Influence of Vanadium Content on the Microstructure and Mechanical Properties of High-Manganese Steel

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Abstract— In this study, the influence of the vanadium content on the grain size and the hardness of a high-manganese steel (HMnS) like Mn15Cr2 were investigated. The HMnS microstructure was studied and determined by using OM (Optical microscopy), SEM (Scanning electron microscopy), EDX (Energy dispersive X-ray spectroscopy), and BSED (Back scattering electron diffraction). The paper results showed that the carbides in steel were created after adding vanadium, the hardness increased, otherwise the austenite grain size decreased. The dispersive distribution of carbides increased the hardness of steel. The highest impact toughness of HMnS with 1% of vanadium was 115J/cm², the highest Brinell hardness (HB) was 223. Besides, the results of reduction in impact toughness and hardness after increasing the vanadium content were shown. Also, the analysis of transmission electron microscopy in the microstructure revealed that fine vanadium carbide particles were dispersed within the steel substrate after heat treatment.

Index Term— vanadium, high-manganese steel, vanadium carbide, microstructure, mechanical properties

I. INTRODUCTION

High manganese steel appeared from a long time ago with the name Hadfield steel, it was patented by Sir Robert Hadfield in 1882. This steel was used in industrial applications such as impact hammers, crusher jaws, grinding mill liners, crawler treads for tractors, and railroad crossings [1, 2]. In high manganese steel, carbon and manganese were the primary alloying elements. Typical concentrations were 0.7%-1.45% of carbon and 11-14%of manganese, although in some cases, manganese steel contained approximately 18% of manganese [3, 4] which stabilized the austenite phase, and strengthened the solid solution. Manganese also lowered the transformation from austenite to martensite temperature, increasing the hardness of steel [5]. A higher austenitizing temperature was necessary for highmanganese steel [6].

The austenitic high manganese steels has been proved high resistance to abrasive wear including blows and metal-to-metal wear [7]. These steels were supposed to harden under use, thus they gave a hard abrasion resistant surface, but it has been reported a good wear resistance in components, even without heavy mechanical deformation [8, 9]. These steels were used in mining machinery like shovels and crushers, and railway [10, 11]. At room temperature, this steel was so ductile and it had a microstructure of austenite and became stiffer under the impacts of the force. This was particularly-strengthened mechanism of the steel [12, 13].

In the world, there were several studies focused on improving the mechanical properties of high manganese steel by alloying and heat treatment [14-16]. According to those studies, this steel might get excellent in wear resistance, well-strengthened, well-hardened by adjusting some alloying elements such as chromium (Cr), molybdenum (Mo), vanadium (V)...in combination with the heat treatment processes [17,18]. The materials with the most accustomed reinforcement used in the alloys based on iron were carbides, and vanadium carbide (VC) was used the most because its hardness was high, corresponding to 2600HV–3000HV (Vicker hardness) [9, 19].

Vanadium was an element of strong carbide formation, and its addition to manganese steels substantially increased yield strength, but decreased ductility. Vanadium was used in precipitation-hardening manganese steels in amounts ranging from 0.5% to 2% [20, 21]. Because of the stability of vanadium carbides, a higher solution homogenization temperature 1120°C to 1175°C was recommended to age in the range of temperature usually between 500°C to 650°C [22, 23]. Yield strength of over 700MPa was obtained, which depended on the degree of ductility that might be tolerated for a given application [7, 22]. Tests of an age-hardened manganese-nickel-molybdenum-vanadium austenitic alloy demonstrated that the abrasion resistance of this steel was not as good as that of the standard grades [8, 24]. When the vanadium content was less than 2%, the carbides VC, V₃C₆ were created, which acted as neutral, hard or small particles distributed in the austenite grain, the carbides positively affected the wear resistance [3, 25, 26]. On the contrary, the carbides that were distributed at the grain boundaries caused brittle and destroyed the mechanical parts.

This paper study object was to investigate the influence of vanadium content on HMnS-microstructure and mechanical properties. Thanks to the results, the optimal vanadium content in HMnS aiming at improving the mechanical properties was shown clearly.
II. EXPERIMENTAL SETUP

The experimental alloy was the HMnS, the sample was melted in an induction furnace and poured into the green sand mould of cylinder ingot with 25mm of diameter. The samples with the different Vanadium (V) content were prepared, the compositions of experimental samples were shown in Table I. The fabrication process of casting sample was shown in Figure 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe (%)</th>
<th>C (%)</th>
<th>Mn (%)</th>
<th>Cr (%)</th>
<th>V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>79.9</td>
<td>1.38</td>
<td>15.2</td>
<td>1.98</td>
<td>0</td>
</tr>
<tr>
<td>Sample 2</td>
<td>80.3</td>
<td>1.36</td>
<td>14.7</td>
<td>1.82</td>
<td>1.02</td>
</tr>
<tr>
<td>Sample 3</td>
<td>80.1</td>
<td>1.44</td>
<td>14.4</td>
<td>1.88</td>
<td>1.99</td>
</tr>
</tbody>
</table>

In this research, heat treatment process was used and shown in Figure 2 where the samples were heated up to 650°C, kept at this temperature for 2 hours, air-cooled down to room temperature, then heated again to 1100°C and kept at that temperature within 2 hours. It was quenched finally. The hardness was determined by Hardness Tester-ARK600, and the microstructure was observed by Axiovert 25A and SEM QUANTA 250. Abrasion value was determined by the loss of mass of cylindrical sample with 4mm of diameter that was loaded with 12N, 240 of grain size glass paper which was installed on a plate to contact to above sample. As this plate achieved 300rpm of rotation and 3000m of distance, the abrasion value of sample was determined by using the SA410 electronic scale with the accuracy of four-digit error after the comma.

The samples for the impact toughness test were fabricated according to ASTM standard with V-scorch, and tested by CHAPPY machine. The samples with a dimension of 10 x10 x 55 mm and the distance between the slots of 2x2mm were used. The sample was put on the test machine and on the dropping line of the hammer. The hammer was taken up to the height (H) to move with a circular orbit, then it struck hard the sample. When the sample was destroyed, the hammer went on moving a distance to the front with height (h). The impact toughness \((a_k)\) was calculated as:

\[
a_k = \frac{mg(H - h)}{S_o} \text{(J.cm}^{-2})\]

Where:
- \(m\) - weight of hammer head, kg
- \(g\) - gravitational acceleration, \(\text{m/s}^2\)
- \(S_o\) - area of the sample at the scorch

Fig.1.. The fabrication process of casting samples

Fig.2.. Schematic of heat treatment
III. RESULTS AND DISCUSSION

A. Microstructure

In this experiment, microstructure images of after-casting samples taken by Optical Microscope (OM) were shown in Figure 3.

From Figure 3, the microstructure of sample was clearly seen that the matrix was the austenite with a few carbides distributed inside and along grain boundaries. The sample 1 shown in Figure 3a contained no vanadium (0% of vanadium), the grain size of austenite was 70μm - 80μm that met the fourth grade following to ASTM standard. The sample 2 with 1% of vanadium was shown in Figure 3b, the grain size of austenite was from 50μm to 60μm, meeting the fifth grade according to ASTM standard. However, as vanadium content was 2%, austenite grain size of this steel was coarser with 70μm to 80μm of diameter; moreover, the carbide distributed in the grain boundaries increased too, this microstructure was observed clearly in Figure 3c. The microstructural images of samples after heat treatment were shown in Figure 4.
Figure 4 showed that the microstructure of samples included the austenite matrix after heat treatment, and there were a few carbides within the grains and the boundaries of austenite. In general, after heat treatment, the grain size of austenite was smaller than that of casting sample. The grain size of sample 1 was 50μm - 60μm, equal to the fifth grade following to ASTM standard and shown in Figure 4a. The sample 2 shown in Figure 4b with vanadium content was 1%, the grain size was 40μm, equal to the sixth grade following to ASTM standard, the grain size of this sample was smaller than that of sample with 0% of vanadium. When vanadium content was 2%, the grain size of austenite was smaller than that of the casting sample, but insignificantly. Similarly to the after-casting samples, the grain size of austenite in microstructure was not smaller than the grain size of the sample with 1% of vanadium, but coarser grain (about 50μm - 60μm) was shown in Figure 4c where the carbides distributed on grain boundaries was presented. The main reason might be due to the austenization temperature was not enough to dissolve all carbides, which precipitated at 650°C. The sample 2 after heat treatment was studied by SEM, BSED, and EDX line, and was shown in Figure 5.
In Figures 5a and 5b, the SEM and BSED images showed no carbides in grain boundaries of austenite. Figure 5c showed the result of the EDX Lines, which was used to analyze the distribution of elements along the 1.2 mm of length. It could be seen that about 20 grains of austenite on distribution lines and visible presence of elements Cr, V, Mn in steel. These elements were uniformly distributed in the austenite grain. Figure 6 showed that Fe, Cr, Mn, V elements dispersed evenly within the austenite base, this proved the dissolved carbides in austenite after heat treatment. Figure 7 to Figure 9 showed the result of the EDS and TEM analysis for the 1% of vanadium sample. Apart from a uniform distribution in the austenite particle, there were high-vanadium content points, especially in the small austenite boundary, indicating the formation of the rich vanadium phase at that point. In the steel alloyed by 2% of chromium and 1% of vanadium, rich vanadium phase could only be carbides and be clearly seen in Figure 9.

![Fig.6. Mapping of 1% vanadium sample](image)

![Fig.7. EDS analysis for sample point with 1% of vanadium](image)

![Fig.8. Schematic of element distribution](image)

The very small size of carbide binders on the austenitic particle boundary was also very small, those were the carbide particles “latch” for inhibiting the growth of austenite during heating and keeping the temperature. V was capable of producing all kinds of VC, V₆C₅, V₄C₃ or V₈C₇ carbides in which the cube lattice-VC had the highest stable. As-presented results, VC with the cube lattice and the lattice parameters were similar to the austenite base, VC acted as a nucleating agent for crystalline austenite to create small particle structure in the crystallization process. When heated, VC was able to be coherent lattice with the base and very difficult to dissolve. Moreover, due to the similarity of the lattice structure, VC strengthened strongly the base durability under the coherent lattice mechanism. At 1% of V, it was capable of creating small particles even after casting (3.910μm²) in comparison with 0% of V (7.940μm²). During the subsequent heat treatment, vanadium retained that role. However, when the vanadium content increased to 2%, the vanadium carbides appeared more, and they were distributed on the grain
boundaries with the coarse grain size affecting the mechanical properties of the steel. In addition, the vanadium element was sensitive to the formation of ferrite as being heated, this resulted in decreasing the mechanical properties of the sample. Figure 9 also showed the finely small-square-VC particles with 50 nm in size. Such nanometer size for particles appearing in the structure of vanadium carbides strongly increased the abrasion resistance of steel, and the possibility of crack and peel as working at abrasion conditions was not possible. The fine particle size of the vanadium carbides greatly increased the strength and impact strength of the steel.

B. Mechanical properties

The hardness and the impact toughness results of samples were given in Table II.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, HB</td>
<td>175</td>
<td>223</td>
<td>149</td>
</tr>
<tr>
<td>Impact toughness, J/cm²</td>
<td>22</td>
<td>115</td>
<td>75</td>
</tr>
</tbody>
</table>

The above results might be understood that the sample 1 was not added vanadium, hence there were not any vanadium carbides in the austenite base, and it resulted in the lowest hardness. Otherwise, sample 2 had the highest hardness. As mentioned in the experimental setup with 1.02% of vanadium content, vanadium carbide-VC was dispersed. Vanadium carbide-VC was high hardness and coherency related to a crystal of matrix and led to an increase in hardness of sample. The hardness result also coincided with the microstructure image, in which the fine carbides distributed within austenite can be seen. The sample 3 with 1.99% of vanadium content showed the lowest hardness value because the vanadium content was greater than 1%, the created vanadium carbides were not VC with cubic lattice, it was like V23C6, which was complex lattice and low hardness.

It was clearly seen from Table 2, the valuable of impact toughness of sample 2 was higher than that of sample 1 and sample 3. That was due to the microstructure includes no-vanadium carbides to prevent the austenite grain from growing up in sample 1, the grain size of austenite was coarser, leading to low impact toughness. In sample 2, vanadium content was 1%, the created carbides were VC and V3C7 that were the cubic lattice defined in the orientation of <111> parallel to {110} plane of austenite lattice. The hardness increase was related to coherency, resulting in increasing the wear resistance of the steel. These results were suitable for other studies [7, 26]. During austenization, residual vanadium carbides but not dissolved in austenite, acted as a barrier to prevent the austenite grain from growing up, and the fine grain size was obtained. Therefore, the toughness of steel increased along with increasing of vanadium content, not very hard carbides like V3C7 might be also created. This phase was coarse, located in grain boundary that made the sample more brittle to decrease impact toughness. The abrasion of the sample was given in Figure 10.

![Figure 10. Abrasion value of samples](image)

Figure 10 showed the amount of abrasion in the sample with the same abrasion test as described in the experiment. From the results in Figure 10, the abrasion of samples alloyed with sample 1 was 0.954 gram, alloyed with sample 2 was 0.3560 gram, and alloyed with sample 3 was 1.154 gram. Thus, the alloyed sample with vanadium had much less abrasion than that of the chromium-alloyed sample. This was explained by the addition of vanadium in combination with heat treatment, there was a presence of vanadium carbides-VC with the finely small-dispersed-hard property, which increased the hardness and the wear resistance of steel. Moreover, with high austenitization temperature of 1100°C, the austenitic phase had been reinforced because of its dissolved-alloying element, high toughness, difficult to crack and peel.

IV. Conclusions

Vanadium was influenced significantly the microstructure of steel by creating carbides with small particles and high hardness equal to the fifth and sixth grade as following to ASTM. As alloyed with about 2% mass of Cr and 1% mass of V, the presence of vanadium carbide-VC with finely small-dispersed-hard property made the grain size of this steel smaller than 40μm. However, no-vanadium carbides or different vanadium carbides from VC might be the cause of the decrease in mechanical properties. The 1% mass of V-alloyed-HMnS showed the optimal mechanical properties such as highest hardness, highest impact toughness, and highest abrasion resistance.

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REFERENCES