AC 2007-947: METEORITICS AND MATERIALS IN AN ME LAB COURSE

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Meteoritics and Materials in an ME Lab Course

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Abstract:

One of the objectives of the ME Senior Lab Course at Rose-Hulman (ME421) is to have students experience a 'test and refine' cycle. During the first half of the ten-week quarter, ME421 students select an experimental project, perform an experimental procedure to obtain data, and present results to the team of instructors. The latter half of the course is spent performing refined experimental work based on instructor feedback.

One of the selected projects during the most recent offering of the course was based on the study of meteorites. A student team embarked on a project of experimentally heat treating meteorite samples, and correlating the grain growth results to similarly heat treated steel specimens. The theory that the students sought to demonstrate was based on a determination of the activation energy for grain growth in meteorites.

Using meteorites in a Mechanical Engineering curriculum is shown to be a cross-disciplinary experience. During the course of the quarter, students interacted with faculty from the Physics, Chemistry and Materials disciplines, as well as within their home Mechanical Engineering Department. Challenges involved determining which heat treatment time and temperature regime give measurable grain growth, and determining suitable polishing and etching procedures for the samples. Recommendations for future course offerings are given.

1. Introduction – About ME 421, Mechanical Engineering Laboratory

Mechanical Engineering Laboratory is a required two-credit course for senior-level students in the ME Department at Rose-Hulman Institute of Technology (RHIT). One of the primary objectives of the course is to have students experience a 'test and refine' cycle. Student teams select an experimental project, perform a literature search, conduct research and report results within the first half of the quarter. After receiving instructor feedback at the formal project review (mid-quarter, at five weeks), the student teams refine their experimental efforts and report the finalized results in a professional-quality written report. The course deliverables are an oral presentation at mid-quarter and a comprehensive written report at the end of the quarter.

Students are responsible for selecting and proposing a project, and the instructors are responsible for approving and supervising the proposed projects. Instructors are responsible for making sure that the scope and objectives of a proposed project are of an appropriate level and neither too easy nor too hard. Usually, students select projects that are interesting to at least one of the individuals on a team, and instructors help steer the project towards a successful conclusion.

2. Meteoritics Project - Research Background

Modern metallurgy has a historical root within meteoritics as is evidenced by Osmond and Cartaud creating an Iron-Nickel phase diagram based on the analysis of meteorite samples[1]as well as other historical events; however, applying current methods of metallurgical analysis towards meteorites and documenting the effects of common materials processing methods on meteorites has only been recently approached[1]. The study herein applies common methods of metallurgical analysis (i.e. grain size determination) to meteorites.

2.1 Goals and Constraints

The general goal of the experiment is to compare the metallurgy of a meteorite sample to the metallurgy of steel.

The specific goals for this experiment are:

1. Determine the average kamacite grain size for the Canyon Diablo meteorite specimens and ferrite grain size for the 1018 steel specimens.
2. Determine the activation energy of grain growth for 1018 steel and explore the feasibility of the same measurement for kamacite in the Canyon Diablo meteorite.
3. Determine the difference between the conditions of optimal grain growth rate for steel and kamacite.
4. Determine the difference between the grain boundary activation energy for steel and kamacite.

2.2 Theory

In creating an experiment to study the behavior of meteoritic microstructures, methods which were comparable to prior microstructure analysis were selected. The meteorite used in this study came from Coconino County in Arizona. The meteoritic samples found in this area were named Canyon Diablo, after a canyon cutting through the Colorado plateau about 5 km west of the crater. Because the Canyon Diablo meteorite broke into more than 20,000 fragments during impact, this meteorite has been extensively distributed and studied in more detail than any other meteorite. Research into the background of meteoritics revealed that the Canyon Diablo samples investigated were octahedrite meteorites, composed of a ferrous alloy of roughly 6%-9% nickel by mass. An octahedrite meteorite obtains its name from its 8 sided, three dimensional crystal structure[3].

The phases commonly encountered in octahedrite meteorites are almost perfect analogs to the phases found in standard carbon steel alloys. While a steel metallurgist is familiar with ferrite, cementite, and mixed pearlite regions, a student of meteoritics will recognize kamacite, taenite, and mixed plessite regions respectively[1]. Figure 1 exhibits the common grain structure of ferrite phase for steel and kamacite phase for meteorite. The body-centered cubic atomic packing and chemical bonding shapes of the species are identical with nickel replacing carbon as the alloy element in steel[2]. Therefore meteorites and steel yield similar microstructures, and perhaps a similar response to materials processing methods. Therefore, steel was selected for the parallel analysis with meteorites. Table 1 summarizes the characteristics of the different phases involved in both metallurgy and meteoritics.

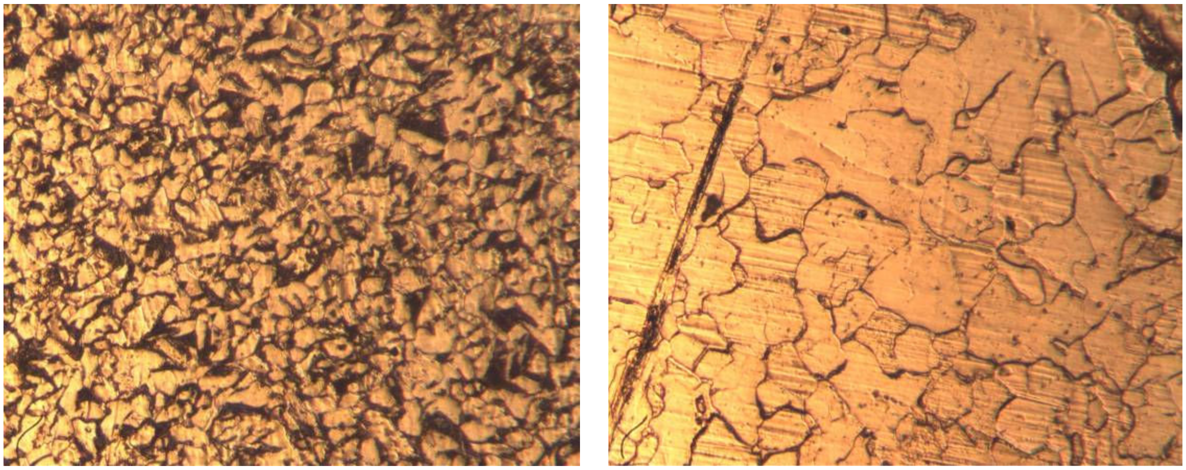

Figure 2.1: Comparison of grain structure for ferrite (left) and kamacite (right). The specimens shown are at a magnification factor of 200 and were photographed at Rose-Hulman Institute of Technology. The specimens were polished and etched using 7% nitric acid in methanol.

Table 2.1: Comparison of Commonly Encountered Octahedrite and Steel Phases

Metallurgical Term	Meteoritic Term	Chemical Form	Atomic Packing	Microstructure
Ferrite	Kamacite	α-Fe	BCC	Grains
Cementite	Taenite	Fe_3X	Amorphous	Inclusions
Pearlite	Plessite	α-Fe + Fe_3X	BCC + Amorphous	Layered Mix
Martensite	Cohenite	γ-Fe	FCC	Brittle Grains

The experiment was planned to target behavior ranges that are applicable to steel. The method of characterizing the microstructure of steel is to determine the average grain size in ferrite. This study focuses on determining the average grain size of kamacite found within octahedrite meteorite samples. The ASTM standard method of grain size determination was used to determine an approximation of average grain diameter for equiaxial grains.

Because grain size affects critical material properties including ultimate tensile strength and hardness, it is important not only to determine the average grain size within a matrix but also understand the mechanism of grain growth. Activation energy quantifies the amount of energy required for a material to change its grain size. The boundary between one grain and its neighbor is a defect in the crystal structure, and so it is associated with a certain amount of energy. From a thermodynamic standpoint, grain boundaries increase the total energy of a material. Therefore, there is a tendency for a material to decrease its grain boundaries in order to achieve a lower energy state[8]. For a material to be capable of reducing the number of grain boundaries, a certain amount of energy must first be supplied to the system. This energy is called the grain growth activation energy.

The larger the activation energy, the longer the duration or higher the intensity of heat treatment the material must undergo in order for a change in grain growth to occur. Figure 2.2 is a representation of activation energy. In this study the reactant is the material with its initial grain size and the product is the increased grain size due to heat treatment.

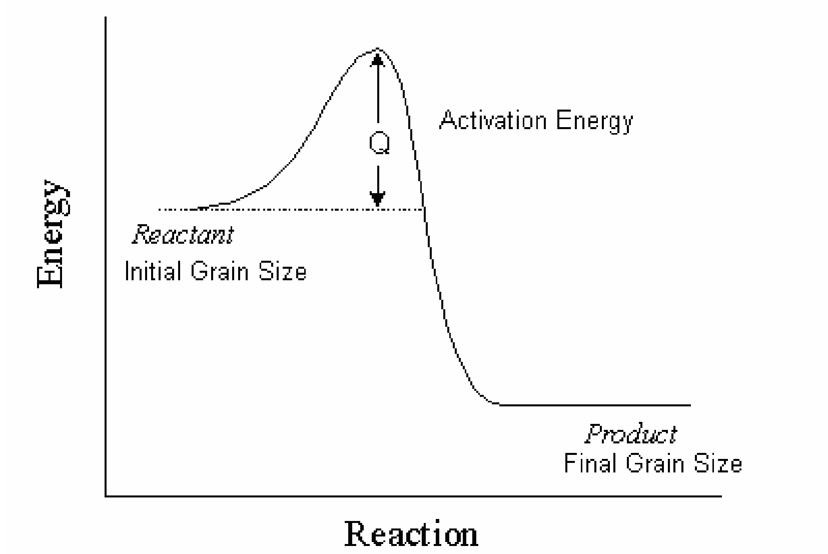

Figure 2.2: Schematic of energy diagram for a material undergoing grain growth. The reactant is the specimen with an initial grain size while the product is the specimen at its final, larger, grain size. 'Q' is the energy added to the system in order for grain growth to occur.

2.3 Broader Impacts / Interesting Questions

The selection of grain size and activation energy as the focus of this study is used to glean answers to several interesting questions that exist in regard to octahedrite meteorites. Not all of these questions will have concrete answers by the end of the study; however, sufficient data should exist in order to guide the response to these questions using rational arguments.

The first question to be addressed is whether or not a meteor's post-entry thermal exposure can be determined. The ability to forensically determine the thermal exposure of a meteorite may assist in identifying the impact location of any meteorite. For example, Canyon Diablo specimens have been circulating since before the early 1900's, and many have been used as sources of stock metal. Some samples, during the course of their use, have also been heat treated[3]. A heat treatment history may be used to identify a group of specimens that were once cut or fragmented from a single meteorite.

Another important question is whether or not the grain growth activation energy can be empirically defined for meteorites. This question is important because it will help establish the reliability of thermal profiling and merits consideration due to the irregular microstructures and materials in meteorites.

An additional pertinent question is at what temperature and time range is the rate of change in grain size at its maximum. This information will allow others to design experiments around regions where large changes in grain structure are expected for both steel and meteorites.

The last question of interest is one common to meteorite collectors and appraisers. Given the results from the first questions, is it possible to synthesize a meteorite from materials found on earth? This information is valuable because hoax meteorites are commonly sold; however, most are obvious fakes to the professional meteorite investigators[7]. Based on this study, a request was made to determine if a mix of materials similar to a meteorite could be heat treated in such a manner so as to obtain grains common for a specific impact incident and sample group. Some sub-questions to help guide the answer to this question could be: Are the grain structures obtainable for rational temperatures and times? Could the inclusions found in meteorites be made here on earth? How does micro-gravity solidification affect real meteor microstructures?

3. Meteoritics Project – Experimental Summary

3.1 Equipment

Various pieces of equipment used in this experimental study were gathered across the physics, chemistry, and mechanical engineering departments at Rose-Hulman. The list below details the equipment needed to complete the experiment.

a.) Testing Samples
- 25 – Meteorite Samples
- 25 – Steel Samples

b.) Heat Treatment Equipment
- 2 – Ney Vulcan 3-550 Furnaces

c.) Cutting Equipment
- 1 – ISOMET Slow Speed Diamond Cutter
- 1 – Standard Metal-Shop Band Saw

d.) Imaging Equipment
- 1 – Buehler Metallograph

e.) Polishing and Sample Preparation Equipment
- 1 – Struers Labopol-25 Polishing Wheel Assembly
- 500ml – Acrylic Sample Mounting Epoxy
- 100ml – Nital Etchant Solution (7% Nitric Acid in Methanol)

3.2 Test Method

The steel used was 0.375" diameter 1018 steel with a nominal composition (0.18% carbon by weight). The meteorite samples from the Canyon Diablo meteorite were provided by Dr. Howard McLean of the RHIT Chemistry Department. Steel was sectioned on a band saw. Meteorites were sectioned on a diamond bladed saw in order to ensure that there was not an excessive amount of material lost during the cutting process due to the width of the blade and also to avoid damaging the microstructure due to excessive heat during cutting. The type of saw used was an ISOMET Slow Speed Diamond Cutter provided by the RHIT Physics Department.

The samples were thermally treated using the heat treatment furnace shown in Figure 3.1. All specimens were 'baselined' (given a uniform, high temperature treatment.) at 850ºC for one hour in order to erase previous heat treatment history. This temperature was chosen for baseline because it is above the eutectoid point for both steel and meteorite. By heating to the eutectoid point, all grain structures should be equilibrated, and new grains would have to form out of this homogenous matrix[6]. The specimens were air cooled after each treatment, allowing them to cool quickly but not so quickly that the specimens become quenched, causing the delta phase of iron in meteorites or the martensite phase in steels to be retained. To better understand the rationale behind these two decisions, see the phase diagrams for the steel and meteorite compositions.

Figure 3.1: Photo of Ney Vulcan 3-550 furnace used to heat treat samples. The upper temperature limit for this furnace is 1100℃ and the quoted accuracy is ±5℃.

The baselined samples were heat treated for the times and temperatures shown in Table 3.1. Each specimen was given a G designation as in the table in order to identify the heat treatment time and duration that it experienced. The temperatures were chosen to be linearly spaced across the reported grain growth temperature range for steel, while the heat treatment durations were exponentially spaced because grain size change has been known to have an exponential relation to heat treatment duration[6].

Table 3.1: Test Matrix of Heat Treating Schedules and Sample Designations

Heat Treatment Time	Heat Treatment Temperature				
	400℃	575℃	675℃*	750℃	800℃*
1 Hour	G1a	G1b	G1d	G1c	G1e
2 Hours	G2a	G2b	G2d	G2c	G2e

5 Hours	G5a	G5b	G5d	G5c	G5e
7 Hours*	G7a	G7b	G7d	G7c	G7e
10 Hours	G10a	G10b	G10d	G10c	G10e

** - Indicates this time or temperature series was added only during the ‘refine’ period.*

The treated samples were mounted in epoxy to hold the sample stable during the polishing and etching phase. The epoxy step was performed under a hood to avoid the harmful byproduct vapors of the epoxy’s curing process.

The specimens were sanded using five varying grits of sandpaper ranging from 80 to 1200 grit. Because sanding created lines on the samples, the specimens could be visually inspected and rotated in 90° increments as they were moved to the next level to ensure they were totally resurfaced to the roughness of the new paper.

Sanded specimens were polished using a 6 micron and 1 micron diamond solution on a Struers Labopol-25 polishing wheel as shown in Figure 3.2. A diamond solution was used because of its effectiveness in retaining the graphite and other inclusions[2] at the polished surface and also the reduced polishing time needed. Each sample was polished for roughly five minutes at 500 rpm by hand with strong pressure in order to obtain a mirrored finish.

Figure 3.2: Photograph of Struers Labopol-25 Polishing Wheels used to obtain a mirrored finish. These wheels are capable of angular velocities from 0 rpm to 500 rpm and support both magnetic mount as well as classic crimp mount polishing pads.

Fully polished samples were etched for 30 seconds with a Nital (7% nitric acid in methanol) etching solution[2] to selectively attack the high energy grain boundaries producing visual crevices. After the samples were etched, they were ready to be photographed.

To count grains, five pictures of each specimen were taken via a Buehler metallograph, equipped with a camera linked to a computer for image acquisition as shown in Figure 3.3.

Figure 3.3: Photograph of Buehler Metallograph used to take pictures of 1018 steel and the Canyon Diablo meteorite. The specimens were etched using 7% nitric acid in Methanol and viewed using a magnification factor of 200x. The software used to view the images was *U-Eye* by IDS Corporation.

For meteorite imaging, a special process had to be implemented, as the retained microstructures consisted of more than just kamacite. The ASTM standard method for obtaining images was thus adjusted so that after the random selection of each image, the microstructure was examined to ensure it was kamacite. If the images were not of kamacite, the process was repeated until five kamacite images are taken. This process can be visualized through the flowchart given in Figure 3.4. The pictures were then printed, and the grain boundaries were counted via the ASTM method described in the following section.

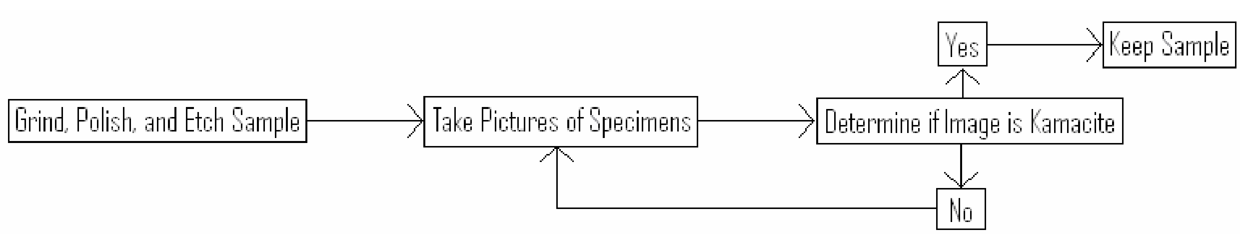

Figure 3.4: Flowchart depicting the decision process used when processing meteorite image samples for counting. The extra step of determining the microstructure being viewed is unique to the meteor process. Steel did not require this extra step because the heat treatment process left it as continuous ferrite.

Grain size calculations were performed according to the intercept method[2]. One or more lines were superimposed on each of the specimen's pictures as shown in Figure 3.5. The black and white transitions were then counted along this line. These transitions signify grain boundaries.

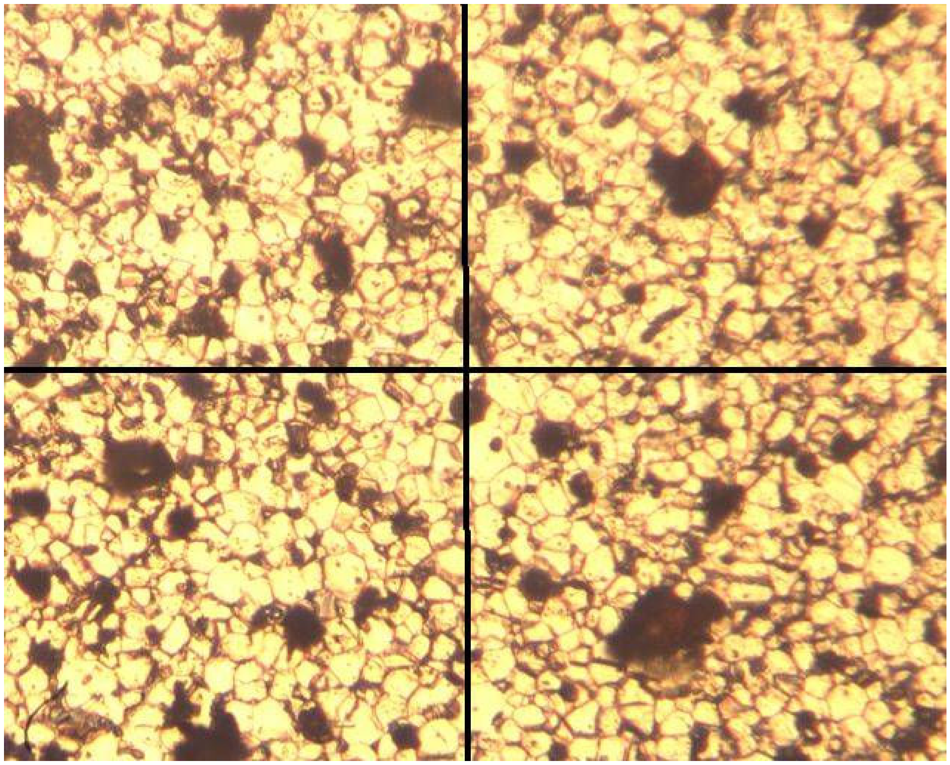

Figure 3.5: Photograph demonstrating the ASTM intercept method for counting grain size. Two lines are superimposed on the picture, and then the transitions from white to black along these lines are counted. This 1018 steel specimen was heat treated at 575 ºC for 2 hours.

Before counting the grains in each randomly selected meteorite image, the image was visually inspected to ensure the picture consisted only of kamacite. The average grain size was then calculated using Eq. 3.1. This equation approximates what the average grain diameter would be for ideal, equiaxial grains.

Average Grain Size:

$$d = \frac{L}{NM} \qquad (3.1)$$

Where:

- d: average grain size (mm)
- L: superimposed line length (mm)
- N: number of transitions
- M: magnification factor

Activation energy is a way to quantify and predict grain growth. The equations used to reduce data to the form needed for this analysis were Eq. 3.2 and Eq. 3.3 as shown below[8]. A plot of the natural logarithm of the grain size increase with respect to the inverse of the treatment temperature allowed us to calculate activation energy as the slope of a fitted line.

Grain Size Growth Rate:

$$d^2 - d_0^2 = kt \qquad (3.2)$$

Where:

d: grain size (mm)
do: initial grain size (mm)
k: rate constant (mm/hr)
t: heat treatment time (hr)

Rate Constant/Activation Energy Relation:

$$k = k_o e^{\frac{-Q}{RT}} \tag{3.3}$$

Where:

k: rate constant (mm/hr)
k_o: initial constant (mm/hr)
Q: grain boundary activation energy (J/mol)
R: universal gas constant (J/mol·K)
T: heat treatment temperature (K)

3.3 Refinement

After completing the first portion of this experiment, a refinement was made in which five pictures were taken of each specimen instead of only two pictures. When only using two pictures to calculate the grain size, the random uncertainty was extremely large due to a small sample size. Adding three more samples greatly reduced the random uncertainty in grain size so that the goal of 20% maximum relative uncertainty was met.

Two additional temperatures (675 ºC and 800 ºC) and an extra time duration (7 hours) were included in order to better specify the maximum rate of increase in grain size. The uncertainty of the calculated grain boundary activation energy was also reduced, because adding two new temperatures created a total of five data points where only three had been previously used to establish a trend line.

The method for counting grain boundaries was also altered from the ASTM standard (as mentioned prior). Before counting the grains in a meteorite sample picture, the randomly selected image of the meteorite was visually inspected in order to ensure the picture consisted solely of kamacite grain structures. The reasoning for this manipulation was to preserve the correlation between heat treatment and grain size; otherwise the data would be disrupted by counting grains of varying microstructures. This process was illustrated in Figure 3.4.

4. Meteoritics Project – Results and Conclusions

The data collected for grain size resulting from the various heat treatments is shown in Figure 4.1 for steel samples and Figure 4.2 for meteorite samples.

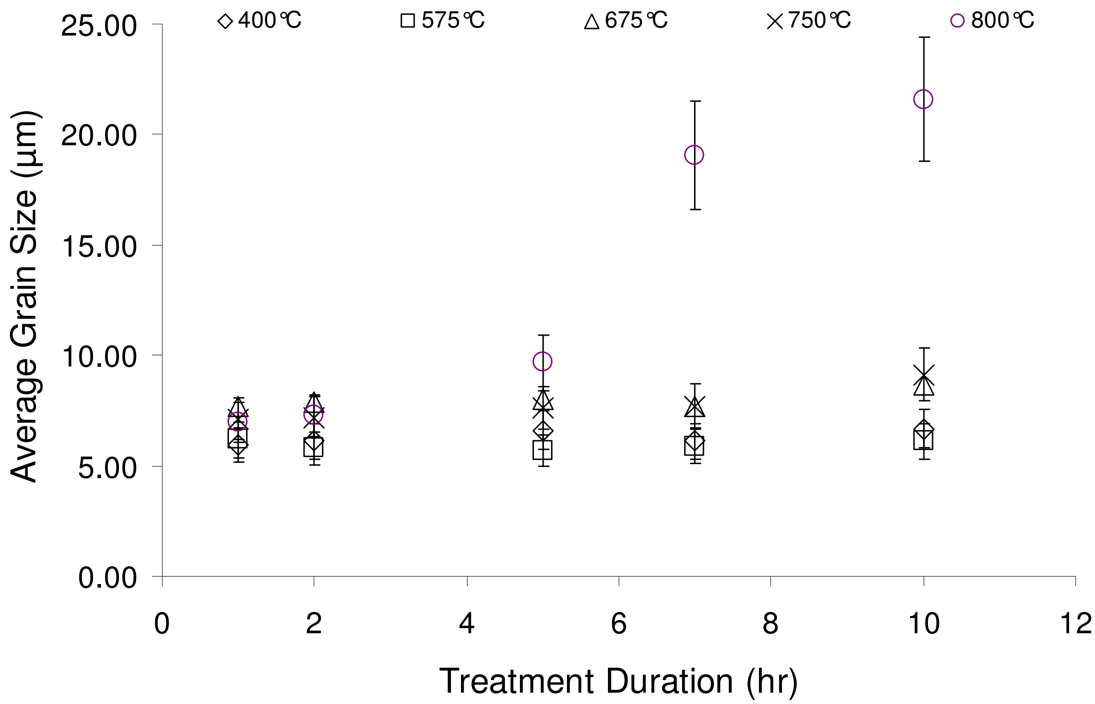

Figure 4.1 Calculated average grain size for 1018 carbon steel after various treatments. The error bars are based off a 95% confidence interval. The samples were given heat treatments as per Table 3.1.

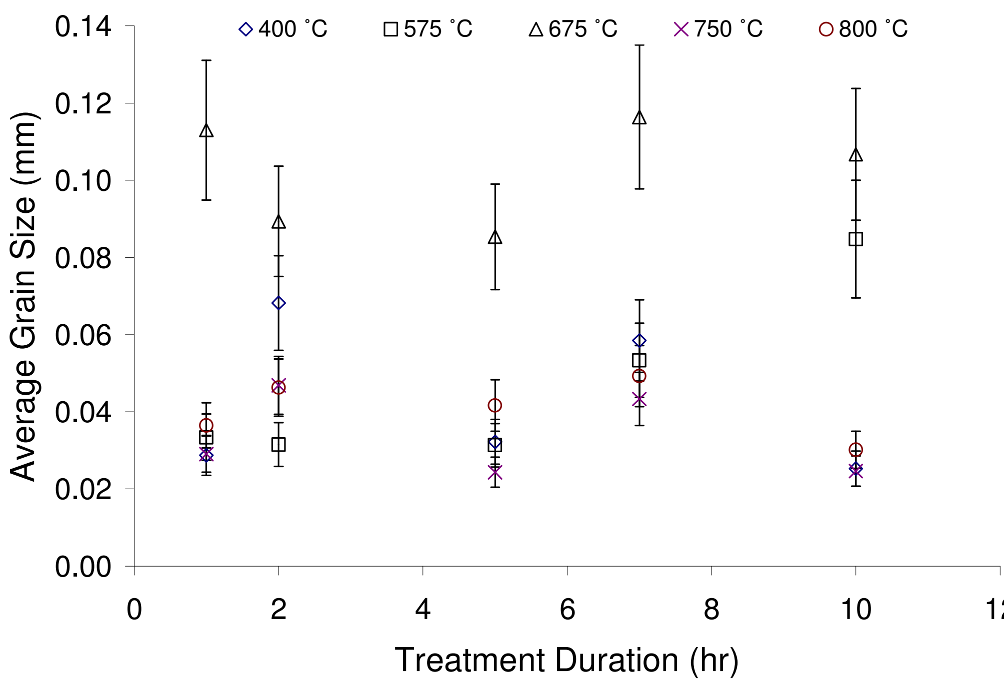

Figure 4.2: Calculated average grain size for the Canyon Diablo meteorite after various treatments. The error bars are based off a 95% confidence interval. The samples were given heat treatments as per Table 3.1.

Because it was desired to characterize the best rate of grain growth, the slopes of each segment of heat treatment were compared for each temperature. Tables 4.1 and 4.2 show the calculated slopes between each data point for steel and meteorite respectively. The maximum increase of grain size for steel occurs during a heat treatment duration of 5 to 7 hours at 800 °C while the maximum increase of grain size exhibited for meteorites occurs during a heat treatment duration of 1 to 2 hours at 400 °C.

In some instances the measured grain size decreased for samples with longer time durations in the furnace (the negative values.) The apparent negative trend line may have been due to uncertainty and the irregular inclusions, which were sometimes counted. Additionally, the same grains were not viewed after each heat treatment because the samples would have to be re-polished and etched. For steel it should be noted that the lower heat treatment temperatures led to very little growth, making negative values due to randomness more likely.

Table 4.1: Comparison of Slopes Between Data Points for 1018 Carbon Steel (μm/hr)

Slope Between Points	Heat Treatment Temperature				
	400 °C	575 °C	675 °C	750 °C	800 °C
1 to 2 hours	0.2	-0.4	0.2	0.1	0.3
2 to 5 hours	0.5	-0.1	0.1	0.4	2.4
5 to 7 hours	-0.5	0.2	-0.3	-0.1	9.4
7 to 10 hours	0.6	0.2	0.9	1.4	2.5

Table 4.2: Comparison of Slopes Between Data Points for Meteorites (μm/hr)

Slope Between Points	Heat Treatment Temperature				
	400 °C	575 °C	675 °C	750 °C	800 °C
1 to 2 hours	39.5	-1.9	-23.6	17.8	9.8
2 to 5 hours	-12.0	-0.1	-1.3	-7.5	-1.6
5 to 7 hours	13.2	11.0	15.5	9.5	3.8
7 to 10 hours	-11.1	10.5	-3.2	-6.2	-6.4

Pictures of the grain structures of steel were relatively easy to obtain, and the behavior of the steel with respect to grain size was more predictable, which led to the accurate determination of the activation energy for grain growth. The method described in section 3 was used, resulting in the relationship shown in Figure 4.3 for steel. The activation energy can be found as the negative slope of the line fit to the data in the figure. Reliable results were not obtained for meteorites due to the variance in grain sizes over the different samples. The variance could be due to the several materials that comprise the microstructure, the added activation energy needed to cause growth due to all of the meteoritic inclusions (graphite pools, diamond pockets, etc.), or just difficulty determining whether kamacite grains were being viewed. It was also difficult to count grain intercepts around plessite, resulting in counts much higher than expected for the microstructure under investigation.

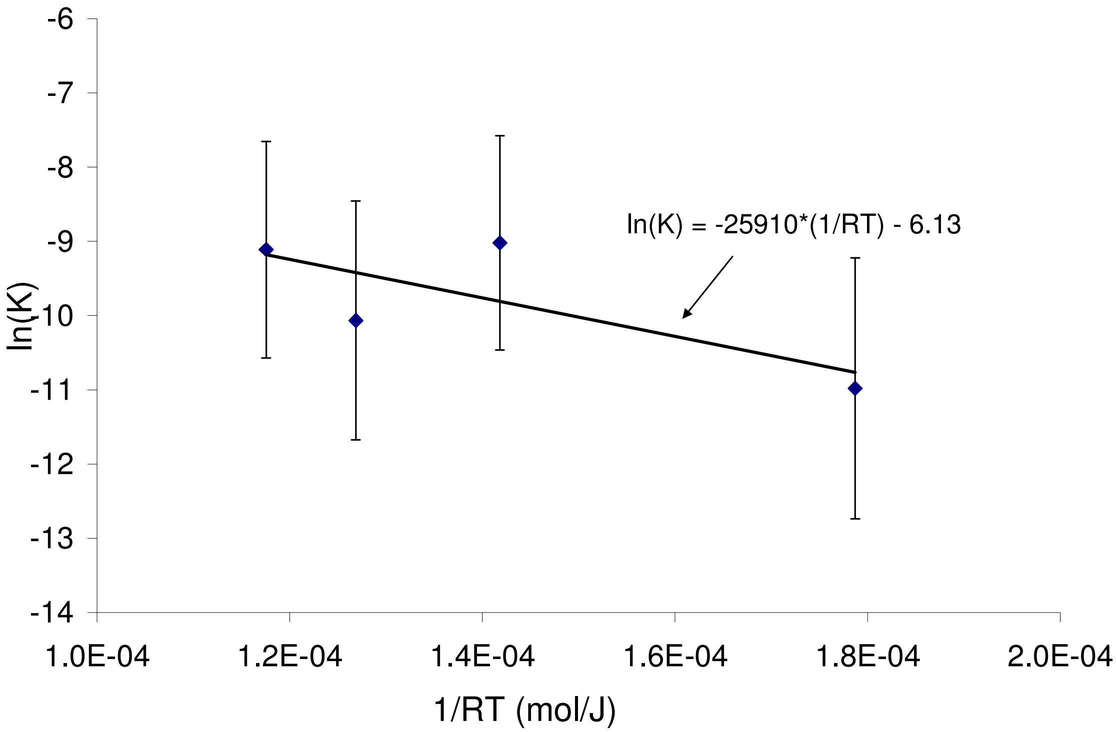

Figure 4.3: Activation Energy for Steel. The slope of the trend line represents the activation energy required for grain growth. The confidence intervals were propagated form grain size calculations at the same level of confidence (95%).

In review of the experimental study carried out as described in this report, it was seen that grain size calculations were able to be performed for both 1018 steel and Canyon Diablo meteorite samples. Clear grains and boundaries were identified. Within each sample, it was possible to calculate the grain size with relative uncertainty in the range of 6%-18. This accomplishment achieved the first experimental goal of obtaining average grain size values for each material.

Using the calculated grain sizes, it was desired to find grain growth activation energies for each material's primary microstructure. The steel grain growth behavior was conducive to the calculation of activation energy and a final value obtained for 1018 steel was:

$$Q = 25.9 \pm 3.4 \text{ kJ/mol}$$

This compares well with the value of 28 kJ/mol obtained for other ferritic steel alloys reported in literature[9].

The behavior of grains in the Canyon Diablo meteorite was not as expected according to normal heat treating of iron alloys. The counts for each sample were reproducible within that specific specimen, but did not lead to a relationship which yielded a physically rational value of grain growth activation energy. This result meets the second experimental goal of investigating the feasibility of measuring activation energy of grain growth for meteorites. The fourth experimental goal is also met because steel has quantifiable activation energy whereas meteorites exhibit no uniform activation energy value (via the methods employed here).

It is suspected that the various regions of the meteor retained most of their properties through the heat treatment due to planning the treatment based on a pure iron-nickel substance. In reality, the meteor is a heterogeneous matrix of materials which all coexist, causing very irregular boundaries and many inclusions which grains must grow around and cope with. Some sections of primarily iron-nickel grew regularly, while regions with inclusions or lamella of other phases grew much more slowly or appear to be unchanged due to the bounding of the structures with the various inclusions.

To compare and contrast the two materials, the difference between the conditions of optimal grain growth rate for steel versus kamacite was determined. As seen in tables 4.1 and 4.2, the highest rate for steel was obtained at 575 °C between the seventh and tenth hours, while for the meteorite samples it appeared to be at 400 °C between only one and two hours. It is difficult to draw any conclusions based on the peak meteor grain growth conditions, as all grain growth rates were quite random showing inconsistent trends. The same rationale can be used to explain the low temperature for peak growth rates in meteorites. Overall, the Canyon Diablo specimen did not behave like a typical iron alloy and as such these results must be taken as very case specific until further studies are available.

Lastly, the interesting questions shall be discussed. Aside from the questions about grain growth activation energy and grain size, which were answered in the conclusions related to the experimental goals, it was desired to address whether the heat treatment history of a meteor can be determined, as well as if it is possible to synthesize a meteorite from materials found on earth.

Due to the irregular nature of the grain size responses to different treatment times (as evidenced in Figure 4.2) and the difficulties found in ensuring only one microstructure was analyzed, it seems that determining the thermal history of a meteor would be quite difficult without viewing a before and after image of the same sample. Additionally, determining the atmospheric entry thermal exposure would also be difficult as research has shown the heat affected zone on meteors tends to only be around ten millimeters deep[3].

When it comes to making fake meteorites, it was found that meteorites are quite distinguishable from steel and iron based on metallographic images. Evidence indicates that it would not be possible to fabricate a false meteorite using ferritic materials commonly found on earth due to several factors. First, predictive growth of meteorite microstructures would be impossible without a grasp of the activation energy for grain growth of the materials or a reproducible heat treatment schedule for these materials. Additionally, the inclusions commonly seen in meteorites have distinct features and are not found in naturally occurring terrestrial metal formations. For example, the Widmanstätten structure, famous for its appearance in iron-nickel meteorites, is said to be a solid state phase transformation that occurs in relation to very slow cooling times (one degree Kelvin per millions of years) in zero gravity conditions[4], both unfeasible conditions to reproduce.

4.1 Recommendations

Future researchers may continue this experiment by studying other alloys and attempting to draw parallels between these and meteorite specimens. The steel samples did not behave similarly to the meteorite samples, but this may be due to the fact that meteorites are composed of a wide variety of substances; whereas, steel itself is one relatively homogeneous microstructure. It is possible that more highly alloyed materials would behave more akin to meteorites than steel.

It is also possible that meteorite samples other than the Canyon Diablo set could have properties more like those of common ferritic materials. The meteorite samples used for this experiment did not appear to behave in the same manner as steel, but there is no reason to assume that there are not other meteorite samples that more closely mirror the properties of steel.

5. Educational Impact of this Project

The project was unusual, risky and had unknown merit at the time it was selected. Due to its relatively open-ended nature, students and instructors alike were not sure what the outcomes would be and if there would be any valid comparison or not between steel and meteorite specimens. Additionally, the methods of analysis to be used and material treatments chosen were documented only for steels and irons, requiring that the students seriously consider what is going on with these methods, and what should be done different when applying them to meteorites. For all of these reasons, the project was excellent from an educational perspective.

Another positive aspect of the meteorite project was it multidisciplinary nature. Bringing together personnel from Chemistry, Physics, Materials and Mechanical Engineering to study a problem allows for collaboration on the project at hand, and creates a network by which other future problems may be studied.

One of the possible problems with an open-ended, outside of the discipline project is that students may become disinterested if they do not see relevance in the project. For example, if students believe that studying meteorites has no bearing on their own personal future as a Mechanical Engineer, they may choose to do and learn very little about the project. It is the responsibility of the instructors to maintain an upbeat working atmosphere, and to create relevance at every opportunity. In the present project, all involved were fortunate in that everyone stayed interested from beginning to end.

6. Concluding Remarks

The study of meteoritic samples in a ME Senior Lab course was shown to be a positive example of multidisciplinary collaboration between personnel in the Physics, Chemistry, Materials and Mechanical Engineering disciplines at Rose-Hulman. A group of four ME seniors were able to etch meteorite and steel samples and measure respective grain sizes. Activation energies for grain growth were measured and compared with literature values. Most of all, the students were made to truly understand the basic principles of the metallurgical methods they used by applying them to a material with little documented history in the realm of metallurgy.

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