AC 2004-650: BROADENING THE SCOPE OF A MATERIALS SCIENCE COURSE BY EXPERIMENTALLY TESTING THE EFFECTS OF ELECTRICITY ON A METALLIC TEST SPECIMEN'S MATERIAL PROPERTIES

Fredrick Nitterright, Penn State Erie, The Behrend College

John Roth,

Robert Weissbach, Pennsylvania State University-Erie

Session Number: 3264

Broadening the Scope of a Material Science Course by Experimentally Testing the Effects of Electricity on Metallic Test Specimen's Material Properties

John T. Roth, Fredrick A. Nitterright, and Robert S. Weissbach
The Pennsylvania State University - Erie, the Behrend College

Abstract
In many engineering situations, load-bearing members are exposed, either intentionally or unintentionally, to electrical currents. This topic, the effect of electricity on the mechanical properties of a material, has not been investigated. Furthermore, laboratory set-up and procedures designed to investigate these effects have not been designed and published for incorporation into typical material science courses. Therefore, in order to begin to identify these effects and to broaden the scope of the traditional laboratory experiments associated with standard materials science courses, a test apparatus was developed that allows hardness measurements to be collected from metallic specimens while varying the levels of current that are passed through the specimen.

The fixtures and the material specimens that were used for the testing were carefully designed and developed so that they could accept the electrical current. Also, the safety and effectiveness of the fixtures were two primary considerations. The electrical current had to be isolated from both the person conducting the tests and from the Rockwell hardness testing machine.

The tests were conducted by supplying an electrical current to the metallic test specimens. At that time, a hardness reading was taken and recorded. Hardness readings were taken at various levels of electrical current. Since the electrical current raised the temperature of the specimens, the laboratory was designed such that students can study the effect of temperature on the hardness of a material and isolate the effect of the electricity from the effects due to temperature changes. Worksheets were developed to aid in the recording of the data collected. Information such as calibration, hardness readings, electrical current, and specimen temperature was recorded.

In this paper, the fixture and specimen designs were provided, along with the laboratory objectives, set-up, procedure, analysis and results.

Introduction
The goal, of the laboratory experiments that are incorporated into a material science course, is to expose students to the various techniques by which material properties are obtained and to help the students understand the various factors that may influence these properties.

In most design situations, it is the mechanical properties of a material that drive the design process, these properties tend to be the focus of the laboratory experiments. Traditionally, these properties are first established through a series of simple tension, compression, shear, impact, and hardness tests. These first laboratories are designed to aid students in understanding how the "typical" value of each mechanical property is obtained.

Once the students have gained an understanding of how the baseline is established, most material science laboratory courses begin a series of tests to help students understand the factors that influence this baseline. These laboratories usually include experiments that focus on the effect of temperature, strain rate, alloys, cold work, and microstructure. These experiments effectively cover many of the traditional design situations that starting engineers will face.

However, with the large and ever-growing electro-mechanical industry, these existing laboratory experiments do not cover a major area of importance: the effect of electricity on the mechanical properties of a material. In 1969, it was first reported that electric current pulses reduce the flow stresses in metals[1]. Since that time, research has demonstrated that current can affect both simple and complex mechanical properties and phenomenon of metals in many ways. For instance, research by Xu et al. demonstrated that continuous current flow can enhance the recrystallization rate and grain size in select materials[2]. Further work by Conrad demonstrated that other mechanical properties are also affected by electrical current flows[3,4,5]. However, in depth investigations of the effects that electricity has on the overall mechanical properties of a material have not been considered. Furthermore, laboratory set-up and procedures do not currently exist and the results are not published concerning the expected effects of electricity on these overall properties. Due to this fact, the results obtained through this investigation cannot be directly compared to results previously published. However, by running several materials and also by comparing the results from these materials to the established effects of temperature on the hardness of each material, the validity of the testing apparatus and procedure can be established.

Considering the effect that electricity can potentially have on the mechanical properties of a material, a technique has been developed and is presented herein that will allow the effect of electricity on the hardness of a material to be investigated as part of a typical material science laboratory. The set-up and procedure presented below is designed to be the first exercise in a series of laboratory experiments that will be designed for dual research/laboratory use that will allow the effects of electricity on the mechanical properties of a material to be fully investigated as part of a traditional materials science laboratory course. By using different materials each semester in the laboratory and recording the results over several years, a general database of the affects on various materials can be developed. These results can then be used for design purposes where electricity may pass through a material while under load. The laboratory objectives, testing set-up, and procedure are all presented, along with techniques for recording, analyzing, and interpreting the data.

The hardness of a material was chosen for several reasons. First, the hardness of a material provides a quick insight into the strength and wear resistance of a material without requiring a lengthy testing time. The students have a limited amount of time in the laboratory to investigate the effect of the electricity on the material, therefore, a shorter testing time allows for a greater range of electrical currents and materials to be investigated. Furthermore, due to the mechanical nature of a hardness test, these machines are relatively easy to isolate without a high risk of injury to students or damage to the equipment.

Laboratory Objectives and Parameters

The objective of this laboratory was to establish the effect of electrical current on the hardness of various materials. Since the electrical current directly causes an increase in specimen temperature, the effect of current was investigated with and without compensating for specimen temperature increases. The current was passed through each specimen from 0 amps to 800 amps. Three material specimens were investigated: aluminum, hot rolled steel and stainless steel. Multiple hardness measurements were taken at each current level and the specimen's temperature was recorded. Hardness measurements were taken on a new specimen at corresponding temperatures generated through the use of a furnace for the purpose of comparison.

Laboratory Test Set-up

There were 5 components of the laboratory test set-up: fixtures, temperature measurements, electrical supply, the hardness testing machine, and safety. Figure 1 presents a schematic of the test equipment and Figure 2 is a schematic of the fixtures. Figure 3 shows a picture of the actual experimental set-up for reference purposes.

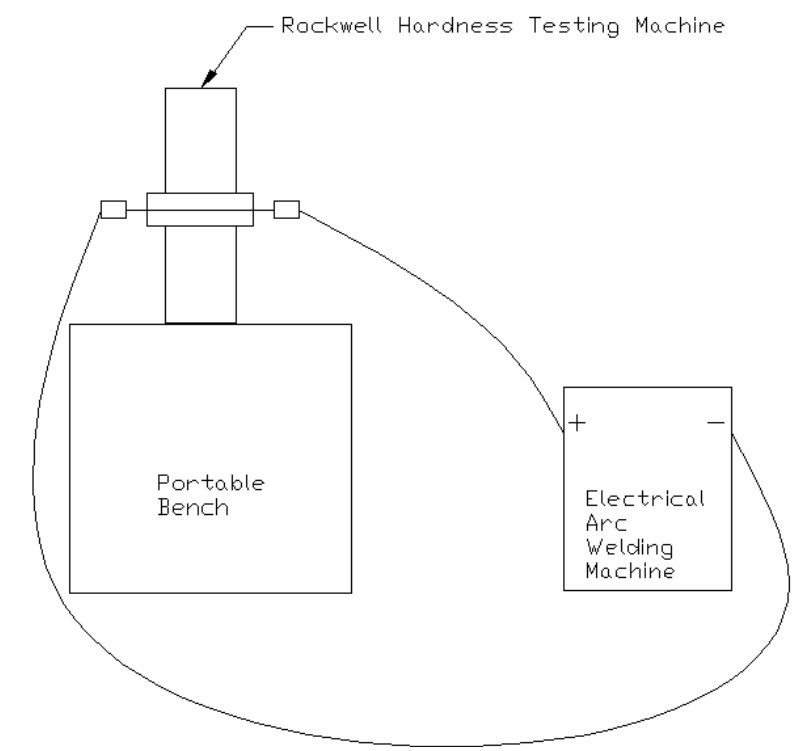

Figure 1 - Schematic of the Test Equipment

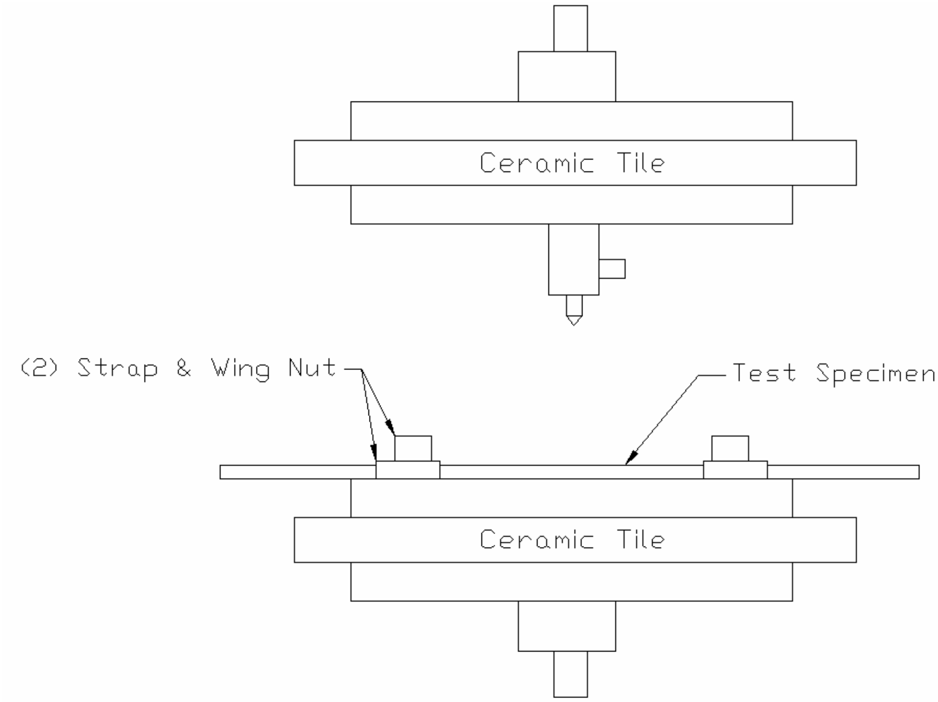

Figure 2 - Schematic of the Test Fixtures

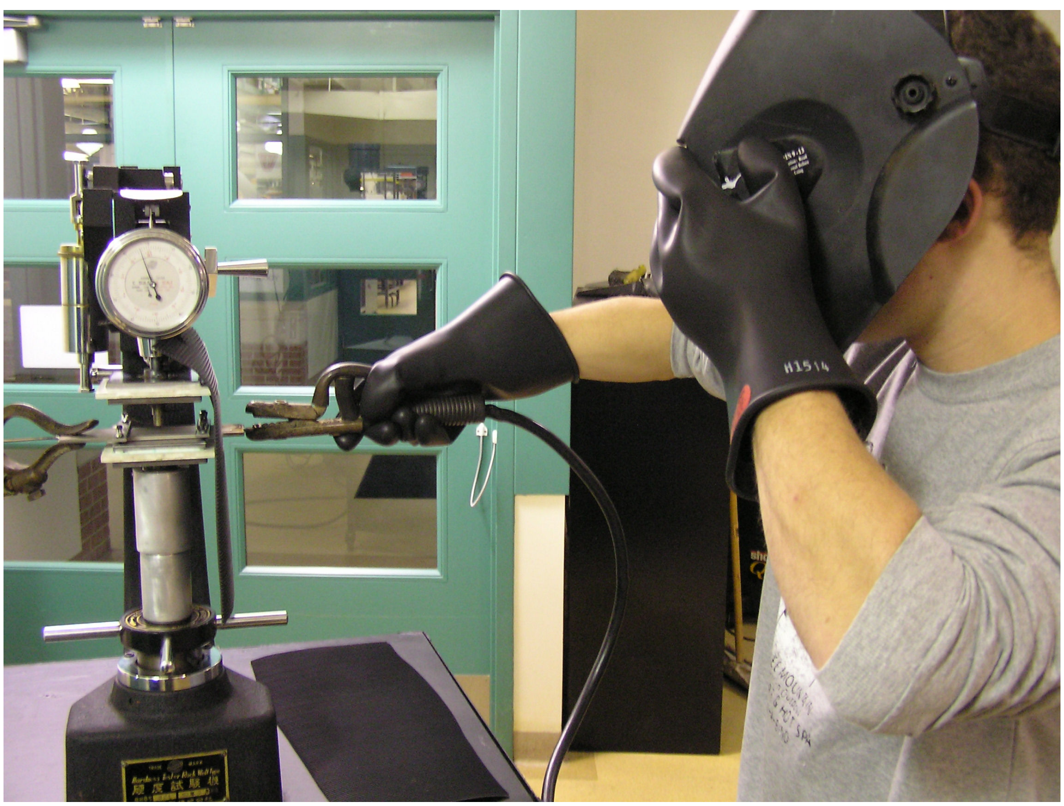

Figure 3 - Overall View of Testing Machine and Fixtures

Fixtures

When designing the fixtures that held the hardness testing indenters and test specimens, the primary concerns were that the fixtures could not distort the hardness measurements nor conduct electricity. To handle these restrictions, a 6" x 6" ceramic tile was epoxied between the original indenter holder and the new indenter holder (refer to Figures 2 and 4). Another 6" x 6" ceramic tile was epoxied between the original anvil holder and the new specimen holder. The ceramic tile is clearly visible in the figures due to its light-green color. The ceramic tiles were used to ensure that the electricity was not conducted through the Rockwell hardness testing machine. The new indenter and specimen holders were precisely machined and assembled to minimize the effects on the hardness readings. Also, to minimize the effects on the hardness readings, the epoxy, used to create the new indenter and specimen holders, was applied and allowed to dry under the same load that the fixtures undergo during testing. The indenter holder was machined very similar to the original indenter holder, and the specimen holder side was machined to securely hold the test specimens with straps and wing-nuts. Since a large torsional force was created by the electrical supply cables, after mounting the cable clamps to the test specimens, straps and wing nuts were used to secure the test specimens to the anvil of the hardness testing machine. The specimens were also used to securely hold the test specimens during the testing.

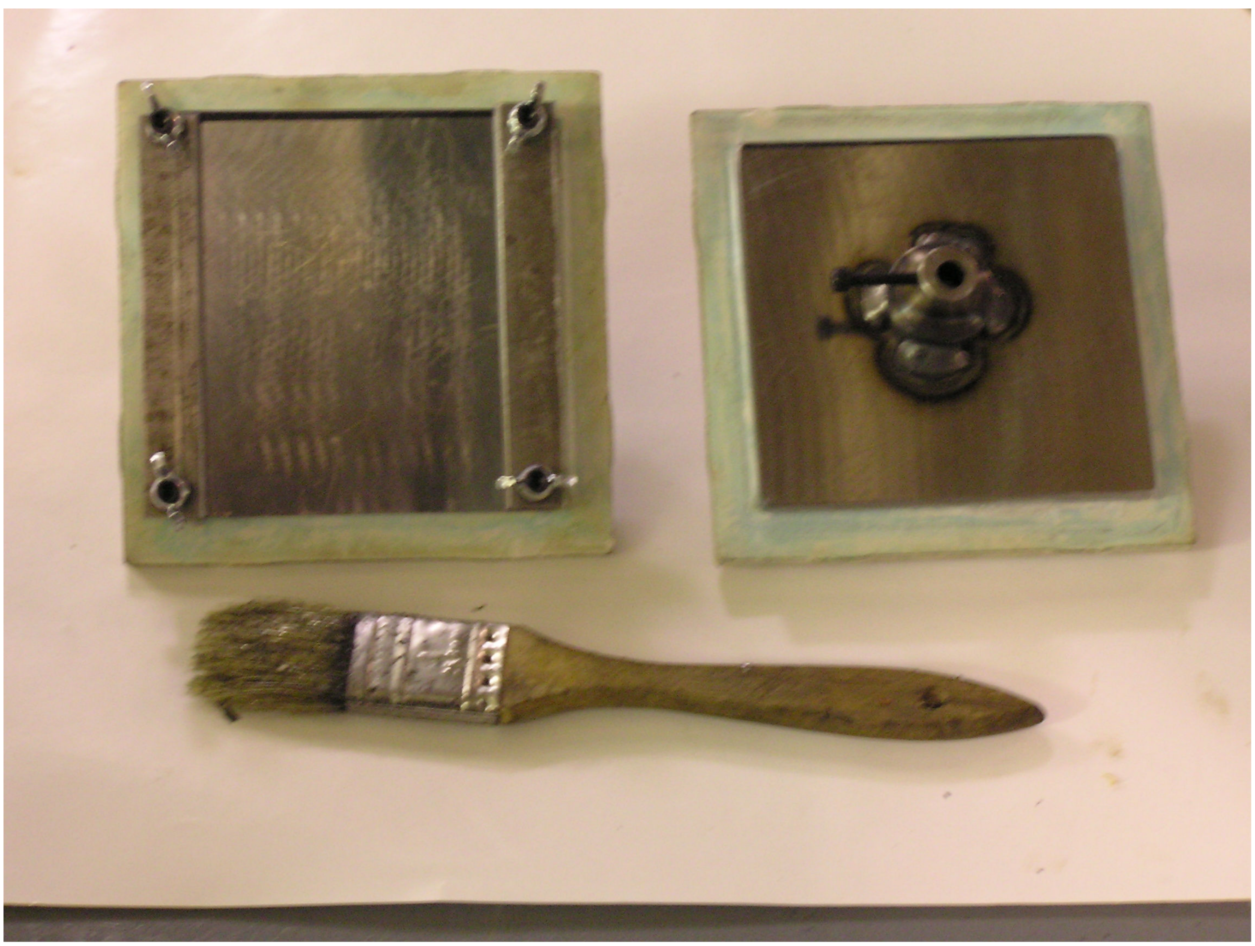

Figure 4 - Fixtures to insulate the Rockwell Hardness Tester from the Electrical Supply

Temperature Measurement

The temperature of the test specimens had to be closely monitored to verify that any material property changes were due to the electricity and not due to temperature. An infrared thermometer was used to record the temperature of the test specimen during each test. The temperature measurements were recorded in the same location as the hardness test in the event temperature gradients were created by the current.

Electrical Supply

Due to the high amperage requirements for the laboratory experiment, a standard Lincoln electrical arc welding machine was used to generate the current flow. For the tests described herein, a unit capable of delivering 850 Amps was used. However, other units of higher and lower amperage can be used to provide the current. Since the application is actually shorting the welder, the resistance is well below that typically found when welding, therefore, in many units; the amperage readings on the welder may not accurately reflect the actual current in the workpiece. To overcome this problem, an ammeter can be used to measure the actual amperage being supplied.

Hardness Testing Machine

For the experiments described below, a standard Rockwell hardness testing machine was used. For our purposes, a mechanically operated unit is used to obtain the measurements. However, since the machine is fully isolated from the electricity, any mechanical or electronic tester can be used. The machine itself was not altered except for the modification to the fixtures as described above.

Safety

Because of the uniqueness and originality of the experimentation, there is not a safety standard that can be directly applied to this application. However, using the General Electric Technical Services Co., Inc. study concerning the effects of electrical shock on the human body, safety issues were addressed[6]. From the investigations presented within the work on electrical effects on the human body, it is known that the open circuit voltage causes electricity to flow through the human body, not the closed circuit amperage. Therefore, although there are high amperages used in this laboratory, this current flow does not present the actual risk. For this laboratory, the highest risk of electrical shock occurs while the machine is on and the clamps are not connected, since at this point the open circuit voltage is the highest.

The work cited above presents several facts that pertain to this laboratory set-up. First, 5mA is the acceptable limit for the maximum harmless current intensity that can pass through the human body and the lower sensation level for humans (below which the current cannot be felt) is listed as 1.0 mA. When designing an apparatus, this current level can be determined by dividing the open circuit voltage by the resistance in body. For dry skin, the minimum value for this resistance is 100,000 Ohms (in most cases, resistance is 10 to 50 times higher than this value, increasing the safety). Using the maximum open circuit voltage (this number is the highest found for typical welding machines) as approximately 80 Volts yields a current of 0.8 mA. Therefore, if both ends of the welder are held in a person's hands, even without protective equipment, the person will not be shocked in a harmful manner and they should not even be able to perceive the current.

However, since students are involved in these experiments, it is important to make this laboratory experiment as safe as possible. Therefore, additional safety procedures were developed and implemented with the assistance of Rob Weissbach, an Electrical Engineering Technology faculty member at Penn State-Erie. People conducting the tests wore insulated attire to further eliminate the potential of electrical shock such as: rubber linesman gloves and a rubber mat to stand on. A welding helmet was worn to protect the eyes of the people conducting the tests from the flash that occurred when completing the electrical circuit.

Laboratory Test Procedure

During the course of the laboratory, the following procedure will be preformed on each of the three different materials that are to be used: aluminum, hot rolled steel, and stainless steel. For each material, the current was passed through the material and was varied from 0 amps to 800 amps in increments of approximately 50 amps. The 50 amp increment can be varied to provide higher or lower resolution of the results. For each level of testing conditions, five separate measurements of the hardness of the material were obtained while the current was passing through the workpiece and the results averaged in order to remove some of the uncertainty from the data. To ease the recording of the data for the students, a data form can be handed out. An example data form is shown below with the experimental results found at low voltages/temperatures (see Table 1).

Electrical Hardness Test   Material: Hot Rolled Steel Sample 2

Current		With Current					Average		Without Current					Average	
Average		Run 1	Run 2	Run 3	Run 4	Run 5	Hardness	Temp	Run 1	Run 2	Run 3	Run 4	Run 5	Hardness	Temp
	Hardness	36.3	34.9	35.8	33.5	38.5	**35.8**		38.8	35.1	36	37.3	34.7	**36.4**	
0	Temp	74	74	74	74	74		**74**	74	74	74	74	74		**74**
	Hardness	30.3	31.5	30.3	32	32.5	**31.3**		34	34.8	35	34.2	34.6	**34.5**	
63	Temp	75	75	76	77	77		**76**	76	76	76	76	76		**76**
	Hardness	33.5	33.2	35.8	34.8	36	**34.7**		34.6	34.8	35.1	34	33.5	**34.4**	
89	Temp	76	78	78	79	80		**78**	80	79	78	78	77		**78**
	Hardness	33	32.3	32.7	33	33	**32.8**		32.9	32.9	32.8	35	34.2	**33.6**	
129	Temp	78	80	83	83	85		**82**	83	82	81	80	81		**81**
	Hardness	33.4	34.8	33.8	34.7	34.5	**34.2**		31.8	32.7	32.6	34	36.5	**33.5**	
179	Temp	82	87	89	91	93		**88**	91	89	86	86	85		**87**

Table 1 - Example data form including the results from tests done at low currents

The testing of each specimen was begun by first placing the specimen in the fixturing device. After securing the specimen in the device, the initial hardness and temperature measurements were obtained to establish a baseline for comparison. After completing these measurements, the power supply was turned on and was set to the first level. The welding clamps were then secured to the specimen and hardness and temperature measurements were taken. Once these are obtained, the clamps were removed and a second series of hardness measurements were quickly taken. This second series of measurements was used to establish what the hardness is in the material due to temperature alone. Then, the welder was adjusted to the next current level and the procedure was repeated until the 800 amp limit was reached.

Once the tests were completed for each specimen at each of the current levels, an additional test can be completed for each material (i.e. if time permits and the equipment is available). For each material, using a furnace, heat a new specimen (one that has not had electricity run through the material) up to the maximum temperature obtained during the previous series of experiments. Remove the material from the furnace and quickly take hardness measurements on the material. Continuously monitor the temperature of the specimen as it cools and as the temperature reaches each value recorded for the material during the current testing, quickly measure and record the hardness measurements.

Analysis of Data

After completing this laboratory experiment, students should carefully analyze the data. Several comparisons and trends can be established. The students should analyze the effect of current on hardness (without correcting for temperature), the effect of temperature on hardness, the effect of current on hardness (with corrections for temperature), and the effect of the application of current to the base material (this can be established by comparing the hardness measurements taken during the current tests to those taken by heating the specimen in a furnace).

Lab Results

Using these comparisons and trends, students should be able to establish:

- The effect of electrical current on the hardness of a material
- If the effect of the current is dependent on material
- The effect of temperature on the hardness of a material
- If the current has an effect beyond that of the temperature rise alone
- If the current has caused a fundamental change in the material's microstructure or grain size beyond that caused by temperature alone

After gaining an understanding of the effects of electricity on the hardness of a material, the students should provide a further discussion on where and when these results are important to implement into the design process.

Concluding Remarks

At this point the laboratory set-up has been designed and the experiments have been conducted with the assistance of several students. These students were several volunteer undergraduate research scholars who were actively interested in the project. These students helped to establish the validity of the procedure and helped to obtain the initial results that will be used for comparison purposes in the future. However, the actual implementation of this laboratory in the materials science course will not begin until the next term in which the course is taught. Therefore, assessment instruments, student comments and student feedback are not provided at this point. It can be noted that the students involved with designing the apparatus and conducting the experiments provided very favorable feedback regarding the value of the laboratory experiment. However, due to the vested interests of the students in the project, the bias involved with this feedback precludes including these comments as impartial or typical student feedback.

Bibliographic Information

1. Troitskii, O.A., zhurnal eksperimental'noi teoreticheskoi kiziki/ akademi'i'a nauk sssr – pis'ma v zhurnal .eksperimental' i teoretiheskoi fiziki, 10, 1969, p. 18.
2. Xu, Z.S., Z.H. Lai, Y.X. Chen, "Effect of Electric Current on the Recrystallization Behavior of Cold Worked Alpha-Ti," Scripta Metallurgica, 22, 1988, pp. 187-190.
3. Conrad, H., "Electroplasticity in Metals and Ceramics", Materials Science & Engineering A287, 2000, pp. 276 – 287.
4. Conrad, H., "Effects of Electric Current on Solid State Phase Transformations in Metals", Materials Science & Engineering A287, 2000, pp. 227-237.
5. Conrad, H., "Thermally activated Plastic Flow of Metals and Ceramics with an Electric Field or Current", Materials Science & Engineering A322, 2002, pp. 100-107.
6. General Electric Technical Services co., Inc, "Effects of Electrical Shock", General Electric Co., 1971.

Biographical Information

JOHN T. ROTH, Ph.D.M.E., Assistant Professor of Mechanical Engineering at The Pennsylvania State University - Erie, The Behrend College, since 2001. Previously an Assistant Professor of Mechanical Engineering at Arkansas State University.

FREDRICK A. NITTERRIGHT, B.S. M.E.T., M.S.M.S.E.P., Lecturer in Engineering in the Mechanical Engineering Technology department at The Pennsylvania State University - Erie, The Behrend College, since 1999. Previously, an adjunct faculty member at Westmoreland County Community College. Previous engineering positions in industry include: Tool Designer, Mechanical Process Engineer, and Project Engineer/Team Leader.

ROBERT S. WEISSBACH is an assistant professor of engineering in the Electrical Engineering Technology department at The Pennsylvania State University - Erie, The Behrend College where he is currently the program chair. His research interests are in power electronics, power systems, and multidisciplinary education.