J. Advanced Cast Austenitic Stainless Steels for High-Temperature Components

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Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Contract No.: DE-AC05-00OR22725

Objectives

- Commercialize new CF8C-Plus cast austenitic stainless steel.
- Complete a high-temperature properties database for test specimens from commercial heats and determine the properties of prototype components.

Approach

- Support Caterpillar (CAT) evaluation efforts to upgrade turbochargers from cast iron to cast austenitic stainless steel.
- Perform and evaluate direct comparisons between commercial CF8C-Plus steel and cast stainless steels used by component suppliers to establish performance benefits at 700–850°C.

Accomplishments

- Demonstrated that CF8C-Plus cast stainless steel is far superior to SiMo cast iron at 600°C and above. CF8C-Plus also shows strength, creep resistance and aging resistance benefits compared with other commercial cast stainless steels being considered for heavy-duty diesel turbocharger housings at 750°C.
- Successfully cast a good-quality 6700-lb gas-turbine end-cover from CF8C-Plus at MetalTek and cast >30,000 lb cast for various applications.

Future Direction

- Characterize the microstructure and properties of several different prototype CF8C-Plus steel components to facilitate various commercial applications.

- Evaluate the properties of commercial heats of new CF8C-Plus Cu/W steel, which boosts tensile and creep strength at 750°C and above.

Introduction

Advanced heavy truck diesel engines are increasingly required to have higher fuel efficiency and reduced exhaust emissions without sacrificing durability and reliability. The most demanding normal duty cycles require exhaust manifolds and turbocharger housing materials to withstand temperatures ranging from 70 to nearly 800°C. Such materials must withstand prolonged, steady high-temperature exposure (which requires tensile strength and creep and oxidation resistance) as well as more rapid and severe thermal cycling (which requires resistance to aging and thermal fatigue). New emissions reduction technology and transient power excursions can push temperatures in these critical components even higher.

Higher diesel engine exhaust temperatures push components made from SiMo ductile cast iron well beyond their current strength and corrosion limits. The first Oak Ridge National Laboratory (ORNL)/CAT cooperative research and development agreement (CRADA) (3y) developed a new, modified CF8C cast austenitic stainless steel (CF8C-Plus) as an upgrade alternative to SiMo cast iron and performed the initial mechanical properties testing on a lab-scale heat. The CF8C-Plus steel was found to have outstanding creep resistance at 850°C. The second ORNL/CAT CRADA project (3y) capitalized on the initial success and began commercial scale-up of the new CF8C-Plus. The new material was found to have good castability, as well as much better mechanical properties at 600–850°C than standard CF8C steel, including resistance to aging, creep, and fatigue/thermal fatigue. The new CF8C-Plus cast steel won a 2003 R&D 100 Award, and in 2004 testing continued of different commercial casting process effects (static, centrifugal, and larger heats). This year, efforts to commercialize CF8C-Plus expanded dramatically, and this CRADA project was extended for 2 more years. In 2004–2005, successful casting trials of CF8C-Plus were carried out for components ranging from exhaust manifolds to industrial turbine casing. In addition, the first commercial heats of CF8C-Plus Cu/W were made in 2004–2005 to boost strength and creep resistance at 750–850°C. Three companies have taken trial licenses and, to date, over 30,000 lb of the new steel has been produced commercially.

Approach

In 2005, three U.S. foundries obtained trial licenses for CF8C-Plus steel: MetalTek International, Wollaston, and Stainless Foundry and Engineering. CAT and ORNL both ordered additional heats of CF8C-Plus and cast pieces in various sizes, using both static casting in sand molds and centrifugal casting of rings of varying thickness, to enable more comprehensive mechanical properties testing. In addition, a large industrial gas turbine end-cover component cast for Solar Turbines (a CAT company) by MetalTek in FY 2004 was evaluated at the CAT Technical Center for quality and defects and then cut up for mechanical testing. ORNL also had MetalTek make a 500-lb commercial heat of the new CF8C-Plus Cu/W, selected for testing from screening of lab-scale heats, to evaluate further improvements in strength and creep-resistance above 750°C. Finally, CAT began exploring CF8C-Plus steel and other commercial cast stainless steels to replace SiMo cast iron for turbocharger casing applications, which should enable increased durability at the increased engine temperatures needed to allow a 3% decrease in fuel consumption for on-highway trucks. Both CAT and ORNL do specific mechanical properties testing and microcharacterization in support of these various applications or efforts.

Technical Progress

Caterpillar

The large industrial turbine end-cover cast of CF8C-Plus steel (8000-lb heat to yield 6700-lb finished component) by MetalTek for Solar Turbines was shipped to the CAT Technical Center, as shown in Figure 1. Visual and other inspection techniques showed no defects. Then sectioning was completed, and those initial observations also found no obvious cases of hot tearing at the side flange. This is significant because fully austenitic alloys such as CF8C-Plus are usually more susceptible to hot tearing than similar steel with a much higher δ-ferrite content (standard CF8C steel has 15–25% such

Figure 1. A-6700-lb gas turbine combustor housing centrifugally cast from CF8C-Plus stainless steel by MetalTek. No indications of hot tearing have been observed (M. J. Pollard is pictured with the casting).

content). Further nondestructive analysis will be performed to ensure a complete absence of internal hot tears. Fatigue and mechanical properties test samples of the bulk material from this housing have been produced, and mechanical testing began at the end of FY 2005. It is hoped it will show that the properties do not change significantly in thick-section components (slow cooling rates) compared with smaller test castings (faster cooling rates).

The 21st Century Truck Partnership technical goal of developing emission-compliant engine systems for Class 7–8 highway trucks is an improvement in engine efficiency from 42 to 50% by 2010. CAT has determined that replacing SiMo cast iron exhaust components with CF8C-Plus cast stainless steels allows a 90°C increase in exhaust gas temperatures, which translates directly into a 3% increase in fuel economy while also significantly improving performance and durability. Efforts to produce prototype cast stainless exhaust manifolds and turbocharger housings began this year. New stainless steel diesel-engine turbocharger housings have been ordered for a small quantity off-road diesel engine application. Because of current supplier agreements, these first trial turbo-housings are being cast from a standard commercial stainless alloy, KN2, produced by Diado in Japan. However, another part of this effort is side-by-side testing of KN2 and CF8C-Plus cast steels at ORNL to directly compare properties. This prototyping effort will give the designers at CAT confidence with cast stainless steel as well as experience with the necessary design changes for cast stainless.

ORNL

In 2004, ORNL began the creep testing that showed an overwhelming advantage of CF8C-Plus steel over SiMo cast iron in terms of tensile and creep-rupture strength and thermal fatigue resistance above 550–600°C. That creep-rupture testing was expanded and completed and includes comparison of CF8C-Plus with standard CF8C steel and Ni-resist austenitic cast-iron (an upgrade for some applications relative to SiMo cast-iron). The results of various creep rupture tests at different temperature and stress levels are plotted as a function of the Larson-Miller parameter (LMP) in Figure 2. CF8C-Plus cast steel is much stronger than either SiMo or Ni-resist cast-irons, and it is almost twice as strong as standard CF8C steel. The latter comparison is important to the potential gas- and steam-turbine applications, as well as many other chemical/petrochemical, energy, or metals processing applications.

Creep-rupture ductility is shown in Figure 3. Clearly, CF8C-Plus has much more creep ductility than standard CF8C steel, despite also being stronger. This is due to the lack of δ-ferrite in the as-cast structure of CF8C-Plus, which makes it resistant to the formation of embrittling σ-phase during aging.

Finally, comparison of CF8C-Plus cast stainless with the best commercially available creep-resistant austenitic stainless steels and alloys on an LMP plot (Figure 4) shows that CF8C-Plus is as strong as or stronger than NF709 austenitic stainless alloy, and comes close to the creep-strength of alloy 617, a Ni-Cr-Co superalloy, particularly at the highest temperatures.

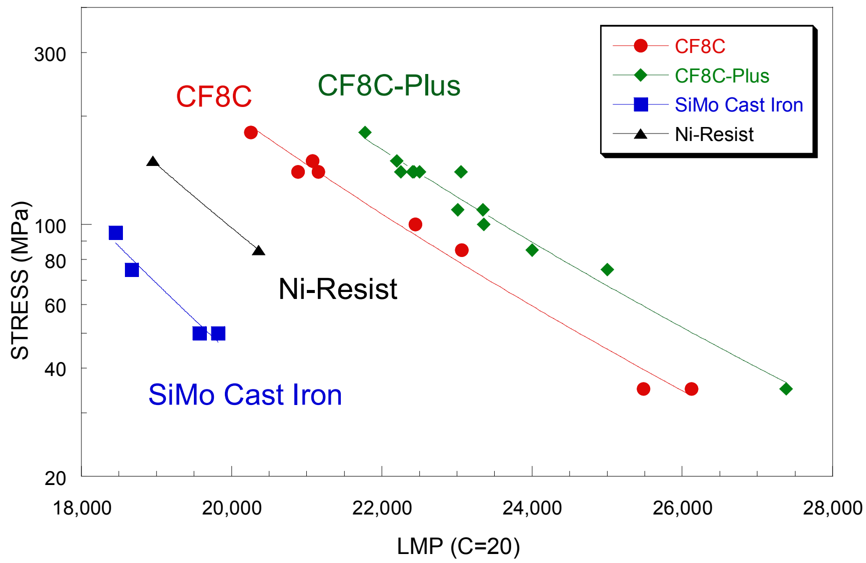

Figure 2. Creep-rupture stress plotted vs LMP for various ORNL creep-rupture tests at 500–850°C in air of various commercial heats of SiMo ductile and Ni-resist austenitic cast irons and standard CF8C and CF8C-Plus. CF8C-Plus shows significant creep-strength advantage over the standard steel or the cast irons.

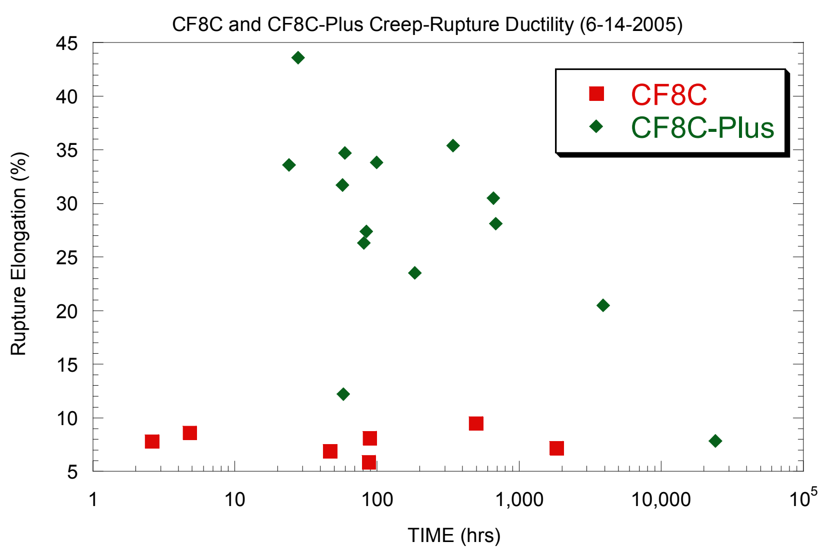

Figure 3. Comparison of creep rupture ductility data vs rupture time for cast CF8C-Plus and standard CF8C (same data as in Figure 2) for creep-rupture testing in air at 650–850°C and 35–200 MPa.

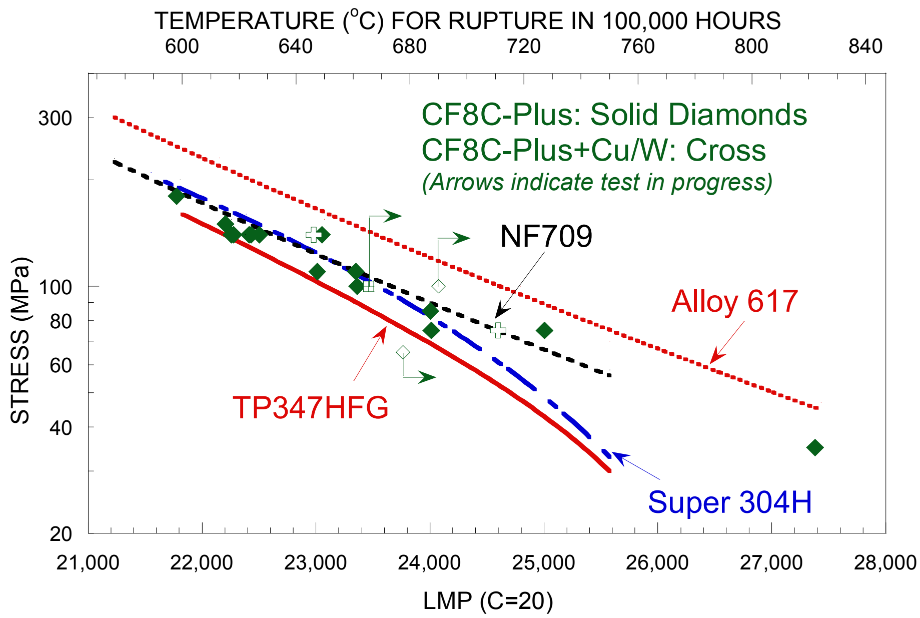

Figure 4. Creep-rupture stress plotted vs LMP for various ORNL creep-rupture tests at 700–850°C in air of CF8C-Plus and CF8C-Plus Cu/W. CF8C-Plus has better creep-strength than most wrought heat-resistant austenitic stainless steels and alloys and compares well with alloy 617, a Ni-Cr-Co superalloy.

In FY 2005, ORNL began testing new commercial scale-up heats of CF8C-Plus Cu/W produced by MetalTek. A 500-lb heat of the new CF8C-Plus Cu/W was cast as centrifugal rings and as kiel blocks in sand, together with similar castings of CF8C-Plus and standard CF8C steels for comparison. The CF8C-Plus Cu/W has higher yield-strength than CF8C-Plus at 600–900°C, and the few creep-tests conducted indicate better creep strength as well (Figure 4). Comparison of creep-strain versus time plots for tests at 750°C (Figure 5) clearly shows that the new CF8C-Plus Cu/W has a

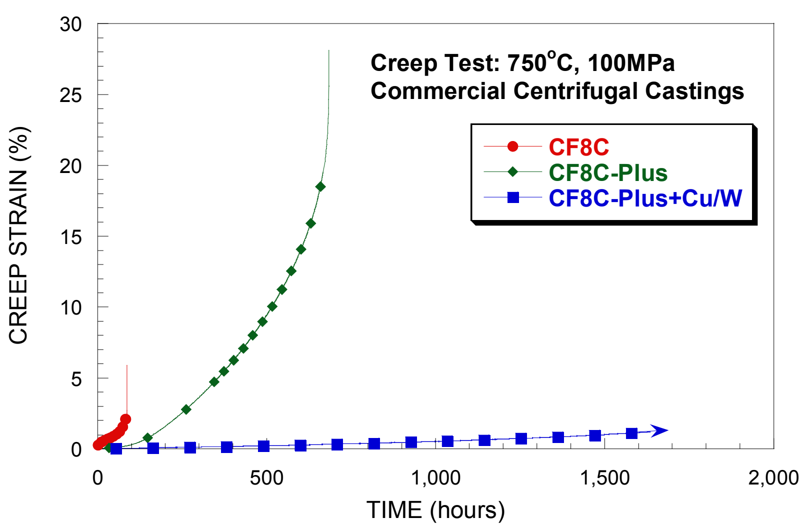

Figure 5. Plots of creep-strain vs time for heats of standard CF8C, CF8C-Plus and the new CF8C-Plus Cu/W, all tested in air at 750°C. Clearly the CF8C-Plus Cu/W has much more creep-resistance, with an extended secondary creep-regime and a very low steady-state creep rate.

prolonged period of creep at a very low creep rate (secondary creep regime) relative to standard CF8C or CF8C-Plus steels.

In 2006, ORNL will continue testing and aging studies on the new CF8C-Plus Cu/W steel. ORNL will also finish and analyze the side-by-side comparison of CF8C-Plus and the Diado KN2 cast stainless steels to support and enable CAT's development of cast stainless steel turbocharger housings.

Conclusions

ORNL and CAT have finished the initial commercialization phase for CF8C-Plus cast stainless steel, and have begun the second stage of producing more and larger heats of steel. They will expand the preliminary testing and include long-term aging, creep-rupture and more complex mechanical testing (fatigue, thermal-fatigue and creep-fatigue) and begin commercial component casting trials. To date, more than 30,000 lb of commercial CF8C-Plus stainless steel has been cast for various applications, and all prototype component castings have been successful on the first trial as a result of good castability. Efforts to expand commercial applications and facilitate licensing continue.

For advanced diesel-engine exhaust manifold and turbocharger applications, CF8C-Plus steel has an overwhelming high-temperature strength and creep-resistance advantage over conventional exhaust component materials, such as SiMo or Ni-resist cast irons. CF8C-Plus also has enough of a creep-rupture strength advantage over standard CF8C steel and other heat-resistant stainless steels and alloys that it is being considered and tested for gas turbines, advanced steam turbines, and various other applications.

Based on ORNL lab-scale trial heats, a new heat of CF8C-Plus Cu/W has been melted commercially by MetalTek. Testing began this year and will continue next year. The CF8C-Plus Cu/W has better yield strength than CF8C-Plus at 600°C and above, and preliminary creep testing at 750°C shows improved creep resistance as well.

Publications/Presentations

P. J. Maziasz, I. G. Wright, J. P. Shingledecker, T. B. Gibbons, and R. R. Romanosky, "Defining the Materials Issues and Research Needs for Ultra-Supercritical Steam Turbines," pp. 602–622 in *Proc. 4th Internat. Conf. on Advances in Materials Technology for Fossil Power Plants*, ASM-International, Materials Park, Ohio, 2005.

J. P. Shingledecker, P. J. Maziasz, N. D. Evans, and M. J. Pollard, "Creep Behavior of a New Cast Austenitic Alloy," to be published in *Proc. ECCC Conference on Creep and Fracture in High Temperature Components—Design and Life Assessment Issues,* London, UK, September 12–14, 2005.

J. P. Shingledecker, P. J. Maziasz, N. D. Evans, and M. J. Pollard, "Alloy Additions for Improved Creep-Rupture Properties of a Cast Austenitic Alloy," pp. 129–138 in *Proc. Conf. Creep Deformation and Fracture, Design, and Life Extension*, The Materials Society, Warrendale, PA, 2005.

P. J. Maziasz, J. P. Shingledecker, N. D. Evans, and M. J. Pollard, "Update on ORNL/CAT CRADA on CF8C-Plus Cast Stainless Steel: Progress on Commercial Scale-Up in 2004/2005," presented at DOE FreedomCAR and Vehicle Technologies Review at Oak Ridge National Laboratory, March 2, 2005.

M. J. Pollard, P. J. Maziasz, and J. P. Shingledecker, "Development of Low-Cost Cast Austenitic Stainless Steel for Diesel Engine and Gas Turbine Applications," presented at DOE Project Review at Caterpillar, Peoria, Illinois, April 27, 2005.

P. J. Maziasz, J. P. Shingledecker, N. D. Evans, and M. J. Pollard, "Development, Properties, and Applications of CF8C-Plus," presented during a visit to Stainless Foundry and Engineering, Inc., Milwaukee, Wisconsin, June 16, 2005.

P. J. Maziasz, J. P. Shingledecker, N. D. Evans, and M. J. Pollard, "Development, Properties, and Applications of CF8C-Plus," presented during a visit to MetalTek International, Waukesha, Wisconsin, June 27, 2005.

J. P. Shingledecker, P. J. Maziasz, N. D. Evans, and M. J. Pollard, "Creep Behavior of a New Cast Austenitic Alloy," plenary session talk at the European Creep Collaborative Committee (ECCC) Conference on Creep and Fracture in High-Temperature Components—Design and Life Assessment Issues, London, UK, September 12–14, 2005.

Special Recognitions and Awards/Patents Issued

The review panel for the FY 2005 DOE Heavy Vehicles Materials Program Merit Review and Peer Evaluation Meeting awarded this project the highest overall score in the Heavy Vehicles Propulsion Materials sub-program. The project also received the highest individual evaluation category grades for relevance, technical accomplishments, and technology transfer.

The original patent application for both CF8C-Plus and CN-12-Plus filed in 2000 by Caterpillar was split and continued as two patents: "Heat and Corrosion Resistant Cast CN-12 Type Stainless Steels With Improved High Temperature Strength and Ductility" (US 2003/0084967) and "Heat and Corrosion Resistant Cast CF8C Stainless Steels With Improved High Temperature Strength and Ductility" (US 2003/0056860), both by P. J. Maziasz and R. W. Swindeman (ORNL), T. McGreevy (University of Bradley/CAT), M. J. Pollard, and C. W. Siebenaler (CAT). Actions to obtain final patent approval continued in FY 2005.