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A Method for Quantitative Analysis of Carbide Network Path Lengths in Ultrahigh Carbon Steel.

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Without special thermomechanical processing and/or chemical additives, ultrahigh carbon steels (UHCS, 1 - 2.1 wt% C) develop an extensive network of brittle carbides upon cooling. The network carbides can serve as initiation sites and paths for crack propagation, reducing toughness/ductility. On the other hand, the high carbide volume fraction does result in very good abrasion resistance, and consequently UHCS have been successfully used for rolling mill rolls at least as far back as 1913 despite their brittleness. In the years following the discovery in the early 1970s that UHCS could be made superplastic [1], there has been significant progress in making them usable for many more applications through break-up of the carbide networks. However no established metric currently exists for quantitatively describing the extent of network connectivity in these hypereutectoid steels.

This study uses a skeletonization method to analyze and compare the carbide network path lengths in 2D images of as-cast and heat treated samples of a commercial centrifugally cast UHCS mill roll alloy, AS-100. Magnification is chosen so that each image contains multiple branches of the carbide network, with each branch containing one or more carbide paths. Secondary electron imaging of Nital etched samples in a Philips XL-30 scanning electron microscope (SEM) provides sufficient contrast between network carbides and pearlite matrix to produce a binary image using manual thresholding. The Skeletonize function (a thinning algorithm) and AnalyzeSkeleton function [2] in ImageJ are then called to quantify the path lengths of the connected carbides. Utilization of the process comparing the carbide network (path lengths greater than 100 μm) in AS-100 before and after heat treatment is shown in Figure 1.

The method was developed during research into the effect of heat treatments on toughness and hardness of AS-100 steel. The area fraction of the carbide network decreased from about 20% to 12% after heat treatment, and it was found that the decrease in network volume was accompanied by a decrease in 2D network path lengths, presumably increasing toughness by shortening crack paths. Skeletonization analysis of both microstructures confirmed that the path lengths post heat treatment had decreased by nearly a factor of three (Figure 2).

Differences in image magnification for the analysis are accounted for by dividing the path lengths by the length of the image diagonal; preliminary results indicate that the ratio may not change significantly as magnification changes (Figure 3), however more investigation is necessary to validate statistical significance of path length measurements at these low magnification SEM imaging settings. Results here suggest that with appropriate and consistent choice of image diagonal length the ratio of the longest continuous path to the diagonal could serve as a useful and quantifiable metric for carbide network connectivity in hypereutectoid steels.

References
[1] Lesuer *et al,* JOM **45** (1993), p. 40.
[2] Arganda-Carreras *et al,* Microsc. Res. Tech **73** (2010) p. 1019.

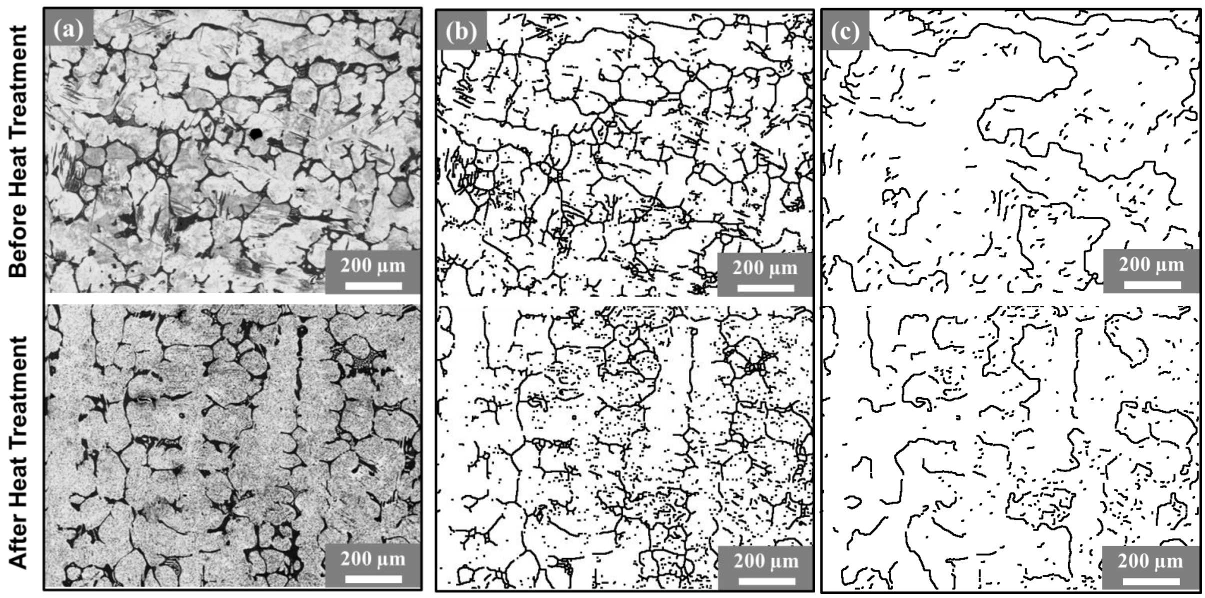

Figure 1. Skeletonization image processing. The (a) original secondary electron SEM images were (b) skeletonized, then (c) longest continuous paths were found using the AnalyzeSkeleton function in ImageJ. Pixels in (b) and (c) have been dilated in ImageJ for better visual clarity.

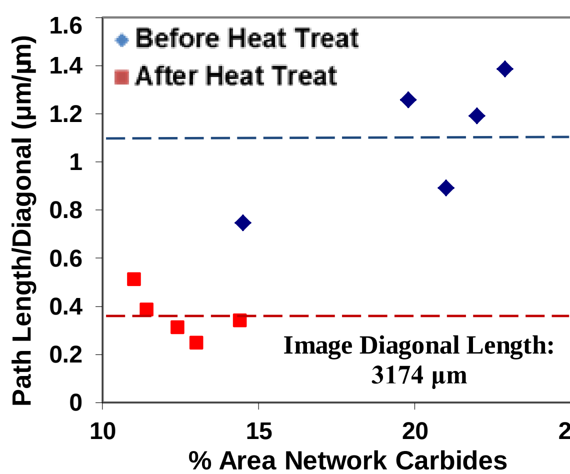

Figure 2. Relationsip between area fraction of network carbides and overall longest connected carbide path lengths (divided by image diagonal length) per image before and after heat treatment. The average longest path lengths for 5 images pre-and post heat treatment are shown by dashed lines on the figure.

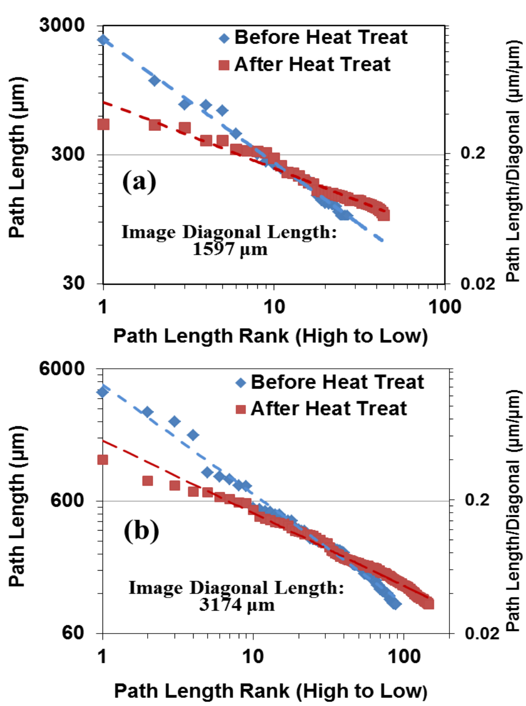

Figure 3. Analysis results at image diagonal lengths of (a) 1597 µm and (b) 3174 µm do not differ significantly in terms of path length/diagonal. Path lengths of the connected carbide network branches are ranked from longest to shortest and show path length reduction due to the heat treatment process.

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