Influence of carbon content on microstructure and mechanical properties of Mn13Cr2 and Mn18Cr2 cast steels

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Abstract: In this paper, a comparison study was carried out to investigate the influence of carbon content on the microstructure, hardness, and impact toughness of water-quenched Mn13Cr2 and Mn18Cr2 cast steels. The study results indicate that both steels' water-quenched microstructures are composed of austenite and a small amount of carbide. The study also found that, when the carbon contents are the same, there is less carbide in Mn18Cr2 steel than in Mn13Cr2 steel. Therefore, the hardness of Mn18Cr2 steel is lower than that of Mn13Cr2 steel but the impact toughness of Mn18Cr2 steel is higher than that of Mn13Cr2 steel. With increasing the carbon content, the hardness increases and the impact toughness decreases in these two kinds of steels, and the impact toughness of Mn18Cr2 steel substantially exceeds that of Mn13Cr2 steel. Therefore, the water-quenched Mn18Cr2 steel with high carbon content could be applied to relatively high impact abrasive working conditions, while the as-cast Mn18Cr2 steel could be only used under working conditions of relatively low impact abrasive load due to lower impact toughness.

Key words: high manganese steel; carbon content; as-cast; water-quenched; microstructure; hardness; impact toughness

Because of its favorable mechanical strength and toughness, outstanding work-hardening capacity as well as better wear resistance, high manganese steel is currently widely used in various industrial fields such as metallurgy, mining, railway transportation, machinery manufacturing and so on. For instance, high manganese steel is extensively manufactured into crusher rolling mortar wall, jaw plate, hammer, railroad switch, ball mill liner, excavator bucket teeth [1-3], etc. However, with the development and application of large equipment, it has become increasingly difficult for casting products made by traditional Mn13 series to meet the anti-wear and anti-impact practical requirements. As a consequence, Mn18 series casting parts have gained much emphasis and development in recent years.

Carbon is one of the most important elements in high manganese steel. Carbon produces an effect of solid solution strengthening in the high manganese steel, promoting the formation of single-phase austenite [4], meanwhile, the carbon content can also exert influence on the properties of high manganese steel such as work-hardening property and wear resistance [5]. Studies by Zhang [6] and Xie [7] showed that providing the carbon content exceeds 1.0%, further raising of the carbon concentration to some degree can result in the improvement of wear resistance of high manganese steels for both Mn13 and Mn18 series; at the same time, the impact toughness will be lessened as well. In order to ensure the security of the application of high manganese steels and to give full play to their wear resistance under working conditions of high abrasive wear, adequate impact toughness is necessary. In some sense, impact toughness is a technical parameter of vital importance for wear resistant high manganese steels.

So far there have been a lot of research reports related to research of Mn13Cr2 steels at home and abroad. Yan Hua, et al [8] studied the influence of different tempering heat treatment processes on Mn18Cr2 cast steel containing molybdenum. The results showed that the steel water-quenched at 1,100 °C and tempered at 250 °C could get an exceptional microstructure of finer
grains and well-dispersed carbide, as well as excellent combined properties. However, this research was merely carried out in a wide scope of carbon (0.9% - 1.6%). It didn’t illustrate in detail how carbon content affected the microstructure and properties of Mn18Cr2 cast steel. In a comparison study on the wear resistance and impact abrasive wear behaviors between Mn13 cast steel with 1.26% carbon and Mn18Cr2 cast steel with 0.98% or 1.35% carbon \(^9\), it was found that when carbon content was comparatively low, the alloyed Mn18Cr2 cast steel could achieve superior impact toughness and inferior wear resistance, which would be quite the opposite if the carbon content was high. The researchers also made a comparison about the mechanical properties between Mn18 (carbon content: 1.0%–1.4%), Mn18Cr2 (carbon content: 1.0%–1.4%) and Mn13 (carbon content: 0.9%–1.4%) cast steels. They believed that a chromium addition could contribute to the increase of initial hardness and work hardening ratio of Mn18 and Mn18Cr2 steels under the condition of same deformation degree. But they didn’t explain in detail what kinds of roles the carbon content could play in properties.

In summary, few reports could be found in open literature on the influence of carbon content on the microstructure and properties of Mn13Cr2 and Mn18Cr2 cast steels. This thesis launches research work in this area accordingly, which is of significant reference value not only for the research and development of Mn13Cr2 and Mn18Cr2 steels, but also for the material selection of cast high manganese steel under abrasive conditions.

1 Experimental materials and testing methods

The nominal chemical compositions of tested Mn13Cr2 and Mn18Cr2 cast steels are shown in Table 1. To study the influence of carbon content on the microstructure and mechanical properties of Mn13Cr2 and Mn18Cr2 cast steels, the addition of carbon content for each tested steel was set to 1.25wt.%, 1.35wt.%, 1.45wt.%, respectively. In the present research, a medium frequency induction furnace was used for melting. Y-blocks were cast in a sand mould. In order to conveniently distinguish Y-blocks, three Mn13Cr2 Y-blocks with different carbon contents were numbered as #1, #2, #3, respectively, and three Mn18Cr2 Y-blocks were numbered as #4, #5 and #6.

Table 1: Chemical compositions of Mn13Cr2 and Mn18Cr2 steels (wt.%)  

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P , S</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn13Cr2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>1.35</td>
<td>12.5–13.0</td>
<td>0.40–0.65</td>
<td>&lt;0.050</td>
<td>1.4–2.0</td>
</tr>
<tr>
<td>#3</td>
<td>1.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn18Cr2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>1.35</td>
<td>17.5–18.0</td>
<td>0.40–0.65</td>
<td>&lt;0.050</td>
<td>1.4–2.0</td>
</tr>
<tr>
<td>#6</td>
<td>1.45</td>
<td></td>
<td></td>
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</tbody>
</table>

First, the above six groups of Y-blocks underwent a process of heat preservation at a constant temperature of 650 °C for 1 h in a chamber electric furnace, followed by a heat preservation at 1,100 °C for 2 h. Then all the Y-blocks were water-quenched immediately when they were removed from the furnace. U-notched impact specimens were cut from the water-quenched Y-blocks by way of electric spark wirecut (10 mm × 10 mm × 55 mm, notch depth 2 mm), four samples for each category. Likewise, the as-cast impact specimens were also cut (10 mm × 10 mm × 55 mm, Unnotched), four samples for each group. The impact test was conducted using a pendulum impact tester. Brinell hardness of as-cast and water-quenched specimens was measured on HBRVU-187.5 optical hardness gauge. The fracture morphologies of all Charpy U-notched impact specimens were observed on a scanning electron microscope.

2 Experiment results and discussion

2.1 Metallographic structure

Figure 1 shows the comparison of the as-cast metallographic microstructures of Mn18Cr2 and Mn13Cr2 steels. Figure 1(c) and 1(d) are the regional magnification of Fig.1(a) and Fig.1(b) respectively. It can be seen from Fig.1 that the microstructures of both as-cast Mn18Cr2 and Mn13Cr2 steels consist of austenite, pearlite and carbide. The pearlite is mainly distributed near the grain boundary since the grain boundary is an area prone to causing structure fluctuation, energy ups and downs. But the percentage of carbide and pearlite of as-cast Mn18Cr2 steel is lower than that of as-cast Mn13Cr2 steel because the manganese concentration of Mn18Cr2 steel is comparatively high, and manganese is an element expanding the austenite area. Furthermore, more carbon is apt to participate in forming solid solution in Mn18Cr2 steel.

In Fig.2, a comparison is made to analyze the water-quenched metallographic microstructure of Mn18Cr2 and Mn13Cr2 steels. It can be seen from Fig.2 that in the microstructure of Mn18Cr2 and Mn13Cr2 steels, the austenitic matrix is dotted with a small fraction of carbide. With the increase of carbon content, the amount of carbide in the two high manganese steels enhances steadily. In comparison, when the carbon content is equal between these two steels, the carbide proportion of Mn18Cr2 steel is slightly less than that of Mn13Cr2 steel. Of particular note is that when the carbon content is relatively high, the ratio of carbide in the microstructure of Mn18Cr2 is strikingly less than that of Mn13Cr2 steel (as shown in Fig. 2(e) and Fig. 2(f)). Another feature which should be pointed out is that the grain size of Mn18Cr2 steel is larger than that of Mn13Cr2 steel.

According to the Chinese national standard \(^9\) on metallographic structure of cast high manganese steel, the blocky carbide of these two steels is the undissolved type of carbide. Chromium is a kind of chemical element that more easily forms carbide than manganese in the matrix of various steels. When carbon content increases, a sort of chromium alloy cementite will form, which is more stable than manganese alloy cementite. This unique sort of chromium alloy cementite is not easily
dissolved in the entire process of water-quenched treatment. Thus, the carbide amount of these two high manganese steels increases. More carbon is apt to form a solid solution in Mn18Cr2 steel. Therefore, the carbide amount in Mn18Cr2 steel is small in fact. Besides, the reason why the grain size of Mn18Cr2 steel is larger than that of Mn13Cr2 steel is that manganese is conducive to the growth of coarse grain. Additionally, chromium alloy cementite can hinder the growth of austenite grain during the process of water-quench treatment [10].

2.2 Hardness

Figure 3 presents the hardness of Mn13Cr2 and Mn18Cr2 steels under as-cast as well as water-quenched conditions, respectively. As can be seen from Fig.3, the hardness of Mn13Cr2 steel is higher than that of Mn18Cr2 steel and the hardness of as-cast steel overtops the one of water quenched when carbon contents are equal between them. Figure 3 also illustrates that an increase in carbon content leads to a simultaneous rise in the hardness for both Mn13Cr2 and Mn18Cr2 steels, but the upward trend of hardness in the former is more noticeable than that of the latter.

Besides, if the carbon contents are equal between Mn13Cr2 and Mn18Cr2 steels, there is more carbide in the microstructure of the former, while less carbide forms in that of the latter as more carbon element participates in the formation of solid solution in Mn18Cr2 steel. As a result, the amount of carbide in Mn13Cr2 steel is greater than that of Mn18Cr2 steel. Due to the fact that there is more carbide in as-cast steels than in water-quenched steels, the hardness of the former is higher than that of the latter.

Furthermore, with carbon content increasing, there is first a growth in the amount of carbon element forming solid solution in these two high manganese steels, and then more carbide forms in the increasing process of carbon content. The combined effects of the above two factors contribute to an incremental change in the hardness of these two kinds of high manganese steels. In addition, when carbon content stays at a relatively high level, there will be more carbide in high manganese steel. Owing to the marked effect of carbide on the steel’s hardness especially when Mn13Cr2 steel contains a comparatively large amount of carbide, the rising tendency in hardness of Mn13Cr2 steel...
becomes more dramatic than Mn18Cr2 steel.

2.3 Impact toughness

The impact toughness of the as-cast and water-quenched Mn13Cr2 and Mn18Cr2 steels is shown in Fig.4. It can be seen that with carbon content rising, a drop takes place simultaneously in the impact toughness of these two kinds of steels. This phenomenon can be ascribed to the synthetic results of solid solution strengthening effect and increase of carbide amount. Figure 4 also indicates that the impact toughness of these two water-quenched steels are both significantly higher than that of as-cast steels, which mainly stems from the combined outcomes of carbide not only forming in just a small amount, but also in the way of an even distribution in the water-quenched microstructure.

Figure 4(a) reveals that the impact toughness of as-cast Mn18Cr2 steel is much higher than that of Mn13Cr2 steel. Furthermore, under the condition of equal carbon content, the impact toughness of the as-cast Mn18Cr2 steel, can reach at least 3.8 times that of as-cast Mn13Cr2 steel, and up to 5.2 times at most. Additionally, when the carbon

![Fig. 2: Comparison of water-quenched metallographic structure of Mn18Cr2 and Mn13Cr2 steels](image1)

![Fig. 3: Comparison of hardness of Mn13Cr2 and Mn18Cr2 steels](image2)
content of as-cast Mn18Cr2 steel is below 1.35%, its impact toughness will not be lower than 31.5 J (unnotched specimen), which creates favorable conditions for the application of as-cast Mn18Cr2 steel. Phenomenon of this kind is primarily due to the great amount of carbide and pearlite in the as-cast Mn18Cr2 steel.

As is illustrated in Fig. 4(b), the impact toughness of water-quenched Mn18Cr2 steel is much higher than that of water-quenched Mn13Cr2 steel when their carbon contents are equal; in other words, the Mn18Cr2 steel can achieve desirable impact toughness 54.5% higher than that of Mn13Cr2 steel at most, which signifies that the water-quenched Mn18Cr2 steel can be applied to working conditions of comparatively high impact load. What should be noted specially is that for Mn18Cr2 steels with 1.35% and 1.45% carbon content, their impact toughness can reach 112 J and 84.5 J respectively (U-notched specimens), which lays a foundation for the application of water-quenched Mn18Cr2 steel with high carbon content. The impact toughness of water-quenched Mn18Cr2 steel is desirable in that this kind of steel possesses less carbide than others and a strong capability of forming a solid solution; then again, the manganese atom is capable of enhancing adhesive force between different austenite grains.[7]

2.4 Fracture morphology

Figure 5 is a comparison analysis of impact fracture morphology of water-quenched Mn18Cr2 and Mn13Cr2 steels. As can be seen from Fig. 5, the impact fracture mode of these two kinds of high manganese steels is ductile fracture. In the sample with low carbon content, a relatively large number of evenly distributed dimples can be found on the impact fracture surface. There are a multitude of fibrous micro pores gathering around the dimples, which is an indicator of good impact toughness. The ductile fracture mode belongs to micropore gathered shaped fracture mechanism. In micropore gathered shaped fracture mechanism, crack initiation first takes place in the micro-holes. Then, before the breakdown of metal materials in the manner of ductile fracture, and deformation to a certain degree, micro-holes first form in those places such as dislocation or grain boundary, where stress concentration is commonplace. The nucleation position of micro-holes can partly be detected to show where the brittle second-phase particles respond to deformation in a way not harmonizing with the ductile austenitic matrix.[10]. When cracks occur by successive processes of nucleation, growth and aggregation, materials ultimately rupture.

When carbon content increases, the dimples on the impact fracture surface of these two high manganese steels drop progressively. This suggests that the impact toughness decreases accordingly. When these two kinds of manganese steels possess same carbon content, dimples of Mn18Cr2 steel outnumber that of Mn13Cr2 steel. Besides, the dimples of the former are greater in depth than that of the latter. Moreover, the microfractograph of Mn18Cr2 steel is more uneven and rough, which is potent proof of higher impact toughness of Mn18Cr2 steel than Mn13Cr2 steel.

3 Conclusions

(1) There are austenite, carbide, and pearlite in the microstructure of as-cast Mn13Cr2 and Mn18Cr2 steels, while there are austenite, and just a small amount of carbide in the steels after water quenching. With the increase of carbon content, the proportions of carbide in these two steels raises accordingly.

(2) When their carbon content is same, the carbide of water-quenched Mn18Cr2 steel is lower than that of Mn13Cr2 steel, and the hardness of both as-cast and water-quenched Mn13Cr2 steel is higher than that of Mn18Cr2 steel. With carbon content increasing, the increasing trend of hardness in Mn13Cr2 steel is more apparent than that in Mn18Cr2 steel.

(3) The impact toughnesses of as-cast and water quenched Mn13Cr2 as well as Mn18Cr2 steels decrease along with the increase in carbon content. The as-cast Mn18Cr2 steel with carbon content below 1.35%, has an impact toughness not lower than 31.5 J (unnotched specimens), which indicates that the as-cast Mn18Cr2 steel can be used in working conditions of...
(4) Under the condition of equal carbon content, the impact toughness of Mn18Cr2 steel substantially surpasses that of Mn13Cr2 steel. This demonstrates that water quenched Mn18Cr2 steel can be applied to working conditions of comparatively high impact load. The impact toughness of Mn18Cr2 steel with carbon content of 1.35% and 1.45% is 112 J and 84.5 J respectively (U-notched samples), which can facilitate the application of water-quenched Mn18Cr2 steel with high carbon content.

References


