ORNL/TM-2014/632

CRADA Final Report for CRADA Number NFE-08-01671 Materials for Advanced Turbocharger Designs

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Materials Science and Technology Division

CRADA Final Report for CRADA Number NFE-08-01671
Materials for Advanced Turbocharger Designs

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Final CRADA Report NFE-08-01671 –Materials for Advanced Turbocharger Designs

Abstract

Results were obtained on residual stresses in the weld of the steel shaft to the Ni-based superalloy turbine wheel for turbochargers. Neutron diffraction studies at the HFIR Residual Stress Facility showed asymmetric tensile stresses after electron-beam welding of the wheel and shaft. A post-weld heat-treatment was found to relieve and reduce the residual stresses. Results were also obtained on cast CF8C-Plus steel as an upgrade alternative to cast irons (SiMo, Ni-resist) for higher temperature capability and performance for the turbocharger housing. CF8C-Plus steel has demonstrated creep-rupture resistance at 600-950°C, and is more creep-resistant than HK30Nb, but lacks oxidation-resistance at 800°C and above in 10% water vapor. New modified CF8C-Plus Cu/W steels with Cr and Ni additions show better oxidation resistance at 800°C in 10% water vapor, and have capability to higher temperatures. For automotive gasoline engine turbocharger applications, higher temperatures are required, so at the end of this project, testing began at 1000°C and above.

Statement of Objectives

The objectives of this CRADA were to assess the materials upgrade opportunities for the turbine and the compressor sides of the turbocharger system, and to evaluate new materials for advanced turbocharger systems. The weld for the turbine wheel and shaft was addressed in terms of residual stress investigations using neutron scattering techniques and processing (heat-treatment) solutions. The challenge of upgrading the turbocharger housing from cast irons to cast stainless steels and alloys was addressed for diesel engine applications (750-800°C) and gasoline engine applications at higher temperatures.

Benefits to DOE/EERE/OVT Mission

The Office of Vehicle Technologies benefits from this CRADA because there is a key technical gap in the Propulsion Materials Program that supports the Advanced Combustion Engine goal to improve thermal efficiency by 20% over the baseline current efficiency in a commercial engine by 2020. Higher engine temperatures required for improved efficiency cause unacceptable creep, fatigue and oxidation of current materials. The objective of this CRADA is to provide advanced turbocharger housing materials with higher temperature capability that contribute directly to this DOE mission goal. The CRADA strategy to reduce the research time between testing and implementing new materials also benefits the timeframe of this DOE mission goal.

Technical Discussion of Work Performed

Residual Stresses in Turbine Wheel/Shaft Components

This CRADA project began in September, 2009, and consists of six tasks, which spanned the 3 year duration of this project. ORNL and Honeywell discussed the priority of various tasks and turbocharger components for materials upgrades at a kick-off meeting held in Torrance, CA in October, 2009. The turbine wheel-shaft assembly was chosen as the first component for analysis of residual stresses near the weld-joint of the Ni-based superalloy wheel to the steel shaft, using neutron-scattering at the HFIR reactor at ORNL. A typical wheel/shaft assembly (WSA) was used for the ORNL residual stress measurements. The Neutron Residual Stress Facility 2 (NRSF2) at the HFIR is shown in Figure 1, with a WSA in place for neutron scattering measurements. Several sets of experiments were completed, and show that there is an asymmetry in the residual stress circumferentially in the as-welded condition (Fig. 2).

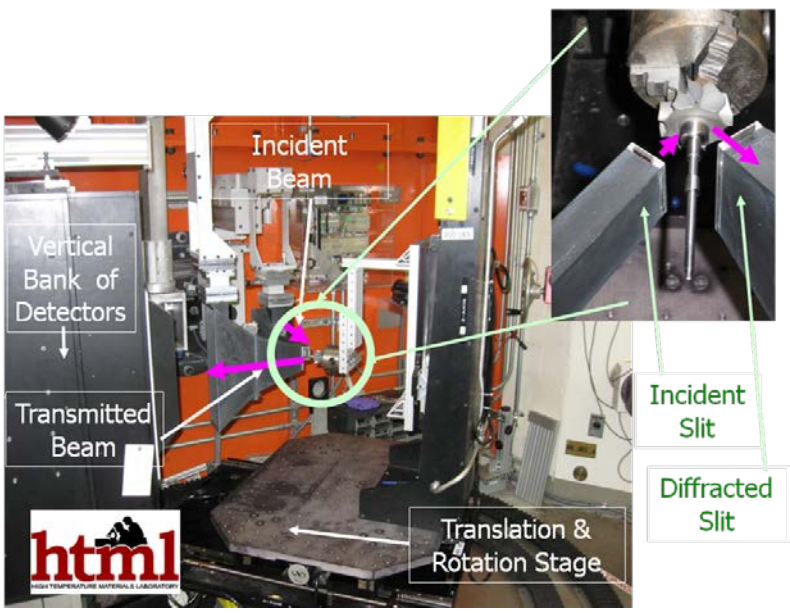

Figure 1 – The Neutron Residual-Stress Facility 2 (NRSF2) at the HFIR beam port, with the specific neutron scattering geometry used for the Honeywell turbocharger wheel/shaft assembly shown in the magnified inset. The NRSF2 was part of the High Temperature Materials Laboratory (HTML) at ORNL, and these experiments were run by Tom Watkins and Cam Hubbard of the Residual Stress User Center.

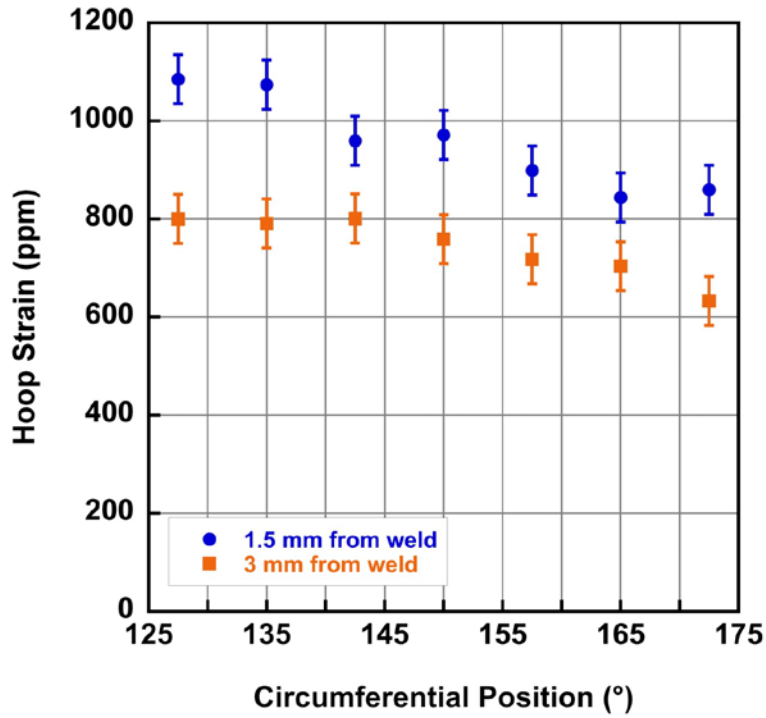

Figure 2 – Neutron scattering results show an asymmetric tensile hoop strain near the weld joint of the wheel/shaft assembly with no heat-treatment after welding. These experiments were run by Tom Watkins and Cam Hubbard of the Residual Stress User Center at the NRSF2 at the HFIR.

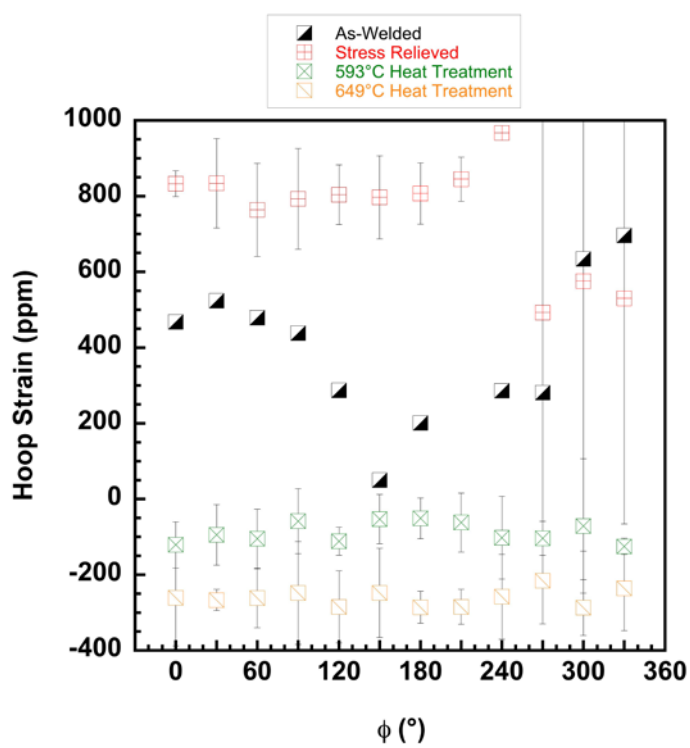

Figure 3 – Neutron hoop strain maps versus circumferential angle of wheel/shaft assemblies in 4 different conditions, as-welded, stress relieved via fast induction coil heating, and conventional furnace stress relief heat treatments at 593 and 649°C. Error bars represent multiple measurements. Furnace stress relief at 593°C reduces the residual stresses and their asymmetry.

Additional measurements were done on larger WSA components with stainless steel shafts, and the asymmetric residual hoop stresses present after welding are shown in Figure 3. Stress relief of the welded regions was done with fast induction-coil heat up, and two conventional furnace heat-treatment conditions at 593 and 649°C. It is implied from Figure 3 that the induction coil stress relief (SR) does not significantly reduce the tensile residual stresses or remove their asymmetry. In fact, the residual stress increases slightly and the point of asymmetry moves. By contrast, the conventional furnace heat-treatment at 593°C is relatively effective at removing both the residual stresses and their asymmetry.

High Temperature Creep Strength and Performance of Turbine Housing Steels and Alloys

The next priority of problems to be solved was the issue of upgrading the temperature capability and durability of turbocharger housings, which for many applications are made of cast irons (SiMo and Ni-resist). Advanced creep-resistant cast austenitic stainless steels like CF8C-Plus are a potential performance upgrade, and are cost effective relative to higher Ni alloys like Ni-resist cast iron and HK30Nb cast stainless steel. Additional testing was done to extend previous CRADA work by ORNL and Honeywell comparing the new CF8C-Plus steel to HK30-Nb, a standard commercially available upgrade material for turbochargers for heavy-duty truck diesel engines (Fig. 4) when temperatures exceed the limitations of SiMo cast iron [1]. Previous work clearly showed that CF8C-Plus had better yield strength at 800 and 900°C than HK30Nb, as shown in Fig. 4. Previous creep-testing at several different conditions at 700-900°C also clearly showed that CF8C-Plus steel had better creep-resistance than the HK30-Nb alloy, as shown in Fig. 5 [1]. New creep data at ORNL conditions not specified by Honeywell showed that CF8C-Plus steel has several thousand hours creep life relatively high stresses at 750-850°C, as shown in Fig. 8. Comparison of HK30Nb at 750°C/100MPa shows that it has significantly less creep rupture life than CF8C-Plus stainless steel (Fig. 6). This creep-rupture testing was adequate for qualifying CF8C-Plus for diesel engine turbocharger applications where maximum temperatures are 750-800°C. However, higher temperature tests, both oxidation and creep-rupture, were needed to qualify CF8C-Plus steel for automotive gasoline engine applications.

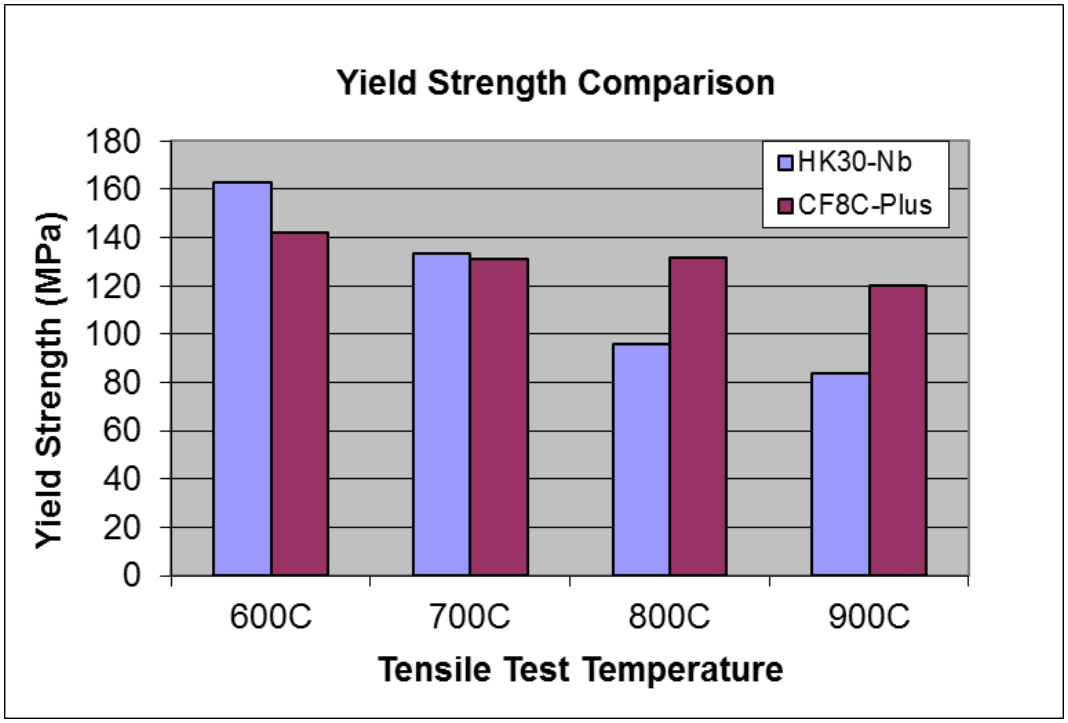

Figure 4 – Histogram of tensile yield strength at several test temperatures for cast CF8C-Plus steel and HK30Nb steel.

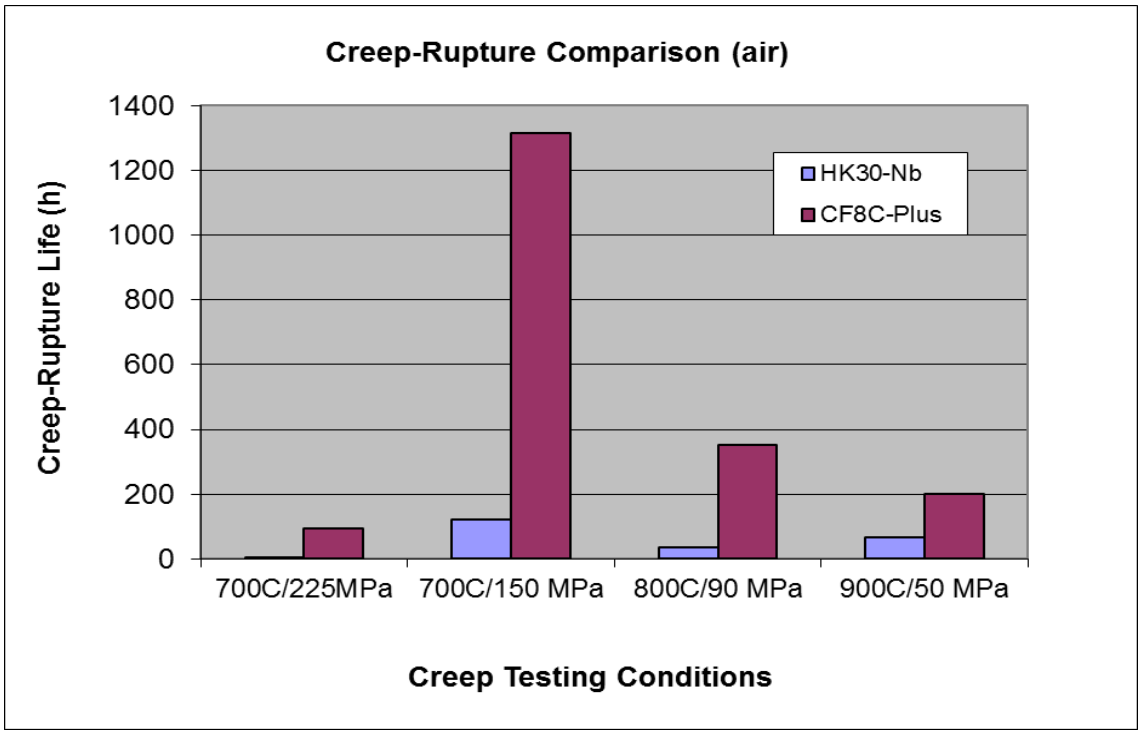

Figure 5 – Histogram of creep-rupture life of cast HK30Nb and CF8C-Plus stainless steels creep tested at various conditions at 700-900°C.

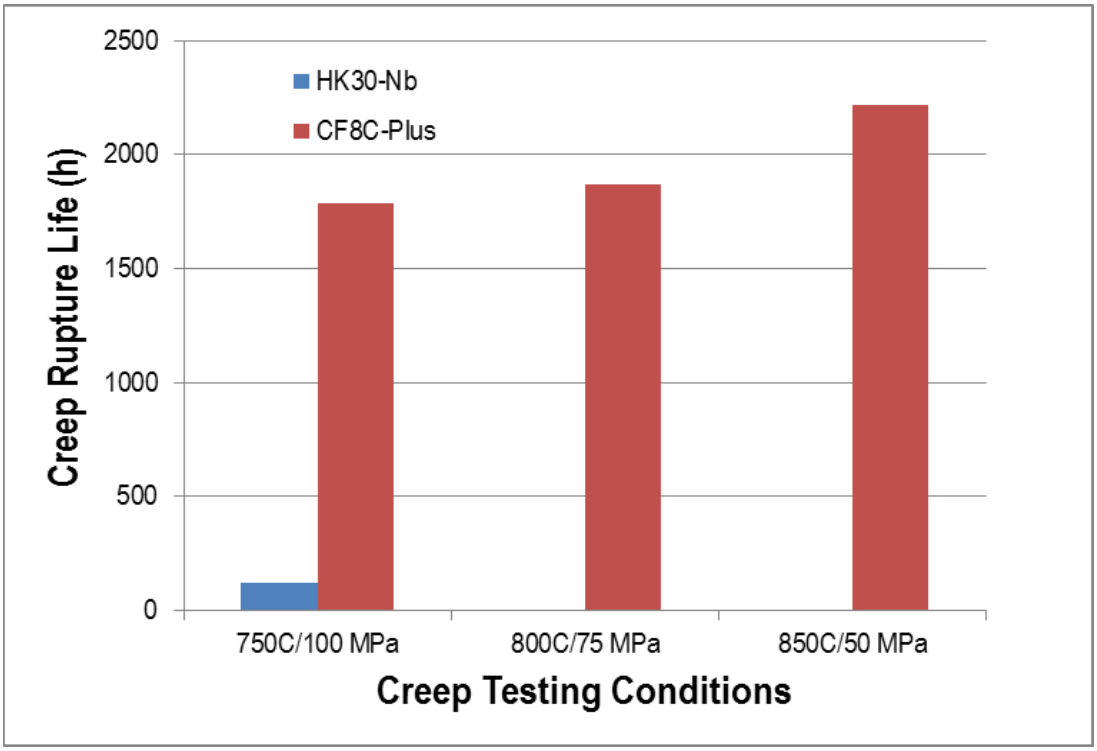

Figure 6 - Histogram of creep-rupture life for cast HK30Nb and CF8C-Plus steels tested in air at various creep conditions at 750-850°C.

Another measure of temperature capability is oxidation resistance, and the oxidation resistance of CF8C-Plus steel is worse than HK30Nb at 800°C in a very aggressive oxidizing environment of air + 10% water vapor. CF8C-Plus steel is, however, more oxidation resistant than SiMo cast iron (Fig. 7). A real diesel or gasoline engine exhaust environment is oxygen-depleted after combustion, so it is reducing rather than highly oxidizing. In order to capture the effects of oxidation in a diesel exhaust environment, a test chamber was built to use exhaust gas from a Caterpillar C-15 diesel gen-set at the NTRC at ORNL. The test chamber was designed to be able to achieve a temperature of 800°C. The results of 100h test in the diesel exhaust environment at 800°C are also shown in Fig.7. Clearly for the timeframe of 100h, the oxidation rates in the real reducing exhaust environment are orders of magnitude lower than those found during laboratory testing in air + 10% water vapor. The old gen-set has been replaced by an updated diesel engine, so longer experiments in the real exhaust environment will be possible in the future.

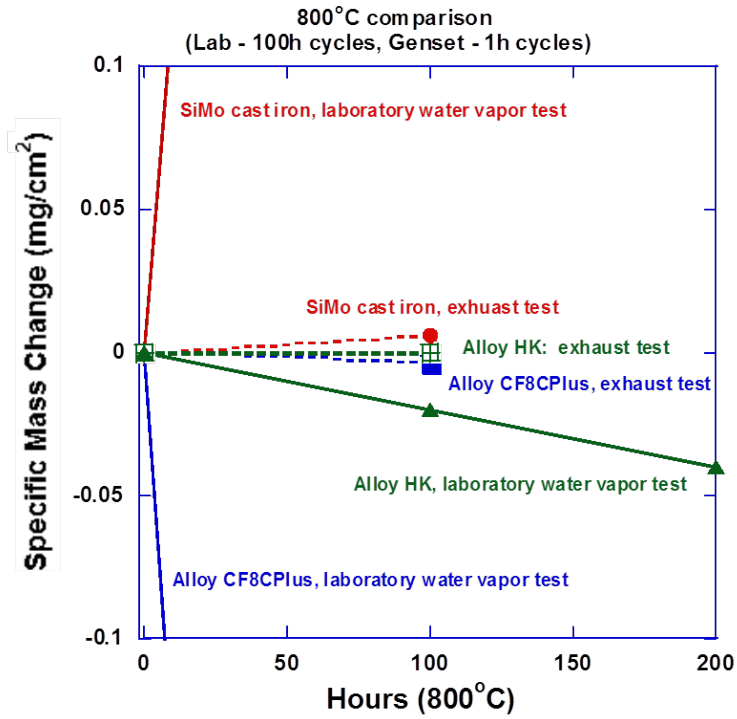

Figure 7 – Graph of mass loss versus time for oxidation testing in an exhaust environment in a specially adapted diesel gen set at 800°C, and for oxidation testing in a laboratory environment with air + 10% water vapor. The materials tested include SiMo cast iron, CF8C-Plus cast austenitic stainless steel, and HK30Nb cast austenitic stainless alloy.

Modified CF8C-Plus Cu/W Steels with More Cr and Ni – Oxidation and Creep-Rupture Testing

Modified heats of CF8C-Plus Cu/W steel with more Cr and Ni were cast into keel bars (from which tensile and creep specimens are machined) by Stainless Foundry & Engineering (SF&E) (Milwaukee, WI). Three heats, one with the standard 19.5Cr/12.5Ni, and two modified heats with 21Cr/15Ni and 22Cr/17.5Ni were made and tested for oxidation and creep-resistance. The oxidation test was a fairly standard 5000h test at 800°C in air + 10% water vapor, with 100h cycling to accommodate weight measurements, and the results are shown in Fig. 8. Standard CF8C (cast 347H steel) and CF8C-Plus steels undergo severe weight loss due to thick oxide scale formation followed by spallation, and testing was stopped at less than 1000h. CF8C-Plus Cu/W steel performed better, and the two modified heats were even more oxidation resistant, with the 22Cr/17Ni steel showing the best results at 5000h.

Another measure of goodness for the modified CF8C-Plus Cu/W steels is their creep-rupture and tensile properties at 700-1000°C. Creep-rupture lives for the various CF8C-Plus steels tested in air at 800°C/75MPa are shown in Fig. 9. Standard CF8C-Plus Cu/W has almost twice the rupture life of the standard CF8C-Plus steel, and the two modified steels with more Cr and Ni have rupture lives

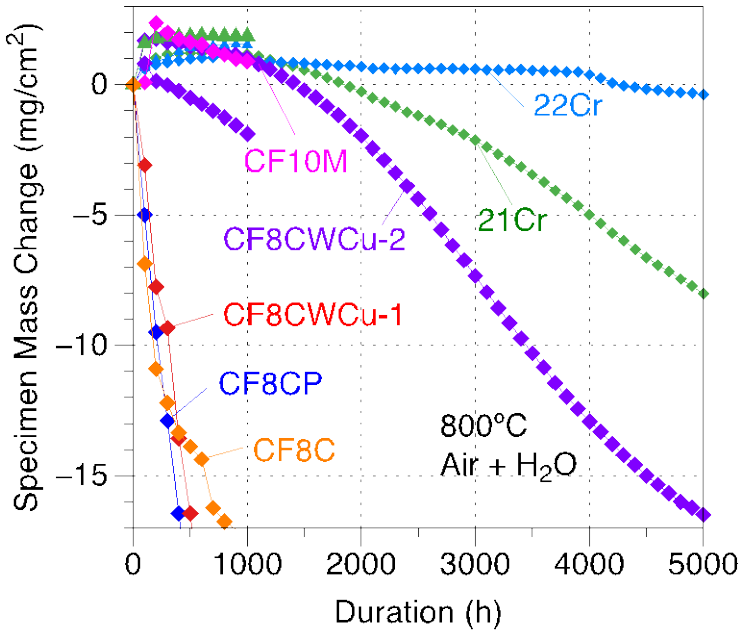

Figure 8 – A plot of specimen mass change versus oxidation test duration (h) for several different cast austenitic stainless steels tested at 800°C in air + 10% water vapor, with 100h cycles in between weight measurements. The alloys include CF8C, CF8C-Plus (CF8CP), CF8C-Plus Cu/W (CF8CWCu-1 and -2), CF10M (cast 316H), CF8C-Plus Cu/W – 21Cr/15Ni (21Cr), and CF8C-Plus Cu/W – 22Cr/17.5Ni (22Cr) steels.

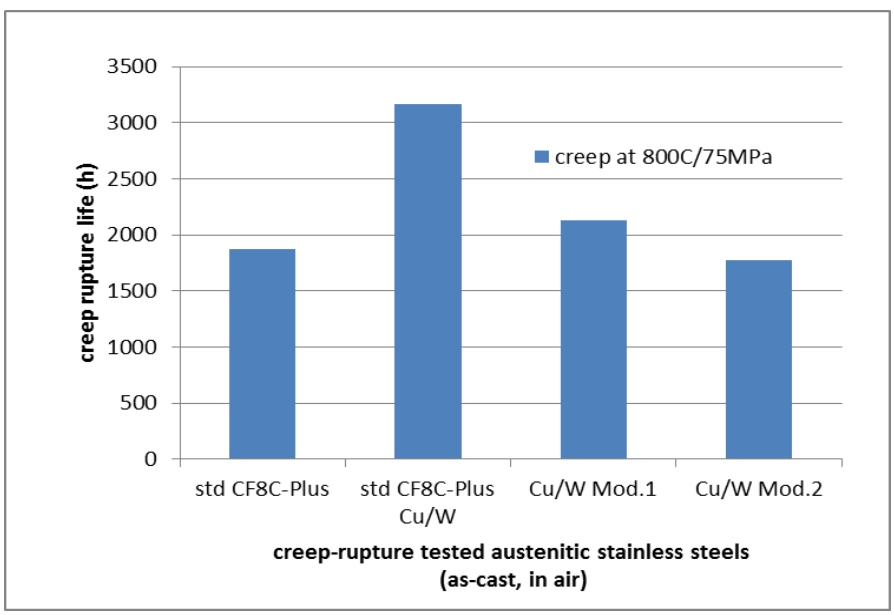

Figure 9 – Histogram of creep rupture life for various cast CF8C-Plus steels tested at 800°C/75MPa in air. Alloys include standard CF8C-Plus, standard CF8C-Plus Cu/W and two modified CF8C-Plus Cu/W steels with 21Cr/15Ni (mod.1) and 22Cr/17.5Ni (mod.2).

comparable to the standard CF8C-Plus steel. Results of creep testing at 800°C/100MPa and 850°C/75MPa comparing the same four alloys were similar. If we combine the creep and the oxidation data, then the best combination of creep resistance and oxidation resistance at 800°C is found in the modified CF8C-Plus Cu/W steel with 22Cr and 17.5Ni.

Tensile, Creep and Oxidation Testing at 1000°C and Above and CN12-Plus Steel for Automotive Gasoline Engine Exhaust Applications

Turbochargers and exhaust manifolds for automotive gasoline engines must withstand much higher temperatures than for diesel engine applications. Therefore, cast austenitic stainless steels should have temperature capability and durability at 1000-1100°C for such applications. Standard CF8C-Plus steel has been shown in commercial applications to have capability and durability at 900°C, for the Caterpillar Regeneration System (CRS) that with 20 min burn cycles has lasted up to 8 years on the road. However, tensile testing at 700-1000°C shows that there is a significant drop off in yield strength (YS) between 900 and 1000°C (Fig. 10), so that properties at 1000°C and above must be evaluated and demonstrated.

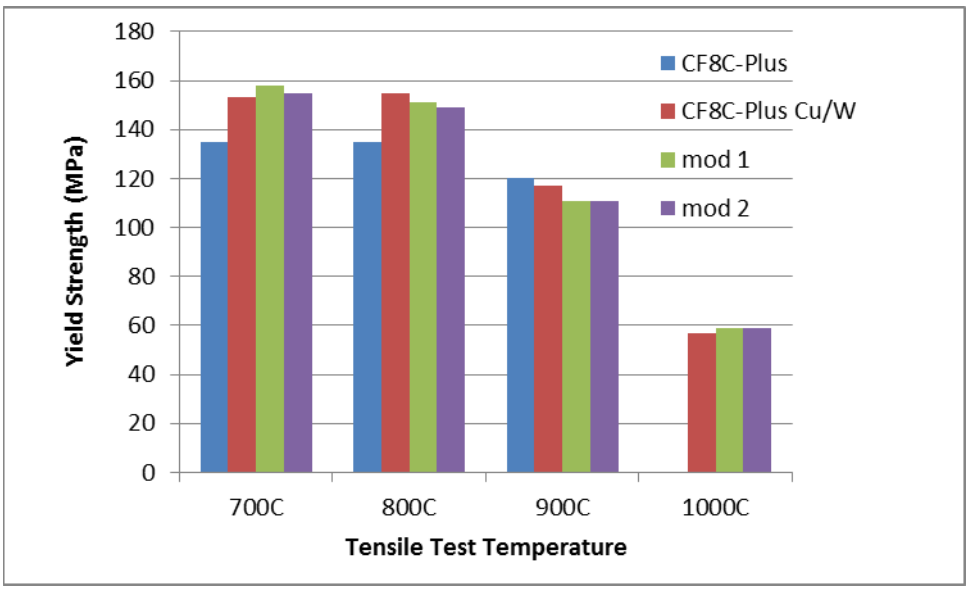

Figure 10 – Histogram of yield strength (YS) for various CF8C-Plus type steels tensile tested at 700-1000°C. Alloys include standard CF8C-Plus, CF8C-Plus Cu/W, and two modified CF8C-Plus Cu/W steels with 21Cr/15Ni (mod. 1) and 22Cr/17.5Ni (mod. 2).

The relative YS of CF8C-Plus Cu/W and the modified alloys compared to standard CF8C-Plus steel changes with increased test temperature. The CF8C-Plus Cu/W and the modified alloys are slightly stronger than standard CF8C-Plus steel at 700 and 800°C, but then become similar at 900°C. Creep-rupture data at 1000°C/25 MPa shows that standard CF8C-Plus steel is now stronger than CF8C-Plus Cu/W, and similar to or stronger than the two modified steels (Fig. 11). Also the relative creep-strength difference between standard CF8C-Plus and HK30Nb steels has also reversed at 1000°C, with the

HK30Nb having a dramatically longer rupture life than CF8C-Plus steel, whereas at 900°C and below, CF8C-Plus has a much better rupture life (Figs. 5 and 6).

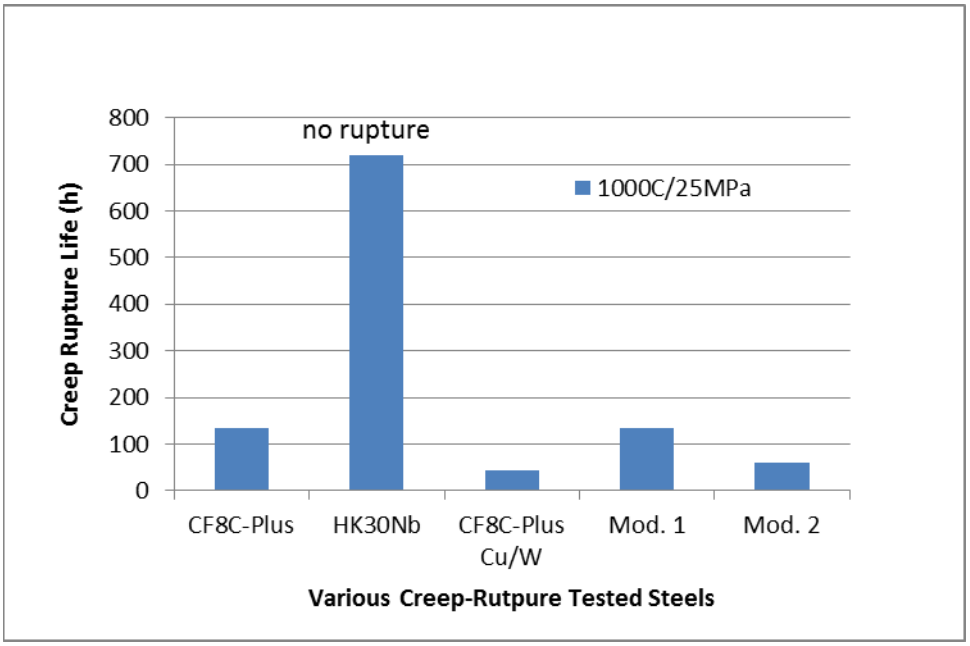

Figure 11 – Histogram of creep rupture life of various stainless steels and alloys tested at 1000°C/25MPa. Note that the HK30Nb has not ruptured (as of 11/06/2014), and is ongoing. The alloys include standard CF8C-Plus, HK30Nb, standard CF8C-Plus Cu/W and the modified alloys with 21Cr/15Ni (mod. 1) and 22Cr/17.5Ni (mod. 2).

Recently, severe oxidation testing began at 1000°C in air with 1h cycles to simulate the starting and stopping operation of automotive gasoline engines, and the results are plotted in Fig. 12. Oxidation testing at 1000°C severely degraded the CF8C-Plus steel in less than 100h, while the modified CF8C-Plus Cu/W with 22Cr/17.5Ni shows the best relative behavior, and seems to saturate as HK30Nb does. The HP40Nb (25Cr/35Ni) and the CW6MC (Ni-based cast version of alloy 625) show no degradation at this point, but this is only 100h in dry air, so their behavior at longer times or in air + 10% water vapor would be a better measure of oxidation resistance. However, the relative behavior of the modified steels and the better behavior of the HK30Nb and HP40Nb, both with 25Cr, argues for more Cr in these Fe-based steels and alloys. However, because of their Ni-content, the HK and HP alloys are 2-3 times more expensive than CF8C-Plus steel, and that is definitely a negative consideration for automotive turbocharger applications.

Finally, the need for more oxidation resistance and creep strength at above 900°C created the opportunity to consider the cast CN12-Plus austenitic stainless steel, also developed by ORNL and Caterpillar in 1999-2002 in the same project that developed CF8C-Plus steel [2]. Standard CN12 was a cast steel with high S content to provide the brittle MnS phase for enhanced machinability that was developed in an earlier project involving Ford, Caterpillar and ORNL. CN12-Plus was developed by

adding more Mn, eliminating S, and adjusting the other elements to provide a more stable austenitic parent phase strengthened by carbide and nitride precipitates. CN12-Plus was patented in 2007 (U.S. Patent 7,255,755), and creep-rupture data at 850°C/110MPa show its improvement relative to the standard CN12 steel in Fig. 13 [2]. CN12-Plus has 25Cr/16Ni, and has more tensile and creep strength than CF8C-Plus steel because it has C+N=0.8, instead of the 0.35-0.40 found in the latter. CN12-Plus should also be stronger than HK30Nb and HP40Nb, because they have 0.3C and 0.4C, respectively, and neither contains any N. CN12-Plus should also cost less than the HK or HP type alloy. CN12-Plus heats of steel were ordered from Stainless Foundry & Engineering during the final months of this CRADA project, but they will not be delivered in time to make specimens and do testing during this project.

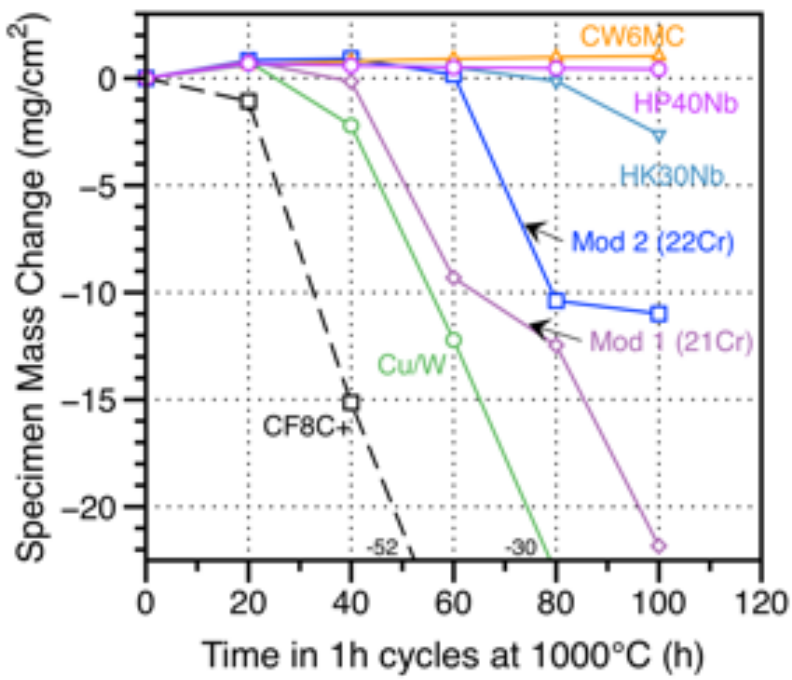

Figure 12 – Plot of mass change versus time for oxidation testing in air at 1000°C and 1h cycle time for various cast stainless steels, alloys, and Ni-based alloys. Alloys include standard CF8C-Plus steel (CF8C+), standard CF8C-Plus Cu/W (Cu/W), modified CF8C-PlusCu/W steels with 21Cr/15Ni (mod.1) and 22Cr/17.5Ni (mod.2), HK30Nb (25Cr/20Ni) alloy, HP40Nb (25Cr/35Ni) alloy, CW6MC Ni-based alloy (cast version of alloy 625) with 21Cr.

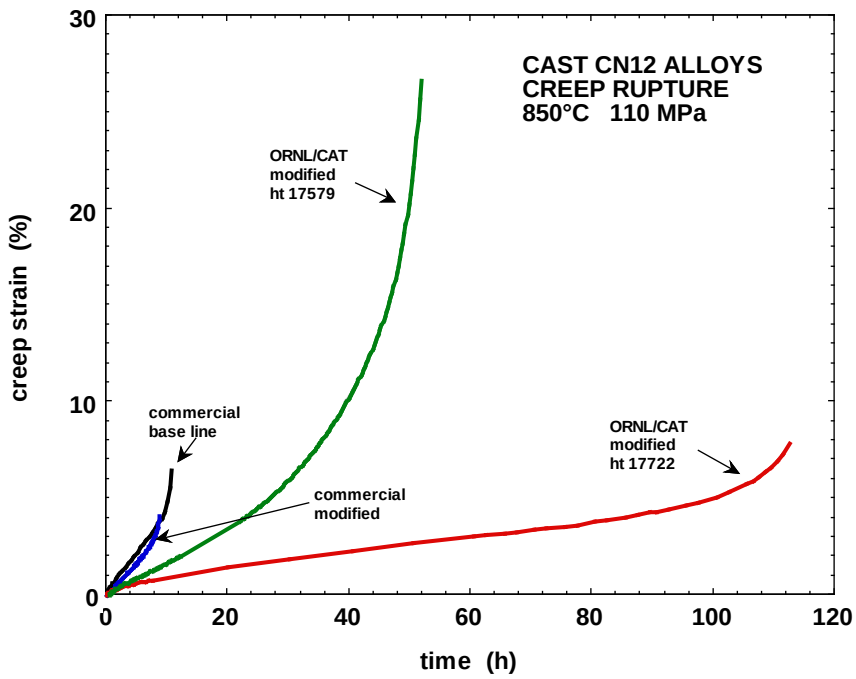

Figure 13 – Plot of creep strain versus time for creep-rupture testing of several cast CN12-type austenitic stainless steels at 850°C/110MPa in air. The alloys include two ORNL/CAT heats of CN12-Plus steels (modified heats 17722 and 17678) and two commercial heats, one standard and one modified, but both with high S (0.15%) [2].

Subject Inventions

None

Commercialization Possibilities

Data on newer potential turbocharger materials like CN12-Plus will be shared with Honeywell to see if they are interested.

Plans for Future Collaboration

ORNL intends to continue to communicate with Honeywell and share data on the newer alloys investigated, ordered or invented in the final months of this CRADA project.

Conclusions

1) Neutron scattering found asymmetric tensile residual stresses in wheel/shaft assemblies (WSA) that had been electron beam welded, but were given no additional heat-treatment. Heat-treating using induction coils did not significantly affect the residual stresses and asymmetry, but convention furnace heat-treatment of the WSA at 593°C removed both the residual stress and the asymmetry.

2) For the turbocharger housing application, oxidation of CF8C-Plus steel in a modified diesel gen-set and diesel exhaust environment at 800°C showed very little oxidation after 100h, which is orders of magnitude less oxidation that shown during laboratory testing at the same temperature in air + 10% water vapor.

3) Oxidation resistance of standard CF8C-Plus steel in air + 10% water vapor at 800°C is very poor, but oxidation resistance is much better in CF8C-Plus Cu/W and modified steels with 21Cr/15Ni and 22Cr/17.5Ni. The CF8C-Plus Cu/W with 22Cr/17.5Ni has the best combination of creep and oxidation resistance at 800°C.

4) Oxidation and creep testing at 1000°C and above is of interest for automotive gasoline engine turbocharger and exhaust applications. CF8C-Plus shows severe degradation during aggressive oxidation (1h cycles) testing, as do the modified alloys. New CN12-Plus steels with 25Cr/16Ni and with C+N=0.8 have great potential for having better oxidation and creep-resistance than CF8C-Plus type steels, and they cost less than HK30Nb. Test bars have been ordered from the foundry at the end of this CRADA project, but they were not available for testing and evaluation when this report was written.

Acknowledgments

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References

1) P.J. Maziasz, A. Shyam, N.D. Evans and K. Pattabiraman, Cast CF8C-Plus Stainless Steel for Turbocharger Applications, C/NFE-08-01259, ORNL/TM-2010/86, Oak Ridge National Laboratory Report, Oak Ridge, TN (2010).

2) P.J. Maziasz, R.W. Swideman, P.F. Browning, M.E. Frary, M.J. Pollard, C.W. Siebenaler and T.E. McGreevy, Development of Low-Cost Austenitic Stainless Steel Gas-Turbine and Diesel Engine Components with Enhanced High-Temperature Relaibility, C/ORNL99-0533, Oak Ridge National Laboratory Report, Oak Ridge, TN (1999).