Influence of the C and Mn Concentration on the Grains Size of the Fe-Mn-C alloy

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Annotation. In the study of the material, the detailed study of the structure in the initial state is an important task. In the present study was studied the influence of Mn content on the average grain size in the hardened alloys with different carbon concentrations (1. C ~ 1 wt. %, 2. C ~ 0.4 wt. %) in the Fe-Mn-C alloys with the addition of alloying elements Cr and V. The grain structure of alloys was studied. It was revealed that after quenching the alloy has regular grain structure. The average grain sizes are within the ranges of 20-45 microns. It is found that in the alloys of the first group (about 1 wt. % C), the grain size decreases with the increased Mn concentration, there is no such relationship in the alloys of the second group (~ 0.4 wt. % C).

INTRODUCTION

Increase of the working time of machine life-limited parts is one of the most important problems of today’s machine-building industry. This applies especially to the ore mining, coal mining, cement and other industries that deal with processing of highly abrasive mineral raw materials (ore, coal, sand, etc.). Service life of machine parts and other products, their reliability and longevity in many cases depend on the wear resistance of the materials they are made of. One of the most widely used wear-resistant materials is Manganese Austenitic Hadfield Steel (110G13L).

The Hadfield steel is generally used in as-cast condition, as it tends to heavy hammer hardening at mechanical processing. The Hadfield steel with low hardness is specified by high wear resistance within conditions of impacts and abrasion. Currently, it is assumed [1] that high wear resistance of the Hadfield steel, namely at friction, is associated with intensive hardening at the plastic behaviour. Mechanisms of high hardening of this steel are complex [2], that’s why they are still being studied. Thus, as it is shown in [3,4,5] were studied grains deformation mechanisms and formation mechanisms of twins, but the process of changing the grain boundaries, and their sizes was not examined in detail. Also, thus, as it is shown in [6], dislocation accumulation rate at deformation of the Hadfield steel is higher than dislocation formation rate in other FCC metals. In addition, the twin formation process contributes additionally [7] and hardening performed by this is higher in comparison with dislocation accumulation [8]. In this case, the main cause of hardening is interaction of twin formation with the glide process and twin formation.

At the present time, it is found that the grain size influences the crystalline transformations, defect structure and polycrystal deformation [9–18]. In this case it is applied to FCC as well as BCC metals, alloys and steels with the grain size from the micro to macro level. Thus, it has been demonstrated that the crystalline transformations take place and are developed with the most intensity in large grains. The plastic deformation frequently starts in the largest grains and they contributes foremost to the form alteration of a sample. The scalar density of dislocations increases at reduction of the size of a specific grain. That’s why a function of grain distribution according to their sizes in each alloy is an essential characteristics.

Also, it is found that mechanical properties of polycrystals depend not only on the grain size, but also on the type of grain boundaries [17, 20, 21, 26]. It is known that there are two types of grain boundaries [19]: ordinary boundaries and special boundaries. According to the morphological characteristics, the curved grain boundaries is the ordinary type of boundaries and faceted boundaries and annealing twin boundaries are the special type.
In its turn, C and Mn content, as well as introduction of alloying elements in the Hadfield steel [20,22] should influence the grain size. Change of Mn concentration and alloying influence on the grain boundary assembly in FCC was also noted earlier [24].

Also, it has been noted that alloying causes change of the stacking fault energy that influences significantly the grain structure of alloys [17, 26]. It has been demonstrated that introduction of such element as Carbon in an alloy causes complex alteration of the value of stacking fault energy [23, 24, 26]. Thus, stacking fault energy is increased at increasing of the Carbon concentration within 0-0.4 wt. % and it is decreased at further increasing within 0.4-1.2 wt. % in Fe-Mn-C alloys (at Mn content of 12-14 wt. %) [27]. Increasing of Mn concentration from 0 to ~20 wt. % at carbon content of ~0.1wt. % causes reduction of the stacking fault energy, and it is increased at further Mn increasing [23].

That’s why the aim of this work was to study the influence of C and Mn and V and Cr alloying elements of the average grain sizes on distribution of grains according to their sizes, structure of grains and nature of grain boundary change.

**MATERIALS AND METHODS**

As the test material we used austenitic alloys, the chemical composition of which is specified in the Table 1. All alloys were homogenized and normalized with subsequent water hardening from temperature \( 1050^\circ\text{C} \) (30 min.) as the final thermal treatment.

**TABLE 1.** Chemical composition of the investigated steel (weight %)

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>V</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.19</td>
<td>6.9</td>
<td>-</td>
<td>-</td>
<td>0.39</td>
<td>0.012</td>
<td>0.015</td>
<td>91.49</td>
</tr>
<tr>
<td>2</td>
<td>1.15</td>
<td>12.0</td>
<td>-</td>
<td>-</td>
<td>0.29</td>
<td>0.014</td>
<td>0.014</td>
<td>97.55</td>
</tr>
<tr>
<td>3</td>
<td>1.16</td>
<td>18.2</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
<td>0.010</td>
<td>0.016</td>
<td>79.73</td>
</tr>
<tr>
<td>4</td>
<td>0.40</td>
<td>6.2</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>0.013</td>
<td>0.022</td>
<td>92.74</td>
</tr>
<tr>
<td>5</td>
<td>0.36</td>
<td>12.2</td>
<td>-</td>
<td>-</td>
<td>0.67</td>
<td>0.012</td>
<td>0.022</td>
<td>86.73</td>
</tr>
<tr>
<td>6</td>
<td>0.35</td>
<td>16.6</td>
<td>-</td>
<td>-</td>
<td>0.68</td>
<td>0.012</td>
<td>0.022</td>
<td>82.03</td>
</tr>
<tr>
<td>7</td>
<td>0.95</td>
<td>7.3</td>
<td>1.91</td>
<td>0.31</td>
<td>0.89</td>
<td>0.041</td>
<td>0.013</td>
<td>88.6</td>
</tr>
<tr>
<td>8</td>
<td>0.98</td>
<td>12.5</td>
<td>1.94</td>
<td>0.31</td>
<td>0.86</td>
<td>0.041</td>
<td>0.013</td>
<td>83.35</td>
</tr>
<tr>
<td>9</td>
<td>0.98</td>
<td>15.6</td>
<td>1.94</td>
<td>0.31</td>
<td>0.86</td>
<td>0.041</td>
<td>0.013</td>
<td>80.25</td>
</tr>
<tr>
<td>10</td>
<td>0.51</td>
<td>9.5</td>
<td>2.31</td>
<td>0.31</td>
<td>0.016</td>
<td>0.035</td>
<td>0.016</td>
<td>87.3</td>
</tr>
<tr>
<td>11</td>
<td>0.51</td>
<td>14.2</td>
<td>1.97</td>
<td>0.31</td>
<td>0.016</td>
<td>0.036</td>
<td>0.016</td>
<td>82.94</td>
</tr>
<tr>
<td>12</td>
<td>0.50</td>
<td>17.2</td>
<td>1.97</td>
<td>0.31</td>
<td>0.016</td>
<td>0.035</td>
<td>0.016</td>
<td>79.95</td>
</tr>
</tbody>
</table>

The study was performed by the optical microscopy method with a MIM-10 microscope at 70-380 operating multiplication. Sample surfaces were treated by the following way. At first, they were chemically polished in a solution: 50ml \( \text{H}_3\text{PO}_4 \) + 100ml \( \text{H}_2\text{O} \). Then, they were electrolytically polished in a saturated solution of \( \text{Cr}_2\text{O}_2 \) in \( \text{H}_3\text{PO}_4 \) at temperature of \( 60^\circ\text{C} \) and current density of 0.5–0.7 A/cm\(^2\). The electrolytical etching mode was additionally performed at the final stage of electrolytic polishing. Current density was increased to 1.5–2.0 A/cm\(^2\) for 3-5 minutes for this purpose. Average grain sizes were measured by the random linear intercept method with microsections according to the standard method. Measurements for each alloy were not less than 300. Distribution of grains according to the sizes was plotted according to the values obtained for each alloy (histograms). The average grain size and dispersion were found by obtained histograms.

**RESULTS AND DISCUSSION**

As shown in the Table 1, all studied alloys can be classified in two groups. The first group is the alloys with carbon concentration of ~1 wt. %. The second group – alloys with carbon concentration of ~0.4 wt. %. Manganese concentration in each group is measured within 6 - 18 wt. %. Additionally, each group of the alloys studied can be subdivided into two subgroups: a) alloys, containing no carbide-forming elements, and b) alloys, containing such elements as Cr and V.

Studies have shown that all the alloys studied in this work demonstrate normal polyhedral grain structure after hardening. Examples of grain structure are shown in Figure 1. As can be seen in the microphotographs shown in Figure 1–4, all alloys include annealing twins. As their size matches that of smaller grains, they can be viewed as separate secondary grains. Since the presence of twins is not that essential to resolve the problems, which are the objective of this study, the twins shall be viewed as separate grains.
FIGURE 1. Image of the grain structure (a, c, e) and distribution of grains according to their sizes (b, d, f) for Fe-Mn-C alloys (~1 wt. % C) at different content of Mn: a,b – 6.9 wt. %; c,d – 12.0 wt. %; e,f – 18.2 wt. %

FIGURE 2. Image of the grain structure (a, c, e) and distribution of grains according to their sizes (b, d, f) for Fe-Mn-C alloys (~0.4 wt. % C) at different content of Mn: a,b – 6.9 wt. %; c,d – 12.0 wt. %; e,f – 18.2 wt. %
FIGURE 3. Image of the grain structure (a, c, e) and distribution of grains according to their sizes (b, d, f) for Fe-Mn-C alloys (~1 wt. % C) alloyed by Cr and V, at different content of Mn: a,b – 6.9 wt. %; c,d – 12.0 wt. %; e,f – 18.2 wt. %

FIGURE 4. Image of the grain structure (a, c, e) and distribution of grains according to their sizes (b, d, f) for Fe-Mn-C alloys (~0.4 wt. % C) alloyed by Cr and V, at different content of Mn: a,b – 6.9 wt. %; c,d – 12.0 wt. %; e,f – 18.2 wt. %

The average grain sizes are shown in the Table 2. It is important to note, that the average grain size is an important characteristics, since it has essential influence on mechanical properties of materials and quantitative parameters of fine structure under conditions of phase transformation and plastic deformation. In the materials, studied for this work, the average grain sizes are within the range of 20-45 μm. For normal materials, this grain size is rather favorable, since, first, there are no coarse or uneven grain effects, and second, with such grain size, the grain structure can be classified in its initial state as quasi-equilibrium. Significantly non-equilibrium grain boundaries can be formed in the process of deformation.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The average grain size in the hardened alloys Fe–Mn–C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Undoped alloys</strong></td>
<td><strong>Doped alloys</strong></td>
</tr>
<tr>
<td><strong>C, wt.%</strong></td>
<td><strong>Mn, wt.%</strong></td>
</tr>
<tr>
<td>~1.0</td>
<td>6.9</td>
</tr>
<tr>
<td>(Group 1)</td>
<td>12.0</td>
</tr>
<tr>
<td>~0.4</td>
<td>18.2</td>
</tr>
<tr>
<td>(Group 2)</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>16.6</td>
</tr>
</tbody>
</table>

The functions of grain distribution according to sizes for studied alloys are also given in Fig. 1-4. It can be seen that there is the single-mode distribution function for all alloys studied in this work. The maximum value of the distribution function, as a rule, approaches the average value. It is important to note the grain size dispersion.
This is significantly smaller than the average grain size. Once again, this indicates the quasi-equilibrium nature of grain size distribution function.

It is seen from the distribution function analysis that the increase of Mn content in alloys of Group I (refer to Fig. 1) causes reduction of grains; large grains disappear, and share of small grains is gradually increased. As crystalline transformation $\gamma \rightarrow \varepsilon \rightarrow \alpha$ begins from large grains, the probability of crystalline transformation is decreased at increasing of Mn content. Introduction of Cr and V alloying element results in further reduction (refer to Fig. 3). Increasing of Mn content to 12.0 wt. % in alloys of Group 2 (refer to Fig.2) results in the fact that a share of small sizes is sharply decreased, but significant quantity of large grains is formed. It means that intensive crystalline transformation should be expected at this Mn concentration. Further increasing of Mn content to 18.2 wt. % results in the fact that a share of small grains was increased again, and large grains were not observed in this alloy. The crystalline transformation probability is sharply decreased in the alloy. Allo ying with Cr and V elements (refer to Fig. 4) results in the fact that a share of small grains is decreased at increasing of Mn content, and simultaneously, large grains are intensively formed. It means that alloying should promote the crystalline transformation in the alloy.

Figure 5 shows the dependence of average grain size on the Mn content of alloy at different carbon concentrations. It is evident that in alloys of the first group (~1 wt. % of C), grain size decreases with the increase of Mn concentration (Fig. 5a, 1). Allo ying with Cr and V elements leads to greater decrease of grain size (Fig. 5b, 1). In the alloys of the second group (~0.4 wt. % of C), this dependence is not observed (Fig. 5a, 2). Allo ying with Cr and V elements does not change the complex dependence (Fig. 5b, 2). Probably, such ambiguous behavior is explained by the complex and ambiguous behavior of the stacking fault energy that associates, on the one hand, with the small carbon concentration, and, on the other hand, with introduction of alloying elements (Cr and V). Just change of the stacking fault energy results in change of the grain structure, and, accordingly, in change of the phase composition of the steel matrix, i.e. to $\gamma \rightarrow \varepsilon \rightarrow \alpha$ transformation.

As noted above, the mechanical properties of polycrystals depend not only on grain size, but also on grain boundary type. That is why particular attention in this study was paid to the grain boundary type and nature of their change. It is found that there are grain boundaries of all types in all the alloys studied in this work: ordinary boundaries (curved) and special boundaries (faceted and annealing twin boundaries). Annealing twins (which means twin boundaries, i.e. special boundaries) are present in all alloys (see Fig. 1-4). Faceted grain boundaries that are special type boundaries are also present in all alloys. Moreover, they are clearly visible in the images, obtained using the optical microscopy. The images of faceted boundaries, which refer to special type boundaries, and curved boundaries, which refer to ordinary type boundaries, in different alloys studied in this work are shown in Fig. 6-7.
FIGURE 6. Faceted grain boundaries in Fe-Mn-C alloys at concentration of ~1 wt. % C (a–c) and ~0.4 wt. % C (d–f) and different Mn concentrations (wt. %): a - 7.3, b - 12.5, c - 18.2, d - 6.2, e - 15.6, f - 16.6

FIGURE 7. Image of curved grain boundaries obtained by using the optical microscopy in Fe-Mn-C alloys at concentrations of ~1 wt. % C (a–c) and ~0.4 wt. % C (d–f) and different Mn concentrations (wt. %): a - 6.9, b - 12.5, c - 18.2, d - 6.2, e - 14.2, f - 17.2

As the undertaken studies have shown, the share of twin boundaries in alloys decreases with the increase of Mn concentration. This is observed both in alloys that refer to the first group and in alloys that refer to the second group. Introduction of alloying elements leads to sharp increase of twin boundaries share. However, the type of dependence on Mn concentration remains unchanged. As for the faceted boundaries, here the influence of Mn concentration is not that pronounced. However, introduction of alloying elements leads to sharp increase of the share of the faceted boundaries in all alloys.

CONCLUSIONS

The studies performed using the optical microscopy have demonstrated the following:

The ordinary polyhedral grain structure is observed in all alloys studied in this work. The function of grain distribution according to their sizes is single-mode. The maximum value of the distribution function, as a rule, approaches the average value.

Increasing of the manganese concentration results in weak decreasing of the grain size in an alloy containing ~1 wt. % C. Introduction of Cr and V alloying elements intensifies this process.

Increase of the Mn concentration due to the complex change of the stacking fault energy results in ambiguous transformation of the grain structure in an alloy containing ~0.4 wt. % C. Introduction of Cr and V alloying elements complicates this process. The phase composition of an alloy can be changed by regulation of the Manganese concentration in an alloy, as well as its alloying with Cr and V elements.
ACKNOWLEDGEMENT

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