Joining of Materials - An Upper Level Undergraduate Course in Materials and Manufacturing Engineering
A Progress Report

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Abstract

An upper level undergraduate course: Joining of Materials, has been designed to require that students perform at the higher level of Bloom’s Taxonomy. Students are required to synthesize the subject matter from several prerequisite core engineering courses (applied materials science, thermal sciences, chemistry, and mathematics) in order to best determine the means to join two materials. To make these engineering decisions the students also must consider non-technical issues such as economics, safety, and human resources. Effective communication is critical.

This ten-week course introduces the students to the following joining methods: welding, brazing, soldering, and adhesive bonding. After completing the course the students should be able to differentiate between the methods, and based on this knowledge decide the best method to join two materials. Because most texts focus on only one of the four methods listed above, and then tend to focus on either scientific background or technique (not both), it was necessary to develop a series of learning modules for this course. These modules include classroom presentation, web-based notes and exercises, laboratory experiences (joining, physical testing, and metalography), and assignments.

This progress report will focus on all aspects of this newly developed course including pedagogy, course content, and course structure. Results of course assessments and continuous improvement will also be presented.

Motivation and Need for Course

Before introducing the details of the course, it is felt that one needs to better understand the motivation for creating a new upper level course. In this section of the paper the motivation for changing undergraduate engineering will be reviewed. This section concludes by demonstrating that there is currently a need to change the upper level courses.
During the last decade (perhaps even longer) there has been a steady call for the reform of undergraduate engineering education. Figure 1 shows the University graduation rates over the last 30 years indicates there is a need for such reform. The number of BS Engineering graduates in 1971 was 44,898, after dipping to 38,388 in 1976, the number steadily increased through 1986 when it reached 76,225, by 1990 the number dropped to 63,309 and throughout the 90's dropped to about 58,000 per year. Major concern regarding engineering education occurred when within 4 years the number of BS graduates dropped by 16.5% or approximately 1 in 6. An analysis of the percentage of students graduating with SMET degrees within the same time period, also shows the need for reform. In 1971 5.3% of the BS degrees awarded were in engineering, in 2001 4.3% of the degrees were awarded in engineering. The percentage of students graduating with a BS in engineering, much like the actual numbers, decreased by 1976, steadily increased through 1986 and declined dramatically by 1990.

In response to the trends mentioned above there has been a plethora of activity focusing on improving lower level courses. This is undoubtedly due to the fact that changes at the lower level will effect more students and therefore have a more cost-effective impact. In 1992 it was reported that the leading reasons why lower division students drop out of SMET majors were: 1) non-technical majors offered a better education, 2) loss of interest in science (engineering not mentioned), 3) rejection of technical careers, 4) poor teaching, 5) ineffective faculty. Several characteristics of lower level courses were identified which drive away SMET majors, large and impersonal classes, failure to stimulate and engage students, emphasis on lower levels of Bloom’s Taxonomy particularly memorization (knowledge and comprehension) with no emphasis on the higher levels of learning (analysis, synthesis, critical reasoning or evaluation), fragmented course offerings where there is no indication of engineering relevance or relation to each other. The National Science Foundation and others have identified several reasons why beginning students who identify the content of these courses with their intended major, dislike engineering. The Boyer reported recommended that the freshman experience be an intellectually integrated one, so that the student will not learn to think of the academic program as a set of disparate and unconnected requirements. This is echoed in a 1999 NSF Call for Proposals (Action in Engineering) which calls for horizontal and vertical integration of subject matter, particularly the introduction of mathematical and scientific concepts in the context of engineering. Three years later, the President of the National Academy of Engineering stated that
the retention rate is a disgrace and rather than weeding out poor students, we are failing to effectively convey engineering to beginning students.\(^9\)

Developing new courses to address these needs had in 1998 been shown to increase retention as measured by continued interest engineering.\(^10\) Such activities are likely to increase the numbers of under-represented populations in engineering, as it must be noted that a much higher proportion of women\(^11\) and minority students\(^12\) find engineering education unsatisfying. The incorporation of hands-on laboratories into the lower-level undergraduate courses has been identified as a proposed solution to address many of the problems in basic SMET education.\(^5,7\) A program initiated at the Colorado School of Mines, Connections, a one-credit experience designed to address the issues identified as causing students to leave engineering\(^3,4\) has had a positive effect on retention. Students who entered their freshman year with nearly identical qualifications (SAT/ACT scores, high school GPA’s) but participated in the Connections program had higher 4 and 5 year graduation rates\(^13\).

Success, in the programs described in the last paragraph, is measured by the number or percentage of retained students. This means that if a program is successful freshmen and sophomores will not change their major. A different perspective is required when analyzing the junior or senior years. The fact that juniors do not transfer out of engineering cannot on its own be taken to demonstrate satisfaction with the discipline. At that point in time the desire to complete the undergraduate degree due to financial reasons is probably paramount. Thus, students will stick out the final year.

If the innovations applied to lower level courses are to have a lasting impact on SMET education the innovation needs to be applied across the board. In too many cases, these innovations are not carried out in upper level courses. An examination of graduation rates supports this claim. Because it was not considered appropriate to examine retention of juniors or seniors, to evaluate satisfaction with upper level courses and the discipline, graduate education was examined.

Interest in graduate education has not increased. The number of students earning a masters degree in engineering remained steady throughout the 1970’s and climbed steadily between 1980 and 1995. Between 1995 and 1998 the number declined by 10-15% and has been steady since 1998.\(^2\) However, since 1993 the percentage of MS graduates receiving a degree in engineering has declined from 7.5% to 5.6% in 2001. The ratio of MS degrees in engineering to BS degrees in engineering has remained constant between 1993 and 2001 44.3%±1.1%, despite climbing from 26% to 44% between 1976 and 1993\(^2\). These figures show that there is still much work to be done.

### Course Development Philosophy

To make engineering education more rewarding for upper level students it is necessary to address the concerns raised by employers and others. Requiring these students to synthesize knowledge
from several courses is most appropriate. The professional component of engineering accreditation standards call for this\textsuperscript{14}.

A senior level course at Kettering University - Joining of Materials has been developed with the need to reform upper level engineering education in mind. The goal of the course is to enable the students to identify the appropriate joining technique to join two materials for a given application. This involves not only analyzing the functional requirements of the joined apparatus, but considering cost associated with a current or potential joining process and the potential benefit of a change-over. The former involves synthesizing knowledge learned in fundamental engineering courses (e.g., statics/strengths, thermal sciences, and engineering materials), the latter requires the non-technical skills required of engineering graduates\textsuperscript{9} (e.g., communication, business).

A brief comparison between two welding processes and a soldering process, shows why a course based on joining processes, has the potential to give upper level engineering students a course which requires performance at the higher levels of learning and incorporates several non-technical issues.

Welding is a process where by a metallurgical joint is formed by melting (and resolidifying) both base and filler metal. The individual processes vary based on the heat source, means to prevent oxidation of molten metal, and the means by which alloying elements are added to the material to be joined. Not all processes are suitable for all materials. For example, shielded metal arc welding is relatively inexpensive, and is effectively used to join low carbon steel. However, joining aluminum requires a different arc welding process. Changing the heat source to localized electric current, resistance or spot welding, allows one to join thin sections of metal and in some cases vastly different metals. Soldering is a low temperature process, where the base metal is not melted. In low temperature processes the area adjacent to the metal is not annealed (caused by heat extraction from solidifying metal), and therefore not weakened. However, unlike welding, environmentally un-friendly chemicals are frequently used and corrosion problems can arise. Comparing the two processes requires the students to synthesize seemingly unrelated (because it is in different courses) subject matter.

The Course - A Summary

The course has four learning objectives.

- Describe and differentiate between adhesive bonding, fusion joining and non-fusion joining processes.
- Evaluate the suitability of the above processes for a given application based on technical requirements.
- Evaluate the suitability of the above processes for a given application based on business issues

• Communicate the above knowledge in written, oral and visual form.

The week-by-week schedule of topics is shown below.

Week 1 - Review of Engineering Materials, Basic Welding and Course Introduction
Week 2 - Geometry of Welded Joints, Melting and Solidification, Heat Transfer
Week 3 - Various Heat Sources for Welding
Week 4 - Welding Applications
Week 5 - Brazing of Metals
Week 6 - Soldering
Week 7 - Chemistry Adhesive Bonding, Mechanical Properties of Adhesives
Week 8 - Adhesive Bonding of Polymers and Composites
Week 9 - Adhesive Bonding of Ceramics, Glasses and Metals
Week 10 - Adhesive Bonding of Dissimilar Materials
Week 11 - Project Presentations and Review

The class meets three times each week as shown below.

• One 90 minute class session which incorporates a small lecture and in-class discussion.
• One 2 hour joining laboratory session in which the students prepare joints through arc welding, oxy-acetylene welding, brazing, soldering, or adhesive bonding. Often, it is possible to perform mechanical testing during this time period.
• One 90 minute session which often takes place in the metallography / materials characterization laboratory. Student will perform metallography in order to better assess the metallurgical structure of the joint. When possible, as is the case when we are discussing adhesive bonding, a recitation is held during this time period.

The course requirements have been designed to require the students to synthesize their knowledge and often apply it to new situations. These are detailed below.

Homework: Students are required to turn in weekly homework assignments, which include the laboratory report. The questions are either multi-step problems, thought questions, or a combination of the two. For example, students may be asked to estimate the power required to join two steel coupons. They are expected to calculate the required energy to heat and melt the required amount of metal, which requires an estimation of the necessary bead width. They need to account for losses due to heat transfer (radiation, conduction, and convection). This must be presented in a well organized manner. The lab report structure is strictly prescribed. A summary is required. The introduction must include a well thought out presentation of hypothesis, students must, based on their prior knowledge justify their prediction. In the discussion they must critically assess their results. For example, in one experiment they compare the width of the heat affected zone, as measured through optical microscopy, for flame welded and brazed 1010 steel.
Tests: There are three tests. Each test is a series of essay questions, some including calculations. The level of difficulty is similar to the homework. However, as the students have limited time, they receive instruction on how to best answer theses questions early in the course. Forming an outline is reviewed, and strongly suggested.

Project: A project is required. Students are given some latitude in this area, however, two types of projects are commonly undertaken. Students evaluate an alternative process for joining two materials, for example, comparing MIG and Friction Stir Welding to join two parts. This requires analyzing both processes, and making a decision. Other students chose to identify a set of process parameters to best join two materials, for example comparing the gap width, thickness, and current to join two steel coupons. The project is graded on the basis of how well they describe and analyze the problem (joining requirements), their decision, the evaluation of alternatives on a technical basis, and the evaluation of alternatives on a non-technical basis. A presentation and written report is required.

Final Examination: There is a take-home final examination. Students are expected to write a process specification and a process justification for three different combinations of joined materials (e.g. Al-2024T6 to Copper or Polypropylene to Steel). They are instructed that these are for two different audiences. The process specification is written for a technician who must make the part. The process justification is written to one’s immediate colleagues and supervisors. It is this document that may justify “extra steps”, or increased cost. It must include analysis and explanation. For example, it would be noted that abrading steel is required prior to the application of an adhesive to ensure mechanical interlock. The second part of the final examination includes four “I don’t understand” questions. One question, may be “How can someone claim to weld and braze ceramics when there is no metal involved?”.

It was not possible to assign a text for this course. There is no single text that covers welding, brazing, soldering and adhesive bonding or which focuses on both scientific principles and technique.

- The ASM Handbook is probably the most complete reference, however it does not discuss adhesives and is quite expensive.
- Some texts focused solely on brazing, or soldering. Again these are excellent reference books and go into much more detail than does the ASM Handbook, however it is not practical to require students to purchase separate books for one portion of the course.
- There are many texts which cover welding, several focus on the scientific principles of welding, others focus on technique and procedure.

Therefore, weekly modules were prepared by the instructor. This provides the students with “reading material”. Usually 8-10 pages of text per week are prepared. Preparing this has been time consuming. Increasing the challenge is the reduction in courses in engineering curricula.

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This means that some engineers will no longer be exposed to thermodynamics, heat transfer, fluid mechanics, or strength of materials prior to graduation. While efforts are being made to develop new courses in this area, it is necessary to cover some of this more basic material in this upper level course. Currently a series of presentations and annotated notes are also being prepared. Annotated notes are similar to the “slides”, but include the bulleted items as simple text, graphics must be copied separately. However, with annotated notes it is possible for the students to write, and better interpret graphs. Students have commented that they like this note format and prefer some (free) reading material.

**Subject Matter Details**

**Review and Demonstration of Fundamental Scientific Principles**

The fusion zone and the heat affected zone of a welded joint are fundamentally different. The fine grained structure of the fusion zone makes it stronger. Solidification kinetics are reviewed to demonstrate this. The coarsening and grain growth which occurs in the heat affected zone reduces the strength as there are fewer barriers to dislocation motion. This is also reviewed. In one experiment the students perform metallography on a surface to better see these structural differences. A sample is shown in Figure 2 (the experimental conditions will be discussed in the next paragraph). Students are asked to evaluate the structure of the “zones” throughout the course: homework, tests, project (if appropriate), and final examination.

A second experiment requires that students combine their knowledge of statistics with materials science, heat transfer, and thermodynamics. They conduct an experiment where they vary current, polarity, gap thickness and beveling in joints prepared by SMAW. The breaking load of each joint is measured. The students are required to perform a 5-factor Analysis of Variance (the fifth factor being the operator) on the data. It is found that the human is the most significant factor. This demonstrates what many assume to be common sense. The second factor is usually an interaction between the operator and current. They are challenged to explain this. They realize the following.

- Different operators work at different speeds
- Different speeds are required as one changes the current
- Moving too slow with high current causes melt through

![Figure 2: Boundary Between Fusion Zone and HAZ in 1030 Steel Joined with E60 Rod. 125A Positive Polarity, Beveled With No Gap.](image-url)
• Moving too slow with low current causes inadequate penetration

They are required to explain this based on energy. The third factor is usually an interaction between current and polarity. Again based on energy the students synthesize their observations and explain their findings.

Throughout the course students are taught that the joint includes the filler material and the affected region of the base material. To compare brazing and welding students are shown that an interfacial region, which is often a solid solution forms. There is also a much smaller heat affected zone. In soldering, the interfacial region is often an intermetallic and the heat affected zone is smaller. The students are presented with the scientific reasons for this, and expected to apply it. For example they may be asked to predict the microstructure of a braze welded copper-steel joint. When adhesives are discussed, the interfacial layer is also emphasized. Three types of layers are possible: mechanical interlock, wetting/absorption, diffusion/reaction. In each case, it is emphasized that the polymer solidifies, as does molten metal in welding, brazing and soldering. The structure and compatibility is also considered.

Special emphasis is placed on the problems which arise due to two metal combinations: thermal stresses and bi-metallic corrosion.

The differences between processes are also considered. Emphasis is placed on the different role of flux in welding, brazing and soldering. In all cases weld pool protection is needed, however oxide removal, wetting and capillary flow are not an issue in welding as the base metal melts. More aggressive fluxes are often required when soldering, due to the lower temperature. However, this may increase cost due to increased disposal and chemical safety requirements. The students are expected to demonstrate they understand this and the implications on homework, tests and the final.

Review of Non-Technical Principles

Business issues such as net present value, costing, and supply and demand are reviewed in order to emphasize that in the “real-world” engineers have to make business cases for their decisions. A tutorial has been prepared which illustrates the time value of money. Through interaction with Industrial Engineering colleagues a cost-accounting module is being developed. Students will be taught how to determine the necessary “income” to justify a purchase or change in procedure. This will include calculating depreciation and required steady income for a required present value.

Ergonomics and safety are also considered. Again, through interaction with Industrial Engineering colleagues modules on ergonomics and safety are being developed. This has started with a class presentation on relevant OSHA regulations associated with a combined gas welding and arc welding laboratory. Students are expected to identify these and understand the associated
cost implications.

The importance of effective communication is reviewed and the students are informed that they will have to prepare process specifications (to technicians), process justifications (to colleagues and supervisors), and answers to technical questions from those with varying knowledge. Oral communication is reviewed based on speech manuals from Toastmasters International.

Assessment of Course

As everyone is aware the accreditation requirements for engineering schools require outcomes assessment where, each school seeking accreditation must establish and document a system of on-going evaluation. To evaluate the effectiveness of this course, course topics were matched to course objectives. Information regarding how effective each course topic was learned by the students was be collected from 1) recorded performance on test questions, 2) detailed questions on the course evaluations addressing specific course topics, and 3) student comments. Recognizing that there is no formula for assessing the effectiveness of a learning experience these data were collected using an outline based on a published assessment guide, and revised so that a three to five page summary will be prepared for review. This summary and supporting documentation is reviewed by the department chair or designee(s) as part of the annual evaluation and promotion / tenure documentation.

This course had been offered for 2 terms during the 2001-02 and 2002-03 academic years and will be offered again in the Winter and Spring of 2005. It is clear from student comments and performance on examinations / projects that the laboratory integration has been successful. The number of students taking the course during any one term is small usually 5-8 students. This is due to several reasons including a change in curricula and course offerings. Students have rated the course favorably. The effectiveness of the course, instructor and individual topics exceeded 3.0/4.0 and all students rated the course as good or better. However, despite the positive comments, I was only marginally satisfied that the non-technical issues effecting joining processes were understood by the students. Therefore, modules are being developed to incorporate these issues in the same way the structure of the interface is, among and throughout the course topics. It also must be noted that students on the final examination hesitated to write 2 documents to answer a single question. Over half the students tried to combine the process specification and justification.

Conclusion

The need for innovation in upper level courses has been demonstrated. The efforts to design a new course in Joining of Materials have been moderately (not to the degree I would have desired as the initiator of the project) successful. This progress report has shown the following.
• Students can be taught about a variety of joining processes in single course. It is possible for them to differentiate between the processes and make decisions about the best possible technique to choose.
• Students can be taught this subject matter in a way that requires them to synthesize their knowledge from core engineering classes. By doing so, they can apply their knowledge and better learn the new subject matter.
• Non-technical issues can be successfully incorporated into upper level engineering courses.

There is more to do to make this effort fully successful.
• More effective learning modules incorporating the internet need to be developed.
• A practical way to introduce the students to MIG and TIG welding during this course needs to be determined.
• Critical evaluation by an independent evaluation board is needed.

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