

CF8C-PLUS HEAT-RESISTANT CAST STAINLESS STEEL

CF8C-Plus is a new cast austenitic stainless steel now being commercialized. It has better high-temperature strength and reliability than more expensive high-nickel alloys.

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A cost-effective heat-resistant cast austenitic stainless steel with better performance, reliability, and temperature capabilities than many nickel-base alloys was designed and developed in 2002 by Oak Ridge National Laboratory and Caterpillar Inc. Called CF8C-Plus, serious commercialization activities did not begin until about January 2007.

The initial story about the scientific development and its scale-up from the lab to commercial heats in about one year, was told in *AM&P* in 2003, just after CF8C-Plus steel won an *R&D100* Award. This article updates the properties data and highlights some important scale-up and component prototyping efforts over the last five years.

Commercialization efforts

Formidable barriers work to slow or even prevent commercializing any new alloy or material, especially the substantial time and effort required to generate the needed data. Designers require thorough physical and mechanical properties databases, including long-term behavior to qualify new materials for service. They are reluctant to upgrade to a new unproven alloy, or a different alloy that requires components to be re-designed.

Commercialization usually also requires patents for licensing, capable foundries willing to cast the new alloy, and end-users brave enough to try it. For CF8C-Plus steel, those pieces began to fall into place in 2006/2007, with the first U.S. Patent and Caterpillar's own commercialization for a critical diesel exhaust component.

Today, well over 300 tons of CF8C-Plus stainless steel have been cast for an exhaust component in

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Fig. 1—Mike Pollard stands next to a prototype centrifugal casting of the end-cover for the Solar Turbines Mercury 50 recuperated gas turbine engine at the Caterpillar Technical Center. It was cast with DF8C-Plus steel by MetalTek International in 2005. An 8000-pound cast heat produced the 6700-pound component.

Caterpillar's on-highway diesel engines since January 2007. An application for a new heat-resistant cast alloy grade for CF8C-Plus (HG10MNN) was made to ASTM A297 Committee in May 2007. Testing is also underway for a wider range of diesel and automotive exhaust components, and for gas-turbine structural components.

Creep testing

Since 2003, a considerable number of creep-rupture tests have generated data on the cast CF8C-Plus steel at 600 to 850°C. Results clearly show that it has far more creep strength than the standard cast irons typically in diesel exhaust components, and almost twice the creep strength of standard CF8C steel (Fig. 2). Alloy compositions are shown in the table.

Creep resistance close to that of the wrought nickel-base superalloy 617 is provided by both the CF8C-Plus steel and the newer CF8C-Plus Cu/W version, which shows even higher strength at 750°C, although alloy 617 is about seven times more costly (Fig. 3). All the CF8C-Plus steel specimens were creep-tested in the as-cast condition, with no additional heat treatments.

Despite its much higher creep-strength, the CF8C-Plus steel still has 20 to 35% creep-rupture ductility at 600 to 850°C, compared to <10% creep-ductility for the standard CF8C steel. This difference in ductility is directly related to as-cast microstructure differences:

- CF8C steel has 15 to 25% delta-ferrite phase

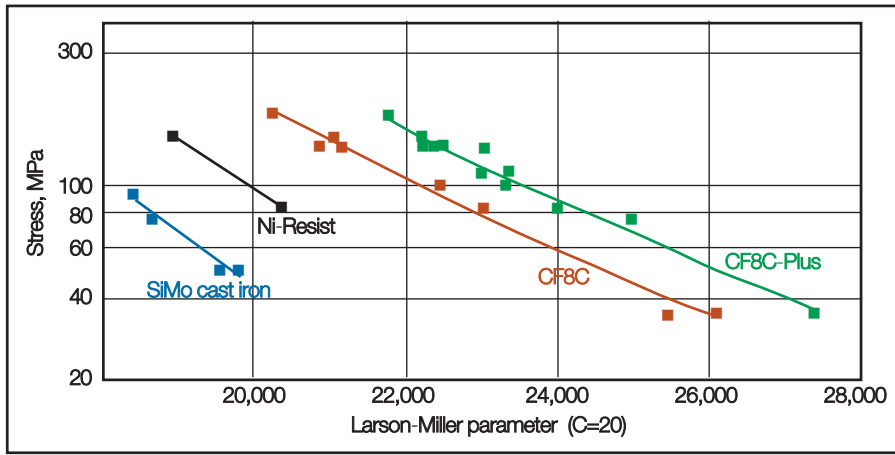


Fig. 2— A plot of creep-rupture stress as a function of Larson-Miller Parameter (LMP), calculated from the rupture time and creep-test temperature, for standard CF8C and the new CF8C-Plus cast austenitic stainless steel, and two cast-iron alloys commonly used for diesel exhaust components.

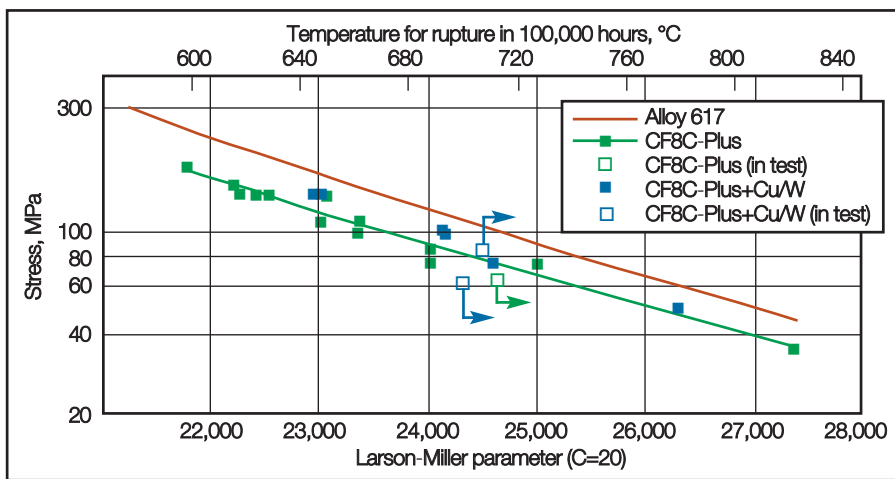


Fig. 3— A plot of creep-rupture stress as a function of Larson-Miller Parameter (LMP), calculated from the rupture time and creep-test temperature, for the new CF8C-Plus and CF8C-Plus Cu/W cast austenitic stainless steels, and the wrought Ni-based superalloy 617, which can be used for very high temperature applications, but is about 7 times more expensive than CF8C-Plus steel.

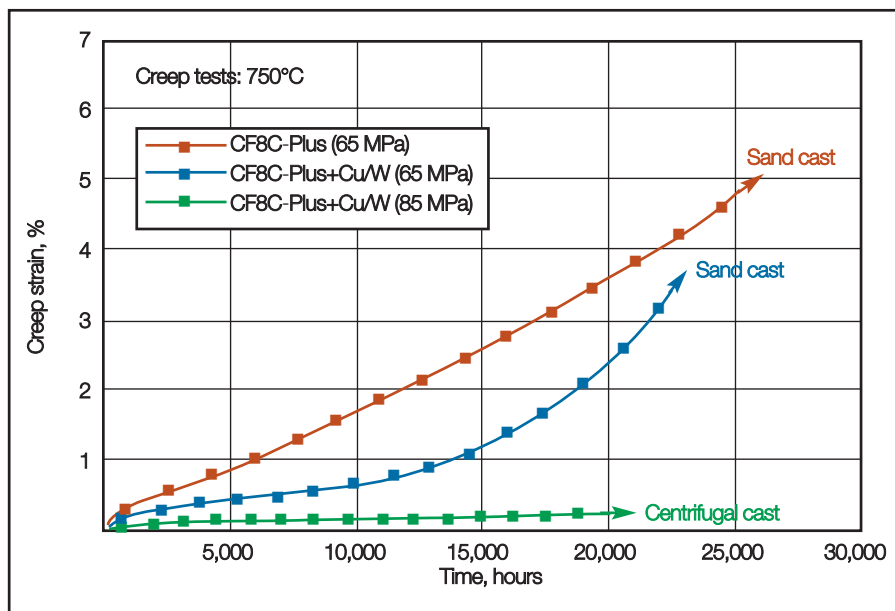


Fig. 4— A plot of creep strain versus time for several long-term tests of CF8C-Plus and CF8C-Plus Cu/W cast austenitic stainless steels. The CF8C-Plus Cu/W steel rapidly hardens to a much lower secondary creep-rate relative to the CF8C-Plus steel.

formed during casting, which then readily transforms to sigma phase during aging or creep. This reduces creep ductility.

- CF8C-Plus steel has no delta-ferrite formed during casting, and hence forms no sigma-phase during aging or creep, even after creep testing at 850°C for 24,000 hours. Microstructural analysis of selected creep-tested specimens shows that the CF8C-Plus steel is strengthened by nanoscale precipitate dispersions of both niobium carbides and Nb/Cr nitrides.

- The new cast CF8C-Plus Cu/W has even more creep resistance than CF8C-Plus steel at 750°C, mainly due to a very low secondary creep-rate (Fig. 4).

Castability and weldability

Since the initial commercial scale-up experiments, CF8C-Plus austenitic stainless steel has shown excellent metal fluidity compared to standard CF8C steel and other comparable cast alloy grades, due mainly to its higher manganese content. In addition, CF8C-Plus cast steel parts require no additional heat treatments, which saves effort, time, and money

- **Stainless Foundry & Engineering (SF&E)** has cast thin sections via step-castings. The company measured metal fluidity by means of fluidity spirals in late 2006, and found CF8C-Plus steel to have good metal fluidity relative to other standard grades such as CF8M steel. The good metal fluidity is manifested in an incredible track record of excellent first-part trials with CF8C-Plus steel, from 45-pound exhaust components for natural gas reciprocating engines, to a 6700-pound end-cover for recuperated industrial gas turbines.

- **MetalTek International** has centrifugally cast the end-cover for a Solar Turbines Mercury 50 recuperated low NO_x gas turbine engine (4.6 MW) from an 8000-pound heat of CF8C-Plus steel (Fig. 1). The test component showed no hot-tearing on the new flange designed for the recuperator, no surface defects or cracking, and no internal cracking upon sectioning.

Another substantial advantage for commercial application of CF8C-Plus cast stainless steel is its good weldability. Although several different component trials showed some hints of good weldability, the first quantitative measure of good weldability and good mechanical properties of welds came as part of the ASTM new alloy grade

Alloy compositions, wt%

Alloy	Fe	Cr	Ni	Mn	Nb	Mo	C	N	Si
CF8C	bal	19	10	<1	0.8	0.3	0.07	0.02	1.0
CF8C-Plus	bal	19	12.5	4	0.8	0.3	0.1	0.25	0.5
SiMo	bal	—	—	0.3	—	0.6	3.45	—	4.0
Ni-Resist	bal	2	35	0.5	—	—	1.9	—	5.0
617 ^a	1.5	22	bal	1	—	9	0.1	—	1

a - wrought, with 12 Co, 0.4 Ti, and 1.2 Al

application (HG10MNN) to the A297 Committee by SF&E. Cast plates were welded together, as prescribed by the ASTM rules, and both U-bend and tensile tested specimens from those welded plates showed excellent ductility of the welds. Good weldability also indicates that cast components could be readily weld-repaired, if needed, or that cast components could be welded together to build more complex structures.

Commercialization

The push toward commercialization began in earnest in about the middle of 2006, with two parallel efforts at Caterpillar and at ORNL.

- **At Caterpillar**, component prototyping and validation testing was underway for the Caterpillar Regeneration System (CRS) components cast of CF8C-Plus stainless steel. The CRS unit was designed to regenerate the ceramic diesel particulate filter (DPF) required to meet the stringent new regulations restricting diesel particulate exhaust emissions for on-highway truck engines in January, 2007. The CRS burner unit undergoes rapid thermal cycling to very high temperatures during the regeneration cycle. To date, over 300 tons of CF8C-Plus stainless steel have been cast for the CRS unit application, and none of these units has failed during service.

- **At ORNL**, a joint effort with Caterpillar and SF&E also began in 2006 to pull together all available data on commercial CF8C-Plus stainless steel heats, focused on room temperature tensile properties from at least ten heats. Welded plates were made and tested, and a package was then put together for the ASTM A297 Committee to acquire a new alloy designation, HG10MNN. The data package was submitted in May 2007 and is in the final approval stages now.

Commercial licensing opportunities became feasible when the first U.S. Patent (7,153,373 B2) for CF8C-Plus steel was granted on Dec. 26, 2006. Other U.S. and foreign patents, filed by Caterpillar, are currently pending. The first non-exclusive commercial license for CF8C-Plus stainless steel was signed between Caterpillar Inc. and Stainless Foundry & Engineering in May 2008.

Currently, Caterpillar, ORNL, and Honeywell Turbo Technologies are engaged in a collaborative effort to test CF8C-Plus steel for turbocharger housing applications for on-highway heavy-duty truck diesel engines. Recently in 2008, ORNL and Honeywell Turbo Technologies signed a Collaborative Research and Development Agreement (CRADA) to focus on this specific commercial application.

In 2007/2008, ORNL was awarded substantial funding for about a year by the Technology Commercialization and Development Program, of the Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy. The goal is to facilitate the detailed testing needed to qualify cast CF8C-Plus stainless steel for the turbocharger housing application.

Commercial licensing

The CF8C-Plus (and CF8C-Plus Cu/W) cast stainless steel technology is available for general exclusive or non-exclusive commercial licensing in various fields-of-use through either Caterpillar or ORNL. Both organizations have executed agreements to share patent rights and royalties, so that an agreement signed with one partner includes the other.

To date, a trial license has been signed by a major U.S. gas-turbine OEM to test CF8C-Plus stainless steel for internal turbine components. Several gas turbine OEMs have indicated an interest in cast CF8C-Plus steels for turbine-casing structural applications. Within the last year, other companies have also expressed initial interest in CF8C-Plus steel as an alternative to wrought or cast Ni-based superalloys for various other high-temperature component applications. ●

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