Characterization of Internal Defects in Open Die Forgings

Alisha Tremaine *
Undergraduate Student
Department of Metallurgical and Materials Engineering
Colorado School of Mines
Golden, CO 80401

Abstract

Occasionally, internal defects are found in open die forgings. The potential origins of these internal fractures can be 1) unconsolidated solidification shrinkage voids, 2) heating or forging "bursts", or 3) hydrogen "flaking". Defect surfaces are often examined in a scanning electron microscope (SEM) to aid to determine their root cause. However, after heating, forging, and post-forging heat treatments, the appearance of the defect is often altered and difficult to characterize. Samples of various internal defects (solidification shrinkage porosity, ductile and brittle "burst" fracture surfaces, and hydrogen "flakes") were systematically characterized before and after high temperature processing (i.e. heating to forging temperature in a vacuum) to see how the appearance of each defect evolves or changes due to the high temperature processing.

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* Contact C.J. Van Tyne for more information:
phone: 1-303-273-3793
fax: 1-303-273-3795
email: cvantyne@mines.edu

1. Introduction and Background

1.1 Objective

The forging industry is facing drastic challenges and growing competition to keep costs down and quality high. The avoidance of conditions that cause internal defects is important from a production and cost containment perspective. It is often difficult to determine the root cause of an internal defect after the material has undergone various heat treatments and deformations. The objective of the present work is to perform a systematic study of several types of internal defects that can be occasionally found in forged products and characterize the defect surface prior to and after high temperature heat treatment.

1.2 Literature Review

Before the experimental part of the project was stated a literature search was conducted to determine the state-of-the-art with respect to types and characteristics of defects in open die forgings. Although there have been some studies to examine internal forging defects reported in the technical literature, the number of articles is not large. In the remainder of this section the articles that were found are briefly summarized.

There are four basic forging processes: 1) impression die, 2) open die, 3) seamless rolled ring, and 3) cold forging. Open die forging can trace its history to the original blacksmith shop of hammers and presses. Open die forging is a controlled plastic deformation process, which improves overall mechanical properties of the workpiece. "Forgings made with open dies are ideal for use where reliability and human safety are crucial" (1).

Sunder, Porter and Ashbaugh (2) compared and contrasted the properties of fatigue defects examined under vacuum and air conditions. They provided a glimpse at the origins of internal defects. Fatigue voids for example are formed around secondary particles. These particles and voids end up forming a bead-like structure that flow along the matrix. The relationship between fatigue void density and crack growth rate are directly proportional, with an increase in crack growth rate dramatically increasing fatigue void density. Based on research conducted in their study, the authors concluded that void density on the fracture surface is dependent on the "mechanism associated with prevailing crack extension per cycle, rather than to applied load level and/or stress ratio" (2). Overall, the authors concluded that the fatigue void closest to the specimen surface is likely to be the dominant crack.

Cost is a significant variable in the production of open die forgings. In comparison to other industries, it is very difficult to conduct trial and error experiments to determine causes for internal imperfections. Shah, Kiefer and Gavigan (3) introduced the concepts of plasticine modeling and the finite element model to aid in the detection of "void geometry". The authors used a combination of hot steel, computer mesh modeling, and plasticine to see if there were any correlations. The approach was successful and all three methods overlapped. A conclusion of the article was that there is an "optimum choice of die width for a given ingot and void geometry and also that staggering the die location during forging will increase the possibility of closing voids" (3).

Kukuyrk (4) argued that there are three principal criteria of "optimization" for open die forging of big ingots: qualitative, intensificational, and energetic. The working surfaces are also discussed and their relationships to local strain and stress distributions. His article is somewhat dated but provides good graphical reference between tool shape, deformation, and modeling.

Vamsi discussed the phenomena of center burst cracking, relating the changes the defect undergoes during the many stages of hot forging. The overall conclusion of the study was that the defects originated in the bar stock of the material and propagated during each phase. The center bursts were formed by a large concentration of "nonmetallic intrusions", providing an interesting argument of examining initial meta quality before industrial processing (5).

The article by Kato et al. examined open die forging of billets of various width and height. Again, the finite element method comes was used and deformation modes and properties were discussed. The diagrams and abstract are in English, while the discussion is not (6).

Hydrogen flaking is in effect internal hairline cracks. The best way to prevent hydrogen flaking is to "vacuum degas the steel prior to casting, and reduce the hydrogen to typically less than 2 ppm". This is not to say that hydrogen flaking is in any way a basic phenomenon. It is a very complex process. Defects can occur in isolated areas or even throughout an entire cross-section (7).

There are several causes of die failures including: mechanical design, grade selection, steel quality, machining processes, heat-treatment operation, grinding and finishing operations, tool and die setup, tool and die operation. Vacuum degassing is recommended to reduce hydrogen content, which will prevent hydrogen flaking. As far as heat-treating is concerned, there is a direct correlation between hydrogen flaking and an error in heat-treating. Longitudinal cracks resulted after heat treatment of some of the samples (8).

Steiner and Murphy describe hydrogen flaking and its causes, reinforcing the fact that hydrogen flaking produces a specific pattern. Hydrogen flaking will also "seek the central zones of a heavy section of a forged or rolled piece" although there are exceptions. A suggestion for the cause of flaking is argued to be non-uniform cooling, specifically after heat treatments (9).

The work by Atkins is extremely relevant to the project because of the complete descriptions and pictures of every discontinuity encountered when working with ferromagnetic alloys. Excellent diagrams are used to show the origins of the defect and how it advances over time (10).

Vander Voort provides methods and techniques that can be used to examine failures and fractures in a variety of metals (11).

2. Experimental Investigation

Samples were obtained from a steel maker who supplies ingots to the open die forging industry. These experimental samples had various types of internal defects. The initial characterization of the defect surfaces used a scanning electron microscope to view the surface defect. Photomicrographs were taken and the surface topography was characterized. The samples were then subjected to a high temperature heat treatment and the internal surface defects were again examined with the scanning electron microscope. Changes in the appearance of the surface characteristics of the internal defects due to the high temperature heat treatment were noted.

3. Pre-Heat Treatment

3.1 Initial Materials and Characterization

The first step in characterizing the defects was using a light microscope to determine defect locations and choose the most suitable samples for heat treatment. Upon further investigation, samples C1, D1, H2, and D2 were chosen as the best representations of internal defects. Table 1 outlines the defect types of each sample.

Table 1 Sample defect classification and material description.

Sample Name (Material)	Defect Type
C1 (34CrNiMo6)	Hydrogen Flake
D1 (ST52.3)	Voids
H2 (34CrNiMo6)	Hydrogen Flake
D2 (ST52.3)	Voids

The four samples described above were examined using the scanning electron microscope (SEM) located at the Colorado School of Mines. Using a magnification range of 200 to 1000 magnification, specific areas on the sample were captured for their unique areas of defect. Photomicrographs for the specific observations of areas of the pre-heat-treated samples as well as the post heat treated samples are attached to the end of this report.

3.2 Sample C1 (34CrNiMo6) – Hydrogen Flake:

At 200x a line appears no more than 10µm wide. The defect contains regions of a constant width, $w_{avg,}$ while other sections show more than a 50% decrease in w_{avg}. Upon an increase in magnification to 1000x, the defect appears crater-like in appearance, with a depth of approximately 20 µm. The walls of the cavity are coarse and irregular. The base of the void appears similar to the walls with additional voids on the order of 1 µm scattered throughout the bottom of the crevice.

3.3 Sample D1 (ST52.3) – Voids:

This sample contained two very distinct types of defects. At 1000x the defect, as shown in the first image, appears to be no more than 100 µm in length, with a maximum width of 15 µm. As seen in the first picture the shape of the defect can best be described as a trough or channel. The surface of the void itself contains internal cracking and a rough surface topography. At higher magnifications the voids appear to be no more than 1.5 µm in diameter, with a depth of less than 1 µm.

3.4 Sample H2 (34CrNiMo6) – Hydrogen Flake:

The defect is approximately 1.2 mm in length, with an additional 0.1 mm secondary section trailing below the primary section. There are definite layered defect sections, with voids intermittent throughout. The walls of the defect appear rough and irregular, with rupture type of topography. The shape, surface topography, and appearance of the defect are similar to that of Sample C1.

3.5 Sample D2 (ST52.3) – Voids:

This sample of voids looks similar to the defect in Sample D1. There appears to be a clearly defined void surrounded by channels with rough subsurface topography. The void is approximately 20µm in length, with a maximum width of 8µm. The surface of the void itself contains internal cracking and a rough surface topography. This sample is unique in that it has an almost 15µm-wide cross section of the surrounding channel network, and appears to be the most ruggedly formed section of voids.

4. Heat Treatment

After initial characterization the four samples were heat treated in a high temperature vacuum furnace. The heat up was at 30 ^{o}C/hr to 1230 ^{o}C. The samples were held at 1230 ^{o}C for 20 hours. Finally, the temperature was cooled at 120 ^{o}C/hr down to room temperature. The heat treatment was designed to simulate the heating cycle that might be used prior to open die forging of a large ingot.

5. Post-Heat Treatment

In all cases the heat treatment caused a large increase in the grain size. The grains were visible to the naked eye on the surface of each sample.

The defects that had been examined prior to heat treatment were again viewed with the scanning electron microscope.

5.1 Sample C1 (34CrNiMo6) – Hydrogen Flake:

The rough surface of the cracked region acquired some smoothness. Some rough regions were still apparent but there was more rounding of the topography and these regions were less extensive than in the pre-heat treated condition. The electron charging (i.e. bright white areas) within the cracked regions in the pre-heat treated condition, was not present post-heat treatment. The cracks also appeared to have less depth, becoming more shallow due to the heat treatment.

5.2 Sample D1 (ST52.3) – Voids:

The crack depth in the pre-heat treated condition seems to be the same as post-heat treatment. The major difference is the significant smoothing of the sides of the crack. The rough surface topography of the original cracks, has disappear from the cracks in the post-heat treated condition. The cracks in the post heat treatment condition seem to be devoid of material. The voids that had an oval shape to them evolved into a more circular shape.

5.3 Sample H2 (34CrNiMo6) – Hydrogen Flake:

The rough crack surfaces have become smoother and the extensive charging in the interior of the crack is no longer present. Some topographically rough regions still remain, but they are less rugged.

5.4 Sample D2 (ST52.3) – Voids:

Post-heat treatment, the voids in the sample have been significantly smoothed. There is very little surface topography seen on the void surfaces after the heat treatment. A note of caution with respect to this particular sample: it is not certain that the post-heat treatment regions correspond to the defect regions examined and photographic in the pre-heat treatment condition.

6. Summary

The major evolution of the defect appearances is as follows:

Upon heat treatment of hydrogen flake defects, the roughness of the cracked region begins to smooth. The cracks appear to become less shallow.

Upon heat treatment of the void defects, the roughness of the cracked region also has a smoother appearance. The cracks appear to still have a great deal of depth. The oval voids seem to evolve to voids with an aspect ratio of one (i.e. they become circular).

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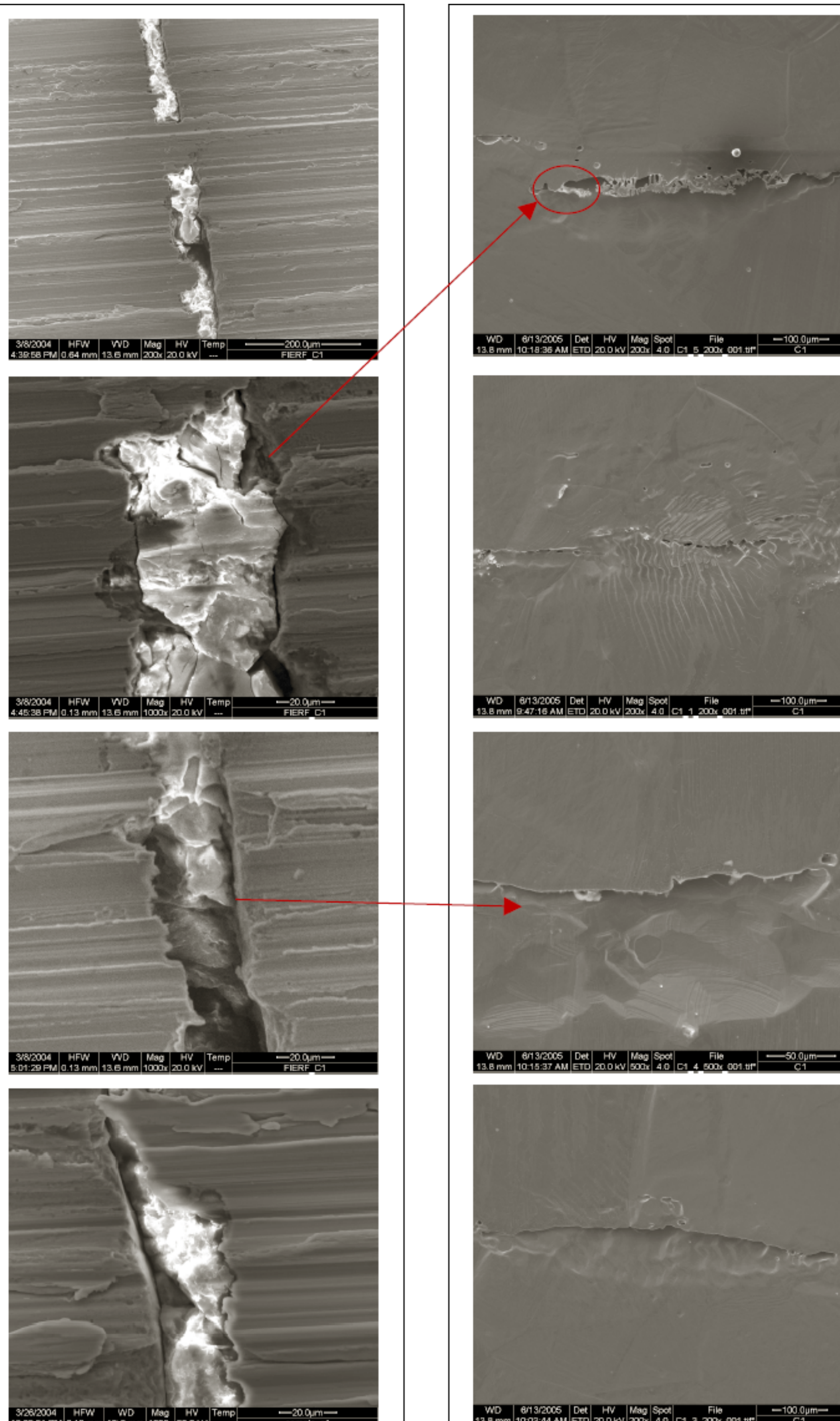
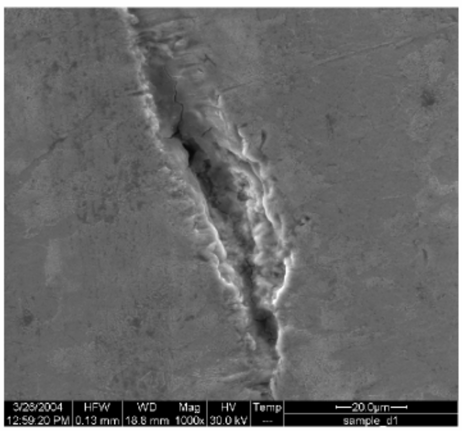
Sample C1 (34CrNiMo6) - Hydrogen Flake

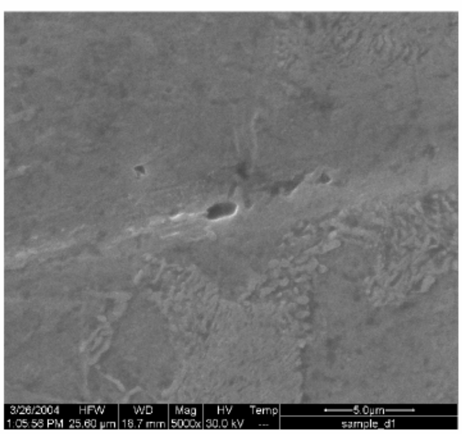


Pre-Heat Treatment

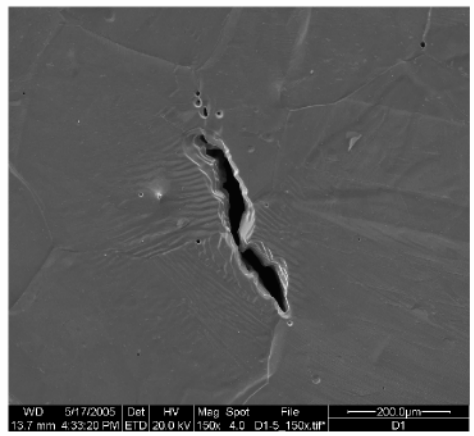
Post-Heat Treatment

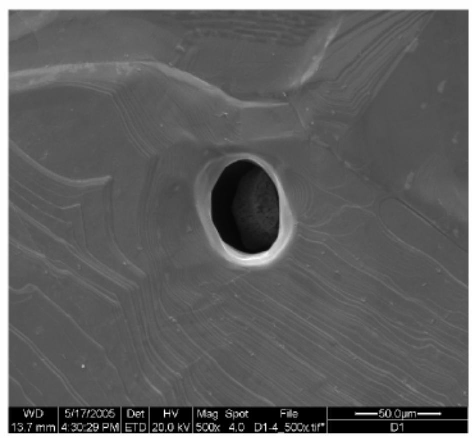
Sample D1 (ST52.3) - Voids





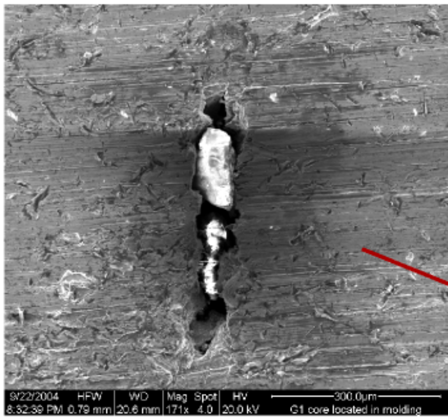
Pre-Heat Treatment

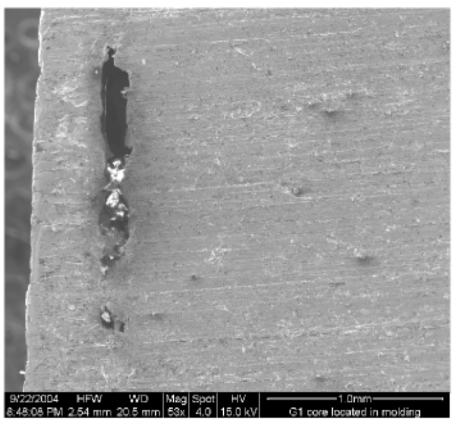


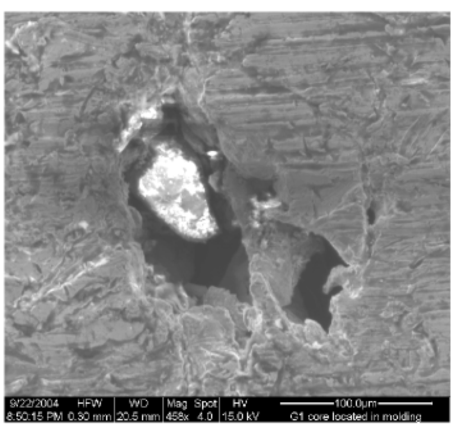


Post-Heat Treatment

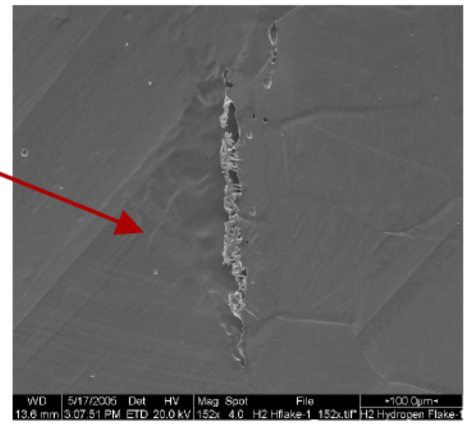
Sample H2 (34CrNiMo6) - Hydrogen Flake

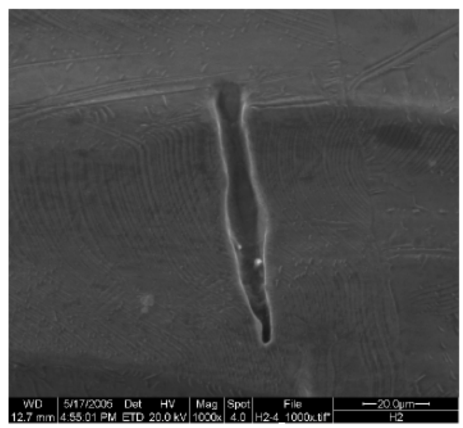






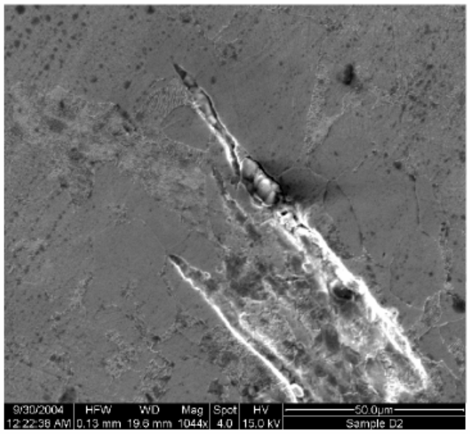
Pre-Heat Treatment

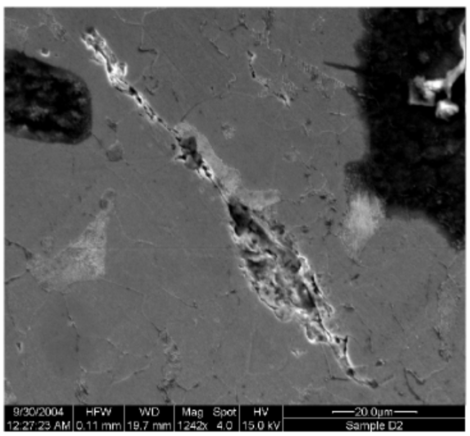


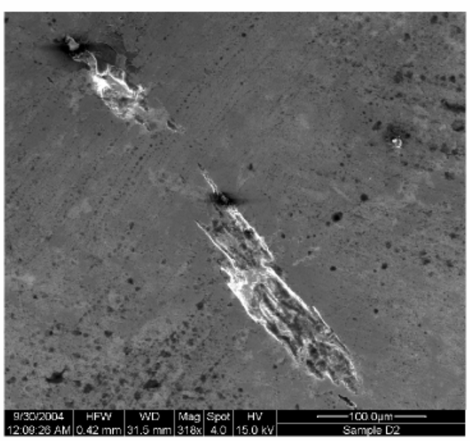


Post-Heat Treatment

Sample D2 (ST52.3) - Voids







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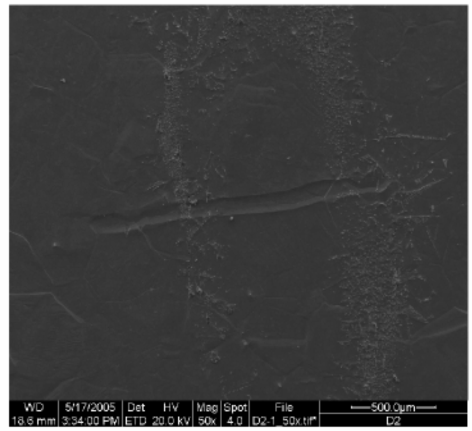

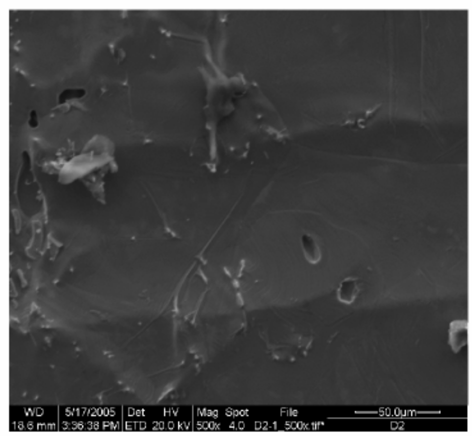

Post-Heat Treatment