Plastic deformation wear in modified medium manganese steel

YUAN Hai-lun¹, *XIE Jing-pei², WANG Ai-qin², WANG Wen-yan², WANG Cheng¹
(1. Huazhong University of Science and Technology; 2. School of Material Science and Engineering, Henan University of Science and Technology, Luoyang 471003, China.)

Abstract: A medium manganese steel with high wear-resistance, strength and toughness has been produced with addition of a complex modifier (or refining agent) containing Nb, N, RE and Si-Ca. The results showed that the wear resistance, strength and toughness of the modified medium manganese steel are respectively 1.92 times, 1.45 times and 3.63 times as high as that of the referenced unmodified medium manganese steel. The plastic deformation characteristic involved in the wear mechanism of the modified medium manganese steel was investigated by means of plastic-elasticity calculation and TEM electro-microscopy. The relationship between wear resistance and yield strength of the steel was established. Since the wear volume is proportional to the square of the loading and to the numbers of the abrasives, and inversely proportional to the square of the yield strength of the materials, the wear resistance can be substantially improved by the enhancement of yield strength of the materials. The calculation results generally agreed with the experimental results.

Key word: modified medium manganese steel; plastic deformation; wear; yield strength

1 Experimental details

1.1 Chemical compositions

Hadfield steel is a well known ferrous alloy for its superior toughness, wear resistance and work-hardening ability under severe impact loading condition. However, a great number of Hadfield steel castings containing high Mn are used under relatively non-severe impact service conditions and their work-hardening ability can not be brought into full play.

The ability of work-hardening of medium manganese steel (Mn7 steel), however, can be increased under non-severe impact loading condition. In such case, the strain-induced martensite transformation and formation of high density of dislocations have been identified in the work-hardening layer, and therefore, the wear resistance of the Mn7 steel has been improved remarkably [1-4]. Many experts in the research field have studied the work-hardening mechanism, impacting wear, alloying treatment, heat treatment and abrasive wear [5-9]. Recently, the authors modified the Mn7 steel grade using a refining agent, established the relationship between wear resistance and the yield strength of the modified Mn7 steel, and investigated the plastic deformation wear by means of plastic-elasticity theory.

1.2 Specimens

The Mn7 steel melt was made in a 150 kg medium frequency induction furnace. The liquid steel was poured into Y-shaped mold. All the test samples were taken from the Y-block casting. The samples were roughly machined, heat treated and finished. The heat treatment was carried out in an electric resistance furnace with a soak temperature at (1 050 ± 10) °C, holding time of 4 h, and then followed by water quenching.

The mechanical properties of test bars were measured under a MTS-810 tensile testing machine. Impact toughness of test samples were evaluated with an Oscillography impact machine, from which the crack forming energy (Wm) and crack extension (or propagation) energy (Wp) can be determined. The hardness of test samples was checked using a HB-3000 Brinell Hardness tester.

1.3 Wear testing

Abrasion wear testing was conducted in a ML-10 wear machine. The testing condition and parameters included emery cloth abrasives, loading level at 50 N, specimen dimension of Φ 4 mm X 20 mm, dish rotation speed at 60 rpm, and feeding rate at 4 mm per revolution. The weight loss of wear...
specimens was measured in a balancer with 1/10 000g accuracy. The wear process and mechanism were studied by means of stress curves (calculated), stress interferometer, Leica-400 SEM and H-800 TEM.

2 Results and discussions

2.1 Effects of complex modifier on the microstructure

The microstructure of the medium manganese steel depends on the compositions of C and Mn. The microstructure is austenite above 900 °C, and it undergoes eutectoid transformation at 650 °C, that is $\gamma \rightarrow \alpha + (\text{Fe, Mn})_3 \text{C}$. The as-cast microstructure of the steel is austenite + carbide + pearlite. Austenite can be obtained after holding at 1 050 °C for two hours and water quenching. Generally, the grain size is coarse without modification treatment (Fig. 1). After the modification, the grain size is refined (Fig. 2) since NbN and Nb$_2$C compounds can serve as heterogeneous nuclei for crystallization of austenite (Figs. 3 and 4) [10].

2.2 Effects of complex modifier on the mechanical properties

It can be seen in Table 1 that the yield strength of the modified medium manganese steel is about 1.45 times as that of medium manganese steel, and the crack forming energy ($W_m$) and crack extension energy ($W_p$) of the modified medium manganese steel are respectively 3.4 times and 3.3 times of that of the medium manganese steel. There are two reasons for the enhancement of strength and toughness. On the one hand, the microstructure of the steel was refined by the complex modifier (or refining agent), and on the other hand, the boundary surface could be purified and the inclusions in the steel became spheroid [11].

2.3 Effects of complex modifier on the wear resistance

Due to the enhancement of mechanical properties and high density of dislocations, wear resistance of the modified medium manganese steel is 1.92 times as high as that of medium manganese steel (Table 2). More specifically, the yield strength, crack forming energy ($W_m$) and crack extension energy ($W_p$) were increased remarkably by the addition
treatment with the complex modifier. Through the study on wear morphology, it was found that wear mechanism is mainly plastic deformation wear (Figs. 5 and 6). Because plastic deformation wear is a process from plastic deformation to work-hardening, crack formation and crack extension in the plastic deformation zone, the increase in yield strength and high density of dislocations are beneficial to the resistance against plastic deformation (Figs. 7 and 8), and the enhancement in crack forming energy \((W_m)\) and crack extension energy \((W_p)\) leads to a higher resistance to cracking. Therefore, the wear resistance of the modified medium manganese steel can be increased remarkably.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fixed abrasive with static loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value of wear mg</td>
</tr>
<tr>
<td>Medium manganese steel</td>
<td>30.6</td>
</tr>
<tr>
<td>Modified medium manganese steel</td>
<td>15.9</td>
</tr>
</tbody>
</table>

### 3 The mathematic model and mechanism of plastic deformation wear

Because the surface of specimens is always rough, wear takes place between hard surface and soft surface. In order to imitate the condition of wear, abrasive is chosen as one unit of the hard surface. The plowing is formed under the normal stress of abrasive with static loading. A part of material is pressed to the two side of the plowing, and the pressed material is worn out because of the repeated plowing, and the plastic deformation wear takes place. For the analysis of stress distribution in contacted area, one abrasive is generally considered. When the abrasive is pressed into the matrix, the boundary of extruded part is considered as straight line AC (Fig. 9), and the vertical pressure can be calculated by means of the elastic contact theory \([12]\):

\[
\theta = \frac{\pi}{4} - \gamma + \varphi, \quad \sigma = -k \text{ (in ACE area)}
\]

where \(\theta\) is included angle between \(\alpha\) line in AC edge and \(x\) axis, and the included angle between \(a\) line and AC, \(AB\) is \(\frac{\pi}{4}\), the included angle between AC and \(x\) axis is \(\gamma - \varphi\). \(\sigma\) is the average stress in AEC area, \(k\) is the shear yield stress of the materials. In ABD area: \(\theta = \frac{\pi}{4} - \gamma\). Because \(\xi\) is the content in the same \(a\)
The wear volume for one abrasive in unit length is

\[ \sigma = 2 (\frac{\pi}{4} - \gamma + \varphi) - 2k (\frac{\pi}{4} - \gamma) \]  

(2)

From equation (2), \( \sigma \) can be calculated:

\[ \sigma = -k - 2k (\frac{\pi}{4} - \gamma + \varphi) + 2k (\frac{\pi}{4} - \gamma) = -k + 2k \varphi \]

(3)

\( \sigma \) is the average stress in AB line, while \( \sigma_x \) is the normal stress at any point, and \( \alpha = k + \alpha' \). From Fig. 9(a):

\[ \sigma_i = \frac{\sigma_x + \sigma_y}{2} \]

(4)

\[ \sigma_i = \frac{\sigma_x - \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \frac{2\sigma_x \pm k}{2}} \]

Here \( \sigma = \alpha = \sigma_0 \), and \( \tau = k \). The average compression stress in AB edge is \( \sigma \), that is \( \sigma = -p \), from equation (4): \( p = -\sigma = 2k (1 + \varphi) \).

The pressing stress in unit length of Z axis is as follows:

\[ P = 2\pi L \sin \gamma = 4kL (1 + \varphi) \sin \gamma = 4kL (1 + \varphi) \sin \gamma \]

(5)

Here \( k \) is the shear yield stress of the materials, \( 2k \) is the angle pressed into matrix, and \( \varphi \) can be measured. \( L \) and \( \varphi \) are unknown quantity. The equation (5) can be rewritten:

\[ P = 2\pi (1 + \varphi) \sin \gamma \]

(6)

Here \( \sigma_\varphi \) is yield strength: \( \sigma = 2\pi \tau = 2k \). Because \( \gamma - \varphi \) is included angle between AC line and x axis, \( L \) and \( \varphi \) can be obtained from Fig. 9(a):

\[ L \cos \gamma - h = L \sin \varphi \]

(7)

Because the material can not be compressed, the triangle OBG is equal to the triangle ACG:

\[ h = \frac{L \cos \gamma - h}{L \sin \varphi} + (L \cos \gamma + h) \frac{L \sin \varphi}{L \cos \gamma} \]

(8)

\( L \) is eliminated from equations (7) and (8), and \( \varphi \) can be written:

\[ 2\varphi = \varphi + \cos^{-1} \left[ \frac{1 + \varphi}{2} \right] \]

(9)

Through calculation: \( \varphi = 32.95^\circ \), \( \gamma = 0.58 \text{rad} \).

The wear volume for one abrasive in unit length is \( W \):

\[ W = h \cos \gamma \]

(10)

Before \( W \) is determined, \( h \) must be calculated from equation (7):

\[ h = L \cos \gamma - L \sin \varphi - \varphi = L \left[ \cos \gamma - \sin \varphi - \varphi \right] \]

(11)

\[ W = \frac{4\pi}{\varphi} \left[ \cos \varphi - \sin \varphi \right]^2 \cos \varphi \]

(12)

If \( \varphi = \frac{1}{2} \),

\[ W = \frac{4\pi}{\varphi} \left[ \cos \varphi - \sin \varphi \right]^2 \cos \varphi \]

(13)

Equation (13) is used under the condition of one abrasive. For practical conditions, the number of abrasives is \( n \). Therefore: Equation (13) can be rewritten as \( W = k a \frac{p a^2}{2a} \), where \( k a \) is a function of abrasive shape and plastic deformation angle \( \varphi \). Under the same wear condition, \( k a \) is a constant. Since wear volume \( W \) is proportional to the square of the loading and to the number of the abrasives, and inversely proportional to the square of the yield strength of the materials, the wear resistance can be increased remarkably from the enhancement of the yield strength of the materials. The yield strength (\( \sigma \)) of the modified medium manganese steel is 510 MPa (Table 1), while that of the referenced medium manganese steel is only 363 MPa. According to the equation (13), the calculated wear resistance of the modified medium manganese steel is about 1.92 times high as that of the medium manganese steel, which matched very well with the experimental results.

### 4 Conclusions

(1) Wear resistance of the modified medium manganese is 1.92 times that of the medium manganese under two-body abrasive wear condition, and the wear mechanism is primarily plastic deformation wear.

(2) Wear volume \( W \) is proportional to the square of the loading and to the number of the abrasives, and inversely proportional to the square of the yield strength of the materials, and therefore the wear resistance can be substantially improved by the enhancement of yield strength of the materials.

(3) The yield strength, crack forming energy (\( W_{m} \)) and crack extension energy (\( W_{p} \)) of the steel can be greatly increased by complex modifiers.

### References


