Effects of Rare Earth Elements (Ce, Y) on Microstructure and Mechanical Properties of P20 Die Steel

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Abstract. Electroslag remelting P20 die steels with different amount of CeO2 or Y2O3 additions have been investigated by using mechanical tests and scanning electronic microscope with energy dispersive spectrometry. The microstructure of P20 die steels is tempered martensite, in which plenty of carbides precipitate along the martensite laths. With addition of rare earth Ce or Y, the matrix microstructure is refined, the quantity of carbides is decreased, and the distribution of carbides becomes more uniform. As a result of these microstructural changes, both the impact energy and tensile strength increase with increasing rare earth content. The samples obtain optimum microstructure and mechanical properties when the amount of CeO2 or Y2O3 additions reach 4 wt.%. However, over-added CeO2 or Y2O3 (>4 wt.%) results in the increase of carbides quantity and the aggregation of carbides, which reduces the impact energy and tensile strength of the samples. Present study indicates that the optimum addition of CeO2 and Y2O3 for the P20 die steels is 4 wt.%. Keywords. P20 die steel, Ce, Y, microstructure, precipitation.

1. Introduction

Having good machinability, wear resistance and polishing performance, P20 die steels are the most commonly used materials for plastic die steels [1, 2]. Nevertheless, the working conditions for P20 die steels are relatively poor which include cyclic impact force combined with the amplified induced friction. This usually leads to wear, plastic deformation and fatigue fracture in the P20 die steels, which not only affects the plastic products quality but also increases their fabrication cost. It is economically important to extend the service life of P20 die steels by further optimizing the microstructure and improving the mechanical properties.

In order to improve the performance of steels, many methods including thermo-mechanical treatments and adding other alloying elements have been widely investigated [3]. Among them, rare earth modification is one economic and effective method. It has been reported that rare earths have many positive effects for the steels, such as purifying the molten steel, refining the matrix structure and networks of eutectic carbides, increasing the hot plasticity and mechanical strength [4-6]. Particularly, research shows that both Ce [7-9] and Y [10-12] can improve the mechanical properties of steels and thus extend their service life. However, the influence of Ce and Y on the microstructure and mechanical properties of P20 die steels has rarely been reported.

In this study, the effects of rare earth Ce and Y on the microstructure and mechanical properties of P20 die steels were systematically investigated, and the precipitation behaviour of carbides under
different amount of rare earth additions was analysed. The present study provides reference for the composition design of P20 steels, which is valuable to the practical production.

2. Experimental

P20 die steel was selected as the experimental material in the present work, the chemical compositions of which are shown in Table 1. The experimental samples were prepared by melting P20 scraps and different amount of CeO$_2$ or Y$_2$O$_3$ together and casting it into an ingot with 30 kg in a vacuum induction furnace. The contents of CeO$_2$ and Y$_2$O$_3$ additions are 2, 4 and 6 wt.%, respectively.

| Steel | C   | Si  | Mn  | P   | S    | Cr  | Mo  | Fe  |
|-------|-----|-----|-----|-----|------|-----|-----|-----|
| P20   | 0.38| 0.29| 0.94| 0.017|0.007 |1.51 | 0.32| Bal.|

The microstructure of P20 steels with different amount of CeO$_2$ additions is shown in figure 1. The P20 steels without addition of CeO$_2$ show typical tempered martensite structure, where the prior austenite crystal boundaries and martensite laths can be observed (figure 1(a)). The tempered martensite is not completely decomposed due to the presence of plenty of alloying elements which improves the tempering resistance of the experimental steels. It is noted that the prior austenite crystals are obviously refined with addition of CeO$_2$ (figures 1(b)-(d)), indicating that the rare earth Ce has the effect of microstructure refinement. In addition, the prior austenite crystal size decreases gradually with increasing CeO$_2$ addition amount until reaches the minimum when the amount of CeO$_2$ reaches at 4 wt.% (figures 1(b) and (c)). Over-added CeO$_2$ (>4 wt.%) results in the increase of prior austenite crystal size instead (figure 1(d)). Furthermore, the lath structure is more obvious in the samples with addition of 4 wt.% CeO$_2$, indicating that the P20-4%CeO$_2$ steel samples have better tempering resistance.

The microstructure of P20 steels with different amount of Y$_2$O$_3$ additions is shown in figure 2. It can be observed that the rare earth Y can also refine the microstructure, and the samples achieve the finest microstructure when the amount of Y$_2$O$_3$ additions reach at 4 wt.%.
3.2. Precipitation Observation

The precipitation particles in the P20 die steel samples with different amount of CeO$_2$ additions are shown in figure 3. It is observed that a lot of particles precipitate along the martensite laths in the samples without addition of CeO$_2$ (figure 3(a)). These precipitation particles should be the carbides of Ce.
Cr, Mo and other elements, which precipitate during the tempering process due to their relative low forming temperatures. It can be seen that the carbides in some areas are aggregated, which will not only reduces the precipitation strengthening effect, but also damages the toughness of the experimental steels. With addition of rare earth Ce, the carbides are refined, the quantity of carbides is decreased, and the distribution of carbides becomes more uniform (figures 3(b)-(c)). The samples obtain the finest carbides which are distributed uniformly when the amount of CeO$_2$ additions reach 4 wt.%.

Over-added CeO$_2$ (>4 wt.%) results in the increase of carbides quantity and the aggregation of carbides, which could reduce the precipitation strengthening effect.

![Figure 3. Precipitation particles of P20 die steels with different amount of CeO$_2$.](image)

The precipitation particles in the P20 steel samples with different amount of Y$_2$O$_3$ additions are shown in figure 4. It is seen that the rare earth Y has the same effects on the carbides as the rare earth Ce. That is adding Y can refine the carbides, reduce the carbides quantity, and make the carbides uniformly distributed. The optimum addition of Y$_2$O$_3$ for the P20 die steels is also 4 wt.%. 


Apart from carbides, rare earth inclusions are also observed in the P20 steels with addition of CeO$_2$ or Y$_2$O$_3$. Figure 5(a) shows one rare earth inclusion in the samples with addition of CeO$_2$. It is observed that most of the rare earth inclusions are elliptical in shape with a diameter of 4-6 μm. EDS analysis indicates that the rare earth inclusions are mainly composed of Ce, As, C, O and other elements (figure 5(b)).

3.3. Influence of Ce and Y Content on Mechanical Properties

3.3.1. Impact Test. The effect of rare earth Ce and Y on the toughness of P20 die steels is shown in figure 6. It is seen that the impact energy increases with increasing the rare earth element content when the amount of CeO$_2$ and Y$_2$O$_3$ additions is smaller than 4 wt.%. For example, the impact energy increases from 22.5 J to 30.0 J as the amount of CeO$_2$ addition increases from 0 wt% to 4 wt% (figure 6(a)). This is consistent with the microstructural observation results. On the one hand, the addition of rare earth Ce refines the microstructure and improves the toughness of the experimental steels; on the other hand, the addition of rare earth Ce reduces the carbides quantity and makes them distributed more uniformly, which reduces the damage of the precipitated phases to the toughness of experimental steels.
steels. When the amount of CeO$_2$ addition increases from 4 wt.% to 6 wt.%, the impact energy decreases from 30.0 J to 25.3 J. This is attributed to the increase of carbides quantity and aggregation of carbides which is induced by the over-added CeO$_2$. Similarly, it can be seen that the impact energy of P20 steels with addition of Y$_2$O$_3$ reaches the maximum when the amount of Y$_2$O$_3$ addition is 4 wt.% (figure 6(b)), and over-added Y$_2$O$_3$ also decreases the impact energy. In addition, it is noted that the impact energy of P20-4% CeO$_2$ steels is larger than that of P20-4%Y$_2$O$_3$ steels. This is because the martensite laths of P20-4% CeO$_2$ steels (figure 3(c)) are thinner than that of P20-4%Y$_2$O$_3$ steels (figure 4(c)), and such microstructure refinement improves the toughness of the experimental steels.

3.3.2. Tensile Test. The tensile strength of P20 steels with different amount of CeO$_2$ and Y$_2$O$_3$ additions is shown in figure 7. It is seen that addition of 2-4 wt.% CeO$_2$ can increases the tensile strength of P20 steels slightly, but further increasing the CeO$_2$ content to 6 wt.% will decrease the tensile strength instead. Previous microstructural observations indicate that the rare earth Ce could refine the microstructure, which contributes to fine grain strengthening. At the same time, the carbides quantity is decreased and more alloying elements are dissolved in the matrix with the addition of CeO$_2$, which contributes to solid solution strengthening. Although some extent of weakening of the precipitation strengthening effect is induced by the reduction of carbides quantity, it is compensated partially by the smaller size and more uniform distribution of the carbides. However, over-added CeO$_2$ results in the increase of carbides quantity and aggregation of carbides, which is detrimental to the tensile strength. Similarly, the samples with addition of rare earth Y also obtain the maximum tensile strength when the amount of Y$_2$O$_3$ addition is 4 wt.%. Mechanical property tests indicate that the optimum addition of CeO$_2$ and Y$_2$O$_3$ for the P20 die steels is 4 wt.%.

Figure 6. Impact energy of P20 die steels with different amount of CeO$_2$ and Y$_2$O$_3$ additions.

Figure 7. Tensile strength of P20 die steels with different amount of CeO$_2$ and Y$_2$O$_3$ additions.
4. Conclusions
In this paper, the effects of rare earth Ce and Y on the microstructure and mechanical properties of P20 die steels were studied, and the precipitation behaviour of carbides with different amount of rare earth additions was studied. The following conclusions can be drawn:

1) The microstructure of P20 die steel is tempered martensite. Adding rare earth Ce and Y could refine the microstructure, which contributes to the fine grain strengthening.

2) Plenty of carbides precipitate along the martensite laths in the P20 die steel samples. With addition of rare earth Ce or Y, the quantity of carbides is decreased, and the distribution of carbides becomes more uniform. The rare earth Ce and Y achieve the most obvious optimization effect when the amount of CeO$_2$ and Y$_2$O$_3$ additions is 4 wt.%. Over-added CeO$_2$ or Y$_2$O$_3$ (>4 wt.%) results in the increase of carbides quantity and the aggregation of carbides, which is detrimental to the toughness and tensile strength of the samples.

3) Both the impact energy and tensile strength increase with increasing rare earth Ce or Y content until reach the maximum when the amount of CeO$_2$ or Y$_2$O$_3$ reach at 4 wt.%. Over-added CeO$_2$ or Y$_2$O$_3$ (>4 wt.%) results in the decrease of impact energy and tensile strength. The results indicate that the optimum addition of CeO$_2$ and Y$_2$O$_3$ for improving the comprehensive properties of P20 die steels is 4 wt.%.

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References
[1] Han Y Q and Wu X C 2018 Die & Mould Industry 44 1-7
[2] Hoseiny H, Caballero F G, M'Saoubi R, Högman B, Weidow J and Andrén H O 2015 Metall. Mater. Trans. A 46 2157-71
[3] Beaudet F, Blais C, Lehuy H, Voyzelle B, L'espérance G, Masse J P and Krishnadev M 2012 ISIJ Int. 52 424-33
[4] Zhu J, Huang H Y and Xie J X 2017 J. Iron Steel Res. Int. 29 513-29
[5] Gao J, Fu P, Liu H and Li D 2015 Metals-Basel 5 383-94
[6] CHEN R C, WANG Z G, HE J G, Zhu F S and Li C H 2020 Metals-Basel 10 918
[7] Bao D, Cheng G, Huang Y, Qiao T and Dai W 2021 Steel Res. Int. 2100304
[8] Van C, Lassila I, Grong O, Kleven O S and Holappa L 2014 Materials Science and Technology 23 199-206
[9] Xiang H M, Meng X L, Meng W, Zhe W and Yun G L 2020 High Temperature Materials and Processes 39 466-76
[10] Zhan D, Qiu G, Jiang Z and Zhang H 2017 Steel Res. Int. 88 1700159.
[11] Zhao W X, Wu Y, Jiang S H, Wang H, Liu X J and Lu Z P 2016 J. Iron Steel Res. Int. 23 553-58
[12] Chen Y, Zhang F, Yan Q, Zhang X and Hong Z 2019 J. Rare Earth 37 547-54