Quantifying Aluminum Crystal Size Part 2: The Model-Development Sequence

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Abstract

We have designed model-development sequences using a common context to provide authentic problem-solving experiences for first-year students. The model-development sequence takes a model-eliciting activity a step further by engaging students in the exploration and adaptation of a mathematical model (e.g., procedure, algorithm, method) for solving a problem for a realistic client. Here we describe an entire model-development sequence in which first-year engineering students are asked to develop, explore, and adapt a model for quantifying the size of aluminum crystals using digital images in response to the needs of an aluminum manufacturer. The intent of this paper is to highlight, by example, the components and educational value of a model-development sequence.

Introduction

First-year engineering students should have experiences that prepare them for the work they will carry out in the workplace. This means that coursework should provide problem-solving experiences that are authentic and support the development of skills and abilities that engineers need to be successful [1-2]. By providing realistic engineering experiences early in an engineering program, students will be more prepared for their upper-level design courses as well as the work they will do as engineers. In addition, these early experiences will help students understand the range of activities, content, and abilities found in engineering work.

The challenge for instructors is the design of authentic engineering tasks that include enough complexity that the tasks are realistic yet accommodate students' lack of experience with engineering work and content (e.g., mathematics, science). In addition, the tasks should challenge and engage students while simultaneously helping them learn the engineering content and develop the skills and abilities needed in the engineering workplace. So, our challenge was to design tasks for first-year engineering students that are representative of authentic engineering work, accessible to students, and present engaging and challenging problem situations that link to course learning objectives and content.

We began to design model-development sequences [3] to attempt to meet these challenges. For our purposes, a mathematical model is a method, procedure, or algorithm that can be used to make a decision, prediction or explanation in an engineering problem situation. For instance, a mathematical procedure that can be used to quantify aluminum crystal size is a model. The model-development sequence incorporates three parts designed to develop students' understanding of engineering tasks and content (Table 1). *The model-eliciting activity* elicits students' current understandings of a problem situation by having them develop a mathematical model [4]. Each team generates a written explanation of the model they design. The *model-exploration activity* exposes students to one or more engineering models or methods for resolving the problem situation. Finally, the *model-adaptation activity* requires the adaptation, examination, extension, incorporation, or modification of both the engineering model and the students' initial problem solution. At all three stages, students work in a technical team. The use of a team capitalizes on the diversity of knowledge and experience of the team members and facilitates the completion of more complex tasks. This paper describes a sequence of activities assigned to first-year engineering students enrolled in ENGR 106: Engineering Problem Solving and Computer Tools at Purdue University.

In Part 1 of this series [4], we provided a deep description of the principles for designing a model-eliciting activity. We also demonstrated

Part of Sequence	Activity for Aluminum Crystal Size
Model-eliciting activity: Elicit students' current understandings of the problem situation by asking them to design a procedure for a client.	Laboratory Activity - Students create a procedure for quantifying crystal size using grayscale micrographs of metal samples [4].
Model-exploration activity: Students learn about an engineering model for solving the problem.	Homework - Students compare and contrast their procedure with the Average Grain Intercept (AGI) method used by materials science engineers (Appendix A).
Model-adaptation activity: Students adapt, revise, and extend the models from the first two parts of the sequence.	Project - Students write a MATLAB® program for quantifying crystal size using pixel information from digital images of micrographs (Appendix B).

Table 1. Aluminum Crystal Size Model-Development Sequence

by example how the model-eliciting activity and model-development sequence can be used to address ABET Criterion 3 a through k.

In the paper, we describe the course in which these activities are used, and we provide some background about model-development sequences. We then describe the engineering theories and content represented in a particular model-development sequence, Aluminum Crystal Size. Finally, we describe the three parts of the model-development sequence in more detail with reference to the Aluminum Crystal Size activities.

Course Description

ENGR 106: Engineering Problem Solving and Computer Tools is required for all first-year engineering students at Purdue University. Throughout the course, students simultaneously learn to use computer tools (Excel and MATLAB®) while solving problems based on introductory engineering content (e.g. economics, statistical methods, and introductory computer programming). In addition to learning the technical content, course goals also include developing students' problem-solving and teamwork abilities. Students enrolled in the course attend two 50-minute lecture periods and one weekly 2-hour laboratory section. The lectures (approximately 450 students per section) are led by a faculty member from the Department of Engineering Education. The computer laboratories (28-32 students per section) are led by a graduate teaching assistant with assistance from an undergraduate teaching assistant. Since fall 1999, the course has evolved from a computer tools focus to a problem-solving focus. There is a balanced emphasis on individual and team problem-solving. The introduction of the model-development sequences described in this paper has increased the relevance of the course to students' future engineering experiences in academia and in industry and aligned the course with ABET EC2000 recommendations.

The Aluminum Crystal Size sequence was designed for this first-year engineering course. The activity was the fourth model-eliciting activity of the semester and the first complete model-development sequence of the semester. The sequence consisted of a laboratory activity, a homework assignment, and a project (Table 1). All three parts were completed in teams of three to four students. The students worked with two different teams during the semester (each for six to eight weeks). The Aluminum Crystal Size sequence was completed when students were working with their second team for the semester.

Modeling Activity Background

Model-development sequences [3] require students to consider and construct models (e.g., procedures, algorithms) for real world application in a three activity sequence. The models develop in the sense that the first activity (the *model-eliciting activity*) asks students to create their own model [5]. We use this activity to launch the model-development sequence, activities that are increasingly aligned to the course content. The second activity (the *model-exploration activity*) encourages further development of the students' model by introducing a model used by engineers to solve the problem. The final activity (the *model-adaptation activity*) requires the integration, extension, and adaptation of the models developed in the first two activities. Model-development sequences are particularly appropriate for engineering contexts that require the design and development of procedures or processes.

Students are asked to develop a model in a realistic engineering context. The context includes a client to whom the students address their procedures. The client's needs are a means for students to self-assess the feasibility of their procedures. The procedures must also be explained clearly enough for the client to be able to implement the procedure in the given situation and in similar future situations.

Selecting appropriate engineering contexts is one of the most challenging parts of the design of the sequences. Since first-year students often have very little experience with engineering and some of the tools of engineering (e.g., calculus, chemistry, physics, statistics), one challenge is to find a context that is simple enough for students to understand and work on, yet complex enough to be considered an authentic engineering problem. The context must also be perceived by the students as authentic – given their limited exposure to engineering, many of the tasks that engineers do as part of their jobs might lack authenticity to first year engineering students. Examples of engineering problems that are perceived by students to be authentic include designing an aircraft wing, predicting the flow behavior in an oil pipeline, optimizing the heating system in a building, or developing a control system for traffic flow. Such authentic contexts may need to be selectively scaled down for first-year students so that they can successfully use and extend their existing knowledge and skills to develop mathematical models. As students are in the first stages of learning what engineers do and how they work, model-development sequences should help them understand engineering work.

A particularly important aspect of the model-eliciting activity in terms of introducing students to engineering is that the activity should be personally meaningful [5]. This does not mean that the context for the activity should be limited to situations where students have personal experience. Rather, the students should be able to draw on their own understanding, knowledge, and experience to develop a model to solve the client's problem. While first-year students are not likely to have experience with aluminum production, they probably have had experience in other contexts where the measurement and quantification of size is important. In addition to personal meaningfulness, as the students work on the task, they should be able to self-assess their work using information provided in the task as well as their own knowledge about similar contexts, mathematics, science, and engineering. The self-assessment characteristic means that the team of students should be able to determine when they are finished and have met the client's needs. For the Aluminum Crystal Size model-eliciting activity, this means that they have accounted for the irregularities in the crystal size and packing, and they can question assumptions and procedures posed by their teammates.

The model-eliciting activity is a critical part of the sequence since it serves as the foundation for the next two activities. This first activity is the students' introduction to the context including background information about the situation and technical data relevant to the activity. By encouraging the students to develop their own models, there is a frame of reference for understanding the engineering models introduced in later parts of the sequence. Their frame of reference should include a greater understanding of the constraints and assumptions relevant in the context as well as limitations of potential models. In later parts of the sequence, the students may be asked to compare and contrast their models to the engineering models. The comparison process can help them to refine and make explicit assumptions and limitations related to the models and the context.

In the Aluminum Crystal Size model-eliciting activity, the students are asked to determine a procedure for measuring crystal size based on two-dimensional micrographs of material in order to correlate crystal size with material strength. Determining crystal size from micrographs is problematic because the crystals are not shaped or packed regularly. In addition, the micrographs may have different scales, so just "looking" at the samples will not yield an accurate measure of size. When evaluating crystal size, it is important to know how the size was determined. Rather than stating which sample has larger crystals, the solution requires a model or procedure for determining crystal size. By describing the model to the client, the students have to reveal their thinking about the problem situation. They have to describe relevant assumptions and inferences they made to generate the model so that someone else can re-use the model. Different assumptions and models may result in different rankings of samples by crystal size. For example, if a student team accounts for the fact that in a two-dimensional section only parts of the crystals are seen, their model may result in a different ranking of samples than a team that does not take this into account. Once students have grappled with the development of their own procedure for quantifying crystal size, they are more able to understand the engineering method introduced and adapted in the model-exploration and adaptation activities.

Connection to Engineering Theories

Model-development sequences are designed to tap engineering content to introduce students to engineering topics they might not encounter until later courses. In particular, the Aluminum Crystal Size sequence introduces three principal materials science and engineering concepts: microscopic visualization of crystal boundaries within materials comprised of many crystals (polycrystals), quantitative assessment of crystal size in polycrystals, and the relationship between strength and crystal size in a polycrystalline material. Each of these fundamental concepts has implicit assumptions that can be simplified. For this reason, the activities in the model-development sequence can be adapted or adjusted in complexity and depth depending on the academic level at which the problems are implemented. In this section, we provide detail about the technical engineering content behind the task. However, this content was simplified for the first-year students both because of their lack of engineering experience and to encourage them to develop their own models for solving the problem.

The visualization of crystal boundaries can be accomplished by a range of experimental techniques and two of them are demonstrated in the "Batter, Batter, Swing" figures in the model-eliciting activity [4]. The boundaries between the grains are visible in the galvanized steel pole because during the formation of this coating differences in the orientation of the individual grains result in corresponding differences in roughness of the surface. These differences in roughness change how each grain reflects and absorbs visible light. The differences can also be produced by chemical treatment of surfaces. Galvanizing consists of coating steel with liquid zinc and allowing it to solidify on the surface of the steel. Zinc melts at 420°C, which is well below any temperature that is likely to strongly affect the properties of the steel, which is an iron alloy that usually contains small amounts of carbon and melts at around 1500°C. When the zinc solidifies on the steel, it has a tendency to form large flat crystals which extend across the typically 0.1-0.4 mm thickness of the coating as shown on the steel poles. The orientation of the zinc crystals results in differences in surface roughness and corresponding differences in reflectivity.

In the microstructure images designated as aluminum, which are actually from metal alloys allowing sharper images than typical baseball bat alloys, the boundaries between crystals are visible due to differences in how chemicals attack the boundaries between the crystals. Implicit assumptions are that the grains are roughly equal in their dimensions and have not inherited directionality that is inherent to the processing of materials into the thin sheets typical for aluminum bats. Quantitative evaluation of size scales in microstructures of materials is part of a well established field called theoretical stereology, and computation of crystal size from two dimensional sections of materials is typical [6]. That material strengthening can be accomplished by decreasing crystal size is an accepted and widely used principle.

Model-Development Sequence Overview

The Aluminum Crystal Size sequence has three parts briefly described in Table 1 which can be used as a prototype for similar sequences. The activities are described below in greater detail. In addition, we present the tasks as they were given to the students in the first-year engineering course ([4] and Appendix A and B). For the implementation we describe here, the students used a WebCT (an online course management system) discussion board to post their responses to questions posed in the activities. However, online discussion postings are not required for the activities to be successfully completed.

Part I: Model-Eliciting Activity

For the model-eliciting activity, the students worked in teams of four in the computer laboratory to design a procedure for quantifying aluminum crystal size using two-dimensional images [4]. The images were intentionally given different scale markers so that the teams would have to design a procedure that goes beyond just looking at the crystals to determine which sample had the smallest crystals. The problem was situated in the context of the manufacture of softball bats that would resist denting. Situating the first task in such a context had two purposes. First, our goal was to provide a reason why engineers would be interested in crystal size. Second, the context established a client who would need a procedure for quantifying crystal size for quality control.

The activity began with a newspaper article about aluminum bats to situate the use of the materials in a context. Then, the students were introduced to micrographic images of metal crystals that are used by materials science engineers. After the introduction, the students began the team assignment which asked them to design a procedure for ranking the given samples by size. At this point, a few different student solutions emerged. The first was to count the number of crystals in a square drawn on the micrograph. Then, they divided the area of the square by the number of crystals. In a second type of solution, the students selected a sample of crystals and measured the length and width of the crystals to approximate the area of the crystals. Then, average area was computed. Both types of solution differed from the actual method for quantifying crystal size described in the model-exploration activity.

Once the model-eliciting activity was complete, the students watched a video made by a materials engineer (Keith Bowman). This video presented the details of the engineering theory and introduced a method for measuring crystal size employed by material science engineers.

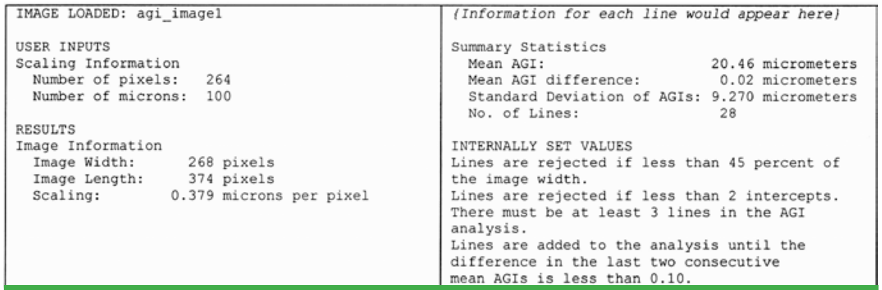
Part II: Model-Exploration Activity

The second part of the sequence introduces an established engineering procedure for measuring crystal sizes - the average grain intercept or AGI method (Appendix A). Students individually compared the AGI method to their own. The purpose was to ask them to critically examine the relative strengths and weaknesses of different methods. Different methods may account for different characteristics of the sample or may be used for different purposes. Because the students had gone through the process of designing their own method, they were more able to examine the strengths and weaknesses of the AGI method. In addition, they had already thought through considerations for a measurement method. For example, did the method account for partial crystals? How? Did the method account for the irregular shapes and packing of crystals in the sample? How?

As engineers, the students will have to evaluate the relative strengths and weaknesses of different procedures for the measurement of quantities. In addition, they will be responsible for the design of procedures as well as the application of known procedures. The first two phases of the sequence (the model-eliciting activity and the model-exploration activity) provided students with both types of experiences. By considering how a procedure could be designed before learning about an established procedure, the students should become familiar with the constraints of the procedure design as well as the aspects of crystal samples to consider when designing a procedure to quantify crystal size.

Part III: Model-Adaptation Activity

In the third part of the model-development sequence, the teams were required to design a MATLAB® program that would use a data file with pixel information from an image of a crystal sample and determine an average crystal size for the sample using the AGI method (Appendix B). As stated in the abbreviated project description in the appendix, the teams had to determine the variability in the AGI method as implemented in their program. The team also had to write a description about how to use the software tool. The purpose of the written explanation is two-fold. First, it underscores the need in engineering for tools which are sharable with other people who may or may not be engineers. Second, the development of a written explanation requires students to communicate assumptions and conditions under which the program would be usable. During three weeks of laboratory, the students completed tasks to code sub-functions that would eventually be integrated into the program for the project. They had to create an executive program to coordinate the sub-functions they had been designing in the laboratory activities. This programming support helped them to step through the process of completing the project.



```
IMAGE LOADED: agi_image1

USER INPUTS
Scaling Information
  Number of pixels:   264
  Number of microns:  100

RESULTS
Image Information
  Image Width:       268 pixels
  Image Length:      374 pixels
  Scaling:         0.379 microns per pixel
```

```
(Information for each line would appear here)

Summary Statistics
  Mean AGI:                      20.46 micrometers
  Mean AGI difference:            0.02 micrometers
  Standard Deviation of AGIs: 9.270 micrometers
  No. of Lines:                   28

INTERNALLY SET VALUES
Lines are rejected if less than 45 percent of
the image width.
Lines are rejected if less than 2 intercepts.
There must be at least 3 lines in the AGI
analysis.
Lines are added to the analysis until the
difference in the last two consecutive
mean AGIs is less than 0.10.
```

Table 2: Sample user input print out.

The Aluminum Crystal Size model-adaptation activity fulfilled a number of course objectives [4]. Students completing the project

- Gain experience using MATLAB® with the focus being on:
  - o The use of repetition and conditional structures and
  - o The creation of an executive program and user-defined functions
- Practice applying statistical analysis concepts,
- Continue to create plots of technical presentation quality, and
- Continue to develop effective teaming skills.

The detailed project instructions and the supporting laboratory and homework exercises lead the students to produce a solution similar to that shown below. Each student team's final MATLAB® project code was required to:

- Load the digitized file for a specified micrograph,
- Generate enough random lines to super-impose on the micrograph to ensure a reliable AGI measurement,
- Compute the mean AGI and the standard deviation of the AGIs used to compute the mean,
- Print all user inputs, assumed values, and key results that are associated with creating the lines used in the determination of the mean AGI (Table 2), and
- Print all required plots (i.e. micrograph with lines used to compute AGI, the running AGI mean versus number of lines, the running standard deviation versus number of lines) to the screen in one figure window (Figure 1).

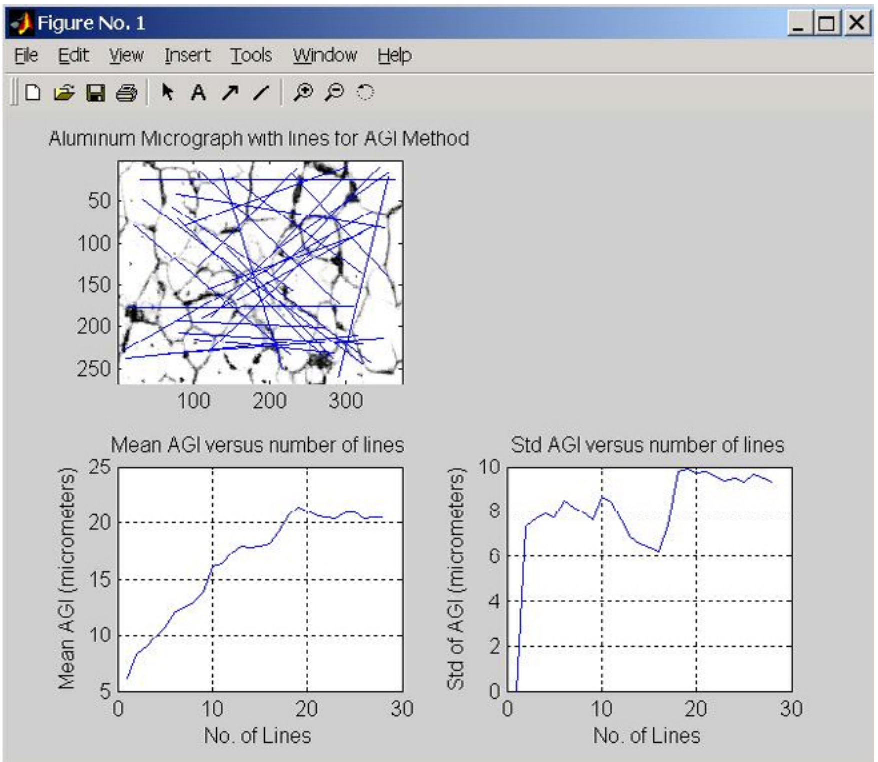


Figure 1. Sample Aluminum Crystal Size project results.

Basis of Design

The materials for this case-like study sequence were derived from methods used within materials science and engineering to quantify crystal size. The problem contexts (e.g., aluminum manufacturing) in which crystal size is important can be drawn from several engineering disciplines, including mechanical engineering, aeronautical and astronautical engineering and materials engineering. The students could do more research about the properties of aluminum, processing of aluminum, microstructure quantification methods, or materials science in general. While this type of background research was not required for the completion of the model-development sequence presented here, it may be highly appropriate when using this problem in an upper-division engineering course.

While we used the sequence in a first-year course that is typically completed before students have selected an engineering discipline, it is also appropriate for courses in some of the disciplines listed above (e.g., materials science, mechanical). Upper-level students may have more experience with engineering content, mathematics and science, but the task will still be challenging. As at the first-year level, we would anticipate different types of solutions to the task based on their engineering experience.

Format for Implementation

Modifications to the implementation of the sequence are possible. While we used a blend of in-class and out-of-class work for the sequence, that could be changed. For all the activities, students worked with their teams on the task. They also posted responses to some phases of the sequence on an online discussion board. This format was proposed as a means to facilitate teamwork outside of class as well as to create an environment that encourages equitable participation from all members of the team. The discussion board postings also allow an instructor to monitor and review the team's discussion of the tasks. Individual work could include responding to questions about the background information. We have begun using an individual assignment at the start of the MEA that instructs students to read the background information and begin solving a small part of the problem before team work begins. This allows everyone on the team time to digest the problem and make early contributions.

The implementation format described here fits within the current course structure at Purdue. However, other formats are possible and have been attempted at Purdue. For instance, the model-eliciting activity has been used in a large lecture (approximately 450 students) with students worked in teams to complete the task in a single 50-minute period with discussion. We've used this format to allow faculty to introduce MEAs and set expectations for students and teaching assistant (TA) participation prior to the TAs implementing MEAs in the laboratory setting. The model-exploration activity could be assigned as homework for the teams to complete outside of class. In a sophomore materials science course, the students posted initial responses to a discussion board and then completed the task via discussion board postings outside of class.

Conclusion

The Aluminum Crystal Size model-development sequence accomplishes a number of educational goals without taking away from engineering content within the course. Rather, the sequence situated the engineering content in a context that was personally meaningful to first-year engineering students. In addition, the sequence capitalized on helping the students examine their own ways of thinking about the situation in order to provide them

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with an authentic engineering method for solving the problem of quantifying crystal size. The sequence of tasks also accomplished one of the main goals of the course, learning MATLAB®, by providing an authentic problem where MATLAB® would be useful. Rather than falling within a particular unit about a particular MATLAB® command, the students had to draw on their knowledge of MATLAB® accumulated over the semester to design a program to use the information from the digital images to implement the AGI method.

The Aluminum Crystal Size model-development sequence represents a class of tasks that allow students to express their understandings, explore engineering methods, and adapt procedures for particular situations. By progressing through such sequences, students are drawn into the engineering content of first-year engineering courses (e.g., MATLAB® programming) as well as other skills such as communication and teamwork that are necessary parts of engineering work. The Aluminum Crystal Size model-development sequence also provides students with information about an area of engineering with which they might be unfamiliar - materials science. So, the sequence of tasks introduces students to what it means to work in engineering as well as different types of engineering work.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0120794. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Appendix A: Part II: Model-Exploration Activity

(as Distributed to Students)

Aluminum Crystal Size

This is a continuation of the activity where your team developed a procedure for determining the average size of aluminum crystals from micrographs. Materials engineers use a micrograph, or microscopic photograph, of aluminum to compare the size of the crystals. To produce these microscopic photographs, pieces of aluminum are chemically treated and polished to make the boundaries between the crystals more visible. Using a camera attached to a microscope, a picture of the boundaries between the crystals can be obtained. The size of the aluminum crystals can be estimated using the micrographs.

Your team is close to winning the job for the contract to develop a software tool to determine the average crystal size for samples of aluminum. Your potential client knows about the AGI method (described below) for determining crystal size and wishes to understand the similarities and differences between your team's method and the AGI method.

Study the AGI method and completely answer the questions below. You may assume that the client is knowledgeable in mathematics and science when writing your responses.

1. How is the AGI method similar to the method your team produced?
2. How is the AGI method different from the method your team produced?
3. What is the average crystal size for the three aluminum samples represented in the micrographs from the model-eliciting activity (samples A, B and C)? To answer this:
   - Use the method developed by your team to determine the crystal size.
   - Use the AGI method to determine the crystal size. Use only three randomly placed lines per micrograph.
4. In what ways does the AGI method lend itself to the development of a software tool?

Average Grain Intercept (AGI) Method

The average grain intercept (AGI) method is a technique used to quantify the grain - or crystal - size for a given material by drawing a set of randomly positioned line segments on the micrograph, counting the number of times each line segment intersects a grain boundary, and finding the ratio of line length to number of intercepts. Thus, the AGI is calculated as:

$$AGI = \frac{\text{line length}}{\text{number of intercepts}}\,.$$

A sample with small crystals will have a low AGI value compared to a sample with large crystals.

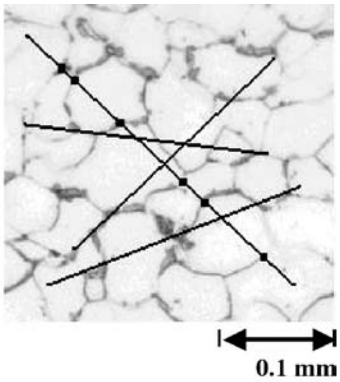

Figure A.1. Micrograph of Crystals with Random Line Segments

Figure A.1 shows a micrograph (microscopic photograph) of a metal sample that has been polished to produce a smooth flat surface and then etched to highlight the boundaries between crystals (or grains). The material within each boundary is a single, or individual, crystal that has been intersected (i.e., sliced through) by the polishing plane. On this micrograph the micron marker indicates the magnified size of the features. A micron marker is more useful than giving the magnification (number of times X) since the micron marker is always scaled properly even when subsequent enlargements or reductions are made of the micrograph.

The line segments that are randomly superimposed on the micrograph of Figure A.1 show the first step in determining the AGI (average grain intercept). The small squares on one of the line segments indicate (approximately) where the line segment intersects the grain (crystal) boundaries. To calculate the AGI, the intersections for the other randomly placed line segments would also need to be obtained. The count of boundaries and the total length of the line segments would then be used to calculate the AGI for the sample.

The picture shown in Figure A.1 is a digitized, gray scale image of the view seen in an optical microscope. The reason that the grain boundaries are darker than the grains themselves is that the acid used to etch the surface preferentially removes material at the grain boundaries. This results in a sample with channels or mini-canyons running along the grain boundaries. Along these boundaries, the light used to illuminate the sample is not reflected back into the microscope eyepiece. This produces the observed variation in gray scales shown in Figure A.1. A digitization of Figure A.1 can be stored as a data file which contains an array of numbers where each number refers to the gray scale value for each pixel of the micrograph. A sub-sample of the complete Figure A.1 file is shown in Table A.1; this sub-sample shows the gray scale values for the square superimposed on Figure A.2

and exploded by itself in Figure A.3. Gray scale values range from 0 for black to 255 for white.

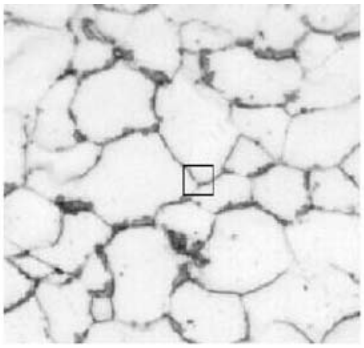

Figure A.2. Micrograph of crystals with sub-

Figure A.3. Sub-sample of micrograph

131	95	38	37	33	15	12	19	13	8	10	12	12	14	3	7	16	18
79	100	81	86	31	20	17	16	7	10	18	19	16	15	11	13	12	15
16	66	70	81	36	27	22	16	7	12	18	15	16	10	16	18	7	13
8	54	81	118	61	37	23	24	20	19	16	9	18	5	19	22	10	18
19	16	40	98	95	48	20	25	28	24	19	15	22	6	22	22	18	25
31	11	38	102	107	57	23	20	20	20	22	23	20	8	20	15	22	26
23	13	34	70	97	77	55	35	18	21	26	22	16	15	25	13	32	37
11	17	29	31	90	103	99	64	30	32	34	21	19	28	37	22	50	57
15	19	19	24	43	93	87	58	21	36	25	25	27	30	31	33	47	78
15	17	18	22	30	44	45	56	55	53	45	59	48	51	57	83	99	110
13	15	15	20	26	15	20	49	91	92	90	98	120	120	106	113	84	64
11	13	14	19	26	23	27	37	101	122	122	100	136	128	99	99	58	39
10	13	14	20	18	27	35	35	92	112	102	67	54	41	17	37	27	22
10	14	15	20	13	19	30	47	81	78	56	38	30	27	20	34	27	18
13	15	16	21	17	22	23	48	59	52	27	28	11	16	22	19	14	8
15	17	16	20	23	32	18	32	30	39	19	25	24	17	20	12	25	22

Table A.1. Digital file for sub-sample from micrograph of crystals shown in Figure 3.

Appendix B: Part III: Model-Adaptation Activity

Project Description

(Note: The detailed project instructions are lengthy and are not included here.)

Your team has been hired by the Aluminum Production Company (AP Co.) to develop a software tool using MATLAB® that will determine the average grain intercept (AGI) for digitized micrographs. Your team will be working with actual pixels from a digitized micrograph. Your team will need to determine how much variability will occur in the AGI measurement when using your tool so that the managers at AP Co. will know the reliability of the measurements. In addition to developing the software tool, your team will document your procedures and demonstrate how your software tool can be used on a series of sample aluminum micrographs. Your document needs to be written in complete sentences and should clarify the tool completely, yet briefly, for your client. Your software tool will be examined and evaluated by the managers at AP Co. You may assume that the managers have some knowledge of science and math but are NOT engineers.