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A Laboratory Experience with Thermal Gradients

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Abstract

An understanding of the behavior of materials at elevated temperatures is a critical component of the education of engineers. Engineers of most disciplines will encounter elevated temperature environments in either the performance aspects of systems they employ and deliver or in the processing of components of systems they are attempting to produce. Sadly, few laboratory experiences that treat elevated temperature behaviors are available, fewer yet really treat the thermal gradients present in these environments or their inherently dynamic nature. This paper describes the development and implementation of a laboratory experience to improve undergraduate students understanding of complex issues related to mechanical behavior in the presence of thermal gradients. Laboratory procedure for the experiment is described in detail.

The laboratory allows students to observe changes in the mechanical properties of materials as a function of temperature, thermal gradient and strain rate. Those rare experiences with materials at high temperatures previously available to students typically stress the need for uniform temperatures throughout test samples. This obfuscates critical information, as there are few, if any, processes or applications operating at elevated temperatures where thermal gradients are absent. Students are able to observe materials in the dynamic and non-equilibrium environments encountered in actual service and processing conditions, rather than in the equilibrium or otherwise artificial contexts discussed in the classroom or specially created in the laboratory. The laboratory discussed presents theory and application in a linked fashion. The paper discusses the exceptionally positive impact that this immediacy has an on student learning.

I. Introduction

Structured educational laboratories are a key component in student learning, and underpin subsequent independent project based learning. Laboratories, are expensive, but are an efficient vehicle to accomplish student learning. They are refreshing for many students, a welcome counterpoint to lecture as they provide the challenge as they teach their lesson, rather than in a deferred quiz. Laboratories allow students to demonstrate outcomes mandated by ABET's Engineering Criteria 2000. In well conceived laboratories students demonstrate an ability to: 1. Apply the tools of modern engineering and science to solve relevant problems. 2. Implement appropriate experimental procedures. 3. Handle data, draw and articulate conclusions. 4. Make distinctions between models and real-world behaviors. 5. Recognize problems and iterate to an appropriate experimental method. 6. Address open-ended situations. 7. Select, alter and operate pertinent engineering tools and resources. 8. Deal with health, safety and environmental issues. 9. Communicate effectively with a variety of audiences, both orally and in writing, ranging from peer communication through executive summaries to comprehensive technical reports. 10. Demonstrate the ability to work in teams, including structuring individual and joint accountability, assigning roles and responsibilities, partitioning work, monitoring progress, meeting deliverable deadlines, and effectively integrating individual contributions into a final deliverable.

As professors, we must ensure that our students understand the goals of the laboratory, but avoid being prescriptive or overly pedantic. We must spice our laboratory experiences with uncertainty so that educational laboratories have the same mystery and excitement about them as research laboratories hold for the scientists and engineers who populate them. Applied researchers go to the laboratory to wrestle answers from an impassive world, their intent is to detect, to appraise, and, eventually, to improve. We must send our students to the instructional laboratory to accomplish these same things.

Furthermore, instructional laboratories offer faculty an opportunity to cater to many different learning styles. They are an occasion to stress the learning in doing, an opportunity to open new pathways to consciousness. They provide physical underpinning for students commonly saturated in the abstract and hypothetical. They are chances for students to triumph over the many "gnomes" lying in wait to sabotage their efforts to solve challenges. They are rife with visions of the gradual transitions and tortuous boundaries that distinguish the incongruous and discordant real from the tidy world of abstraction described by exact equations and found in the answers to the even numbered problems in the back of textbooks. They are a respite for intrinsically self-interested, antisocial, latent self-promoters to learn the value of shared experience and teamwork, and to evolve skills in sharing and exchanging information. In short, laboratories create a microcosm of, and a brief segue to, engineering activities which parallel the invigorating environment encountered in actual work. They provide an opportunity for genuine discovery experiences of the sort that kindle intellectual flames which can burn for decades and which provide illumination that reaches far beyond supposed boundaries of the experiment. Laboratories that steep students in meaningful tasks create tolerance for ambiguity and contradictions that lead to the development of engineering judgment.

One key to productive laboratories is the acknowledgment of each students individual responsibility for group achievement. The effort required to accomplish laboratory goals should exceed the capacity of any single student, and require the sustained coordinated effort of the laboratory team. The instructor must develop an open learning environment, promote interdependence while fostering individual responsibility. As instructors, we can take a lesson from corporate America – rewards available to each lab group are based on group outcomes, individual rewards to group members are based on a collective assessment of each member by the instructor and by the group.

II. Desired Outcomes / Laboratory Objectives

Background

In accordance with ABET outcomes oriented assessment, laboratory objectives are shared with students at the beginning of each laboratory, as are the instructor's desired outcomes. The course objectives are measurable goals that indicate how well the instructor's laboratory outcomes are achieved.

Benjamin Bloom (Bloom, B., and 1956 *Taxonomy of Educational Objectives: Handbook I, Cognitive Domain*. New York; Toronto: Longmans, Green.) created a taxonomy for categorizing the level of abstraction in, (and therefore the depth of knowledge required to answer), questions that commonly occur in educational settings. The taxonomy was meant to provide a useful structure in which to categorize test questions, since professors will characteristically ask questions within particular levels. Bloom listed six levels in his taxonomy. *Each laboratory* should provide the opportunity to exercise all of these cognitive levels. *Each student's* personal interaction with equipment/tools will lead to the accumulation of knowledge and skills required in the practice-oriented engineering profession.

Bloom's first level was **knowledge**, which involved observation and recall of information, knowledge of facts, and knowledge of major ideas. Activities to measure outcomes desired at this level involve listing, defining, describing, identifying, labeling, and quoting. The second level is **comprehension** which involves understanding information, grasping meaning, translating knowledge into new context, interpreting facts, inferring causes, and predicting consequences. Activities to measure outcomes desired at this level involve summarizing, contrasting, predicting and estimating, differentiating and extending. The third level is **application,** which involves using information, methods, concepts and theories in new situations, and solving problems using required skills or knowledge. Activities to measure outcomes desired at this level involve demonstrating points, calculating solutions, and solving challenges. The forth level is **analysis,** which involves seeing patterns, organizing parts and identifying components. Activities to measure outcomes desired at this level involve analyzing, separating and classifying. The fifth level is **synthesis,** which involves using old ideas to create new ones, generalizing from given facts, relating knowledge from several areas and drawing conclusions. Activities to measure outcomes desired at this level involve combining information, integrating concepts, planning additional experiments, formulating hypothesis, and generalizing based on experience. The sixth level is **evaluation,** which involves comparing and discriminating between ideas, assessing the value of theories, reasoned argumentation and verifying value of evidence. Activities to measure outcomes desired at this level involve assessing, ranking, recommending, convincing, judging, explaining and concluding.

The Instructor's Desired Outcomes

Many outcomes are universally associated with laboratories, and differ only in context. However, three key outcomes, specific to this laboratory exist.

In many engineering and science courses, engineers are often instructed through convenient abstractions, discussions of the elevated temperature properties of materials are no exception. Elevated temperature tests of materials have been carried out for many years. The foremost criterion of these tests is that the specimen be at a single temperature, that is, the temperature is constant throughout the test sample. The tests performed on the material yield results which are tabulated as the elevated temperature properties of the material. Such data are used in the processing and application of the material. Unfortunately, there are few, if any, processes or applications operating in the elevated temperature region where thermal gradients are absent. The constant temperature properties of materials are just a starting point for processing or applying these materials. The procedure of improving processes and applications requires far more information than is available in constant temperature tests. The behavior of materials in engineering applications can be understood only if this is appreciated. **The first outcome specific to this laboratory is that the students will appreciate the importance of thermal gradients in materials processing, and the impact they have on material behavior.**

A second outcome specific to this laboratory is that students will appreciate physical simulation. During the past three decades, industry has seen costs multiply many times. Where it was once practical to operate a process to study and optimize it, present day costs mandate the use of less lavish methods. The past three decades have also witnessed the greatest change in the ability to handle and control information ever experienced. Computer models of processes have proliferated, but basic information needed to improve the precision of the models is lacking. However, low cost, high performance computing enhances the design of simulators and testing machines. The coupling of computing and suitably designed simulators provides a tool to circumvent costs associated with direct process studies and the inaccuracies associated with computer modeling. The era of physical simulation has begun. The physical reproduction of processes or material applications provides information necessary for the improvement of processes, materials and their uses. Little has been published about the requirements of physical simulation. Students in this lab will receive a state-of-the-art exposure to thermo-mechanical processing simulation. Variables considered include stress, strain, peak temperature, and thermal gradients.

Physical simulation is considered to lie between computer simulation and actual processes or applications. The performance range of physical simulation is generally less than that of computer simulation but greater than that of the processes or applications being simulated. This is a result of physical simulation having to deal with real time and energy constraints, just as in the actual process or application. Computer simulation has no such bounds, and often provides other-worldly answers because it is not constrained by real-world limitations.

Physical simulation of materials processing or use involves the exact reproduction of the thermal and mechanical processes in the laboratory that the material is subjected to in the actual fabrication or end use. A small sample of the actual material is used in the simulation. The material follows the same thermal and mechanical profile that it would in the full-scale fabrication process or end use of the material. Depending on the capability of the machine performing the simulation, the results can be extremely useful. When the simulation is accurate, the results can be readily transferred from the laboratory to the full size production process.

A final outcome, specific to this laboratory, is that students will learn how to use the Gleeble simulator, and extrapolate to other potential uses for the test system. Students will understand the relationships between specimen diameter, free span, constitution, and peak temperature and thermal distribution in the sample. Students will appreciate the difference between electric resistance and inductance heating

Laboratory Learning Objectives
By completing this laboratory participating students will demonstrate an ability to: 1. Apply the Gleeble simulator, quantitative microscopy and optical microscopy to make measurements of physical quantities, including testing and debugging an experimental system. 2. Devise an experimental approach, specify appropriate equipment and a set of procedures and implement those procedures. 3. Demonstrate the ability to collect, analyze, interpret data, and form and support conclusions. Make order of magnitude judgments about data correctness. 4. Identify the limitations of theoretical models as predictors of real world behaviors. Be able to evaluate whether theory adequately describes a physical event and establish and/or validate a relationship between data and underlying physical principles. Integrate thermodynamic and kinetic data. 5. Recognize unsuccessful outcomes and faulty construction or design, and modify the experimental approach accordingly. 6. Demonstrate appropriate levels of independent thought, creativity, and capability in problem solving in the real world. 7. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources. 8. Recognize health, safety, and environmental issues related to technological processes and activities and deal with them responsibly. 9. Communicate effectively with a specific audience, both orally and in writing, ranging from executive summaries to comprehensive technical reports. 10. Demonstrate the ability to work in teams, including structuring individual and joint accountability, assigning roles and responsibilities, partitioning work, monitoring progress, meeting deliverable deadlines, and effectively integrating individual contributions into a final deliverable.

III. Theory

The Gleeble has a long and proven history as a tool for both the study of metallurgical phenomena at the research level and for materials testing to predict service behavior at the production level, and is employed here as a laboratory tool. Longitudinal thermal profiles in test specimens can be engineered based on an understanding of the effects of specimen diameter, peak temperature, jaw separation, and material type on the thermal profiles in specimens that are subjected to similar thermal programs.

We may consider a Gleeble sample as a system in dynamic thermal equilibrium with its surroundings. Thus, to maintain any given temperature profile, heat is supplied by the electrical current passing through the specimen, and heat is lost by three mechanisms. The first is conduction along the specimen itself, in which the heat is transferred to the water-cooled jaws. The rate of this heat flow is directly proportional to both the thermal gradient and the thermal diffusivity of the material. The second mechanism is convection in the gaseous atmosphere, which removes heat and dissipates it to the surroundings by mixing. The third is in the form of radiation emitted by the specimen. The amount of heat lost through this mode is proportional to the fourth power of the absolute temperature, and therefore becomes more important at high temperatures. Thus, the thermal profile generated by a given peak temperature, jaw separation, specimen diameter and material type is determined by a complex interplay of these mechanisms in establishing a thermal balance.

The Gleeble specimen used in this laboratory may be treated as a uniform cylindrical bar with internal generation of heat. If convection and radiation losses are neglected, the principle of the conservation of energy leads to the following relationship for the instantaneous temperature distribution in the bar:

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C_p} \nabla^2 T + \frac{I^2}{\rho C_p w^2 \sigma} \qquad \boxed{1}$$

K = Thermal conductivity
T = Temperature
ρ = Density
C_p = Heat capacity
t = Time
w = Cross-sectional area
σ = Electrical conductivity
I = Current

If we simplify the system by limiting the heat flow to one dimension, Equation 1 becomes:

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C_p} \frac{\partial^2 T}{\partial x^2} + \frac{I^2}{\rho C_p w^2 \sigma} \qquad \boxed{2}$$

This relationship closely approximates the behavior of a resistance-heated specimen. If the temperature distribution within the bar is assumed to be steady state, Equation 2 reduces to the Poisson relation below:

$$\frac{\partial^2 T}{\partial x^2} = \frac{-I^2}{K w^2 \sigma} \qquad \boxed{3}$$

Therefore, if radiation and convection losses are ignored, the temperature distribution in the bar will be a parabolic one. This can be demonstrated by double integration of Equation 3 to obtain:

$$T_{(x)} = \frac{-I^2}{K w^2 \sigma} x^2 + c' x + c'' \qquad \boxed{4}$$

The constants of c' and c' can be deter- mined for specific boundary conditions. Solutions to this equation have been applied to the determination of the lengths over which the temperature of the bar lies, between the maximum and some arbitrary lower temperature. This length is given by the following:

$$L = L_0 \left(\frac{\Delta T}{T_{max} - T_0} \right)^{1/2} \qquad \boxed{5}$$

L_0 = Jaw separation
T_0 = Temperature at the jaw
ΔT = Temperature difference

However, problems exist for this simplified treatment, since experimental results do not fit the model well. Several factors contribute to this. The thermal conductivity, k, is not a constant, and being itself a function of temperature can be presented as:

$$K = K_0 (1 - bT) \qquad \boxed{6}$$

However, since the value of b is small, an average value of k can be used over a small range of temperatures without generating an excessively large error. The mathematics of the system become more complex when treatments for either convection or radiation heat transfer are included. Heat loss by either mechanism will tend to flatten the parabolic profile predicted by Equation 4. Convection losses can be represented by adding a single term to the Poisson equation to obtain:

$$\frac{K}{\rho C_p} \frac{\partial^2 T}{\partial x^2} + \frac{I^2}{\rho C_p w^2 \sigma} - \frac{h\gamma}{\rho C_p w}(T - T_0) = 0 \qquad \boxed{7}$$

h = Convective heat transfer coefficient
γ = Geometry = dependent constant

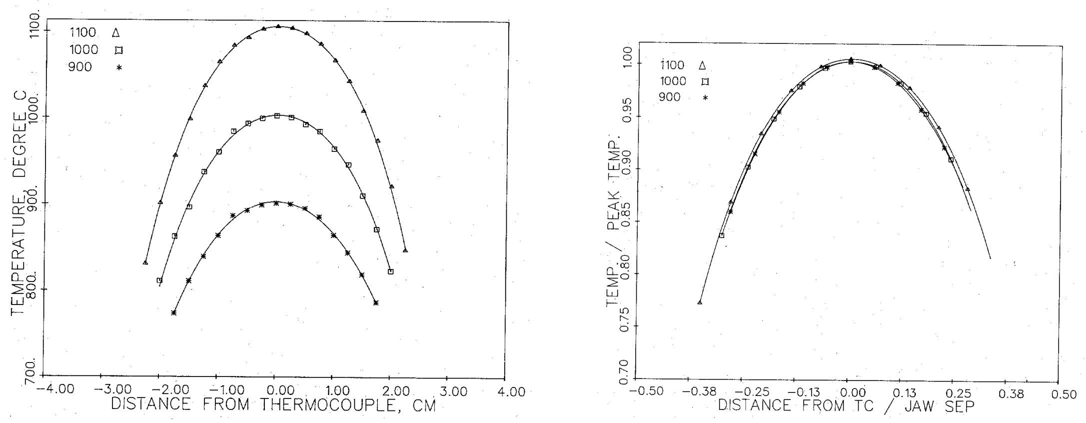
The inclusion of another temperature dependent term makes the solution to the differential equation more complex, and leads to solutions involving hyperbolic functions. The addition of a term for radiation losses further complicates the solution, since the radiative heat loss is proportional to the fourth power of absolute temperature, as shown below:

$$Q_{12} = F_{12}\alpha(T_1^4 - T_2^4) \qquad \boxed{8}$$

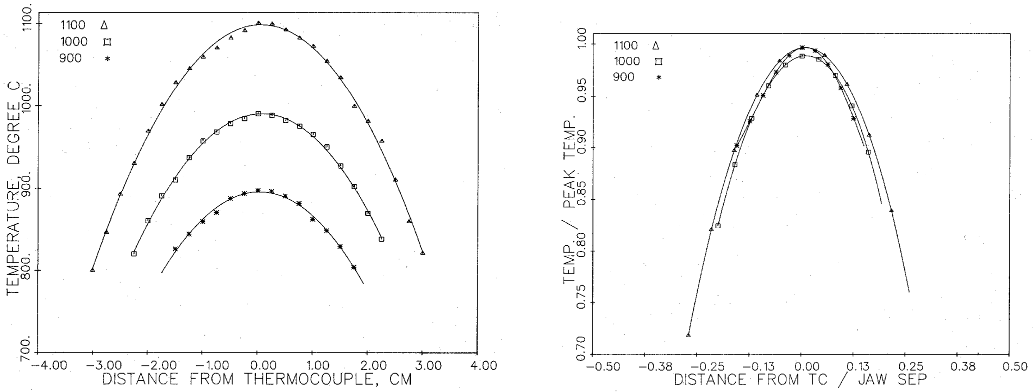
Q_{12} = Heat transfer from Body 1 to Body 2
F_{12} = View factor, Body 1 to Body 2
T_i = Temperature of Body 1
α = The Stephan-Boltzman constant

In this laboratory, students make use of previously published data (Walsh, Cieslak and Savage, 1986, Longitudinal Thermal Gradients in resistance heated Samples, Welding Journal, 65 (7), 184s-192s). Figure 1A presents data collected for a 10.0 mm stainless steel bar with a 6.35 cm jaw separation and peak centerline temperatures of 1100, 1000 and 900C. The symbols on the plots are actual data points, while the curves are fourth-order polynomial least-square fits. Note that these plots are parabolic in appearance, and have the same general form for all three peak temperatures. Since the bar can be considered to be in dynamic thermal equilibrium, this suggests that similar modes of heat flow are involved at all three temperatures. This conclusion is supported by Fig. 1B, where the data used to generate Fig.1A are converted to a nondimensional form. The abscissa is the distance from the specimen center divided by the jaw separation, and the ordinate is the temperature at the particular location divided by the programmed temperature. Note that the curves for three different peak temperatures appear to be superimposed in this figure. At this jaw separation of 6.35 cm, the conduction of heat to the jaws is the primary mode of heat loss from the bar, with convection and radiation losses being insignificant. Thus, the parabolic shape is exactly as predicted by Equation 4. However, Equation 5 fails to predict the zone length, L, because changing the peak temperature alters the effective values of both Lo and To. The lack of agreement with experimental data becomes even greater under conditions where convection and radiation losses are significant.

In Fig. 2A, sample data are presented for 10 mm diameter AISI 1018 plain carbon steel specimens with an 11.5 cm jaw separation for peak temperatures of 1100, 1000, and 900C, a combination of variables not equivalent to that for the stainless steel bar discussed above because the jaw separation is greater. Under these conditions, the carbon steel bars generate thermal profiles that are approximately parabolic in every case. The parabolic nature is also evident in the nondimensional plots shown in Fig. 2B. In the case of 10 mm carbon steel bars, the heat flow mechanism is not conduction limited, even at the greater jaw separation. This is not surprising, since the thermal diffusivity of carbon steel is much greater than that of stainless steel. Furthermore, in the complete study we note that the slopes are steeper for the carbon steel samples in equivalent configurations. This difference is a direct result of the higher thermal diffusivity of the carbon steel.



Figures 1A and 1B. Thermal profiles in 10mm 304 SS bar heated to three different peak temperatures with a jaw separation of 6.35cm. (A absolute data, B normalized data).



Figures 2A and 2B. Thermal profiles in 10mm AISI 1018 bar heated to three different peak temperatures with a jaw separation of 11.5 cm. (A absolute data, B normalized data).

Based on studying the samples, and using the data provided students conclude that higher peak temperature, smaller bar diameters, greater jaw separations and lower thermal diffusivities all decrease the thermal gradients in the test specimens. They make use of polynomial fit equations to estimate the thermal profiles which exist in test samples under a wide variety of operator-controlled conditions. They learn that at particular peak temperature, a span in which the temperature lies within a desired percentage of the peak temperature can be generated by a judicious choice of operating conditions and specimen geometries, and that any operation that diminishes the thermal conductivity at the jaw will promote the generation of a region in the specimen with a minute longitudinal thermal gradient.

III. Materials

Two different materials were used in this laboratory, each group was provided with ten samples each of Type 304 stainless steel and AISI 1018 carbon steel. Samples were supplied as 10mm diameter round bar stock, cut to 4.5 inch lengths, with 0.5 inch lengths threaded on each end.

IV. Equipment and Procedure

The Gleeble Simulator

The Gleeble is a fully computer interfaced device capable of simulating any thermal and/or mechanical history experienced by a material. The device employs a low frequency (60 cycle) alternating current to heat a specimen by resistance (impedance). The specimen is actually the secondary of a transformer in which the voltage is stepped down from 480V to 10V. The device switches 0.25 MW, so very high currents can pass through the sample. Specimen geometry is arbitrary, but is typically round bar or flat bar. Cross sections can be as great as 625 square mm, and heated lengths can be over 400mm. Specimen temperature is controlled by either thermocouples mounted directly to the sample or by an optical pyrometer. Pyrometer control is required for experiments involving carbon/carbon composites. The device can heat/cool at controlled rates from 10,000 C per second to 1 C per hour. Jaws that provide electrical contact grip the specimen. These jaws form the bed of a hydraulic mechanical test apparatus. Mechanical control is provided by any one of several modes; force, stroke, dilation. Thus the Gleeble allows the experimenter to control temperature and one mechanical variable while recording up to eight other signals. A transient data recorder incorporated into the control system gathers information. The Gleeble has been developed with both mechanical and thermal simulation capabilities; neither capability was developed in a secondary manner. The Gleeble is unique among simulators in that it performs thermal and mechanical tests equally well.

The equipment allows the study and test of materials in the same dynamic fashion they are fabricated and used. **The application of the Gleeble to any materials laboratory course is limited only by the exposure, resourcefulness and, occasionally, the fortitude of the user.**

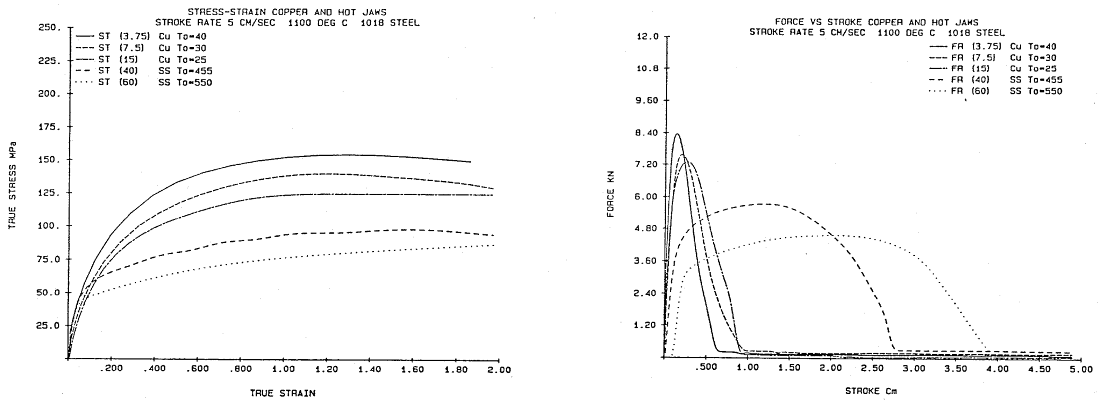
In this experiment, students are not told *a-priori* that they will be studying the effects of thermal gradients on mechanical properties! Students are asked to design a test matrix to examine the range of thermal profiles available to them in the simulator, based on the variables of material tested, peak temperature, jaw separation and specimen diameter. Samples are heated to a specific temperature, and pulled to failure. Students measure loads at failure, and the sample ductility. As part of the study, students characterize the microstructure of the material at room temperature, and at the series of test temperatures selected. Everything proceeds normally until students start to notice a wide variation in measured strength and ductility, even when the material is tested at a constant temperature, based only on a difference in thermal gradient. The unexpected result gets every ones attention, and starts to beg ethical questions. Groups typically feel that they should repeat the test; because the initial consensus is that there was some sort of procedural or material problem with that particular sample. At this point, the real voyage of discovery has begun.

V. Data / Analysis

The presence of thermal gradients in most processes requires that true physical simulation must include the appropriate thermal gradients. The direct resistance-heated/conduction-cooled type of simulator permits the thermal simulation 1) by programming material at the proper maximum temperature (thermal program) and 2) by adjusting longitudinal temperature gradients to replicate the thermal gradients present in the process under study.

The effect of thermal gradients on physical simulation are considered by testing specimens with distinctly different thermal gradients. Two materials (304 stainless steel and SAE 1018 carbon steel) were programmed on the GLEEBLE simulator at five distinctly different thermal gradients ranging from 9C/mm to 283 C/mm. All specimens were heated at a linear rate of 100C/second to 1100 C and held at temperature for 20 seconds before pulling. The thermal gradients were arranged by changing the jaw material, jaw contact area and free span (distance between jaws).

Students collect force versus stroke and true stress versus true strain data for the samples tested. Examples of data collected are shown in figures 3A and 3B.



Figures 3A and 3B. True stress versus true strain (A) and force versus stroke (B) data for five different thermal gradients.

Clearly the maximum force is significantly larger for the steeper thermal gradients and the reduction of area at fracture is much poorer for the steep thermal gradients. The true stress is somewhat larger, no doubt due to the non-axial strain present in the specimens with steep thermal gradients. The thermal gradient of 283 C/mm is representative of thermal gradients found in welding and some thin materials being formed with cold dies. To provide a baseline, the 9 C/mm thermal gradient may be typical of surface conditions for billets with large cross sections. Intermediate specimens would represent sheet and strip operations. For larger surface to volume ratios the thermal gradient would be steeper. This condition exists near corners of thin strip during processing. When working with thermal gradients using the resistance heated specimens, the work zone is a series of isothermal planes. The isothermal plane at the mid-span of the specimen provides a suitable place for measurement. The diameter measurement on this isothermal plane is used in the instantaneous calculation of true stress and true strain. Since there is a lengthwise thermal gradient, the measurement of elongation by conventional means is not feasible.

Figure 4 graphically depicts ten specimens (five of austenitic (304) stainless steel, upper row and five of plain carbon steel SAE (1018), lower row) which were tested at a constant temperature (1100C in the fracture region), the same stroke rate (5 cm per second), and all other conditions the same except for their axial thermal gradients. The differences in ductility based on the area of the fracture surfaces are dramatic with the best ductility exhibited by the specimens with near zero thermal gradients (on the right) and the poorest ductility occurring in the specimens having thermal gradients of hundreds of degrees per millimeter (on the left). As the thermal gradient increases along the axis of the specimen, the ductility decreases for both types of materials.

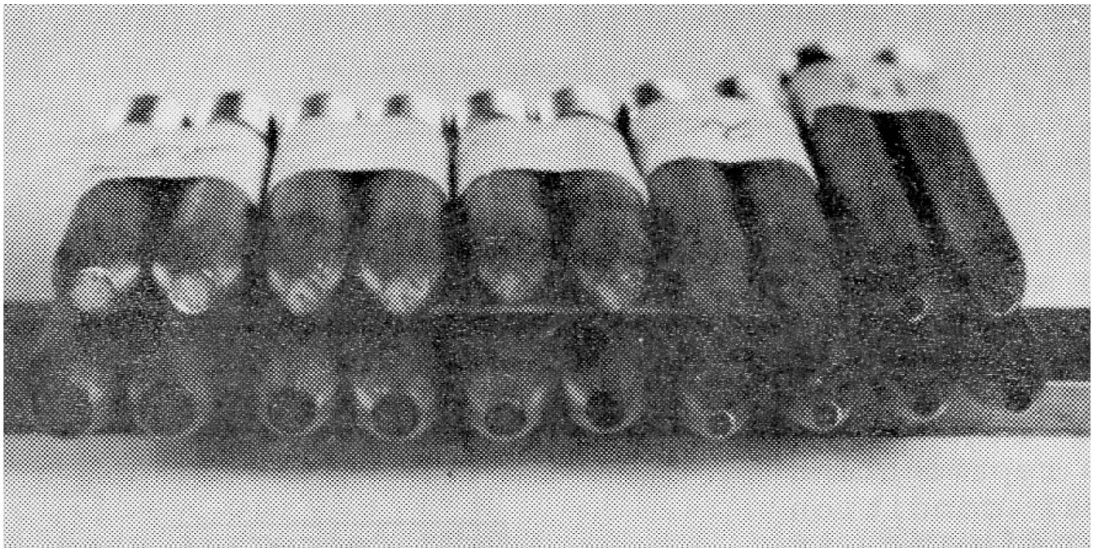


Figure 4. Examples of actual tests. Five samples of type304 austenitic stainless steel, upper row and five samples of plain carbon steel - SAE 1018, lower row. Samples tested at 1100C with constant stroke rate. Thermal gradients increase left to right.

Students analyze the microstructural data, and the mechanical properties they measured. The key point of discussion is typically the difference in microstructure, strain at failure and load at failure in the samples tested. The rapidly heated sample exhibits markedly lower strength, and lower ductility. Students then begin to piece the important microstructural information from the other samples together. Eventually, they are able to reconstruct various approximations to thermal gradients in the 1018 material based on the microstructure observed in the bars.

VI. Reporting

Students are required to keep a laboratory logbook, listing work done and observations made on each lab day. The lab book is signed and dated by all group members. Each group is asked to prepare a detailed formal laboratory report describing the experiment, providing data, discussing results and offering conclusions and suggestions for further study. The report must contain a one-page executive summary. In their report, the students are also asked to evaluate the laboratory and asked to suggest improvements. In addition to the verbal communication inherent in daily laboratory operation, groups are also asked to report their findings orally. During the oral presentation groups are asked questions about other alloy systems, and the effects of other process parameters that provide the students with “intellectual launch-pads” and mental “room to roam”.

VII. Evaluation

Students are evaluated by group and as individuals. Rewards (grades) are provided based on a corporate model. The instructor evaluates groups; rewards (points) available to each lab group are based on group outcomes, such as the quality of the report and presentation. The instructor bases individual rewards (grades) to group members on a collective assessment of each member by other members of the group; however, the total points available to the group delimit rewards.

VIII. Conclusion

Student experience with the laboratory has been very positive. Comments indicate that students are interested in the material and energized by it. The opportunity for genuine discovery, even though “engineered” into the laboratory, is considered a strong vehicle to help students develop true professionalism, even while cloistered in the academic setting.

IX. References

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