Quantitative image analysis of WE43-T6 cracking behavior

A Ahmad¹ and Z Yahya
Department of Mechanical Engineering, Universiti Tenaga Nasional,
Jln. IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
E-mail: aazmi@uniten.edu.my

Abstract. Environment-assisted cracking of WE43 cast magnesium (4.2 wt.% Yt, 2.3 wt.% Nd, 0.7% Zr, 0.8% HRE) in the T6 peak-aged condition was induced in ambient air in notched specimens. The mechanism of fracture was studied using electron backscatter diffraction, serial sectioning and in situ observations of crack propagation. The intermetallic (rare earthed-enriched divorced intermetallic retained at grain boundaries and predominantly at triple points) material was found to play a significant role in initiating cracks which leads to failure of this material. Quantitative measurements were required for this project. The populations of the intermetallic and clusters of intermetallic particles were analyzed using image analysis of metallographic images. This is part of the work to generate a theoretical model of the effect of notch geometry on the static fatigue strength of this material.

1. Introduction
Image analysis operations are normally employed to evaluate an image quantitatively and descriptively, so that more information would be gained from it [1]. The operation aims to improve the visual appearance of images as well as preparing for the measurement of their dimensions. Image morphology involves the study of structure of features and objects in an image which requires that features to be well defined in all factors, such as its brightness, colour, texture etc. By having all these factors optimized, the maximum amount of information may be quantified from the image. Binary morphological processes work on binary images, composed of pixels which are either black or white. The grey-scale morphological processes progress from the binary techniques, in which pixels are defined by their grey-scale level. Erosion and dilation are two of the primary morphological operations which employ masks to remove small, unwanted features like noise spikes and ragged edges [1]. Erosion is often used to remove uniformly pixels that should not be there, like irrelevant pixels representing point noise or scratches which have size that is normally only a single pixel wide. It removes any pixel touching another pixel that is part of the background. This removes a layer of pixels from around the edge of all features and areas, and can cause the dimensions to reduce.

Dilation is used to add pixels to the object, resulting in expansion. Typically, it adds a background pixel that touches another pixel that is already part of a foreground area. The effect is to add a layer of pixels around the edge of all features and areas. The overall dimensions can increase and features may merge. It also fills in small holes within features. Opening and closing are considered as the secondary operations to the erosion and dilation morphological operations. An opening is the combination of an erosion operation followed by a dilation operation. This combination will open up gaps between just-touching features. It works by removing single-pixel object anomalies like small spurs and single-pixel noise spikes, resulting in object contours being smoothed. In contrast to erosion, this operation should retain the original shapes and...
sizes of objects in the image. Even though erosion shrinks the objects by one pixel, dilation will expand them back to their original shape size. The closing operation employs a dilation followed by an erosion operation. It can close breaks or gaps in objects by closing fills in single-pixel object anomalies, like small holes and gaps. This results in smoothed object contours. This operation should also maintain the shape and size of the object. In order to achieve the necessary effect, both opening and closing operations may be applied many times. In using the erosion and dilation operations, several parameters can be used to adjust them according to the requirement, particularly the neighbour pattern (neighbourhood size) and the number of iterations. These are described below. The neighbourhood size setting is employed in erosion and dilation binary filters, and refers to the minimum number of pixels which must be a different colour to cause a pixel to be changed. For example, in an erosion filter, this number refers to the minimum number of neighbouring pixels that must be white to cause a black pixel to turn white. In the dilation filter, it refers to the minimum number of neighbouring pixels which must be black to cause a white pixel to turn black. The smaller this number, the more aggressive the operation will be. The open/close iterations is the number of consecutive dilations that are performed for a close filter before the erosions are performed (erosions followed by dilations for an open filter). The larger this number, the more aggressive the filter will perform [2].

2. Experimental
Simple image analysis of the raw micrographs can only provide details of the individual particle sizes. The intermetallic tends to appear in clusters, which are readily apparent to the eye (Figure 1). Manual identification and measurement of the size of these clusters is very time consuming. It was therefore decided to use the image analysis techniques of closing (dilation followed by erosion) operations to artificially coalesce the individual particles to form a single feature, which was more readily measurable automatically by the image analysis software. This was done by finding the best convolution setting of intermetallic to represent the realistic crack coalescence mechanism (with the assumption that cracks initiated from the intermetallic cluster). Joining together of the individual intermetallics in a cluster (Figure 1) is chosen as a representation of the crack coalescence mechanism, and was done using the closing operation. This operation fills in single-pixel object anomalies such as small holes and gaps between intermetallic itself. The closing operation was applied multiple times to fill-up larger anomalies and gaps (Figure 1). Besides oxide and pores, the microstructure of WE43-T6 magnesium alloys mainly contains intermetallic clusters of the rare earth-enriched divorced eutectic retained at some grain boundaries and mostly at triple points (Figure 1) and this feature plays a significant role in initiating cracks which leads to failure of this alloy [3].

![Typical arrested cracks in run-out static fatigue test specimen. (a) Crack coalescence, (b) initiation by fracture of intermetallic, (c) intergranular cracking, (d) transgranular crack arrested at grain boundary ((a) secondary electron, (b–d) backscatter electron images) [3]](2)

3. Results and Discussion
It was observed that the mean gap between intermetallic particles within a cluster was approximately 4µm. Dilation and erosion of thresholded metallographic images were therefore used to coalesce most if not all intermetallic particles with a spacing of equal or less than 4µm (Figure 1). The closing operation was used to simulate the coalescence of the
features that were separated by less than this distance, and thence to estimate the cluster sizes that could develop from such a coalescence. The best convolution setting had to be determined in this analysis to show that dilation of 4µm would join most if not all gaps. Since the size of the largest clusters was of the order of 200 - 300µm, this level of dilation/erosion was not expected to cause significant error. The operation was therefore expected not to cause growth of the features and the largest features should therefore saturate at single value. At the magnification employed in the analysis of the data (Figure 1), the size of 1 pixel was 0.312µm. The mean gap of 4µm between intermetallic features in the optical microscopy images was therefore 13 pixels. The effects of the dilation and erosion settings (neighbourhood size and number of iterations) on typical intermetallic clusters are shown in Figure 2, in which larger dilations to coalesce more widely separated features were found to saturate.

**Figure 2.** a) Effect of typical image analysis convolution setting on the size of an intermetallic cluster and b) the legend for the convolution settings. 7 iterations are predicted to be sufficient to coalesce features separated by 4µm.

For example, 5 iterations perform 5 dilations and 5 erosions, each iteration typically increasing the coalescence distance by 0.6µm (*i.e.* 0.312µm x 2). The maximum defect saturates at 5 iterations for neighbourhood 1 and 2 and saturates at 7 for neighbourhood setting 3, which is less aggressive. The setting (2,7) was selected as giving optimum coalescence of features, *i.e.* to coalesce features that are separated by 4µm. Examples for the selected settings of (3,7), (2,5) and (2,7) are shown in Figure 3a, b and c. In Figure 3a, when the setting was (3,7), there were still some parts, separated by less than 4µm, not coalesced. These are shown by the red circles. For the (2,5) setting (Figure 3b), all the intermetallics separated by less than 4µm were coalesced except for one (shown by the red circle). When the neighbourhood size and number of iterations were set at (2,7), Figure 3c shows that all the intermetallics in the cluster that were separated by equal or less than 4µm were coalesced.

**Figure 3.** Image processing of intermetallic clusters of the optical image (left) and thresholded image (right) after applying dilation/erosion convolution filters (neighbourhood, iterations) to coalesce.
features separated by less than 4µm (a) (3,7) (b) (2, 5) and, (c) (2, 7) settings. Red circle indicates features that were still not coalesced.

Comparison with the mean distances between cracks (Figure 4) shows that they were separated by 4µm. Hence, the observation of saturation of maximum cluster size at the setting (2,7) analyzed above was used to simulate the coalescence of the co-linear crack-like features typically as shown in Figure 4a, based on the assumption that the microcracks were originated from the intermetallic particles within a cluster.

![Figure 4](image.png)

**Figure 4.** Comparison with mean distances between cracks, (a) typical surface cracks on notch root surface, (b) frequency distribution and cumulative probability of the separation distance between crack tips (data from 119 cracks, stress 279MPa).

4. **Conclusion**

- Image analysis techniques could be employed to artificially coalesce the individual particles to form a single feature, which is more readily measurable automatically by the image analysis software. This achieved by finding the best convolution setting of the feature to represent the realistic crack coalescence mechanism.
- This method is more practical compared to manual identification and measurement which is very time consuming.
- This analysis shows that the best convolution setting of the intermetallic to represent the realistic crack coalescence mechanism is (2, 7).

**References**

[1] Baxes G A 1994 *Digital image processing - principles and applications* (John Wiley & sons)
[2] Russ J C 2002 *The Image Processing Handbook 4th ed.* (Boca Raton)
[3] Marrow T J, Ahmad A, Khan I. N, Sim, S M A and Torkamani S 2004 Environment-assisted cracking of cast WE43-T6 magnesium, *Materials Science and Engineering A* 387-389, 419