Influence of impact energy on work hardening ability of austenitic manganese steel and its mechanism

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Abstract: To further understand the hardening mechanism of austenitic manganese steel under actual working conditions, the work hardening ability was studied and the microstructures of austenitic manganese steel were observed under different impact energies. The work hardening mechanism was also analyzed. The results show that the best strain hardening effect could be received only when the impact energy reaches or exceeds the critical impact energy. The microstructural observations reveal that dislocations, stacking faults and twins increase with raising impact energy of the tested specimens. The hardening mechanism changes at different hardening degrees. It is mainly dislocation and slip hardening below the critical impact energy, but it changes to the twinning hardening mechanism when the impact energy is above the critical impact energy.

Key words: austenitic manganese steel; work hardening; impact energy; microstructure; hardening mechanism

Since austenitic manganese steels came out, they have been used in a variety of fields, such as mining machines, railroads, grinding mill liners, crush jaws, and impact hammers. The reason is that the steels exhibit a unique combination of properties such as high strength, high toughness, resistance to wear, and especially the excellent strain hardening behavior. Numerous studies have been carried out to investigate the strain hardening behavior of austenitic manganese steels [1-4], and different explanations were suggested to explain these phenomena, but there was not a consistent conclusion. Early work on austenitic manganese steel showed that strain hardening caused from strain induces transformation of γ austenitic to α or ε martensitic structure in austenitic manganese steels [5]. Detailed studies suggest the dislocation hardening theory [6], the twinning hardening theory [7], and the dynamic strain ageing hardening theory [8]. But the impact experiments in most of these investigations are traditional small energy impact [9], static load compression or tension deformation [10]. These impact loads are different from the actual working conditions. If the impact energy is as much as that in the actual working state, what would be the law of strain hardening, the microstructure morphologies and the hardening mechanism?

In this study, the impact hammers and grinding mills of austenitic manganese steels which are mostly used in production were selected to approximately simulate the impact energies in the actual work state. Then four different “impact energies” (50, 80, 100 and 200 J·cm², here “impact energy” is defined as the explosive shock load per unit area) were chosen. The experiments were undertaken with the newly-designed impact testing machine. Microstructures of test samples were observed with an optical microscope and a transmission electronic microscope (TEM). Then the microstructure morphologies and work hardening mechanism at different hardening degrees were analyzed.

1 Experimental procedure

1.1 Calculation of impact energies at actual working conditions

To calculate the impact energy, some assumptions were made, for example, assuming the hammer to be a rigid body. Table 1 lists the related parameters and the calculated impact energies of three types of hammers. Take the PC-S 0808 hammer mill as an example, the calculation process is as follows:

Angular velocity of the hammer:

\[ \omega = 2\pi \cdot n \]

where \( n \) is rotational speed.

Line speed of the hammer:

\[ v = \omega \cdot r = 102.6 \times \frac{0.8}{2} = 41 \text{ m/s} \]

where \( r \) is gyration radius.

The mass of the limestone:
the hammer to different heights. The different impact energies were obtained by raising the hammer, weight of 18 kg, to a certain height by the crown block, then fell vertically to impact the limestone. The hammer mills were designed and Fig. 1 shows its schematic diagram. Its principle is as follows:

\[ m = \rho \frac{4}{3} \pi r^3 = 2 \times 10^3 \times \frac{4}{3} \times 3.14 \times (\frac{120}{2})^3 = 1.8 \text{ kg} \]

where \( \rho \) and \( r \) are density and radius of the limestone, assuming the limestone is spherical, and the maximal diameter is 120 mm.

Impact energy endured by the hammer:

\[ E' = \frac{E}{s} = \frac{0.5 \times m v^2}{s} = \frac{0.5 \times 1.8 \times 41^2}{10 \text{(to 20)}} = \frac{1514}{10 \text{(to 20)}} = 75 \text{ to } 151 \text{ J cm}^{-2} \]

where \( E \) is the maximal impact energy, \( s \) is the impact contact area.

According to the shape and size of the hammer and the limestone, we assumed it was approximately 10 to 20 cm². From Fig. 2, for each impact energy, up to 10 impacts, the increase in hardness is the fastest; then, with the increase in number of impacts, the rate of hardness increase decreases gradually until the hardness reaches a maximum and then remains almost unchanged. The maximum hardness is lower at or below 80 J cm⁻² for sample A and 50 J cm⁻² for sample B. The specimens do not reach the best hardening effect simply with enough impact numbers. It can gain the best hardening effect only when the impact energy reaches or exceeds a critical value. According to Fig. 2, the critical impact energies are 100 J cm⁻² for sample A and 80 J cm⁻² for sample B. The two samples are similar, and the hardening behavior vs. impact energy is consistent with the previous work. From Fig. 2, for each impact energy, up to 10 impacts, the increase in hardness is the fastest; then, with the increase in number of impacts, the rate of hardness increase decreases gradually until the hardness reaches a maximum and then remains almost unchanged. The maximum hardness is lower at or below 80 J cm⁻² for sample A and 50 J cm⁻² for sample B. The specimens do not reach the best hardening effect simply with enough impact numbers. It can gain the best hardening effect only when the impact energy reaches or exceeds a critical value. In other words, in order to take full advantage of the hardening behavior, the impact energy reaches or exceeds a critical value. According to Fig. 2, the critical impact energies are 100 J cm⁻² for sample A and 80 J cm⁻² for sample B. The specimens do not reach the best hardening effect simply with enough impact numbers. It can gain the best hardening effect only when the impact energy reaches or exceeds a critical value. In other words, in order to take full advantage of the hardening ability of austenitic manganese steel, the impact energy should equal or exceed the critical value. According to Fig. 2, the critical impact energies are 100 J cm⁻² for sample A and 80 J cm⁻² for sample B. The austenitic manganese steel could achieve the best hardening effect with the impact hammer mill. But with

### Table 1: Parameters of hammers of three types of hammer mills

<table>
<thead>
<tr>
<th>Model</th>
<th>Rotation speed (r·min⁻¹)</th>
<th>Rotation diameter (m)</th>
<th>Calculated Max. impact energy (J)</th>
<th>Calculated impact energy (J·cm⁻²) [Impact area (cm²)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-S 0808</td>
<td>980</td>
<td>0.8</td>
<td>≤1514</td>
<td>≤75–151 [10–20]</td>
</tr>
<tr>
<td>PCK-M 1430</td>
<td>735</td>
<td>1.43</td>
<td>≤1449</td>
<td>≤120–241 [6–12]</td>
</tr>
<tr>
<td>MB70/90</td>
<td>209</td>
<td>2.7</td>
<td>&gt; &gt; 200</td>
<td></td>
</tr>
</tbody>
</table>

\[ m = \rho \frac{4}{3} \pi r^3 = 2 \times 10^3 \times \frac{4}{3} \times 3.14 \times (\frac{120}{2})^3 = 1.8 \text{ kg} \]

### Table 2: Parameters of lining boards of four types of ball mills

<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter of grinding ball (mm)</th>
<th>Height of ball sinking (m)</th>
<th>Calculated impact energy (J·cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ3.2</td>
<td>120</td>
<td>2.13</td>
<td>147</td>
</tr>
<tr>
<td>Φ2.5</td>
<td>100</td>
<td>1.67</td>
<td>67</td>
</tr>
<tr>
<td>Φ2.0</td>
<td>100</td>
<td>1.33</td>
<td>52</td>
</tr>
<tr>
<td>Φ1.5</td>
<td>80</td>
<td>1.0</td>
<td>21</td>
</tr>
</tbody>
</table>

Take Model Φ3.2 as an example, the calculation process is as follows:

The mass of the ball:

\[ m = \rho \frac{4}{3} \pi r^3 = 7.8 \times 10^3 \times \frac{4}{3} \times 3.14 \times (\frac{120}{2}^3) = 7.054 \text{ kg} \]

where \( \rho \) and \( r \) are density and radius of the ball.

Impact energy endured by the lining board:

\[ E' = \frac{E}{s} = \frac{mgh}{s} = \frac{7.054 \times 9.8 \times 2.13}{1} = 147 \text{ J cm}^{-2} \]

where \( s \) is the impact contact area.

Table 1 and Table 2 show the “impact energy” which the hammers and lining boards endured, respectively. The two tables show that the impact energies of these two kinds of machines are changed from 21 J cm⁻² to much more than 200 J cm⁻². According to the calculation of impact energies, we chose 50, 80, 100 and 200 J cm⁻² to carry out the experiments of work hardening. For the impact experiments, a new impact testing machine was used. The investigated alloys were smelted using scrap steel, metal manganese, graphite, chromium iron and molybdenum iron in a medium frequency induction furnace. The compositions were measured using a SPECTROLAB Photo-electric Spectrum Analytic Instrument, and are shown in Table 3. The specimens with different impact energies were solution treated, water quenched and cut into 1 cm × 1 cm × 1 cm cubes for impact experiments.

### Table 3: Chemical compositions of experimental materials (wt.%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>0.8</td>
<td>0.28</td>
<td>12.8</td>
<td>1.78</td>
<td>0.48</td>
</tr>
<tr>
<td>Sample B</td>
<td>1.23</td>
<td>0.505</td>
<td>14.33</td>
<td>2.25</td>
<td>0.863</td>
</tr>
</tbody>
</table>

The hardness was measured with a Brinell hardness tester. Metallographic specimens were etched by FeCl₃+HCl water solution. The microstructures of the austenitic manganese steel after work hardening were observed using JP-100 and 4XB-TV optical microscope and Hitachi H800 (TEM). Specimens for TEM were cut from the surface. The thin foils were carefully ground to 50 μm and then double-sided thinned by electro-polishing. The foils were examined using H800 TEM at 200 kV. Structural analysis was done using Electron Diffraction and XRD.

### 2 Results and discussion

Figure 2 shows the change of hardness with impact energy. The results for the two samples are similar, and the hardening behavior vs. impact energy is consistent with the previous work. From Fig. 2, for each impact energy, up to 10 impacts, the increase in hardness is the fastest; then, with the increase in number of impacts, the rate of hardness increase decreases gradually until the hardness reaches a maximum and then remains almost unchanged. The maximum hardness is lower at or below 80 J cm⁻² for sample A and 50 J cm⁻² for sample B. The specimens do not reach the best hardening effect simply with enough impact numbers. It can gain the best hardening effect only when the impact energy reaches or exceeds a critical value. In other words, in order to take full advantage of the hardening ability of austenitic manganese steel, the impact energy should equal or exceed the critical value. According to Fig. 2, the critical impact energies are 100 J cm⁻² for sample A and 80 J cm⁻² for sample B in this study. Comparing Table 1 and Table 2, the austenitic manganese steel could achieve the best hardening effect with the impact hammer mill. But with
the ball mill, it is difficult to reach the best hardening effect.

Figure 3 shows the microstructures of the sample A at impact energies of 50 J cm$^{-2}$, 100 J cm$^{-2}$ and 200 J cm$^{-2}$, respectively. Slip bands are visible in the specimens after work hardening. From Fig. 3, the density of slip bands is in proportion with the impact energy. So at 50 J cm$^{-2}$, the slip bands are wide and the density is low. But the dislocations stack to a network when crossed slip bands appear at 200 J cm$^{-2}$.

Figure 4 shows the typical TEM micrographs of the hardening specimens at 50 J cm$^{-2}$ (Sample A). The dislocations interact to form cellular structure as shown in Fig. 4(a). The stacking faults can be observed in Fig. 4(b), which is formed in the partial dense dislocation area for uneven stress. The fault is difficult to slip, so austenitic manganese steel has to twin to deform [Fig. 4(c)]. At the impact energy of 50 J cm$^{-2}$, the microstructure is mainly composed of cellular dislocations, faults and a small quantity of twins, and the specimen does not achieve the best work hardening effect. So when the impact energy is increased, the microstructure will change.

Figure 5 shows a comparison of twin structure observed in the sample A tested at 50 J cm$^{-2}$, 100 J cm$^{-2}$ and 200 J cm$^{-2}$, respectively. The twins can be observed frequently and their density increased with the impact energy.

In austenitic manganese steels, the twins form at the (111) face. When there are two directions of twins forming, the latter will cross the former, which leads to the secondary twin band. Figure 6 shows the density of the secondary twinning at 50 J cm$^{-2}$ and 100 J cm$^{-2}$ (sample A), which increases with the impact energy. Because these twin bands cross and block each other, it is difficult to move across the dislocation. The higher the density of twin bands, the higher the degree of hardening.

The above analysis shows that the microstructure of the austenitic manganese steel is mainly composed of dense dislocations, faults and a small quantity of twins at 50 J cm$^{-2}$, and it is made up of dense dislocation and twins at 100 J cm$^{-2}$ and 200 J cm$^{-2}$. So it can be speculated that the strengthening of the steel caused by twins is higher than that by faults. The reason is concerned with the relationship
between twin and fault. Xie Jingpei \cite{11} considers the stacking fault is the minimum twin and the formation of twins needs higher stress. Furthermore, the finer the twin bands and the more twins there are, the higher the degree of hardening is.

As for the work hardening mechanism of austenitic manganese steel, there are two branches: the deformation induced martensite transformation hardening theory and the dislocation twinning hardening theory. In order to observe the martensite in the specimens after work hardening, electron diffraction was carried out for sample A using H800 TEM in the area of dislocation and twin. Diffraction spots indicate that there is no martensite in the hardening area, as shown in Fig. 7(a). Figure 7(b) shows further research on the hardening area at 200 J cm\(^{-2}\). The result indicates there is only an austenitic diffraction peak. No evidence that the strain induced transformation from austenite (\(\gamma\)) to \(\alpha\) or \(\varepsilon\) martensite was observed in these specimens, which is in agreement with previous work \cite{12-13}. So it can be concluded that the work hardening mechanism is not martensite hardening theory.

3 Conclusions

The hardness and microstructure of austenitic manganese steels were studied at different impact energies of 50, 80, 100 and 200 J cm\(^{-2}\), which were chosen based on the calculation of impact energies of actual working conditions. The conclusions are as follows:

(1) Hardness experiments show work hardening ability increases with the impact energy. For austenitic manganese steel of the given composition, the best hardening effect is achieved only when the impact energy reaches or exceeds the critical impact energy, i.e., 100 J cm\(^{-2}\) for sample A and 80 J cm\(^{-2}\) for sample B.

(2) Observations of the microstructures revealed that the slip bands, dislocations, faults and twinning increase with the impact energy. Below the critical impact energy, the microstructure is composed of dislocations, faults and little twinning; the hardening mechanism is dislocation and slip mechanism mainly. Above the critical impact energy, the microstructure is composed of twinning and dense dislocation, so the work hardening mechanism is twinning hardening mechanism. There is no deformation martensite present, even when hardened at the 200 J cm\(^{-2}\) impact energy.

(3) The effect of twinning on strengthening the steel is higher than that of faults, so it is beneficial to form dense twinning to make full use of the work hardening ability of austenitic manganese steel.

References


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This work was supported by the Special Foundation for Introducing and Selecting Talent in Hefei University of Technology, China (No. 2004000197).