Measurement of the 2-Dimensional Fractal Dimensions of Alumina Clusters Formed in an Ultra Low Carbon Steel Melt during RH Process

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1. Introduction

Control or removal of non-metallic inclusions during the secondary refining process is one of the most important operations in producing high-quality steel products. The first step in controlling or removing inclusions is to understand the behavior of inclusions. Many different types of inclusions are produced in refining processes. Different shapes might arise from different formation and growth mechanisms. Therefore many different theories of inclusion formation and growth have been reported.1–4)

Dekkers et al.5) have reported that the major aspect of alumina inclusions is their agglomerate-cluster shape. Some researchers have adopted the concept of fractals to specify the shapes of the clusters.3,6,7) For fractal clusters, the most important parameter might be the fractal dimension, which accounts for many of the characteristic properties of clusters, such as their compactness. Particularly, the removal behavior of inclusions in the steel-making process strongly depends on the fractal dimension of inclusions.6) However, it is very difficult to find reports on fractal dimensional analysis. Only the value of 1.8 was reported by Tozawa et al.7) based on the cross-sectional images of inclusions.

The present research focuses on the shape of alumina inclusions produced by Aluminum deoxidation in a low-carbon steel RH refining process. The observed alumina inclusions exhibited irregularly spaced clusters composed of many small inclusions, a finding similar to those of other reports.5) One of the interesting characteristics of alumina inclusions is that the inclusions are composed of many small particles of similar size and shape. Inclusion shape can be analyzed using fractal theory and identified by fractal dimension. The fractal dimension of clusters shows a relation between the number of particles and to the radius of the clusters, as shown in Eq. (1):

\[ n \sim r^{D_f 2} \] ............................................(1)

In Eq. (1), \( n \), \( r \), and \( D_f 2 \) are the number of small particles, the radius from the center of the cluster, and the two-dimensional fractal dimension, respectively.

Because it is very difficult to obtain the value of \( D_f 3 \) from experiments, the value of the two-dimensional fractal, \( D_f 2 \), was obtained from the projected images of the clusters. And then the value of \( D_f 3 \) was suggested based on a reported relation between \( D_f 2 \) and \( D_f 3 \).

2. Experimental Techniques

Samples were obtained from a melt of the ladle at POSCO Kwang-Yang works during an RH deoxidation treatment. Some of the operating conditions are listed in Table 1. A total amount of 200 kg of aluminum was added to 270 tons of melt. Three minutes was required for the aluminum addition. The content of other elements are listed in Table 2.

Samples were taken after the last feeding of aluminum during the RH process with an automatic sampler, to extract oxides. The sampling point was located 20 cm below the slag surface near the center of the ladle.

The samples were cut in hexahedron specimens of 1 g and the sizes of each edges were 1 cm, 0.5 and 0.3 cm. These specimens were put in a 100 mL solution of 90% methanol and 10% Bromine. Within 24 h the Fe was dissolved and the remaining inclusions were observed by SEM. The components of the oxides were analyzed by EPMA.

3. Results and Discussion

Most of the inclusions obtained from the samples exhibited the cluster shape. After dissolving the samples in the solution, many alumina oxide clusters had accumulated, as shown in Fig. 1(a). Figures 1(b) and 1(c) show magnified images of selected clusters. The clusters were composed of small inclusions. Some inclusions of dendrite structure were also obtained, as shown in Fig. 1(d).

The clusters exhibited irregular shapes. And because many natural formations having irregular shapes can be explained using the fractal theory,8) the shapes of the alumina clusters were analyzed according to that theory. The most important reference for the fractals of cluster shape is the fractal dimension which specifies the order and density of

<table>
<thead>
<tr>
<th>Table 1. Operating conditions of RH process.</th>
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<tr>
<td>Operating conditions</td>
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<tr>
<td>Vacuum level</td>
</tr>
<tr>
<td>Ar gas flow-rate until sampling</td>
</tr>
<tr>
<td>Amount of melt</td>
</tr>
<tr>
<td>Diameter of snorkel</td>
</tr>
<tr>
<td>Submerged depth of snorkel</td>
</tr>
<tr>
<td>Temperature of melt (start)</td>
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<tr>
<td>Temperature of melt (end)</td>
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<table>
<thead>
<tr>
<th>Component</th>
<th>(total)</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (ppm)</td>
<td>230</td>
<td>19</td>
<td>470</td>
<td>69</td>
<td>80</td>
<td>-</td>
</tr>
</tbody>
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gathering of small inclusions to form large clusters.\textsuperscript{9)}

Because usual fractal theories of clusters are based on the assumption that clusters are composed of the same size of small particles, the size distribution of the small inclusions composing the clusters was analyzed to confirm that the fractal theory could be applied to the present study.

Figure 2 shows the cumulative number density, corresponding to the size, of the small inclusions. The data were obtained from all of the cluster shape inclusions. The dendrites and partially covered particles were not included in the size analysis. Rather, the size reflects the largest dimension of each particle. Even though the sizes of the clusters varied from 10 to nearly 100 $\mu$m, the sizes of ninety percent of the small inclusions fell in the 1–2 $\mu$m range. Therefore, the alumina clusters could be assumed to be composed by small uniform inclusions, and thus the fractal analysis could be applied.

The three-dimensional distribution of small particles has to be known in order to obtain the value of $D_{f3}$ based on Eq. (1). However, it was very difficult to identify the three-dimensional position of each of the particles of the cluster. Thus, instead of the $D_{f3}$ value, the $D_{f2}$ values were obtained based on the SEM image of each cluster. A fractal dimension analysis was performed using the method suggested by Forrest et al.\textsuperscript{10)} The procedure of the method is as follows:

1) Select a point of the cluster as the center.
2) Plot a square whose edge length is $r$ and whose center is the selected point.
3) Calculate the area occupied by the cluster in the square.
4) Increase the side length $r$ and repeat steps (2) and (3).
5) Plot the side length $r$ versus the area on a log–log scale.

If the cluster has a fractal shape, the resulting plot should be linear, and the gradient of the plot is the fractal dimension. Figure 3 shows a result of such a cluster analysis. The pixels of the image were used for the area calculation and the difference of the gray level was used to distinguish the cluster from the background. The nearly linear length-area aspect of Fig. 3 strongly suggests that this cluster could be considered to be of a fractal form. The fractal dimension of this sample was determined, from the gradient of the linear interpolation line, to be 1.82. The $D_{f2}$ values of the 23 clusters fell in the 1.80–1.95 range; the average value was 1.88, with a standard deviation of 0.051.

The values of $D_{f2}$ in the present study showed the relative compactness of the clusters, and thus could be used as a reference for measurement of the fractal particles observed in the melt. However, it is very difficult to assign absolute physical meaning, because the values obtained were of the projected images of the clusters. The value of fractal dimension which has a great effect on the inclusion removal behavior\textsuperscript{6)} is the value of $D_{f3}$.

A relation between $D_{f2}$ values of projection images and $D_{f3}$ values of aggregates was suggested as shown in Eq. (2).\textsuperscript{11)} Using the equation, the $D_{f3}$ value of the alumina clusters could be suggested to have the values between 1.88 and 2.07 and the average value is about 1.98 with a standard deviation of 0.065.

$$D_{f3} = 1.391 + 0.01 \exp(2.164 \cdot D_{f2}) \quad \text{(2)}$$
This value is higher than the value of 1.8 suggested by Tozawa et al.\textsuperscript{7)} The main reason of the difference might come from the difference of sampling time. Samples of the present study were taken no later than a few minutes after last feeding of aluminum. On the other hand the samples of Ref. 7) were obtained from the vicinity of the pouring pipe in the tundish, from the straight part of the immersion nozzle and in the slab. Because the removal rates of inclusions of higher $D_3$ are faster than those of lower value\textsuperscript{7)} and usually more than 90\% of the oxides are removed during deoxidation process, the value of the fractal dimensions of remaining inclusions after refining process should be lower than that of initially formed inclusions. There exists other possibility that the $D_f$ value might be affected by the operating conditions of refining process. However the effect of operating conditions on the $D_f$ value has not been sufficiently studied and further research should be necessary.

4. Summary

Alumina clusters formed in RH processes were investigated in detail. The clusters were composed by small rounded inclusions. The sizes of these inclusions were distributed in a very narrow range. The clusters, of irregular shape, showed a fractal structure. The average value of measured $D_2$ was about 1.88, and the $D_3$ value was suggested about 1.98.

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REFERENCES