A Demonstration of Heat Affected Zone from Welding

Richard Englund, Shannon Sweeney, David Johnson
The Pennsylvania State University at Erie, The Behrend College

Abstract

Heat effects on base metals caused by welding are often described to students in courses in manufacturing, design, or materials. An example where students may measure these effects was developed, is presented here, and is intended for programs and students who prefer to learn from concrete examples, as is typical of many engineering technology students. Description of situations where heat effects may be deleterious are provided to place this work in the context of welding operations.

Presented in this paper is a simple demonstration of heat effects from welding, using commonly available materials and equipment, which allows students to measure changes in material properties. Significant changes in material properties have been achieved by butt welding two socket-head cap screws end to end, then measuring Rockwell hardness values incrementally from the weld out to the ends of the part. Sample preparation, welding, and measurements for this demonstration could easily be assigned to students in its entirety.

An approximate finite element analysis of the heat applied during welding of the demonstration part, and the material changes that should be expected as a result of the welding operation are included. This demonstration combines several elements of the desired accreditation criteria program outcomes, drawing upon and extending student knowledge of manufacturing processes, materials, and thermal sciences. Possible extensions to this demonstration are also presented.

Introduction

Heat effects on base metals caused by welding are often described to students in abstract or theoretical terms. These descriptions are offered in courses in manufacturing, design, or materials, but typically students do not have opportunity to measure these effects. A theoretical presentation is contrary to the concrete example learning style of many engineering technology students. Since they have not seen or measured any changes, students sometimes believe that welding is a simple process that does not change the material properties. If they have a chance to try welding in a laboratory setting it may reinforce this belief when inexpensive materials are used that do not change properties very much due to the welding process.

Particularly on heat treated parts, heating during the welding process can cause grain growth in the volume of material adjacent to the weld. This grain growth and any other tempering effects caused by the elevated temperatures in the area of the weld combine to reduce the strength of the metal near the weld[1]. This is the heat affected zone (HAZ). Since this zone will be weaker than the un-welded material these heat effects may lead to failures of welded products, unless the designer has made special effort to place welds at locations of lower stresses and strains. This type of heat effect is the subject of the demonstration described in this paper.

Another type of heat affected zone may be produced during welding. While it is not the subject of this paper, students need to be aware that any stray arc strike on a part can produce a small zone of rapidly quenched but not tempered material. This quenched material may be hard and brittle, potentially leading to local brittle fracture of the part, and failure propagating from the local fracture.

Material Property Background

The focus of the present effort was to identify a material that met three criteria: (1) readily available at moderate cost, (2) hardenable enough to show a distinct change from heat effects, and (3) not requiring an exotic welding process. From materials available in ourstock, the most likely candidates were cold-drawn AISI 1045 steel bar stock and socket head cap screws. Samples were prepared from each material, but the cap screws were welded and tested first with acceptable results. While 1045 or any of several materials not in our inventory may show similar results, the present work is based on socket head cap screws alone. Socket head cap screws are available in small quantities and have reasonably uniform material properties and heat treatment from a variety of manufacturers. According to ASTM A574[2], socket head cap screws should be expected to have hardness due to heat treating in the range of 37 to 45 HRC, for 5/8 inch diameter and up, when received from the manufacturer. During the manufacture, the screws are required to have been oil quenched followed by tempering above 650°F.

Carbon steels, containing essentially iron and carbon, are the least expensive steels. Low-carbon steels are used for low strength, non-heat-treated fasteners. High-carbon steels are used for higher strength, heat-treated fasteners. There is a practical upper limit of carbon content due to the loss of ductility and susceptibility to hydrogen embrittlement and stress corrosion cracking. Hardenability, which is a measure of the depth to which steel can be hardened, is limited for heat-treated carbon steels. When the diameter of the fastener is too large for plain carbon steel to result in through-hardening during heat treatment, alloy steels are used. The selection of alloy steels is based on their ability to provide higher hardenability and on the lowest alloy content that will provide the required strength[3]. The user does not select the carbon or alloy grade but leaves it to the the fastener manufacturer.

The required strength of alloy steel socket-head capscrews, as used in this experiment, is defined by ASTM-A574. Manufacturers of alloy steel socket head capscrews commonly use AISI 4037 to meet the strength requirements of ASTM-A574. AISI 4037 is a carbon-molybdenum alloy steel having good cold-forming properties in the annealed condition and is heat-treatable (or hardenable) for the best combination of strength and toughness. Because the cap screws are tempered during manufacture at a minimum of 650°F, moderately elevated temperatures in service will not change either the hardness or the strength significantly. For purposes of this demonstration, the elevated temperatures are from welding, and if any change in properties is to be detected must be above whatever tempering temperature was used during manufacture.

Tempering is usually a carefully controlled process performed after quenching of the steel. The Metals Handbook[4] shows final hardness for samples of 4037 steel tempered at times between .1 and 20 hours at constant temperatures from 400°F to 1200°F, from an originally martensitic structure. For this exercise, meaningful tempering can occur for only a few minutes since the heat input is short and cooling begins as soon as welding ceases. If tempering may be assumed to continue for .1 hour (6 minutes), the resulting hardnesses should be HRC 42, 35, and 28 for 800°F, 1000°F, and 1200°F respectively. Higher temperatures likely result in softer material, but data has not been found to quantify the expected values.

Experiment

Prior to welding the cap screws, a flat was milled on each one. The screws were ¾-10 UNC and the milling provided a flat surface for alignment during welding and for hardness testing. We milled the screws full length including the head, removing approximately 1/16 inch of the diameter of the threaded portion. Feeds and speeds were selected for the milling operation such that significant heat would not be induced into the screws. A chamfer of approximately 1/8 inch was manually ground around the threaded end of each screw to act as a bevel for welding.

The screws were positioned on a steel welding table with the threaded ends almost in contact, flat side down, and the shanks of the screws aligned. The screws were welded using 1/8 inch diameter E7018 electrode, by the GMAW (stick) process. The round side was welded first and then the part flipped over and the flat side welded. The entire welding operation took approximately 20 seconds including turning the part over. After welding, the part was allowed to air cool, requiring approximately 20 minutes to be cool enough to be handled.

When the part had cooled enough to be handled, it was hand filed to remove weld buildup above the surface. The raised portion of the weld was removed so that the flat could be hardness tested. On the round back surface, material that would interfere with good support during hardness testing was removed. The part was Rockwell hardness tested at 1/8 inch increments from the centerline of the weld out toward the ends of the part. Measurement stopped at the point where the head interfered with the anvil of the Rockwell machine. One group of students was assigned to measure one direction, and a second group of students measured going the other direction.

Results

As of this writing, this exercise has been used four times; two times with students and two times to see if the data was repeatable. Changes in material properties near to the weld were observed each time, but the heat effects were not identical. The observed trend appears to be similar, but not close enough to assume that it will always be the same. Figure 1 is a graph of Rockwell C hardness as a function of distance from the center of the weld on one of the tests.

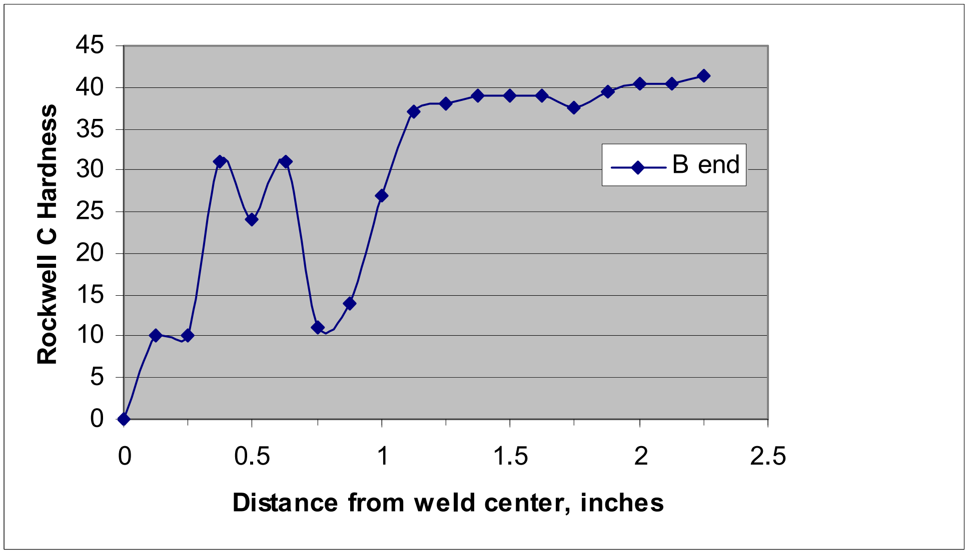

Figure 1: Hardness of sample, heat affected zone

This graph is the smoothest and most pronounced of the tests run to date, and clearly shows the common features observed in each of the tests.

- The weld itself is generally soft, at or below the useful range of Rockwell C hardness measurement. For this sample, the weld fusion zone extended out about .25 inch from center.
- Immediately outside of the weld and into the unmelted base metal of the screw, there is a region of hardness only slightly less than the hardness of the screw as-manufactured.
- At a distance of .5 inch to 1 inch, there is a region of softer material, although not always as dramatically softer as for this sample.
- Beyond an inch or so from the weld, the hardness is little changed from the hardness as-manufactured.

Student reaction to this demonstration has been mixed. Sample preparation and welding has been performed by technicians and faculty thus far. Marking of test locations and hardness testing has been the assignment to students. The students have faithfully executed the assignment and presented the data in laboratory reports. These measurements were performed by third semester students in strength of materials lab courses. The students made no comments indicating they connected the lab test to manufacturing. At the same time, the specimens and data have lain in faculty offices and have aroused the curiosity of several students coming to office hours. The intent of the odd-looking specimens and the significance of the results have been readily comprehended by these students. It appears that the significance of heat effects from welding is better understood with broader knowledge than that possessed by our third-semester students.

FEA Simulation

A finite element (FEA) model in the ANSYS[5] general purpose finite element program was used to examine the physics of the welding/cooling heat transfer processes. A one-half symmetry model, Figure 2, was chosen since it permitted better visualization, and a model with flat surfaces on both sides was used for easier modeling. The minimum model could be one-eighth symmetry based on geometry and assumed loading.

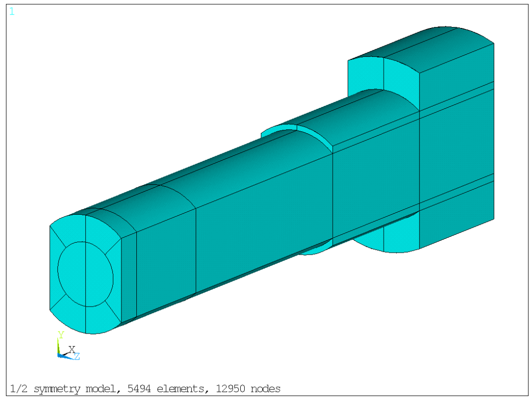

Figure 2: FEA Model Geometry

The model was meshed with 3D solid thermal elements (4030 brick, pyramid, and tetrahedral shapes) and surface-effect elements (1464) on all exposed faces for cooling by free convection in room temperature air. The model included 12,950 nodes for the thermal element mesh.

The simulation was performed under the following assumptions:

- Simplified geometry: ignoring threads, socket hole cutout
- ~1% carbon steel properties[6] with constant values for density (7801 kg/m^3) and specific heat (0.473 kJ/kg-^{o}K); and temperature dependent thermal conductivity, Figure 3.
- Free convection to room temperature air approximated as a horizontal cylinder[6] with laminar flow given by the formula: $h = 1.32\left(\frac{\Delta T}{d}\right)^{0.25}$

  where "ΔT" is the difference between the surface temperature and the free-stream air temperature (in ^{o}K) and "d" is the cylinder diameter (0.0191 m). Figure 4 shows the variation of the film coefficient with "ΔT"

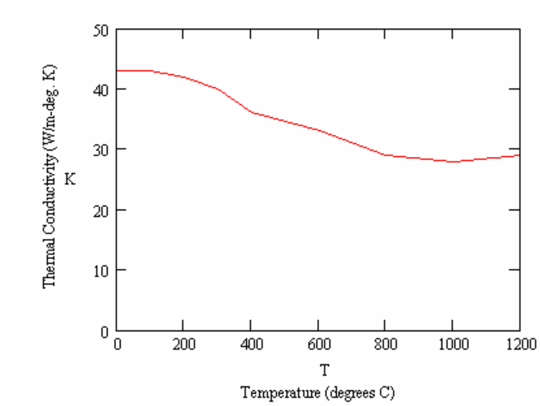

Figure 3: Thermal Conductivity

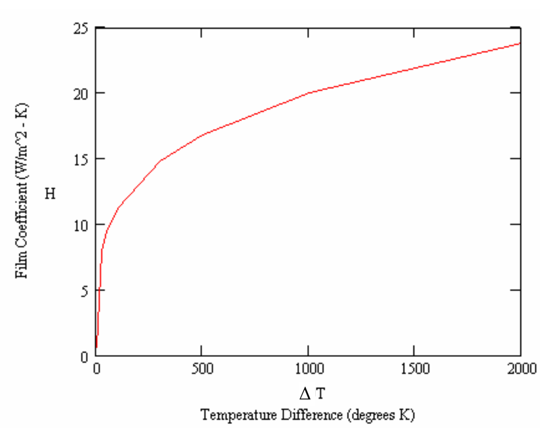

Figure 4: Film Coefficient

The welding process was simulated by applying constant heating over a 2.0 second time interval, uniformly throughout the weld volume (Figure 5). The part was initially at room temperature.

The heat was applied to the weld volume at a rate of ~2638 W, and distributed over the weld volume as 6.44 x 10^9 W/m^3 (99.97 BTU/sec-in^3). The weld volume was 0.41x10^{-6} m^3 (About 2% of the total model volume is heated with the input for welding). This level of heating was selected in order to produce temperatures in the weld region characteristic of molten steel, i.e., 1450°C (2640°F). The volume-averaged temperature for the elements in the weld region was 1417°C (2583°F). The temperatures on the weld region varied from 793 to 1800°C (1460 to 3270°F).

After the 2.0 second heating period, the simulation continues for 30 seconds allowing heat to conduct away from the weld zone and dissipate from the model by convection from the exposed surfaces.

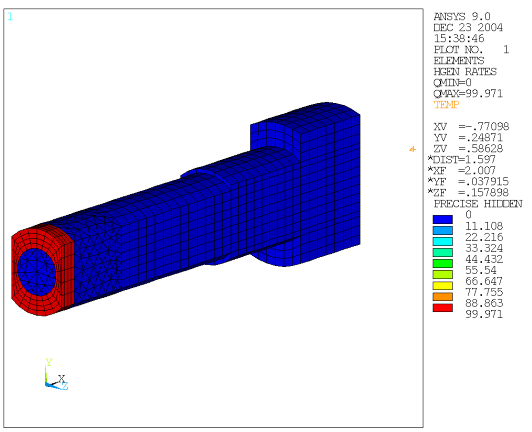

Figure 5: Weld Process Heat Load

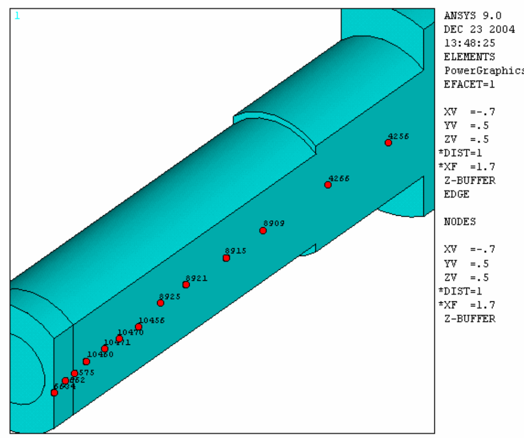

Figure 6: Temperature History Point Locations

After running the thermal transient simulation, temperature histories were requested at various locations along the flat face of the model. These locations are shown in Figure 6.

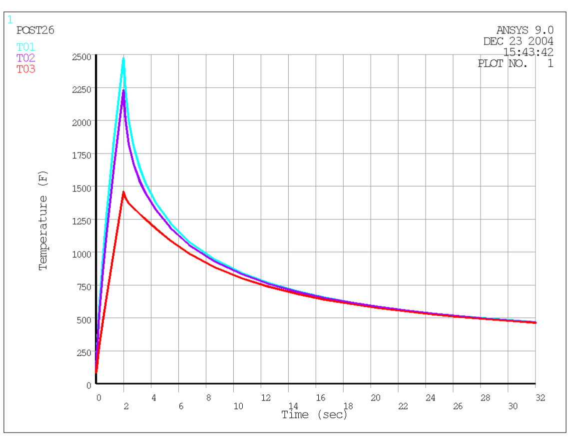

Figure 7: Temperatures in the Weld Zone

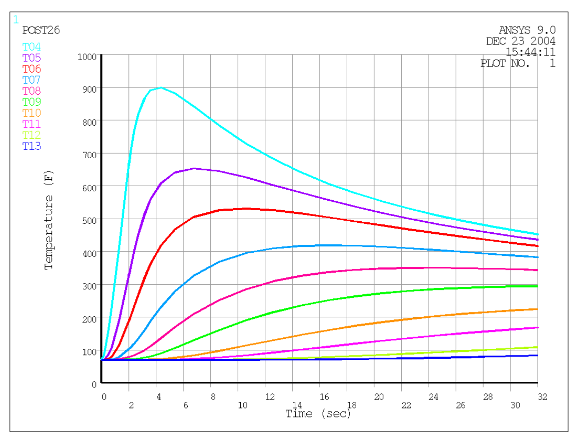

Figure 8: Temperatures Beyond the Weld Zone

Figure 7 shows the temperature history at three locations on the face of the weld zone. The rapid heating (2.0 second heat input) is obvious, followed by cooling of the weld zone as heat conducts into the cooler regions of the cap screw and escapes the model to the surrounding air by free convection. These three points are approximately 0, 2, and 4 mm. (0, 0.08, 0.16 in.) from the symmetry plane of the model, respectively.

Figure 8 shows the temperature history at ten locations beyond the weld zone. These points range from approximately 7 to 68 mm. (0.270 to 2.71 in.) from the symmetry plane of the model. This region was heated entirely by the conduction of heat energy from the weld zone into the adjacent, cooler volume of steel.

Figure 9 presents the maximum temperature results measured from the center of the weld. This graph does not include the soak-time at elevated temperature, but can be compared with the hardness measurement locations shown in Figure 1.

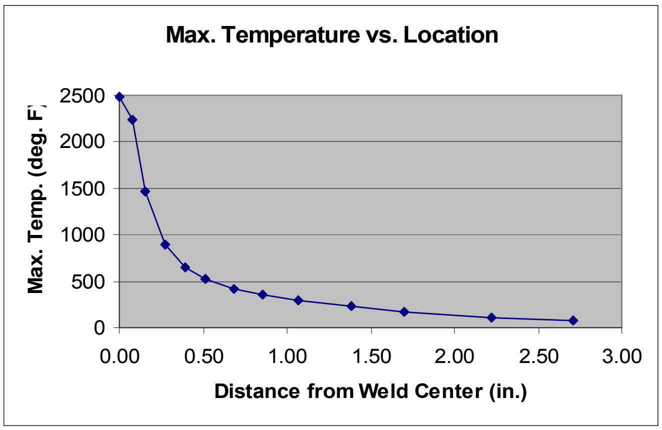

Figure 9: Maximum Temperatures from FEA Model

Discussion

No measurements of time-temperature history were made, either during welding or during the cooling phase. The graph of time/temperature from the simulation, Figure 8, shows that although the heat does conduct into the cooler regions of the cap screw, it should not be expected to result in enough heat treatment to develop significant changes in hardness. The simulation assumed that heat input was entirely complete in a 2 second period, which is not realistic but has not been measured. For the simulation, the heat input was limited to that necessary to raise the weld volume just to the melting point of the steel. Probably the actual maximum temperature is higher than the melting point, but was not measured. The FEA model does show that there is a gradation of temperatures induced into the part for a period of time. The model illustrates the expected trend of heat transfer and local temperature rise. However, this simplified model cannot yield precise temperature levels and “dwell-time” for tempering of the steel.

The first requirement for improving the agreement between simulation and actual welding is better knowledge of the time/temperature history. Measurement of temperature above the melting point of steel in the weld puddle would be an interesting problem. Thermocouples of refractory metals might withstand the temperature of molten steel but the wiring would enhance the heat transfer from the weld pool. The electrical current from welding might also cause some damage to the thermocouple readout equipment. Optical methods of temperature measurement would provide the least thermal loading on the system yet the light and heat produced in the arc may interfere with usable temperature measurement. Optical thermometry would be ideal if the equipment could record the entire temperature field as a function of time. Standard thermocouples attached to the part away from the weld proper could be used for calibration of the optical equipment. Sufficient electrical isolation of the thermocouples would be necessary. These measurements are left undone at present.

The FEA model simulation could be refined to improve the convection film coefficient value and to more closely match the welding process. While the horizontal cylinder approximation for convection behavior was a good initial guess, it should be validated or replaced with a more accurate model. Simplifying the welding process to a uniform heat input over the entire weld volume for 2 seconds could be more closely defined to match the actual process. This would require adding heat gradually around the perimeter of the model over a time interval matching the welding process.

Lacking complete knowledge of temperatures and the times they are present in the part, we suspect that the following has occurred. The weld itself is the first 3/16 inch or so of the length of the part. The 7018 weld wire used is not particularly hard or strong. It is laid down with plenty of heat so that it is probably almost fully annealed, hence the first region of low hardness. The region about 3/8 inch to 5/8 inch from the center of the weld has probably been raised to a temperature above the transition/re-crystallization temperature, but has not melted. This metal is alloy steel, unmixed with the weld metal. Cooling is fairly rapid so this region may act like it has some air quench hardening. Further from the weld, around 3/4 inch to 1 inch, the temperature probably has not gone above the transition temperature. Temperature in this region has gone high enough to temper the material more than when the cap screws were originally produced. The maximum temperature in this region may be above 1200°F for a few minutes to get hardnesses below HRC 25.

Conclusion

The purpose of this demonstration is to show students that welding may cause changes to materials. It has been partially successful thus far. We are confident that this demonstration will result in measurable changes each time. The simulation is valuable to the students since it shows the trends in temperatures that should be expected, and if properly framed to the students it may be used to show the students that a solved finite element analysis is only as good as the underlying data and assumptions. Time-Temperature-Transformation (TTT) data is available for many steels, and if temperature and time were measured it is probable that a better understanding of the metallurgy could be attained by correlation with TTT diagrams. This measurement of cooling, and indeed the FEA modeling could be an assignment for students studying heat transfer.

Students could be assigned the milling and welding operations as well as the hardness measurement. It might be useful to have the students weld one screw to a piece of AISI 1020 bar stock of similar size instead of welding two screws together. The advantage of this modification to the demonstration would be that the students could see the heat effects on the cap screw and the relative lack of heat effects on the 1020 material, for the same heat input. Additional data showing what happenes to the material during the welding and cooling periods could be obtained by metallographic examination after the hardness measurements are completed.

This demonstration could be used to link multiple courses simultaneously if desired. The cost of the materials and the time to perform the work is not particularly large but requires efforts in measurement and instrumentation, heat transfer, finite element analysis, manufacturing, mechanical testing, and metallurgy. This could be utilized as a fully integrated exercise tying together knowledge from several areas of mechanical engineering.

Bibliography

1. Groover, Mikell P., Fundamentals of Modern Manufacturing, Prentice-Hall, Inc., Upper Saddle River, NJ, 1966.
2. Standard Specification for Alloy Steel Socket-Head Cap Screws, ASTM A 574, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2004.
3. Bickford, John H., Sayed Nassar, Handbook of Bolts and Bolted Joints, Marcel Dekker, Inc., New York, 1998.
4. ASM Handbook, 10th ed., ASM International, Materials Park, OH, 1990.
5. ANSYS, Release 9.0, ANSYS, Inc., Canonsburg, PA, 2004.
6. Holman, J. P., Heat Transfer, 4th ed., McGraw-Hill, Inc, New York, 1976.

Biographical Information

Richard Englund, Shannon Sweeney, and David Johnson are all Mechanical Engineering Technology faculty members of Penn State at Erie, The Behrend College.

Richard Englund received a BSME from Washington State University and MSME from The State University of New York at Buffalo. His teaching and research interests are in the areas of mechanical design and experimental measurements. Mr. Englund is a Professional Engineer in Pennsylvania and is involved in new product design and research with local industry. Prior to coming to Penn State he was a design engineer in industry.

Shannon Sweeney received Associate and Baccalaureate degrees from West Virginia Institute of Technology, and the Masters of Science degree in Mechanical Engineering from Case Western Reserve University. His primary teaching responsibilities are in mechanics of materials and vibrations, and his research concentrates on vibration measurement and analysis and quality assurance. Prior to joining the faculty of Penn State, Mr. Sweeney spent eleven years at Lord Corporation as a designer of vibration isolators.

David Johnson is the Program Chair of the MET department at Behrend College. He received the Bachelor of Science degree and Masters of Science degrees in Mechanical Engineering from the Pennsylvania State University. He worked for five years as a development engineer for Airco Carbon, St. Marys, Pennsylvania. Then, for seven years, he worked as a customer support engineer for Swanson Analysis Systems, Inc., Houston, Pennsylvania (now, ANSYS Inc.). Throughout his career, Dave has focused on applied finite element analysis (FEA) and has been using the ANSYS FEA software as an engineer since 1981, and as an educator since 1992.