Primary Al Grain Size Measurement of Al–Si Hypo-Eutectic Alloy Using Mathematical Morphology Algorithms

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Homogeneous distribution of primary Al phase grain (hereafter, primary Al grain) size in an Al–Si alloy casting is desirable. Traditional image processing techniques found difficulties in making proper image segmentation for the individual primary Al grains. Recently, a new image processing technique, mathematical morphology, is paid attention to because of its capability for a flexible image processing. In this paper, an image processing method based on mathematical morphology algorithms was proposed for the appropriate image segmentation and measurement of primary Al grain size in aluminum alloys. Opening algorithm was applied to identify primary Al grains and Watershed transformation (WST) using Euclidean distance map (EDM) as marker-image was used to separate individual primary Al grains. Finally, a second implementation of WST was used to classify the isolated small primary Al grains that had not been individually identified in the first time WST. The results showed that the proposed method appropriately identified primary Al grains with enough quality to evaluate the size distribution. The quality of primary Al grain size measurement result was as high as human operations. Meanwhile, the proposed method also was more efficient than the subjective measurement by hands. [doi:10.2320/matertrans.M2018076]

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1. Introduction

Aluminum alloys are widely used in automobile industry for the sake of its low density and comparable mechanical performance to ferrous alloys. As is known, mechanical properties are the key parameters to evaluate the performance of products. They have significant correlation to the material microstructure.1) Recently, die casting using semi-solid aluminum alloy slurry is drawing attention due to its outstanding performance,2) and Al–Si hypoeutectic alloys are commonly used in the process. Generally, primary α-Al phase is the primitive phase that emerges in the solidification process. In this paper, we name the visually isolated primary α-Al phase as primary Al grain. The primary Al grain size is concerned while Al in eutectic phase is ignored. We name the Al phase in eutectic phase as eutectic Al grains. The semi-solid slurry with uniform primary Al grain size is desirable.3-8) Therefore, the primary Al grain size distribution is one of the important factors to evaluate the quality of the slurry.5) In the practice, primary Al grain size is measured from an optical image due to its convenient acquisition and low equipment cost. A human subjective manner by drawing approximate polygons to fit phase boundaries can assure the precision of the measurement. However, it is usually a tedious and labor intensive process to repeatedly draw hundreds of polygons on the image. Therefore, a computational image processing technique has been applied to improve the measurement efficiency and to relieve the labor intensity. However, the conventional image processing algorithms had difficulties in dealing with complex shaped phases with image noises and consequently in identifying individual primary Al grain efficiently. As a result, the distribution of primary Al grain size is difficult to evaluate and most of the relevant reports tend to use some typical and unified parameters to evaluate the characteristics of primary Al grains, e.g. average grain area,9,10) fractal analysis,11) run length13) and chord length,14) to evaluate primary Al grain size in products.

Recently, mathematical morphology has been widely developed and applied in many fields15-21) to segment the overlapped cells or congregated grains on the image with noises or unclear grain edges. Watershed transformation (WST) algorithm22) is the most frequently used image segmentation algorithm to segment congregated grains in an image. L. Wojnar23) gave several application examples of image processing techniques on acquiring grain edges for simple shaped single-phase microstructures. In his comparison of several edge detection methods, it was shown that WST algorithm gave the best result for grain identification. However, several problems still remained to apply the WST algorithm to semi-solid Al–Si slurry microstructure. Firstly, an optical contamination of primary Al grain with the other phase prevents accurate identification of primary Al grain. Eutectic phase of Al–Si alloy consists of very fine eutectic Al grains and Si phase, and the eutectic Al grain has the same color with large primary Al grain. Secondly, the WST algorithm with conventional immersion model22) is easy to bring over-segmentation for individual regions. To suppress the generation of over-segmentation, markers are applied to specify the origins of WST operation.10) Ultimate eroding point (UEP) method is one of the automatic methods to prepare markers. It has been plugged in the well-known image analysis software ImageJ and widely used to segment simple-shaped grains.24,25) However, UEP method was incapable of dealing with complex-shaped grains.26,27) It produces excess UEPs for one complex-shaped primary Al grain and then leads to over-segmentation. To suppress such over-segmentation, more flexible method is desirable. Euclidean distance map (EDM) method15) is another automatic preparation method for marker-making, which uses some threshold in the EDM and realizes more flexible marker-making than UEP method. Therefore, the EDM method has possibility to make more appropriate markers for the segmentation of complex shaped grain.

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The WST algorithm is one of the most effective methods to identify target grains, however, still has difficulty in identification of primary Al grains in Al–Si hypoeutectic alloy, even the operation is not so complicated for humans compared with many other commercial alloys. Therefore, we proposed an image analysis procedure based on the combination of mathematical morphology algorithms to overcome the problems above, and tried to properly identify the primary Al grain and obtain accurate primary Al grain size distribution of Al–Si hypoeutectic alloy.

2. Methodology

A basic image processing procedure includes four steps in sequence. Firstly, optical images should be taken from the specimens. Secondly, object grains should be identified in the pre-processing procedure to eliminate the influence of noises or other bad factors on the subsequent procedures. In the third step, the object grains would be segmented and identified with image segmentation algorithms. The objective in the third step is to achieve proper separation of individual object grains. Finally, each object grain size could be measured with certain method. The details of the image analysis steps are as follows.

2.1 Original image acquisition

Commercial AC4CH (A356), which is commonly used alloy for semi-solid die casting process, was used as a target Al–Si hypoeutectic alloy. AC4CH melt (893 K) was poured into a SKD61 mold (473 K) and held for about 10 s to obtain semi-solid slurry. Afterward, a SKD61 plate was used to press the slurry from the upwards and got the solidified sample. This procedure is adopted to obtain a little complex shaped primary Al grains, whereas the procedure is different from common semi-solid slurry making method. The original optical image was taken with an optical microscope at 450× magnification. The image size was 1600 × 1200 (pixel × pixel). The pixel is square shape and its unit length of each side is 0.356 µm. Firstly, good quality image without considerable noises such as shade and scratches was selected to discuss the segmentation procedure.

The optical image was converted into grayscale image. The grayscale value, GS, varied from 0 (black) to 255 (white) according to the pixel brightness. There are two reasons for the use of grayscale images. Firstly, the optical images of aluminum alloys were originally not colorful. Secondly, segmenting color images usually consumed much longer time and higher computation resources than segmenting grayscale images.

2.2 Image pre-processing

2.2.1 Separation of primary Al and Si by binarization

The Al phase and Si phase of Al–Si hypoeutectic alloy appear two different grayscales in the optical images. The Al phase is bright (high grayscale value) and Si phase is dark (low grayscale value). Al phase includes primary α-Al phase and eutectic Al phase while Si phase only exists in eutectic phase. In this paper, primary α-Al phase is the phase of interest. In a good quality image can be obtained, we can easily identify the Si phase by implementing binarization.28)
they should be filled properly with black color in the next step.

2.2.2 Identification of primary Al grains by opening

Optically, small dispersed eutectic Al grains can be recognized as white “holes” in the black matrix Si phase. Opening operation\(^{16}\) is a powerful morphological operation to fill such holes while preserving the primary Al grains. It consists of two steps. The first step is to shrink the Al phase (white pixels) with a certain structuring element. The next step is to enlarge the residual primary Al grains with the same structuring element to recover their original morphology. By the implementation of the two steps, eutectic Al grains disappear while the other primary Al grains were preserved. There are two main factors to characterize a structuring element, which are shape and size of kernel, respectively. The shape can be any type. Rectangle and ellipse are the two most commonly used shapes and they have little influence on the opening result. Thus, we use squared rectangle as the structuring element shape. The kernel size determines the size of holes opening operation can fill. Opening operation will fill the holes which has smaller size than the structuring element. Therefore, the size of the structuring element should be larger than the maximum size of eutectic primary Al grains, and smaller than the minimum size of primary Al grains. Figure 2 shows the application result of opening with different structuring element kernel size. In this result, the white pixels should denote the primary Al grain and the black pixels should represent the eutectic phase. Figure 2(a) shows the original grayscale image used in this application. The opening results with structuring element kernel size of 4, 7 and 12 pixels are shown in Fig. 2(b)–Fig. 2(d), respectively. It can be seen that many eutectic Al grains remained when the kernel size was too small (4 pixels, Fig. 2(b)). In contrast, some small primary Al grains were mis-eliminated when the kernel size was too large (11 pixels, Fig. 2(d)). The circles in Fig. 2(c) and Fig. 2(d) indicate the mis-eliminated primary Al grains. When the kernel size is 7 pixels, it can be seen from Fig. 2(c) that not only more eutectic Al grains were eliminated than those of 4 pixels, but also more primary Al grains were preserved than those of 11 pixels. This means that kernel size of 7 pixels yields better result than 4 pixels and 11 pixels. Some small primary Al islands, e.g. the small primary Al grain in the upper right part, disappear. This is because that it is impossible to exclude all eutectic Al from primary Al with sample size filtering. We should judge the exclusion of eutectic Al and preservation of primary Al with a subjective manner and make an acceptable compromise solution. In this paper, kernel size of 7 pixels in opening operation is such an optimum solution.

2.3 Image segmentation

2.3.1 Image segmentation using Ultimate Eroding Point method

In the early models of WST,\(^ {17,22}\) over-segmentation is very common due to the sensitiveness to the grayscale variation among neighboring pixels. Watershed transformation with markers\(^ {10}\) well solves such a problem. It uses markers to specify origins of individual regions. The quality of the prepared marker-image determines the results of segmentation. In the frequently used image analysis software ImageJ, the marker image is prepared with ultimate eroding points (UEP) method.\(^ {22}\) The UEP markers can be prepared by finding local Euclidean distance maxima.\(^ {10}\)

Euclidean distance is depicted in eq. (1). Here, set \(X\) and \(Y\) represent white pixel set and black pixel set in a binary image, respectively. \(d(x, y)\) is the Euclidean distance between pixel \(x, x \in X\) and pixel \(y, y \in Y\). The Euclidean distance from a white pixel \(x\) to the black pixel set \(Y\) is defined as shown in eq. (2). It is the minimum of the distance from \(x\) to all the pixels in set \(Y\).

\[
d(x, y) = \sqrt{(y_i - x_i)^2} \tag{1}
\]

\[
d(x, Y) = \min\{d(x, y) | x \in X, y \in Y\} \tag{2}
\]

UEP method works well for the simple-shaped grains. However, the UEP method would generate excess number of UEPs for one primary Al grain if the grain was complex-shaped. Figure 3 shows an example of over-segmentation with markers prepared with UEP method. Figure 3(a) is a magnified grayscale image achieved from Fig. 1(a). Figure 3(b) is a result of segmentation by WST with UEP markers on the binary image obtained by opening operation using ImageJ as shown in the Fig. 2(c). Figure 3(b) shows that there are many UEP markers in one grain, and many false boundaries were constructed compared with the original grayscale image. UEP method uses distance map in target

\[\text{Fig. 2} \quad \text{Result of opening operation with different structuring element kernel size. (a) Original image, and opening result with a rectangle structuring element which kernel size is (b) 4 pixels, (c) 7 pixels, and (d) 12 pixels.}\]

\[\text{Fig. 3} \quad \text{Example of over-segmentation by using UEP markers. (a) Original grayscale image, (b) Binarized image with UEP markers (gray ellipses are used to indicate the markers).}\]
grains from their edges, and markers are set at local maximal of the map. Therefore, if a grain has some dents on its edge, the distance map tends to have more than one extremals in one grain, thus UEP method tends to generate more than one marker. Then, large and complex shaped primary Al grains tend to be split into small regions, resulting in over-segmentation.

2.3.2 Marker-image preparation with Euclidean Distance Map method

To overcome the over-segmentation by UEP method, marker-image based on Euclidean distance map (EDM) were adopted in this study. EDM method also uses distance map in each grains and makes markers with certain range using some kind of threshold, whereas the UEP method uses local maximal. By using markers with proper range, the segmentation accuracy can be improved.

The preparation of marker-image with EDM method is as follows. In the first step, the Euclidean distance was calculated at all the white pixels in the binary image. In the next step, the distance map was binarized with a threshold ($\tau_{EDM}$) to prepare the markers for WST. An optimum $\tau_{EDM}$ should assure that each primary Al grain was specified by one marker. Larger $\tau_{EDM}$ is prone to lead to excess markers for one individual primary Al grain. In contrast, the smaller $\tau_{EDM}$ fails to cut off the connections between adjacent primary Al grains. Figure 4 shows the markers prepared by binarizing Euclidean distance with different $\tau_{EDM}$. The $\tau_{EDM}$ values were 0.1, 0.2 and 0.25 times of maximum Euclidean distance, respectively. $\tau_{EDM}$ is defined as the ratio between $\tau_{EDM}$ and maximum Euclidean distance. Figure 4(a) is the magnified image from Fig. 1(a). When $\tau_{EDM}$ is small ($\tau_{EDM} = 0.1$, Fig. 4(b)), the marker-image failed to prepare separated markers (gray regions) for some adjacent primary Al grains, as specified by the ellipses and arrows. In comparison, when $\tau_{EDM}$ is getting larger ($\tau_{EDM} = 0.25$, Fig. 4(d)), excess markers were generated for individual primary Al grains, as specified by the ellipses in Fig. 4(d). An intermediate value, $\tau_{EDM} = 0.2$, yielded better result, shown in Fig. 4(c) than those of 0.1 and 0.25, although there are still some mistakenly prepared markers as indicated by ellipses. Thus, we select $\tau_{EDM} = 0.2$ as the optimum distance threshold for preparing markers.

Figure 5 shows the image segmentation result with markers prepared from EDM. $\tau_{EDM} = 0.2$. The WST algorithm was implemented on Fig. 1(a). It used the markers in Fig. 4(c) as the origins of WST operation. Figure 5(a) is the WST result of Fig. 1(a) using Fig. 4(c) as marker-image. Obviously, the eutectic phase was contained into the neighboring primary Al grains. It could be eliminated by filtering Fig. 5(a) with Fig. 2(c). Figure 5(b) shows the result after filtering eutectic phase from the WST result. Those grains with same color were recognized as same grain. It can be seen that most of the primary Al grains were well segmented from the adjacent eutectic phase. One problem is that some small primary Al grains were identified as part of their adjacent large primary Al grains. They have been specified with ellipses in Fig. 5(b). This is because that the markers prepared with EDM method failed to prepare markers for some small primary Al grain. This will lead to the under-estimation of small primary Al grain number.

2.3.3 Identification of small primary Al grain

A second implementation of WST was used to identify the small primary Al grains that had been recognized as part of other grains in the first WST shown in Fig. 5(b). The identified grains in the first WST were eroded with a rectangle structuring element to prepare the marker image of second WST. We used 1 pixel as the kernel size. This was because most of these mistakenly identified primary Al grains...
were not large and a too large kernel size would fail to generate markers for them. The individual grains obtained in the first WST were eroded one by one. Then, the grains that were visually connected in the original image but individually segmented in the first WST would not connect in the marker-image of second WST. Finally, the markers obtained by erosion were united to create marker image of the second WST. Figure 6(a) shows the second WST result and Fig. 6(b) shows the segmentation after eutectic phase elimination. Obviously, the small primary Al grains which had been taken as part of other grains were identified.

2.3.4 Image segmentation procedures

Through the series of image processing steps, we proposed the procedures to segment primary Al grains of Al-Si hypoeutectic alloy as shown in the Fig. 7. The original image was firstly pre-preprocessed with binarization algorithm to identify the primary Al grains. An opening operation was used subsequently to filtering eutectic Al grains. WST algorithm with markers prepared from Euclidean distance map was used to identify individual primary Al grains. A filtering operation to the WST result with opening result yielded the first segmentation result. Subsequently, WST algorithm was implemented on the original grayscale image for the second time so as to reduce under-estimation of small size primary Al grains. Similar to the acquisition of first segmentation result, the second WST result was also filtered by opening operation result. Then we achieved the final segmentation result. Figure 8 shows the merged image of original image and result of proposed method. It can be seen that the proposed method well identified the primary Al grains in the original image.

2.4 Primary Al grain size evaluation

After the individual primary Al grain extraction using proposed image segmentation procedures, we performed primary Al grain size measurement on the segmented results. We used equivalent diameter\(d_{\text{equivalent}}\) [mm] to characterize primary Al grain. It is depicted in eq. (3), where \(A\) [mm\(^2\)] specifies primary Al grain area.

\[
d_{\text{equivalent}} = 2\sqrt{\frac{A}{\pi}}
\] (3)

In this study, we took manually measured result as the most accurate result and used it to compare with the result of image analysis methods. It is to be noted that we focus visual aspect of primary Al grains using optical images, so we neglect the crystallographic separation of primary Al grains in this study. A primary Al grain would be regarded as an individual primary Al grain if it visually appeared isolated with other primary Al grains. The methodology for manual measurement is to draw approximate polygons to fit the boundaries of primary Al grains on the optical images.

The number of primary Al grains in every 5 µm increment was counted and plotted to output the primary Al grain size distribution histograms. The primary Al grains on the border and corner of the image were not removed for the consideration that they have little influence on the comparison of measuring accuracy.
3. Measurement of Primary Al Grain Size Distribution

3.1 Result by WST with UEP markers

There are many eutectic Al grains dispersed in the space of the primary Al grains. These small grains could be eliminated with opening operation. Figure 9 shows the primary Al grain size measurement result with WST using markers prepared by UEP method before and after opening operation. The structuring element is a rectangle with kernel size of 7 pixels. Before the opening operation, the measurement result overestimated the primary Al grain number dramatically in Al grain size of [0 µm, 10 µm]. In contrast, after the opening operation, the over-estimation became much smaller. The opening operation had little influence on the results over 10 µm. Although the opening operation relieved the over-estimation of extremely small primary Al grains, but the severe over-segmentation of WST with UEP markers brought dramatic over-estimation for those in [10 µm, 45 µm]. In addition, the manually measured maximum primary Al grain size was 155 µm, while that of the UEP method was only 60 µm. This is because large primary Al grains were over-segmented into small grains.

3.2 Results by WST with markers prepared from EDM

The primary Al grains were over-segmented by the WST with UEP markers. A segmentation of WST with markers prepared from EDM is capable of suppressing the over-segmentation. According to the comparison in Fig. 4, markers prepared with $\tau_{\text{EDM}} = 0.2$ yielded the best segmentation result for Al–Si hypoeutectic microstructure. Figure 10 shows the comparison of primary Al grain size distribution measurement results with different marker preparation methods. The eutectic Al grains were removed by opening operation with a rectangle structuring element which size is 7 pixels. The markers of EDM were achieved
by binarizing the EDM with $t_{EDM} = 0.2$. The WST with UEP markers over-estimated the number of primary Al grains in $[10 \ \mu m, \ 45 \ \mu m]$. In contrast, the combination of opening operation and WST with EDM markers gave a much closer result to the manual result. Not only primary Al grain number in $[10 \ \mu m, \ 45 \ \mu m]$ matches the manual result well, but also those over $40 \ \mu m$ are much closer.

### 3.3 Result with identification for small primary Al grains

Some small primary Al grains were difficult to be specified by the markers prepared from EDM. A second time implementation of WST with marker image prepared from the result of first WST was applied to identify them. Figure 11 shows the comparison of results before and after the second WST. It shows that the second time WST has little influence on the result over $30 \ \mu m$. However, the evaluated primary Al grain number below $30 \ \mu m$ is larger than that of only one time WST. This is because the second time WST separated the small size primary Al grains from the large grains. This separation had little influence on the evaluated large primary Al grain size, but increased the number of small primary Al grains. In this paper, the measurement result with one time WST is closer to the manual result than that with two times’ WST. This is caused by the existence of porosities. It led to the generation of excess markers for individual primary Al grains. The first WST recognized some small grains as part of other grains, thus it should underestimate the number of small grains. However, the excessive grains caused by the porosities make up the loss. Thus, it appears that the first WST generated better result than the second WST for the evaluation of small grain number.

The image segmentation procedures based on mathematical morphology in this paper well segmented the primary Al grains in Al–Si hypo-eutectic alloy. By selecting appropriate structuring element kernel size and Euclidean distance threshold, the measurement result of the proposed method could be very close to the manual result. The image segmentation procedures are semi-automatic as many parameters should be determined manually. In the future, the automatic determination of threshold for identifying primary Al grains, the structuring element kernel size and the Euclidean distance threshold will be paid attention.

### 4. Conclusions

An image analysis procedure for semi-automatic primary Al grain size measurement of aluminum alloys was proposed in this paper. In the first step, the primary Al grain was identified with binarization algorithm and opening operation. In the next step, a Watershed transformation with marker-image prepared by binarizing Euclidean distance map was implemented to separate individual primary Al grains. Finally, a second implementation of Watershed transformation was conducted to identify small primary Al grains. The image segmentation results with proposed procedures showed that the proposed method well segmented the primary Al grains. The primary Al grain size measurement results showed that the opening operation dramatically decreased the number of tiny primary Al grain. The WST with UEP markers over-segmented the primary Al grains and thus over-estimated the homogeneity of the microstructure. The WST with EDM markers improved the results greatly. However, it still generated over-segmentation owing to the porosities. The measurement after small size primary Al grain identification relieved the under-estimation of small size primary Al grains. Owing to the over-segmentation generated by porosities, the measured result for small size primary Al grains by proposed method is higher than the manual result. In the future, further attempts should be made to improve the efficiency of opening kernel size determination and Euclidean distance threshold determination.

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