of steel tested 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#  | 0.34 | 0.32 | 0.96 | 0.009 | 0.0032 | 0.003 | 1.06 | 2.05 | 0.43 | 0.18 | 0.033 | 0.0034 | 0.0025 |
| 3#  | 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 |

After the steel plate is homogenized and annealed, in accordance with the requirements of GB/T 2975-2018 "Sampling Location and Sample Preparation for Mechanical Properties Test of Steel and Steel Products", a transverse sample blank is taken at 1/4 of the width of the steel plate, and the sample
size is 10 mm×12 mm×58 mm, each group of test steels shall take 6 samples, including 3 samples per group for room temperature impact and 3 samples per group for -40 °C low temperature impact. Put the sample into a box-type resistance furnace for heat treatment. The heat treatment process is 850°C×1 h oil cooling + 200 °C×1 h air cooling. After the heat treatment is completed, prepare U-shaped impact specimens in accordance with GB/T 229-2007 "Charpy Pendulum Impact Test Method for Metallic Materials", the size of the specimen is 7.5 mm×10 mm×55 mm, U-shaped groove opening. The direction is perpendicular to the rolling surface.

The shooting test uses a 1951 type B 7.62 mm steel core pistol, the test temperature is normal temperature, and the shooting distance is 5m; According to the requirements of GB/T232-1999 "Metallic Material Bend Test", the steel plate is subjected to bending test, and the specimens are prepared by electric spark cutting at different positions of the steel plate. The size of the specimen is 200 mm×20 mm×4.5 mm; According to GB/T22-2002, the welded joint strength test of the rare earth impact-resistant steel plate was carried out on the UNT-300 universal electronic testing machine.

3. Results and discussion

3.1. The effect of mixed rare earth La-Ce on the structure of test steel

Figure 1 shows the metallographic structure of 1# test steel (excluding Re) and 3# test steel (Re solid solution content 102×10^{-6}). It can be seen that the metallographic structure of 1# and 3# test steel is mainly tempered martensite structure, the tempered martensite structure of 1# test steel has flaky and obvious black needle-like characteristics, and that of 3# test steel The tempered martensite structure is characterized by small flakes, fine needles and inconspicuous, indicating that rare earth can refine the tempered martensite structure of steel.

![Figure 1. Microstructure of steel tested before and after adding Re](image)

Data[11] indicates that low-carbon martensite will separate and resolve flaky carbides during low-temperature tempering, and the addition of rare earth elements to steel can inhibit the decomposition of low-carbon martensite during low-temperature tempering, and hinder the flaky Cementite precipitates and delays its growth process. Other data show that[12-13] rare earths concentrated on grain boundaries are easy to combine with carbon to form REC3, RE2C3 and other rare earth carbides with high melting points, and the rare earth carbides are difficult to exist stably, and can only be replaced by cementite The Fe atoms in the alloy form cementite, which makes the carbides
finer. This may be the reason why the tempered martensite structure of the steel after the addition of rare earths is fine and not obvious.

Comparing the grain size of 1# test steel and 3# test steel, as shown in Figure 2, it is not difficult to find that the grain size of 1# test steel is larger than that of 3# test steel. According to GB/T 6394—2017 "Metal Average Grain Size Measurement Method", its grain size is rated, the grain size of 1# test steel is 4.5 to 8.5, and the grain size of 3# test steel It is Grade 7 to Grade 10, indicating that adding mixed rare earth La and Ce to the impact-resistant protective steel can play a role in refining the grain, and then refine the structure of the steel. This is because rare earths are surface-active substances, which are easy to adsorb on the grain boundaries, which reduces the surface tension of the grain boundaries, and reduces the driving force required for the formation of crystal nuclei at the grain boundaries, which facilitates nucleation[14-15]. The fine rare earth inclusions have a pinning effect on the grain boundaries. The rare earths in solid-dissolved steel are concentrated on the grain boundaries and may drag the grain boundaries and hinder the migration of the grain boundaries, thereby inhibiting the growth of grains[16-17].

![Figure 2. Grain size of steel tested before and after adding Re](image)

3.2. Influence of Mixed Rare Earth La-Ce on Inclusions in Test Steel

Figure 3 shows the scanning SEM spectra and corresponding EDS spectra of inclusions in the dimples of the 1# test steel and 3# test steel at room temperature impact fracture. It can be seen from Figure 3a that in the 1# test steel that does not contain rare earths, the shape of the inclusions is long and the length is about 6 μm; It can be seen from Figure 3b that in the 3# test steel containing mixed rare earth 102×10^{-6}, the shape of the inclusions is spherical, and the diameter is about 2 μm. Compared with the 1# test steel, the inclusion length is reduced by 4 μm. It shows that the morphology and size of the inclusions have changed after adding the mixed rare earth to the impact-resistant protective steel, and the inclusions have changed from long strips to spherical shapes and reduced in size.

It can be seen from the energy spectrum of Figure 3c that the inclusions of the 1# test steel are mainly MnS inclusions and a small amount of carbides; from the energy spectrum of Figure 3d, it can be seen that the inclusions formed by the 3# test steel are mainly mixed rare earths La, Ce of sulfur oxides. It can be seen that after the mixed rare earth La and Ce are added to the test steel, the rare earth La and Ce interact with the oxygen and sulfur in the steel to generate rare earth sulfur oxides, which changes the size and morphology of the inclusions, thereby causing deterioration. The role of inclusions. The strip-shaped MnS inclusions have strong plasticity. The steel will elongate in the rolling direction during the rolling process, thus exhibiting the characteristics of long strips. Rare earth
elements are added to the steel. Because it is very active, it is easy to interact with the steel. Oxygen, sulfur and other elements react to produce spherical rare earth oxysulfides with high melting point and high hardness, which will not elongate in the rolling direction during rolling, and spherical inclusions also reduce the stress concentration caused by inclusions and are not prone to transverse fracture, thereby improving the impact performance of the steel plate[18-20].

![Figure 3. SEM and EDS diagrams of inclusion in the steel before and after adding Re](image)

a: SEM image of 1# steel inclusion; b: SEM image of 3# steel inclusion; c: EDS analysis of 1# steel inclusion; d: EDS analysis of 3# steel inclusion.

3.3. Effect of Mixed Rare Earth La-Ce on Impact Performance of Test Steel

3.3.1. Impact performance.

Figure 4 and Table 3 show the impact test results of test steels with different mixed rare earth contents at room temperature and -40°C low temperature. The average value of 3 impact tests for each group of test steels is taken. It can be seen from Figure 4 that with the increase of the amount of rare earth in the steel, the room temperature and -40°C low temperature impact properties of the test steel increase. It can be seen from Table 3 that the average room temperature impact energy of the 1# test steel without rare earth is 25.3 J, and the average low temperature impact energy at -40°C is 23.5 J; the 2# test with a rare earth content of 59 × 10^{-6}. The average room temperature impact energy of steel is 27.2 J, and the average value of -40°C low temperature impact energy is 25.7 J. Compared with 1# test steel, the room temperature impact energy has increased by 7.5%, and the -40°C low temperature impact energy An increase of 9.4%; the room temperature impact energy of the 3# test steel with a rare earth content of 102 × 10^{-6} is 31.5 J, and the -40°C low temperature impact energy is 27.6 J, which is an increase of 24.5% compared with the room temperature impact energy of the 1# test steel. -40°C low temperature impact energy increased by 17.4%. This shows that adding mixed rare earths La and Ce to impact resistant protective steel can effectively improve the impact performance of steel.
3.3.2. Fracture morphology.

The impact fracture morphology of the test steel is shown in Figure 5. It can be seen from Figures 5a, 5b, and 5c that under impact at room temperature, the impact fracture of the 1# test steel shows the characteristics of quasi-cleavage + dimple mixed fracture, the dimples are shallow, the number is small, and there are long strips of inclusions in the dimples. Steel has the lowest room temperature impact performance; the impact fractures of 2# test steel and 3# test steel show the characteristics of dimple fracture. There are fine granular inclusions in the dimples, and the size of the inclusions is significantly smaller than 1# test steel, so the impact performance is higher than 1# test steel; Compared with 3# test steel, 2# test steel has fewer dimples, uneven size distribution, larger inclusion size, and lower impact performance than 3# test steel; 3# test steel’s toughness The number of nests is large, the size distribution is relatively uniform, the size of inclusions is small, and the impact performance is the best.

Table 3. Average value of impact energy absorbed by each group of test steels

| Samples of test steel | 1#   | 2#   | 3#   |
|-----------------------|------|------|------|
| Room temperature impact (AKu) (J) | 25.3 | 27.2 | 31.5 |
| −40 °C impact (AKu)(J) | 23.5 | 25.7 | 27.6 |
It can be seen that in terms of room temperature impact performance, the addition of mixed rare earth to steel can form fine rare earth inclusions, which is beneficial to the formation of dimples, increases the number and depth of dimples, and improves the room temperature impact performance of steel. When the content of rare earth is higher, the size of rare earth inclusions formed is smaller and the number of dimples increases, which is beneficial to improve the impact performance of steel. Therefore, the impact performance of the test steel is improved through the effect of rare earth metamorphic inclusions.

It can be seen from Figures 5d, e, and f that the fracture of the test steel under low temperature impact at -40 °C is a quasi-cleavage fracture. Quasi-cleavage fracture is a kind of micro-fracture that basically belongs to the range of brittle fracture, and it is a transition form between cleavage fracture and dimple fracture. It can be seen that there is a small amount of dimples along the grain in a local area on the fracture of the test steel, indicating that there is a small amount of plastic deformation locally when the material fractures. The number of crystalline dimples on the quasi-cleavage fracture of 1# test steel is the least, indicating that the test steel participates in less plastic deformation during low-temperature impact and almost brittle fracture; the number of crystalline dimples on the fracture of 2# test steel is more, and the test steel There is greater plastic deformation during low temperature impact, and the low temperature impact toughness is higher than 1# test steel; the 3# test steel has the largest number of dimples along the grain and the largest plastic deformation during impact fracture. The spherical rare earth inclusions in the dimples will not produce obvious stress concentration when subjected to impact load, and the low temperature impact toughness is the best. It can be seen that the increase in the amount of rare earths in the steel during low temperature impact at -40 °C is beneficial to increase the number of intergranular dimples on the quasi-cleavage fracture. The formation of spherical rare earth inclusions is also beneficial to reduce stress concentration, thereby improving the low temperature impact of the test steel performance.
3.4. Protection performance detection and result analysis

The gun shot test is one of the methods to test the impact resistance. The test preparation specification is 9 mm×130 mm×300 mm impact-resistant rare earth alloy steel plate sample for the test of gunshot protection determination. The 1951 type B 7.62 mm steel core pistol was used to test the 3# rare earth steel plate. The test temperature is normal temperature and the shooting distance It is 5 m.

It can be seen from the test results in Table 4 that for the impact-resistant rare-earth alloy steel plate with a thickness of 10.5 mm, the designed projectile velocity is 695–725 m/s, the normal incident angle is 0°, and it is effective after three shots. The steel plate was not penetrated by the shooting, and the back of the steel plate was all Grade 1 qualified damage (refer to GJB59.18-88 for steel plate damage evaluation standard), and the protection grade reached NATO Grade 2.

| Table 4. Test results of shooting test |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| No. | Measured thickness (mm) | Shot order | Warhead speed (m/s) | Gunpowder (g) | Firing angle (°) | Shot situation |
| 1    |                  | 1           | 702.4            | All            | 0               | Not penetrated |
| 1    |                  | 2           | 720.6            | All            | 0               | Not penetrated |
| 1    |                  | 3           | 697.7            | All            | 0               | Not penetrated |

4. Conclusions

(1) After adding mixed rare earth La-Ce to the impact-resistant protective steel, the structure of tempered martensite is improved, the grains of austenite are refined, and the flaky shape of tempered martensite becomes smaller and needle-like. Fine, the austenite grain size is increased from 4.5 to 8.5 to 7 to 10, which in turn refines the structure.

(2) The mixed rare earth La-Ce has the effect of modifying inclusions. The inclusions of the test steel without rare earths are mainly elongated MnS inclusions. After adding rare earths, small spherical composite rare earth inclusions appear in the steel, and the morphology of the inclusions, size has changed.

(3) After adding the mixed rare earth La-Ce, the impact performance of the impact-resistant protective steel is significantly improved with the increase of the rare earth content. The impact energy at room temperature is increased by 24.5%, and the impact energy at -40 °C is increased by 17.4%; The fracture characteristics change from quasi-cleavage + dimple mixed fracture to dimple fracture. There are more dimples along the crystal on the quasi-cleavage fracture of low temperature impact. These changes help to improve the impact performance of steel.

(4) The 10.5 mm-thick rare earth armored steel plate was not penetrated in the shooting test with a projectile velocity of 695~725 m/s, a normal angle of incidence of 0°, and a firing range of 5 m, and the protection level reached NATO 2.

5. References

[1] Czyryca E J 1968 Advances in high strength steel technology for naval hull construction Key Eng.Fract Mech 1 55
[2] Fan C G, Dong H, Shi J, et al 2006 Microstructure and mechanical properties of 2200MPa grade ultra-high strength low alloy steels *Ordin. Mater. Sci. Eng.* **29** 31

[3] Grujicic M, Arakere A, Ramaswami S, et al 2013 Gas metal arc welding process monelighting and prediction of weld microstructure in MILA46100 armor-grade martensitic steel *J. Mater. Eng. Perform.* **22** 1541

[4] Zhang Z Q, Zhao B R, Zhang R S, Wei C Z 2000 *Basis of Armor Protection Technology* (Beijing: Ordnance Industry Press) pp 181-187

[5] Crouch I G, Cimpoeru S J, Li H, Shanmugam D 2017 Armour steels *The Science of Armour Materials* 67-70

[6] Kasonde Maweja, Waldo Stumpf 2008 The design of advanced performance high strength low-carbon martensitic armour steels *Materials Science and Engineering* 140-153

[7] R yan S, Li H, Edgerton M, Gallardy D, Cimpoeru S J 2016 The ballistic performance of an ultra-high hardness armour steel: An experimental investigation *International Journal of Impact Engineering* 60-73

[8] Li C L 2013 New development of research on rare earth application in steels *Chinese Rare Earths* **34** 78-83

[9] Fu X Y, Yang J C, Jiang X Z, Zhao L P, Wu P 2015 Effects of Ce on the inclusions and impact toughness of T91 Heat-resistant steel *Chinese Rare Earths* **36** 60-65

[10] Yang J C, Cao X E, Yang C Q, Guo J M 2013 Effect of Ce on low temperature impact toughness of X80 steel *Chinese Rare Earths* **34** 1-4

[11] Xiao J G, Cheng H J, Wang F M 2010 Effects of rare earth in ship hull plate steel on its microstructure and low temperature toughness *Chinese Rare Earths* **31** 52-57

[12] Yao Y L, Shao T H, Wang X T 1994 The mechanism of tempering martensite brittleness of low and medium carbon Si-Mn-V steel and the effect of rare earth elements *Journal of Xi’an Jiao Tong University* **28** 45-49

[13] Xi X J, Lai C B, Li J S, Wang Z G, Sun L F, Chen Y J 2017 Effect of Y-base rare earth on the microstructure and impact toughness of E36 steel plate *Chinese Journal of Engineering* **39** 244-249

[14] Zhang H W, Gao X Y, Wang H Y, Ren H P, Chen X Y, Li Z G 2014 Effect of rare earth on carbide dissolution and precipitation behavior in pipeline steel *Journal of the Chinese Society of Rare Earths* **32** 482-486

[15] Chen L., Zhang Z G., Guo F X., Chen K Y., Su H 2016 Effect of La on time isothermal transformation of low carbon microalloyed steel *Chinese Journal of Engineering* **59** 39-63

[16] Dong F, Cui Z F, Shen G H, Guo S L 2016 Effects of cerium on microstructure and mechanical properties of bullet proof steel *Journal of the Chinese Society of Rare Earths* **34** 320-325

[17] Xu G X 2002 *Rare Earths (ii)* (Beijing: Metallurgical Industry Press) pp 418-462

[18] Lin Q, Guo F, Zhu X Y 2006 Behavior of lanthanum and cerium on grain boundaries in carbon manganese clean steel *Journal of the Chinese Society of Rare Earths* **24** 729-733

[19] Li Chunlong, Wang Yunshe, Chen Jianjun, Liu Chengjun, Jiang Maofa 2005 Effects of rare earth on structure and mechanical properties of clean BNbRE steel *Journal of Rare Earths* **23** 470-473

[20] Yu Y Q, Yuan X M, Lu X Y, Gao R Z 2018 Development of high strength protection steel plate with rare earth *Chinese Rare Earths* **39** 1-6