2006-2434: FAILURE ANALYSIS PROJECTS AS TEACHING TOOLS IN MATERIALS SCIENCE

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Failure Analysis Projects as Teaching Tools in Materials Science

Abstract

Mechanical Engineering students at the Rochester Institute of Technology are required to take a Materials Science course in their second year; the course includes both lecture and lab components. Materials Science is not a prerequisite for any other course and, as a result, students may not see the need to be able to learn and apply the course content. Several years ago, a failure analysis project was added to the laboratory component of the course. After several iterations, the failure analysis projects have been fit in to complement both the lab and lecture material throughout the 10-week quarter, in addition to requiring a basic knowledge of Mechanics of Materials. The projects step students through the process of finding a component that has failed in service, identifying probable failure mechanisms based on fracture surface analysis, microstructural analysis, and a basic stress analysis of the incident that caused failure. Students are responsible for sectioning, hardness testing, metallographic sample prep, and background research on the component and/or material. All project deliverables, including the final summary report, consist of presentations made to their peers in lab.

Feedback from students indicates that they find the project to be a valuable part of the course. The students make noticeable improvements in their presentation skills over the course of the quarter. In some cases, the in-lab presentations lead to discussions of different failure modes or loading scenarios among the students. Interviews with graduating seniors indicate that many students feel their failure analysis project was the only project they had prior to capstone design where they truly had free reign to perform anything other than a "canned" experiment.

The paper will outline the process for meshing project content with lecture and lab material, and some examples of student work will be presented.

Background – Materials Science Course

The Materials Science course at RIT is taken in the winter or spring quarter of the second year, typically either with Mechanics of Materials or in the immediate preceding or following quarter. Materials Science is a three-credit course (30 contact hours) with a one-credit lab, while most other RIT-ME lab courses are four-credit lectures with one-credit labs. Approximately 210 students take the course each year. The course is broken into three sections – structure of materials, mechanical properties of materials, and microstructure of materials – with about 75% of the lecture time devoted to metallic materials and about 15% devoted to plastics and ceramics. The remaining 10% is allocated for three in-class tests. A typical course/lab breakdown is given in Table 1. There is no follow-on course, and Materials Science is not a pre-requisite for any other ME department courses. With limited time for in-class instruction and a student population that saw Materials Science as a terminal course, something needed to be done to make the students participate more actively in their learning and to give clear value to the course content.

A great deal of work has been done to investigate the effects of design courses, particularly in the first year when they serve as introductions to engineering, on student success later in the engineering curriculum. These courses emphasis teamwork, problem solving for open-ended projects, communication, and student intellectual development that will be needed for upper-level courses[1-4]. While RIT's Materials Science course is not a broad introductory engineering course, in that it is taught at the second year level and has a specific technical focus, it (1) has connections to other courses that students are required to take, (2) lends itself to project work, and (3) is taken early enough in the curriculum that the students taking it are still developing their problem-solving skills. In addition, RIT does not have a first-year, comprehensive introductory engineering course where students can start to build the skills they will need in upper-level courses and in industry. Therefore, Materials Science seemed an appropriate place to apply some of the principles learned from freshman engineering courses, through the incorporation of a hands-on, real-world group project.

The failure analysis project was implemented as a team learning experience starting in the 2000-01 academic year as part of the Materials Science Lab component. Since the lab allows for more free time and independent or group work, the project was a natural fit, and was expected to improve the students' learning experience[5]. The project also requires students to solve a relatively ill-defined problem, similar to the type they may see as a practicing engineer, and should contribute to their ability to think critically about the answers they find[4]. It has been modified several times to make the best use of time and instructional value. The concept is based on the "Failure of the Month" projects assigned by the Duke University Mechanical Engineering and Materials Science department[6]. Some other universities[7,8] have used failure analysis case studies as teaching tools, but unlike the project outlined in this paper, they do not allow students to select their own failed components and instead provide background information to the students.

Table 1. Materials Science course and lab structure

	Weeks 1-3	**Weeks 4-7**	**Weeks 7-10**
Lecture	Structure of Materials: atomic bonding, crystal structure, defects in crystals, polymer structure	Properties of Materials: Stiffness, strength, ductility, toughness, slip, strengthening mechanisms	Microstructure: Phase diagrams, TTT diagrams
Lab	Metallographic sample prep, hardness testing, polymer structure	Fracture surface analysis, impact testing, concrete testing, strain hardening	Precipitation hardening, steel microstructures, Jominy testing, hardenability
Project	Obtain part, perform hardness test, expose fracture surface or otherwise section part	Fracture surface analysis, stress analysis, estimate actual strength of part and compare with stresses	Microstructure analysis, determine probable alloy and heat treatment, assess appropriateness of material choice

Failure Analysis Project Objectives and Overview

The failure analysis project is a team effort that involves learning material beyond the immediate scope of the class in a relatively independent setting. The overall mission is to provide students with the sort of cooperative learning experience that would not only challenge them to learn beyond the lecture material, but would also cement the knowledge they gained for future applications. The specific project objectives are to:

1. Provide students with an opportunity to learn material as a team that is not covered in lecture
2. Provide students with a real-world application of Materials Science
3. Challenge students with a problem-solving project
4. Provide a link between Materials Science and other Mechanical Engineering courses
5. Incorporate communication skills into the Materials Science class

The general procedure for the project is broken out into four separate deliverables and a final summary.

<u>Deliverable</u> 1: Explain what the part is, how it fits into the overall system, and any background information known about its history and the events surrounding the failure.

<u>Deliverable 2</u>: Examination of the fracture surface of the failed part part. Was it a brittle fracture? Ductile? Fast? Slow? Were there other factors involved?

<u>Deliverable 3</u>: Analysis of the part from a strength of materials standpoint. Develop an analytical model of the part and estimate/determine the loads/stresses acting on it. Sketch a free body diagram. What strength is required for the part to perform adequately? What is the part's strength (based on hardness readings)?

<u>Deliverable 4</u>: Describe the composition of the part. This should be a concise summary of any material characterization work done in the laboratory. Photos of the failed part and pictures of comparable microstructures should be included.

<u>Summary</u>: Based on what was learned from each of the deliverables, explain the reason(s) for failure and how it could be prevented in the future, or explain why failure should not be prevented.

Several aspects of the projects have remained constant throughout:

- Students work in teams of 2 or 3, all from the same lab section
- The project is divided into a final summary and four intermediate deliverables
- The failed components must have failed in normal use in a mechanical manner (i.e., not corrosion or excessive deformation with no fracture)
- The failed components must be iron, steel, or aluminum (limited by current etching capabilities)

Some aspects of the projects have been changed since its initial offering:

- Projects were written documents, with memos or short reports for deliverables and a longer report for the final presentation. This resulted in a considerable grading load, and projects are now presentations done in lab.
- Projects were all graded by the course instructor or lab coordinator. This also created a large grading load. Presentations are now graded by lab instructors according to a detailed rubric.
- Lab activities have been reordered to better compliment project activities

A particular emphasis is made on the connection with the Mechanics of Materials course that most students take concurrently with Materials Science. Since most students in the class are Mechanical Engineers, their primary concern with Materials Science is in material selection and understanding mechanical properties as related to the structure and treatment of a material. Therefore, students are required to perform stress analyses on their components at a level corresponding with their education to date. Typically this means that by the end of the quarter, students are capable of doing a combined stress analysis – such as a car axle that might have experienced combined bending and torsion. Other times, with the help of an instructor, students are able to do basic machine element calculations, such as stresses in bolts or stresses in compression springs.

Sample Student Projects

Student projects range from things as small as a sewing needle or bolt to larger items such as bicycle frames and car suspensions. Because of the preliminary background knowledge required, project parts are typically objects the student or a friend has broken. Some parts are things that have failed at home, like a towel rack which a younger brother attempted to do chin-ups on, or a jig saw blade that failed in use. These two project examples were some of the simpler projects to analyze from a stress analysis point because of the simple, constant load applied. The towel rack was modeled as a beam simply supported at each end with a constant force (the brother's weight) applied at the center. The jig saw blade was modeled as a cantilever beam with a force (estimation of push applied by user) applied at the end. While the stress analysis may have been simpler, both materials were very thin. This made the hardness testing and fracture surface analysis more challenging. Figures 1-3 are excerpted from the towel rack project, and are examples of the fracture surface, stress, and microstructural analyses done for the failure analysis projects.

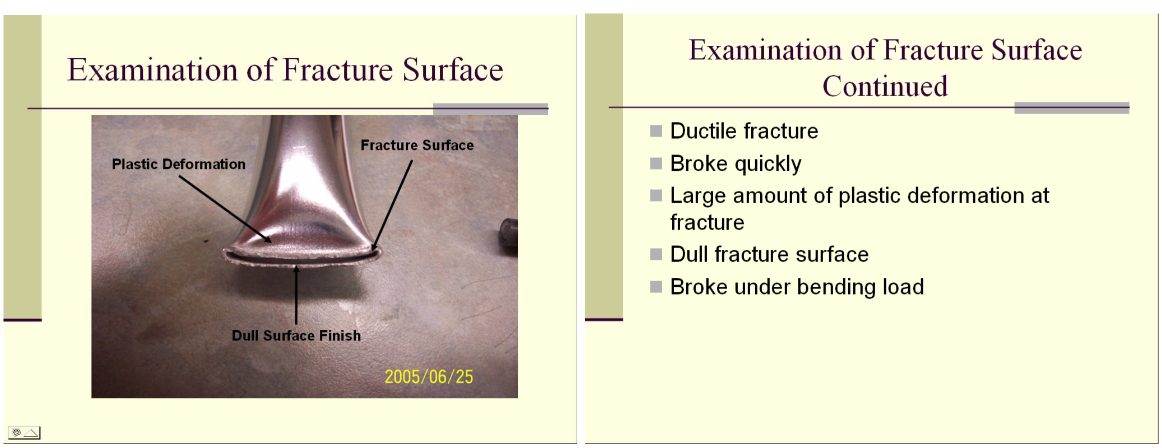

Figure 1: Fracture surface observations from a fractured towel rack.

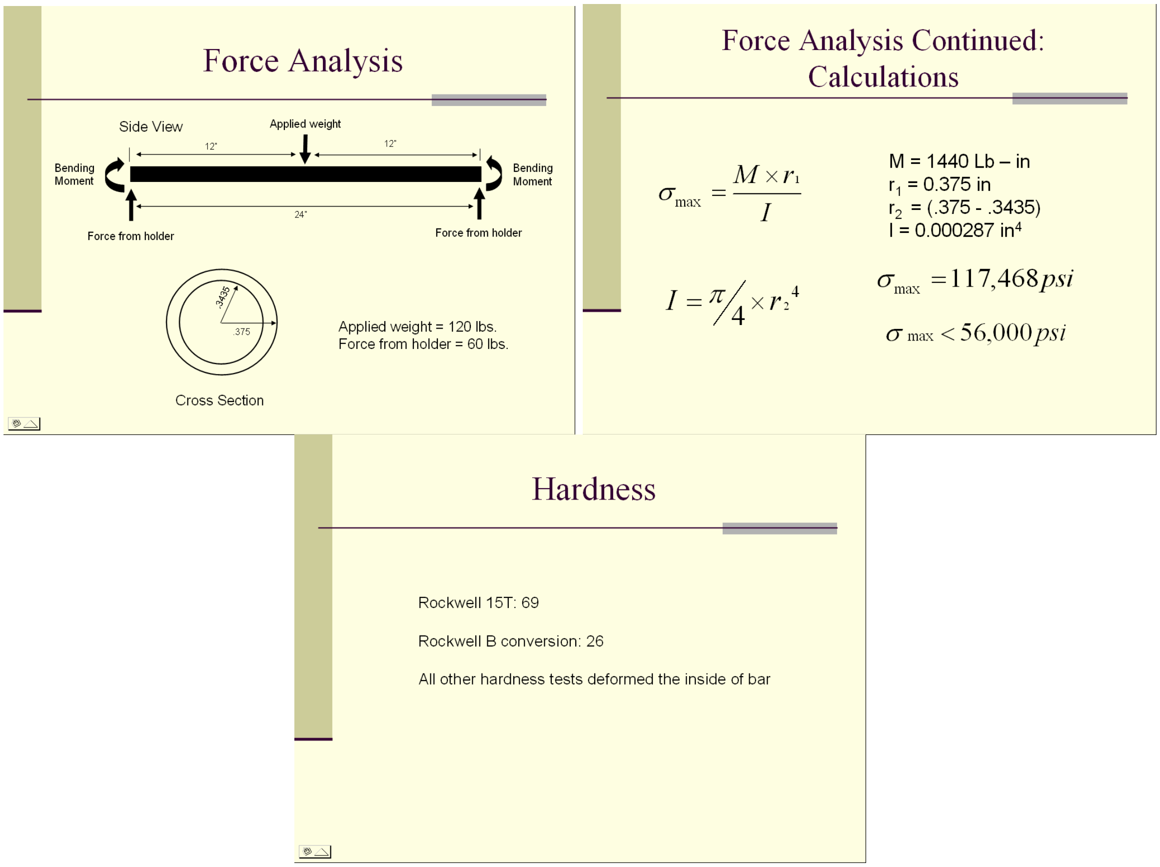

Figure 2: Stress analysis of a fractured towel rack.

Representative of the student athletes in the lab, other projects have involved broken lacrosse sticks, and softball bats. These parts involve a more complex analysis. An impulse, which caused the failure, is estimated to be a force applied over a period of time. Reasonable estimation of this time is critical, as it greatly impacts the estimated force. Not only is the stress analysis challenging, but the microstructure analysis can go beyond the typical steel or aluminum microstructures covered in class. The materials of the bat and lacrosse sticks have been specialized, trademark alloys. These materials have been difficult to etch, making it difficult to do the standard analysis. In these cases, the students, with the help of the lab instructor, research the equipment's material composition. Manufacturer's websites often provide the commercial, trademarked material name. Finding examples of these materials microstructures has proven to be a challenge at times. Because the students do not have the microstructure photo comparison, just one photograph of the material with composition details and justification of hypothesized material is presented to the class.

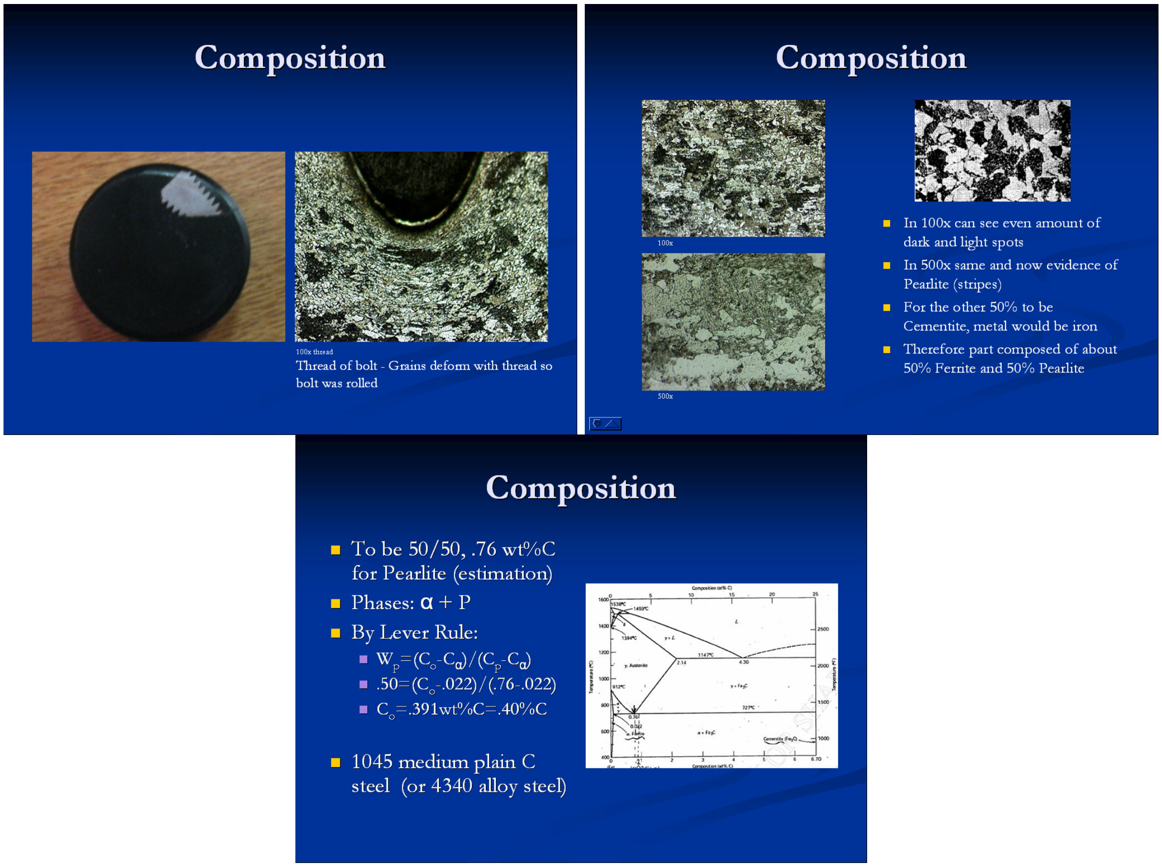

Figure 3: Microstructure identification from a failed snowmobile steering arm bolt.

Presentations and Grading

All presentations for project deliverables use Microsoft PowerPoint as a visual aid and also as experiential preparation for future work at RIT. Coinciding with the material and methods presented during laboratory, the students gain hands-on experience by applying those techniques demonstrated in lab to their selected specimen. A typical deliverable presentation is approximately five minutes long for each group, so a lab with 15 students will require about 30 minutes of lab time for presentations. The final summary presentations are longer and can require up to an hour of lab time. The grading forms used by lab instructors are included in and Appendix to this paper.

In preference to deliverables in report form, where only the instructor would read them, presentations are instead made to assist student learning and interaction and are visual evidence to their improved understanding of the material as the quarter progresses. Over the series of deliverables, students show marked improvement in presentation skills, which is part of the grade they will receive for the project. For some students, the Materials Science Failure Analysis Project is their first experience in presenting to a group of peers on a technical subject and they are often uncomfortable with an audience. For the second presentation, it is easy to notice the increased comfort amongst the students. Since the class as a whole gives a common presentation with similar topics (but different projects), students ease into presenting for peers as well as a grader; the presentation grades ultimately end up as a final project grade for the student groups. Along with presenting skills, content, both technical and graphical, also improve with each presentation. Presentation features, such as technical diagrams with call-outs or bullet lists of important calculations that are demonstrated by one group may be incorporated in a presentation by a different group for the next deliverable. Presentation feedback by the grader also helps improve presentation delivery, content, and subsequently presentation preparation.

The failure analysis project and corresponding presentation also have very valuable hands-on lessons. It is one of the few opportunities a student has to apply engineering methods to a non-text-book example. The project introduces students to another side of engineering that is not commonly thought of when talking about the profession. While methods such as hardness testing, metallographic sample preparation, and fracture surface analysis are covered both in theory and in demonstration during laboratory, the students' individual project serves as reinforcement to the lab instruction since each project must undergo similar analyses. The students' analytical skills are also improved through a stress analysis for the project part and the development of an engineering solution to prevent the mode of failure. Free body diagrams for the project parts are not as straightforward as typical engineering examples and help students learn how to make appropriate assumptions or simplified models. This material is often coincident with Mechanics of Materials and is useful practice and exposure. Grades for this deliverable tend to be lower than the other deliverables; this is mostly due to a lack of experience with stress calculations. However, it is an opportunity for the lab instructor to help the students correct any mistakes made with calculations and to review better techniques for solving such problems. A valuable lesson is also made here: does the answer make sense? Stress values are sometimes wildly low or high and are not always represented with proper units. But again, theses issues are taken care of in early deliverables so that a better presentation is made for the final project grade.

Through the sets of deliverables, various skill sets are improved amongst the students. They are able to take a problem, a fracture specimen in this case, and analyze it using various engineering techniques to develop an engineering solution to prevent future failure. Engineering topics such as metallurgy, mechanics of materials, and testing are covered and practiced. This culminates in a final presentation of the project part, with the highest grade weight attached to it, and is a comprehensive package of everything the student has learned about their particular specimen. Any errors made in previous presentations are corrected and presentation quality is often the best of all deliverables; the grades reflect the students' progress. Lessons learned from this project are easily applied to future course work including Senior Design where many presentations and analyses are required.

Student Feedback

The Materials Science course was traditionally very straightforward: memorize this information, and it will be on the test. Early feedback was less than favorable when an open ended out-of-class project was introduced. Students were surveyed at the end of each quarter to collect their feedback on aspects of the project that they liked and disliked; that information is presented in this section, along with instructor observations.

Initially, students seemed bothered by the fact that their instructor often did not know the answer to questions like "Here's my microstructure – what is it?", but they have gradually become more accepting of the fact that they need to figure these things out on their own, and the fact that the instructors are still learning, too. While use of random internet searches still occurs, many students now know that manufacturers' websites and the ASM Metals Handbook are good references. Word-of-mouth seems to have changed students' preconceived expectations about the course, and most understand that they have to do some library or internet research for the Materials Science project. Similarly, preliminary survey feedback indicated mixed reviews on the usefulness of the failure analysis project, but student opinion has changed over the past 5 years. Many students have returned from co-op assignments with components from their employers or they return after vacation with their own personal broken pieces, asking if they can leave them for future students to use. Word-of-mouth is suspected here, as well.

In the initial years of the project, when written reports were submitted, many students commented on surveys that the grading was too harsh, particularly in terms of their writing skills. In reality, most students' grades were helped by the failure analysis projects. Once projects were changed to a presentation format, student complaints dropped. Since students already submit written weekly lab reports for the course, they still get feedback on their technical communication. Most students seem more comfortable accepting constructive criticism on their oral presentation skills than on their writing skills, even when they claim to hate giving presentations. The quality of presentations generally improves over the course of the quarter, particularly if students can see examples of well-done presentations by their peers.

Students are now regularly commenting on surveys that they are glad to see the connection between the Materials Science course and the rest of their Mechanical Engineering courses. Each quarter, several students comment that the link between the failure analysis project and their Mechanics of Materials class was clear and beneficial. In addition, most students learn some valuable lessons that can be applied in their other courses, such as varying reliability of information available on the internet and cause-effect relationships (e.g., hardened 1040 steel is expected to have an R_C of 50, but an R_C of 50 doesn't necessarily mean it's hardened 1040 steel).

Summary and Future Plans

Future plans for the failure analysis project include group discussions of individual projects and peer evaluation of presentations. Once lab facilities are upgraded to include projectors and microscope-mounted digital cameras, students will be able to present their materials to the class directly. This will allow discussion of various fracture surfaces and microstructures during lab. Additionally, students will eventually be asked to submit peer evaluations on each deliverable. There is currently some discussion around the presentations, but it is voluntary and some students are still not active participants when their team is not presenting.

The failure analysis projects have evolved into a successful method for involving students in a project of interest to them, relevant to Materials Science, that can enhance their knowledge of the course material. Student feedback is generally positive and the additional workload for the instructors is manageable.

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Appendix: Grading Rubrics for Project Presentations

Name(s)___________________________________ Project Part_______________

Deliverable 1: Part Identification

Part Identification ___/2
(What is it? Is a picture, sketch, or schematic included?)

Part function ___/3
(How does the part fit into a larger system, or what does it do on its own? This is important for figuring out how to model the forces/stresses!)

Acknowledge the part provider ___/2

Presentation (speaking) ___/2

Questions ___/1

Total ___/10

Comments:

- -

Name(s)___________________________________ Project Part_______________

Deliverable 2: Fracture Surface Analysis

Identification of Key Features ___/3
(beachmarks, rivermarks, corrosion, discontinuities, welds, etc.)

Fracture Surface Photo ___/2
(Are they key features actually visible?)

Proposed Mode of Failure ___/3
(Does the conclusion make sense, given the application of the part and the features identified on the fracture?)

Presentation (speaking) ___/1

Questions ___/1

Total ___/10

Comments:

Name(s)__________________________________ Project Part______________

Deliverable 3: Force/Stress Analysis

Free Body Diagram ___/3
(correct/reasonable approximation?)

Force/Stress est./calc. ___/2
(are the estimates reasonable, could actual loads be used after some research?)

Hardness Test/Strength ___/2
(are observations and conclusions on fracture surface correct?)

Presentation (speaking) ___/2

Questions ___/1

Total ___/10

Comments:

Name(s)__________________________________ Project Part______________

Deliverable 4: Microstructure Analysis

Microstructure Photo ___/3
(Is microstructure visible?)

Determination of Material ___/2
(Is it based on a reasonable comparison to other photo(s)?)

Feasibility of Material ___/2
(Does the material conclusion make sense, given the application of the part?)

Presentation (speaking) ___/2

Questions ___/1

Total ___/10

Comments:

Name(s)__________________________________ **Project Part**______________

Final Presentation

Introduction/Background ___/10
(Is part function clearly explained? Etc.)

Fracture Surface Analysis ___/10
(Are conclusions accurate? Is picture clear? Etc.)

Stress Analysis ___/10
(FBD? Hardness Testing? Reasonable loads/stresses/approximations? Etc.)

Microstructure Analysis ___/10
(Is the material identified feasible for the part in question? Is the picture clear? Etc.)

Conclusions ___/10
(Does the team bring together and consider all results from 4 deliverables? Does the conclusion make sense? Recommendation for fixing the problem, if applicable? Etc.)

Presentation (speaking) ___/5
(Was the presentation professional? Were references included? Etc.)

Questions ___/5

Total ___/60

Comments: