T. Development of Titanium Component Applications in Heavy Duty Diesel Engines

Jesus Chapa-Cabrera, Principal Investigator
John Grassi, Co-Investigator
Caterpillar Inc.
Tech Center 854-80 TC-E
14009 Old Galena Rd.
Mossville IL, 61552
(309) 578-8347; fax: (309) 578-2953; e-mail:chapa-cabrera_jesus_g@cat.com

DOE Technology Development Area Specialist: Dr. Sidney Diamond
(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Prime Contract No: DE-AC05-00OR22725
Subcontractor: Caterpillar Inc., Peoria, Illinois

Objectives

- Design and fabricate a cost-competitive diesel engine turbocharger using lightweight titanium materials that reduces both fuel consumption and transient emissions.

Approach

- Design a series turbocharger for use on multiple engine platforms. The turbocharger consists of one turbo wheel and two compressor wheels that are attached to a single rotating drive shaft.
- Use this compact design to simplify complex multi-turbocharger systems presently installed in different engine platforms.
- Use titanium aluminide (TiAl) for the turbine wheel and a titanium alloy for one of the compressor wheels.

Accomplishments

- Procured cast TiAl turbine wheels and test materials from two suppliers.
- Finalized subcontracts with two vendors.
- Completed three iterations of simulation and friction welding experiments to produce turbine-to-shaft joints. Produced welds with higher joint strength than the base TiAl turbine wheel.
- Established a nondestructive inspection methodology to assess robustness of the joints.
- Conducted preliminary turbocharger bench tests using base nickel alloy and TiAl turbines.

Future Direction

- Conduct a complete redesign of the wheel to increase the overall strength and create a robust joint.
- Complete detailed material characterization of two TiAl alloys processed by counter-gravity and gravity casting.

- Perform turbocharger bench tests and engine tests.
- Assess the commercial viability of using titanium alloys for turbocharger applications for heavy-duty diesel engines.

Introduction

Turbochargers on diesel engines play an integral role in meeting emission regulations and controlling fuel economy. A recently designed series turbocharger by Caterpillar will use TiAl and titanium alloys for the turbo wheel and compressor wheel, respectively. The dual turbocharger has two complete systems that are connected in series, as shown in an ACERT® engine in Figure 1, while the proposed turbocharger design is one system with two compressor wheels attached to a single drive shaft. Lightweight titanium materials are important technologies for this turbocharger design and are anticipated to provide faster response time (reduced transient emissions) and better fuel economy.

Figure 1. ACERT® engine. The two turbochargers in series are circled.

Approach

Caterpillar has selected candidate TiAl alloys for a series of characterization tests and development of a joining process. These tests will examine mechanical and physical properties of selected TiAl alloys. Friction weld trials will determine the optimal parameters for joining the TiAl wheel to the drive shaft. Based on the turbocharger validation tests, modifications to the turbo wheel will be modeled and the performance will be assessed. Bench tests will be completed before engine tests are scheduled.

Results

Two of the three parties that were initially identified as potential subcontractors for the project have completed contract agreements with Caterpillar. After further consideration, it was determined that the third vendor would participate in the program solely as a materials supplier.

Finite element modeling of the existing HEAT® turbocharger design was completed. The objective of this analysis was to evaluate the critical stresses that develop during an extreme operating cycle and compare the results for TiAl with the nickel-based alloy Inconel 713, which is typically used in similar applications. The modeled cycle consisted of going from a cold start to peak torque, followed by low idle conditions. Identical operating conditions and wheel design were used in both analyses; thus the different results can be attributed only to differences between the two materials. The code ABAQUS® was used for the analysis, using loads and boundary conditions obtained from aerodynamic simulations. Only an angular portion of the wheel and shaft was modeled, owing to symmetry, as shown by the mesh in Figure 2. This wedge consists of a blade, a section of the wheel hub, and a section of the shaft. Temperatures and stresses were obtained from the analyses, and the results showed that transient peak stresses on the wheel are reduced by approximately 50% by replacing the Inconel 713 with TiAl. Critical stresses result from superimposing centrifugal and thermal effects, and the significant reduction in operating stresses corresponds to the lower density and higher thermal diffusivity of TiAl relative to Inconel 713.

Thirty TiAl wheels produced by the counter-gravity casting method were procured, in addition to more than 30 wheels produced by a second supplier using a gravity investment casting process. Analysis of the castings produced with these two techniques is ongoing to determine the optimum and most cost-efficient process for the application. Test bars for

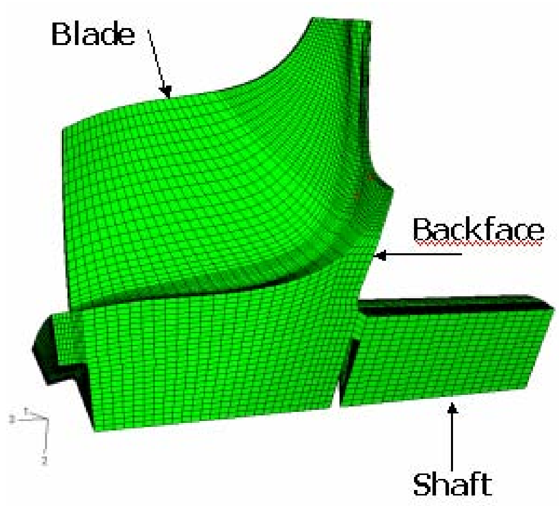

Figure 2. Mesh of an angular section of the wheel modeled in ABAQUS®. Using TiAl reduces the operating stresses by approximately 50% relative to Inconel 713.

welding experiments and material characterization were procured in addition to the wheel castings.

Test bars were machined from the wheel and shaft materials. The surfaces of the TiAl wheels were conditioned for friction welding trials. The cross section of the TiAl bars used for welding experiments was identical to that of the wheels. Joints were produced between the TiAl and the shaft material using bar-to-bar and shaft-to-wheel configurations. The friction welding process parameters were varied to produce the joints, and the resulting bar-to-bar jointed specimens were tested to failure in bending. A combination of parameters was established that produced bar-to-bar joints with a strength higher than that of the TiAl base material. Friction welding experiments showed a large dependency of the quality of the weld on the different process parameters. In addition, mass changes were shown to have a significant impact on the strength of the welds. This effect was evident after TiAl bars were welded to bars of the shaft material, producing joints with strength higher than that of the base TiAl. The conditions that produced strong bar-to-bar welds were used to make two prototype shafted wheels. Weak, flawed joints with a strength of approximately 50 MPa resulted; this was attributed to the higher heat dissipation from the weld area due to the increase in thermal inertia and resulting sharper temperature gradients.

Simulation was conducted to increase understanding of the sensitivity of the joint strength to the different process parameters. Modeling of the friction welding process was conducted using commercial simulation tools and customized user subroutines. Analyses were conducted using systematic combinations of rotational speed, frictional and forge loads, and frictional time and evaluating the effect of these factors on the resulting temperatures and thermal stresses. A proportional relation between the severity of the temperature gradients and the thermal inertia was observed. A higher thermal inertia increases the severity of the temperature gradients, which leads to higher thermal stresses and cracking. This correlates with cracking observed on the heat-affected zone of the shafted wheels.

Simulation results were used to define improved processing conditions for an additional round of welding experiments; and 16 additional joints, including bar-to-bar and shaft-to-wheel joints, were produced. The jointed specimens were heat-treated to relieve stresses, machined to remove the flash, and subjected to non-destructive evaluation (NDE). After NDE, the specimens were tested to failure in tension, and the tensile strengths were recorded. Subsequently, fractography was conducted to determine the nature of the failures and to correlate with features observed with NDE. The strength of the joints was increased in this round of tests, producing shafted wheels that, when tested in tension, failed away from the weld on the base TiAl material. However, the strength recorded was lower than expected for TiAl because of stress concentration. A parametric study is being conducted to modify the back face geometry of the turbine, with the purpose of increasing the overall strength of the component by reducing stress concentrations and thermal stresses. The results of the parametric study will be used for another iteration of welding experiments with the objective of completing the development of the joint.

Two different NDE techniques were used to identify subsurface defects on the weld and the heat-affected zone. A specimen with a poor weld was selected for initial evaluation to establish a baseline by identifying and characterizing features that are not desirable in sound welds, such as incomplete bonding and radial cracking. The first technique employed was eddy current, using a setup for automatic scanning by attaching the specimen to a turntable and controlling the vertical position of the probe. A prototype TiAl wheel shaft undergoing eddy current inspection is shown in Figure 3. The second

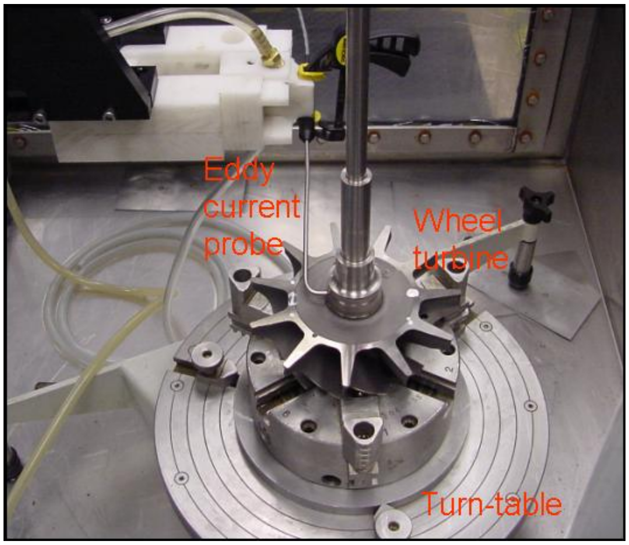

Figure 3. Shafted TiAl turbine wheel during NDE inspection.

technique was immersed ultrasound inspection, setting the specimen up in a similar automated configuration. Ultrasound inspection, with its finer resolution, showed not only the features observed with the eddy current but also smaller cracks. Features observed with both techniques were correlated with features observed on fractographic analysis, positively identifying defects on the weld plane as well as radial cracks.

A prototype HEAT® turbocharger was built using an Inconel 713 turbo wheel and tested on an internally designed Caterpillar gas stand as well as on an engine. The purpose of these prototype tests was to validate the compression capacity of the HEAT® turbocharger design and to obtain baseline data for comparison with a HEAT® turbocharger to be built using a TiAl turbo wheel. Steady and transient test results indicate that the HEAT® turbocharger likely has the potential to meet the performance and emission requirements of the engine after redesign of the wheel.

The decision was made to use one of the prototype TiAl wheel shafts produced during the second round of experiments to assemble a HEAT® turbocharger unit and to obtain all performance information possible in gas stand testing, knowing of the limited strength of its weld. This test was intended as a proof of concept and in no way intended to be a reliability or durability checkpoint. This HEAT® turbocharger unit was tested in the gas bench, and data were collected at two speed lines above 60,000 RPM. The weld failed at 330°C after 9 hours of operation and immediately following an engine surge. After failure, the loose wheel continued rotating inside the housing, impacting the leading edges with the housing, and four blade tips fractured. The wheel did not burst, even though it failed below its brittle-to-ductile transition temperature. Post-test inspection of the wheel revealed that the damage on the TiAl wheel blades was similar to that observed on Inconel wheels after a weld failure, even with the severity of impacts it received. These results strengthened the position of the entire team that TiAl has great potential for this application. Joints with strengths close to three times the strength of the specimen tested in the gas stand have been produced after iterations of experiments and simulation. Further gas stand testing will be conducted after fully optimizing these joints.

Joined by a representative from a turbocharger manufacturer, the Advanced Materials Technology and Air Systems team conducted on-site initial assessments of the TiAl casting processes of two suppliers. Test materials, including wheels and bars, have been procured from both suppliers and are under evaluation.

Conclusions

Titanium aluminide is an important material for less complex and more efficient air systems for Caterpillar engines. The lightweight nature of the material reduces the inertia of rotating components, enabling more compact and reliable turbocharger designs that will potentially lead to increased fuel efficiency and reduced transient emissions. An additional benefit of TiAl, demonstrated with finite element analyses, is the reduction of stresses during operation by 50% relative to Inconel 713, as a result of lower centrifugal loads and higher thermal diffusivity.

Initial assessment of two foundries was completed, and TiAl wheel castings and test bars were procured from both suppliers. Materials obtained from these suppliers have been used to develop a process to join the TiAl wheel to shaft materials. An iterative approach for this development has been applied, conducting welding experiments and simulation. Optimization of the geometry of the wheel and shaft and of friction welding parameters is ongoing to increase the overall strength of the component.

A methodology for conducting NDE of the wheel-shaft joints has been developed using eddy current and automated immersed ultrasound. Features observed on fractographic examination of specimens tested in tension have been positively correlated to features observed with the NDE techniques used.

A shafted TiAl turbine wheel was assembled into a turbocharger and tested on a gas stand rig. This test was intended as a proof of concept and not as a reliability or durability checkpoint. Damage on the wheel was similar to that observed on failures of Inconel 713 wheels. These results strengthened the position of the team that TiAl has great potential for this application. Joints with strength close to three times the strength of the specimen tested in the gas stand have already been produced after iterations of experiments and simulation. Further gas stand testing will be conducted after fully optimizing these joints.