CTME Project Final Report

September 11, 2012

Project title:
Advanced Ceramic-Metallic Composites for Lightweight Vehicle Braking Systems

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ABSTRACT

According to the Federal Transit Administration Strategic Research Plan [1]: “Researching technologies to reduce vehicle weight can also lead to important reductions in fuel consumption and emissions. The power required to accelerate a bus and overcome rolling resistance is directly proportional to vehicle weight. Composite materials are one example of an FTA research area aimed at reducing vehicle weights.” One way to reduce vehicle weight is through the development of lightweight components for advanced braking systems. Gray cast iron has been the material of choice in braking systems (such as in brake rotors and drums) because it is inexpensive and a large supply chain infrastructure is in place for engineering and manufacturing gray cast iron components. However, gray cast iron is a relatively heavy material. Utilizing lighter weight materials in braking systems would not only achieve better fuel economy by reducing the vehicle’s static weight but, since brake rotors and drums are rotating components, there would be a large multiplying effect on reducing the amount of energy required to increase their rotational speed as the vehicle accelerates. Finally, as the braking system is an unsprung weight, a lighter system would significantly improve vehicle handling performance and safety.

In spite of obvious benefits to lightweight materials, there are significant technical and commercial challenges to overcome. Most lightweight materials do not have the physical, thermal, and tribological performance characteristics required for brake applications, such as a high strength and high thermal conductivity at elevated temperatures. Lightweight alternatives to cast iron that currently do exist are prohibitively expensive for general use in most vehicles.

The TCON® materials produced by Fireline, Inc. are a class of interpenetrating phase composites produced by a unique reactive metal penetration process. TCON materials contain continuous, microscopic networks of ceramic and metallic phases that are co-continuous and strongly bonded together. This unique material structure is substantially different from traditional metal matrix and ceramic matrix composites, therefore TCON materials exhibit mechanical, physical and thermal properties that are quite distinctive. Through process variations, the properties of TCON composites can be tailored to meet the requirements of specific applications. TCON materials can be net-shaped or near-net shaped in a wide variety of useful forms and sizes, making the process relatively low cost.

In collaboration between Fireline and Youngstown State University, this project investigated how TCON materials may be utilized in lightweight vehicle brake systems. The project results are very promising, showing that TCON composites exhibited friction and thermal management properties similar to or better than cast iron, but with half the weight and less wear. It is expected that Fireline will continue on with the further development and evaluation of prototype TCON brake rotors, possibly leading to the commercialization of TCON brake components.

OVERVIEW OF GOALS & ACCOMPLISHMENTS

Goal 1 – Identification of the critical material properties and performance requirements

- We compiled a list of the performance requirements for braking systems on passenger cars, racing/performance cars, trucks, and buses.
- We established a list of the critical properties of the materials used in braking systems as they relate to performance expectations.
- We benchmarked the properties of gray cast iron used in brake components.

Goal 2 – Benchmarking the physical, thermal, and tribological properties of TCON composites

- Per the critical material properties expected for brake system components, we established a list of material property tests that could be used to characterize current and newly developed TCON composites for brake rotors. Most of these tests are based on procedures published by the American Society for Testing and Materials (ASTM).
- Material property tests selected from this list were used as a screening system to select which TCON composites to consider for brake rotor prototype evaluations.

Goal 3 – Development and analysis of new TCON composites

- Processing and compositional modifications were made to TCON grades in order to improve the properties and subsequently improve their anticipated performance in brake rotor applications. These TCON variants were evaluated at Oak Ridge National Laboratory (see Goal 4).
- Alternative raw materials synthesized by YSU researchers were evaluated for potential use in new TCON composite variants.

Goal 4 – Evaluation of prototype TCON brake components

- Appropriate brake pad materials for use with TCON rotors were identified.
- Seven TCON rotors for Oak Ridge National Laboratory's Sub-Scale Brake Tester (SSBT) were fabricated and tested at ORNL's Tribology Research User Center in the High Temperature Materials Laboratory, and benchmarked against cast iron and titanium. A peer-reviewed technical article on this evaluation will be published.
- Prototype brake rotors were fabricated and supplied to Dr. Darrell Wallace for evaluation on YSU's tribometer.
- Prototype brake rotors for a Ford Mustang were fabricated.
- Fireline has identified a commercial laboratory that can evaluate full scale brake rotors on dynamometers per industry standards such as the Society of Automotive Engineers (SAE).

PROJECT DETAILS

YSU Students

Many YSU students played important roles in this project, both as interns employed at Fireline and/or through their studies at YSU:

- YSU student interns who worked at Fireline
    - William Purnell (Mechanical Engineering, undergraduate student)
    - Devin Wilmouth (Mechanical Engineering, undergraduate student)
    - Eric Wojcik (Mechanical Engineering Technology, undergraduate student)
    - Kyle Myers (Chemistry, Master's graduate student)
- YSU students who help support the project through their YSU studies
    - Dominic Loiacona (Chemistry, Master's graduate student)
    - David Milush (Industrial Engineering, Master's graduate student)
    - Brittany Wilkins (Industrial Engineering, undergraduate student)
    - Kyle Myers (Chemistry, Master's graduate student)

All of these students have since graduated from YSU, but we are proud to point out that Kyle Myers has recently enrolled in YSU's new PhD program for Materials Science and Engineering as a result of the interest he gained in materials research while working at Fireline.

As part of their Master's theses research and under the direction of Dr. Tim Wagner, both Dominic Loiacona and Kyle Myers researched the synthesis of unique precursor materials for potential use in TCON composite shapes, such as lightweight brake rotors.

As student interns at Fireline, William Purnell, Devin Wilmouth, Eric Wojcik, and Kyle Myers all assisted with the fabrication and testing of TCON composite samples and brake rotor prototypes for this project. As will be further explained below, Kyle Myers also played a critical role in the testing of TCON brake rotor prototypes at Oak Ridge National Laboratory. Devin Wilmouth collected information on braking systems used in high-performance/racing cars, passenger cars, mass transit buses and heavy trucks, such as performance requirements, performance issues, materials used in the system components, and names of key original equipment and replacement part manufacturers. As part of this effort, Devin met with Ohio Department of Transportation Manager Michael Celedonia and received a tour of ODOT's Trumbull County garage. There he learned about the issues that ODOT faces with the performance of braking system components in their heavy-duty trucks and plows. Through his association with the Nelson Ledges Road Course in Warren, Devin also met Mike Puskar, owner of Carbotech Performance Brakes. Carbotech manufacturers automotive brake pads, primarily for the high performance market, and Mr. Puskar provided assistance in the selection of brake pads for TCON brake rotor evaluations.

Finally, Dave Milush and Brittany Wilkins provided Fireline with an eleven page report outline the benefits achieved by utilizing lightweight materials in brake rotors. (A copy of this report has been previously provided to CTME.) By compiling information on passenger vehicles (quantities, annual miles driven, and annual fuel consumption) and calculating the effects of weight reduction, David and Brittany concluded that every one pound reduction in brake rotor weight could result in an annual energy savings of 5.35×10^{12} BTUs, as well as a reduction of nearly one billion pounds of air pollutants in the United States.

Leveraged Funding

In addition to the cost sharing directly provided by Fireline, this project has indirectly benefited from two other projects that were also supported by government funds.

A collaboration between the YSU College of STEM and Fireline won a Wright Project award of $2.1 million from Ohio's Third Frontier Project to establish a Center of Excellence in Advanced Materials Analysis at YSU, with Dr. Tim Wagner as the director. This Center has provided support to Fireline's efforts to commercialize TCON products, including lightweight brake system components, through micro and nanoscale structural and chemical analysis of our composites.

Also, a collaboration between the U.S. Army Research Laboratory (ARL), the YSU College of STEM, and Fireline began in September, 2010 on a project entitled "Advanced Nano-composite Materials for Lightweight Integrated Armor Systems" (Agreement No.: W911NF-10-2-0090). YSU has set up testing systems which allows Fireline to evaluate the ballistic and high strain rate properties of TCON composites. The data generated from these evaluations has been beneficial in selecting improved TCON composites for prototype brake rotor evaluations.

Brake System Requirements & Critical Material Properties

Braking systems are expected to serve the following purposes [2]: intermittent braking to reduce the speed of the vehicle; continuous braking to prevent unwanted acceleration while driving downhill; continuous braking to bring the vehicle to a stop; and parking braking to prevent the vehicle from movement while at rest. The systems must consistently perform in such way that the vehicle can decelerate comfortably and reliably while achieving braking distances as short as possible during emergencies and maintaining the dynamic stability of the vehicle [3]. While braking systems are comprised of several components and sub-systems, such as the pads, calipers, a hydraulic system, and an anti-lock braking system, the primary focus of this project is on lightweight brake rotors. According to Ihm [4], the following outlines the desirable properties for brake rotors:

- High strength and durability to sustain torque loads from braking
- Stable mechanical & frictional properties through all expected service temperatures
- High wear resistance through all expected service temperatures
- High heat absorption capability to absorb braking energy
- High thermal conductivity to transport frictional heat away from braking surfaces
- High vibration damping capacity to minimize noise, vibration, and harshness (NVH)
- Minimal thermal expansion to minimize performance variability
- High degree of corrosion resistance
- Excellent machinability
- Inexpensive material and processing costs

While the evaluation of TCON composites for all of these parameters was beyond the scope of this project, several of these properties were measured from test bars and others where measured during brake rotor prototype evaluations.

Many TCON variants were evaluated during this project and it would take considerable space in this report to provide all of the property data. However, the data clearly showed that

TCON composites have the following advantages over grade G3000 grey cast iron (which is typically used in brake rotors):

- Grey cast iron is over 2 times heavier than TCON (density)
- TCON is 2 times stiffer (Young's modulus and shear modulus)
- TCON has ~50% greater thermal conductivity

Even though titanium (such as Ti-6Al-4V) is universally recognized as a lightweight material and could be considered as a potential alternative to cast iron in brake rotors, TCON composites also have specific property advantages over this metal:

- Titanium is 50% heavier than TCON (density)
- TCON is 1½ times stiffer (Young's modulus and shear modulus)
- TCON has 10 times greater thermal conductivity

These properties were further validated during prototype brake rotor evaluations, as will be explained below.

Materials Development and Evaluation

Test bars were prepared out of TCON composites and then evaluated for the effects of varying chemical composition, particle size distribution, and raw material selection on the properties of the transformed product. The following properties were measured: Cold Modulus of Rupture, Hot Modulus of Rupture, Apparent Specific Gravity, Sonic Velocity, Young's Modulus, Shear Modulus, and Poisson's Ratio. (All of these tests are based on procedures published by the American Society for Testing and Materials.) The data generated from these evaluations were utilized in selecting specific TCON composites for prototype brake rotor fabrication and testing.

As mentioned above, YSU Master's students Dominic Loiacona and Kyle Myers carried out research on the synthesis of unique precursor materials for potential use in TCON lightweight brake rotors. While the results have been promising, no useable precursor materials were developed for use in this project. Dr. Wagner is continuing on with this research at YSU and we look forward to future opportunities to consider the utilization of any resulting precursors.

Prototype Brake Rotor Testing – Brake Pad Selection

Mike Pushkar of Carbotech Performance Brakes assisted us with the selection of appropriate brake pad materials for use with TCON composite brake rotors. The Carbotech pads were successfully utilized in the TCON Sub-Scale Brake Tests at Oak Ridge National Lab, and can be utilized during further TCON brake rotor evaluations at YSU or outside commercial laboratories (see below).

Prototype Brake Rotor Testing - Oak Ridge National Laboratory

The Tribology Research User Center (TRUC) is one of six user centers in the High Temperature Materials Laboratory (HTML) at Oak Ridge National Laboratory (ORNL), and is a U.S. Department of Energy User Facility dedicated to solving materials problems that limit the efficiency and reliability of systems for power generation and energy conversion, distribution and use. TRUC facilities and staff support tribological research and characterization of new materials, coatings, and surface treatments for diverse applications like energy-efficient engines, brakes, farming equipment, medical implants, and manufacturing. The mission of

TRUC is to provide a collaborative environment and a variety of tools and techniques to investigate the response of materials to friction- and wear-causing environments. Consequently, TRUC's vision is to be a national resource for providing solutions to technology-enabling barriers related to the friction, wear, and lubrication characteristics of high-performance materials.

The HTML User Program is sponsored by the FreedomCAR and Vehicle Technologies Program through the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Because the focus of Fireline's project with CTME is on lightweight materials for use in automotive applications, we qualified to carry out free materials property testing at HTML as long as we provided the personnel necessary to run the test equipment (plus cover travel and housing costs) and agreed to publish the results in a technical journal within six months. We subsequently submitted a proposal to the HTML User Program on carrying out tests on our TCON materials at the Tribology Research User Center, and our proposal was accepted (HTML Project: 2011-005).

Per discussions with Dr. Peter Blau, HTML TRUC Leader, we selected the Sub-Scale Brake Tester (SSBT, see Appendix A) as the primary method to measure the suitability of TCON composites for brake rotor applications. We prepared SSBT disk samples out of seven different TCON compositions: these samples were varied by the amount and size of silicon carbide (SiC) particles, the amount and distribution of aluminum, as well as the sample fabrication method. We also obtained the necessary brake pads from Carbotech.

During week of March 14, 2011, Brian Hetzel, Kyle Myers, and Mark Peters visited ORNL to carry out the TCON material evaluations. Working with Peter Blau, Kevin Cooley (HTML Senior Engineering Technician), Dr. Ralph Dinwiddie (ORNL Research Scientist), and Dr. James Hemrick (ORNL Research Scientist), the TCON samples were tested on the Sub-Scale Brake Testing system over a wide range of conditions. In addition, thermal image analysis was carried out on several of the disks during the SSBT evaluations, and the amount of disk wear was measured after completion of each test. During the week of September 12, Brian Hetzel and Kyle Myers returned back to Oak Ridge for additional testing of the TCON samples over a broader range of SSBT conditions, as well as evaluate cast iron and titanium SSBT samples in order to benchmark the performance of the TCON materials.

The tests were successfully carried out at equivalent vehicle speeds up to 90 miles per hour, under different braking pressures and temperatures: each TCON SSBT disk was successfully evaluated, the best performing version of TCON was benchmarked against cast iron and titanium, the Carbotech brake pads performed as expected, and significant amount of data was generated. The conclusions can be summarized as follows:

- TCON composites achieved coefficients of friction equal to or better than cast iron, and significantly better than titanium.
- TCON did not exhibit brake fade and was more consistent than cast iron and titanium, including at higher braking pressures.
- TCON ran as cool as cast iron and much cooler than titanium.
- TCON cooled off much more rapidly than cast iron.
- The brake pads run on the TCON rotors exhibited very little wear, while the pads run on cast iron and titanium experienced 2 to 13 times more wear.

See Appendix B for examples of the data collected during these visits. All of the data from these evaluations will be presented in a technical paper, which is currently being drafted. We will continue to collaborate with Drs. Blau, Dinwiddie, and Hemrick on finalizing the paper for publication in a peer-reviewed journal, such as the International Journal of Applied Ceramic Technology.

Prototype Brake Rotor Testing – YSU Tribometer

A tribometer has been built and installed at YSU by Dr. Darrell Wallace through a separately CTME-funded project. Fireline fabricated TCON rotor prototypes (see drawing in Appendix C) to be tested on this tribometer and has supplied these rotors to Dr. Wallace. This tribometer will provide an opportunity to test full sized TCON and conventional cast iron brake rotors and compare the results with the SSBT data collected at Oak Ridge National Laboratory.

Prototype Brake Rotor Testing – Dynamometers at Link Engineering

Link Engineering Company's test laboratories perform and develop testing for friction material, brake, axle, transmission, and vehicle manufacturers around the world. They offer a wide array of testing services to evaluate product compliance with FMVSS, ECE, ISO, or JASO standards; or evaluate specific product characteristics, such as balance, squeal, roughness and judder, drift-pull, off-road dust intrusion, and durability. Many procedures were developed by Link in cooperation with the automotive industry. Link facilities in the Detroit-Metropolitan area operate over 50 dynamometers, multiple friction material evaluation tools, driveline and wet friction test capabilities, as well as over 20 vehicle lifts, full vehicle instrumentation test and analysis expertise.

Fireline will consider using Link's services to evaluate TCON brake rotor prototypes in addition to tests already carried out at Oak Ridge National Laboratory and any future YSU tribometer evaluations.

Prototype Brake Rotor Testing - Nelson Ledges Road Course

Two brake rotor prototypes were fabricated out of a standard grade of TCON and machined to mimic the current cast iron vented brakes used on a Ford Mustang. We intended to have these prototypes evaluated by Scott Lane, President of Nelson Ledges Road Course (located near Warren, Ohio) in his Ford Mustang race car, in order to correlate real-world results with the ORNL and YSU laboratory data. Unfortunately, we no longer have the opportunity to carry out this testing due to ongoing mechanical problems with Lane's car. As part of its efforts to commercialize TCON composite brake rotors, Fireline will consider alternative approaches to conducting field trials.

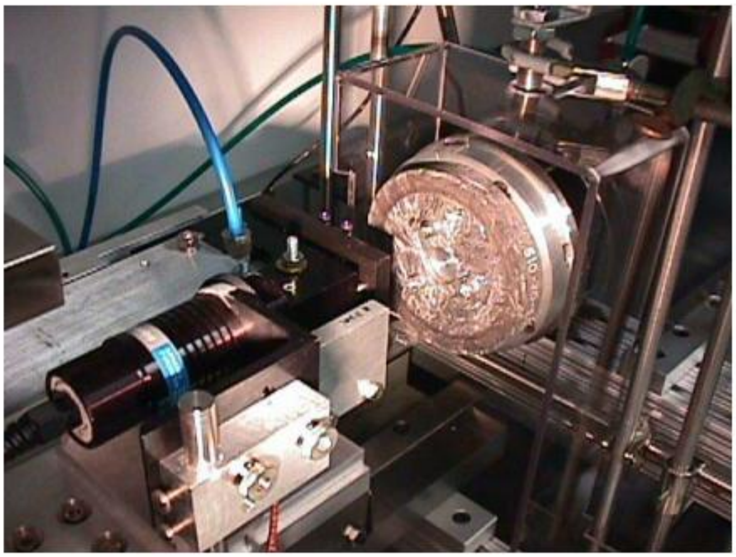
CONCLUSIONS

The objectives of this project were successfully completed, the concept of utilizing TCON ceramic-metallic composites in lightweight automotive brake rotors was validated, and Fireline is now considering opportunities on moving forward with the further development and market introduction of full-sized TCON brake rotors.

Appendix A – Description of Sub-Scale Brake Tester (SSBT)

The ORNL Sub-Scale Brake Materials Testing System

The ORNL Sub-Scale Brake Testing system (SSBT) has a 10 hp 480VAC variable speed motor driving a high-precision machining spindle. The maximum practical speed is 3600 rpm. That speed equates to more than 72 mph on a heavy truck-sized brake rotor. Test specimens are 5" diameter discs (see next page) and ½" x ½" square-faced blocks of material cut from a variety of commercial and experimental pad materials. A close-up of the fixtures, with a ceramic composite disc mounted on them, is shown below.



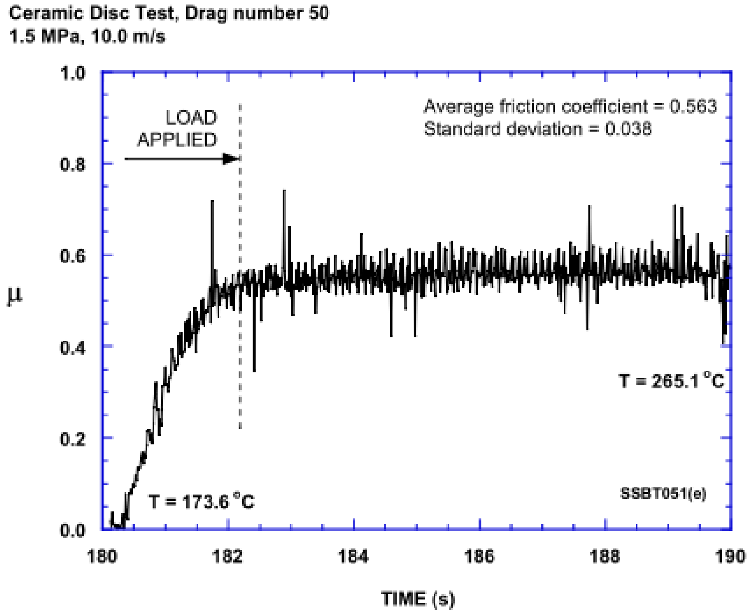
SSBT test configuration. IR sensor at bottom left aimed at the disc track at approximately the 1 o'clock position. The RPM sensor is looking down at the disc holder, contained in a plastic shroud. A circular wear track is visible on the surface of the disc specimen.

Sensors measure friction forces and temperature, displaying the data in real time on a computer monitor located near the machine. An example of the friction data from a single drag is shown on the following page. Friction force can be sampled at a rate of more than 1000 times a second to get detailed information on the stability of the friction coefficient.

A water nozzle and shroud, not shown here, are available to conduct friction tests under wet conditions. The time to recover frictional performance after the water is spun off is measured.

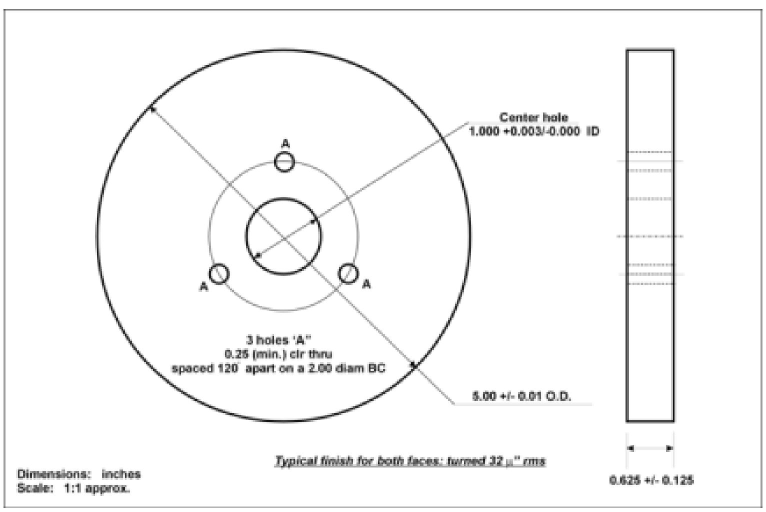
Materials subjected to brake tests can be characterized to determine the nature of the brake wear dust and the processes of wear on both pad and disc specimens.

Appendix A – Description of SSBT (continued)



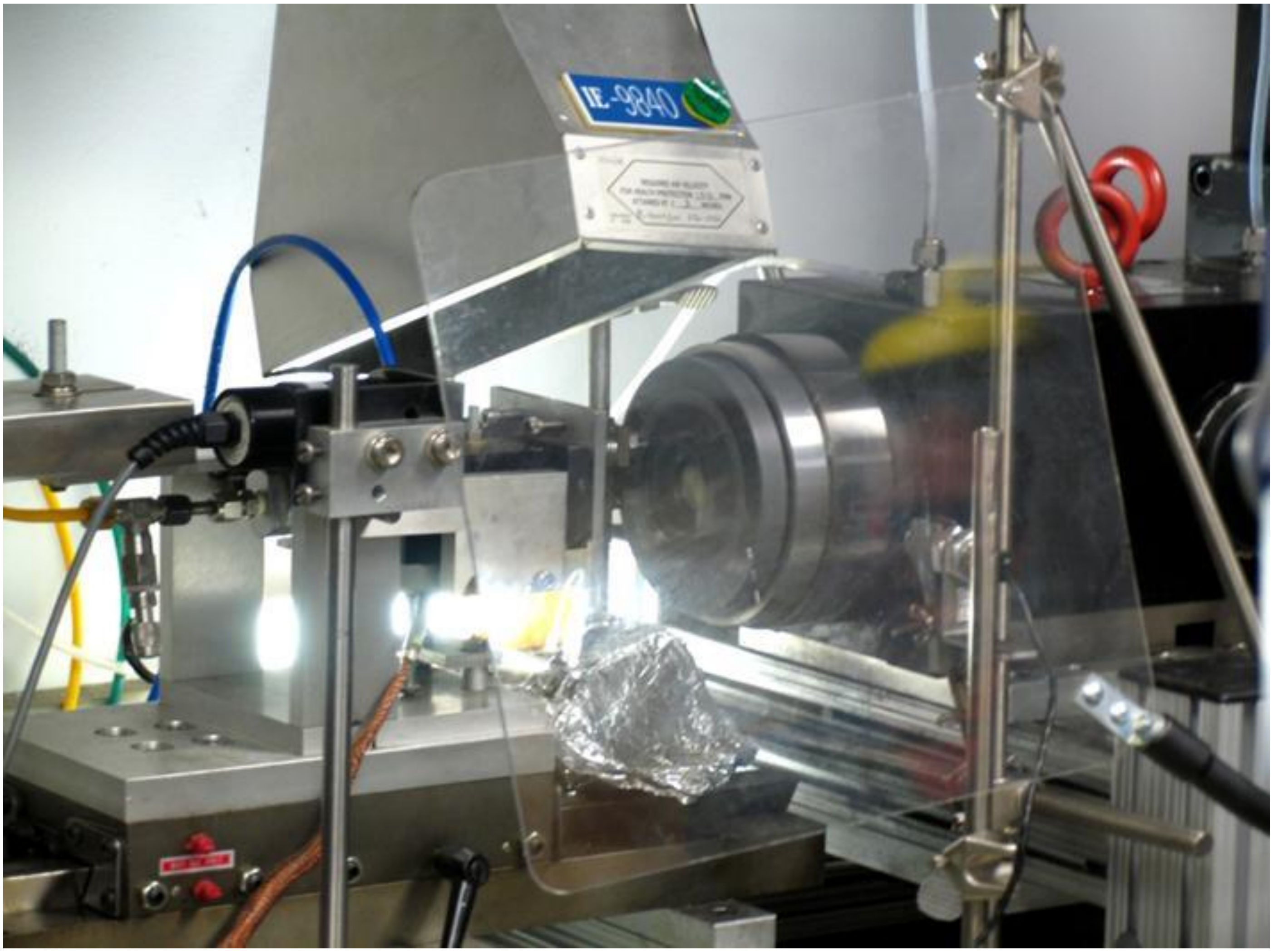
Example of a friction record from a test of a ceramic pad/disc combination.

The SSBT is available for both sponsored materials research and for Tribology Research user projects under the High Temperature Materials Laboratory User Program at ORNL – visit our website: http://www.html.ornl.gov/ For further information on this testing facility or other tribology programs, contact: Dr. Peter J. Blau, Oak Ridge National Laboratory, P. O. Box 2008 (Mail Stop 6063), Oak Ridge, TN 37831-6063.



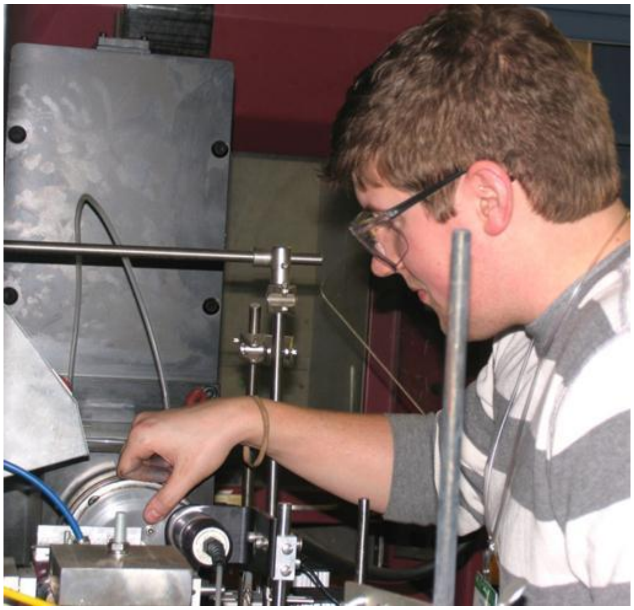
Typical SSBT disc specimen dimensions.

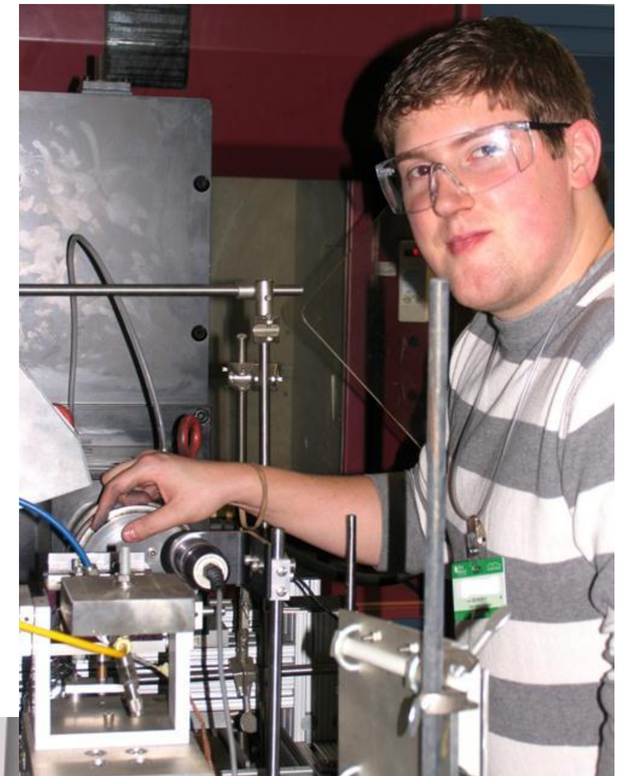
Appendix B – ONRL SSBT evaluations



Testing of a TCON disk on the Subscale Brake Testing System

Appendix B – ONRL SSBT evaluations (continued)





Kyle Myers
(YSU Chemistry graduate student and Fireline intern)

Appendix B – ONRL SSBT evaluations (continued)

Brian Hetzel
(Fireline R&D Technology Manager)

with

Dr. Ralph Dinwiddie
(Research Scientist, Oak Ridge National Lab)

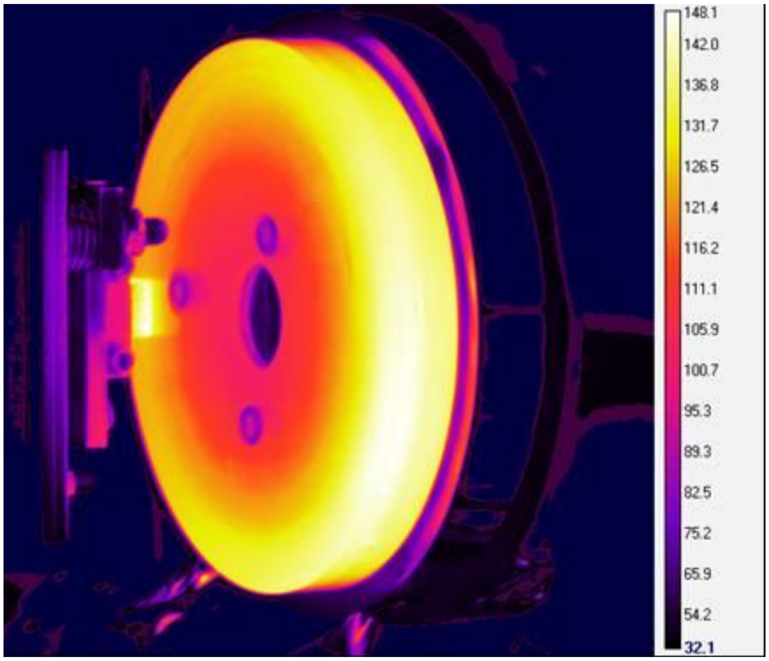
Kyle Myers

with

Dr. Dinwiddie

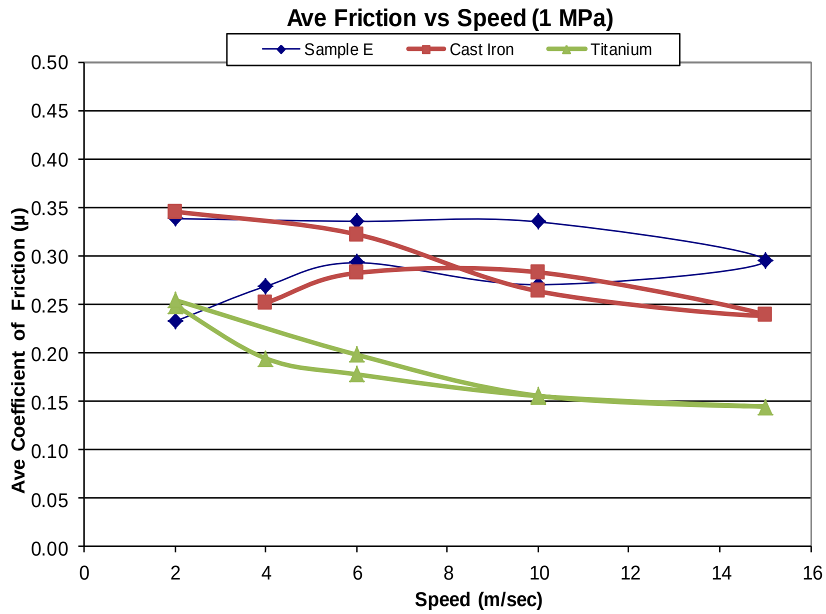
Appendix B – ONRL SSBT evaluations (continued)

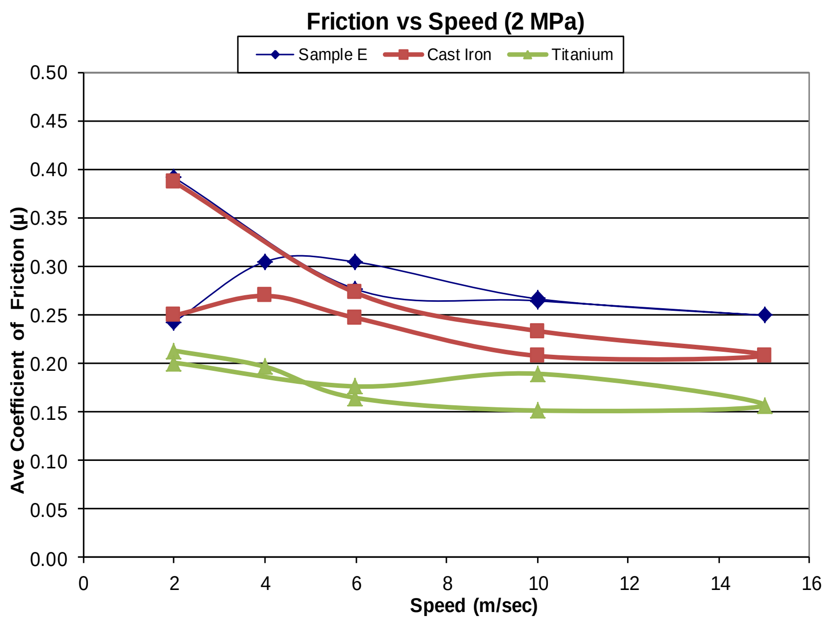
Mark Peters (General Manager – TCON Division, Fireline, Inc.)
with Dr. James Hemrick (Research Scientist, Oak Ridge National Laboratory)



High speed thermal image of a TCON rotor during a SSBT run

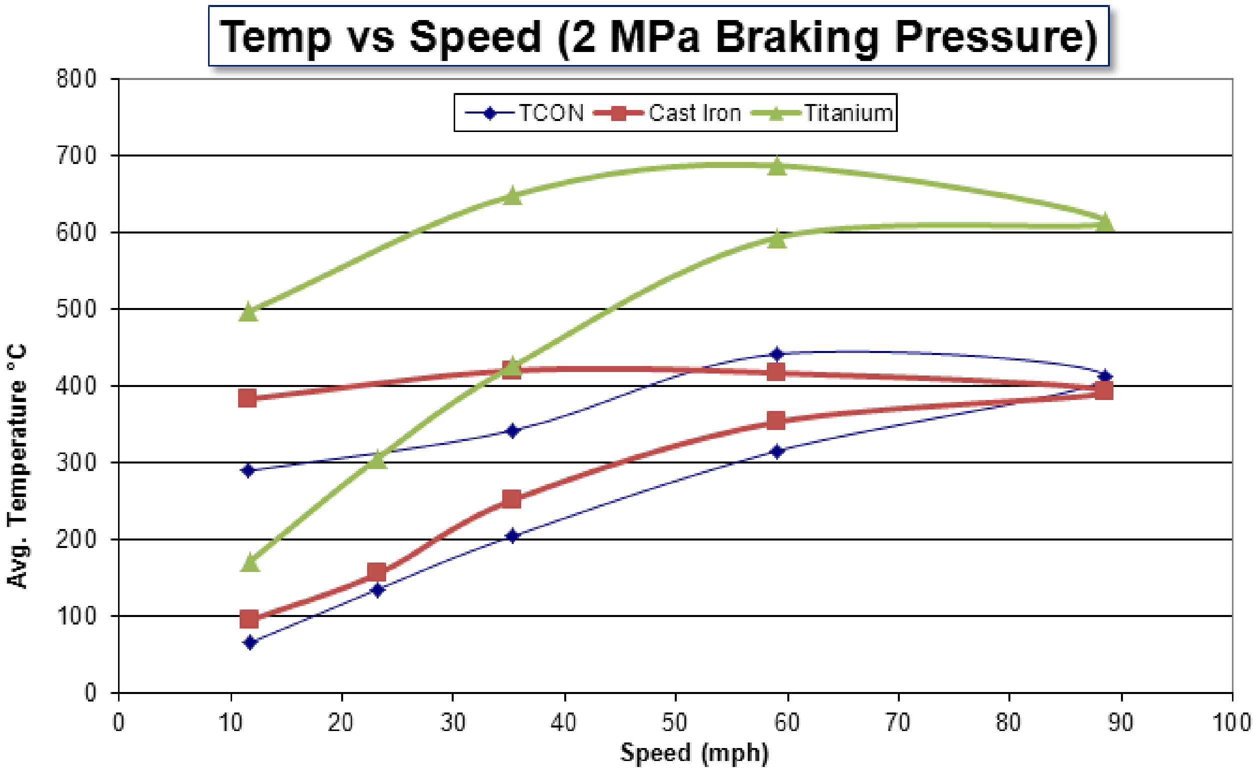
Appendix B – ONRL SSBT evaluations (continued)



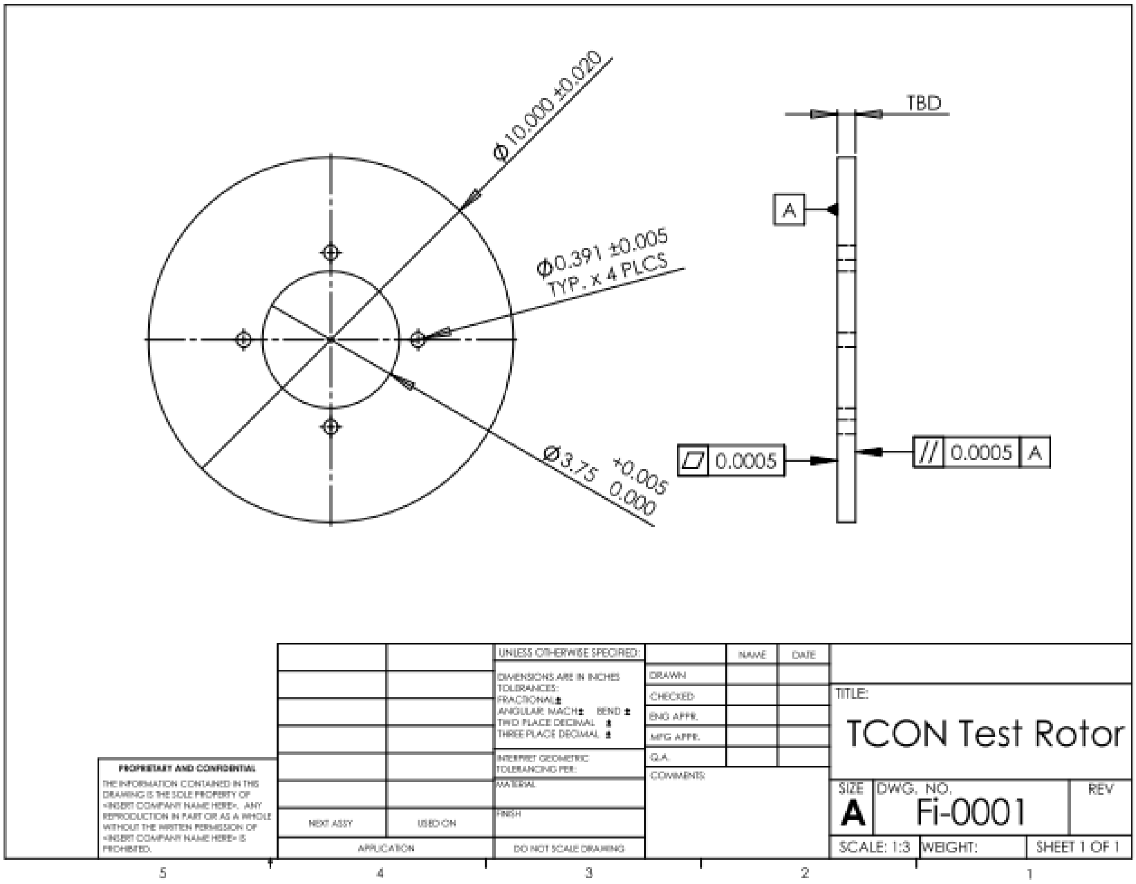


TCON Sample “E” versus Cast Iron and Titanium

Appendix B – ONRL SSBT evaluations (continued)



Appendix C – Brake Rotor Prototype for YSU's Tribotester



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1. "U.S. Department of Transportation Federal Transit Administration Strategic Research Plan", September 30, 2005
2. "Brake Technology Handbook", Edited by B. Breuer and K. H. Bill, SAE International, p 11, 2008
3. *Ibid.*, p 18
4. M. Ihm, "Introduction to Gray Cast to Brake Rotor Metallurgy", SAE International Brake Colloquium, October 2003