DER MATERIALS QUARTERLY PROGRESS REPORT

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For:

Department of Energy
Office of Distributed Energy

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January—March 2004

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MATERIALS FOR ADVANCED RECIPROCATING ENGINES

Recuperator Alloys – Composition Optimization for Corrosion Resistance

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Objective

In order to provide a clear, fundamental understanding of alloy composition effects on corrosion resistance of stainless steel components used in recuperators, the oxidation behavior of model alloys is being studied. The first phase of this study narrowed the range of Cr and Ni contents required to minimize the accelerated corrosion attack caused by water vapor at 650°-800°C. Other factors that continue to be investigated include the effects of temperature, alloy grain size, phase composition and minor alloy additions. These composition and microstructure effects also will provide data for life-prediction models and may suggest a mechanistic explanation for the effect of water vapor on the oxidation of steels. This information will be used to select cost-effective alloys for higher temperature recuperators.

Highlights

The oxidation behavior of commercial alloy foils and model alloys are being evaluated in order to better understand the role of alloy composition on the accelerated attack (AA) observed in exhaust gas at 650°-700°C. Long-term testing to 10,000h has been performed on a variety of commercial and experimental foil specimens in order to study their behavior. However, the mass gain data obtained from these specimens does not reflect the extent of reaction due to the combination of mass gain from oxidation and mass loss from evaporation

Technical Progress

<u>Experimental Procedure</u>

As outlined in previous reports, foil of commercial alloys was obtained for testing or rolled from thicker product at ORNL. Foil specimens (≈12mm x 17mm x0.1mm) were tested in the as-rolled condition without additional surface preparation. The oxidation tests were done in air + 10vol.% water vapor with 100h cycles at 650°, 700°·or 800°C. After oxidation, selected specimens were Cu-plated, sectioned and polished to examine the oxide scale.

<u>Results of oxidation testing</u>

Testing at 650°C to 10,000h has been completed on a number of foil materials, Figure 1. Commercial type 347 foil showed AA between 1,000 and 2,000h under these conditions. Four modifications of type 347 foil also were tested and showed superior performance. The third modification began to show AA at 8,000h but the other three compositions did not show AA after 10,000h. Higher alloyed commercial alloys also were tested, Figure 1. These alloys showed low mass gains or mass losses likely due to volatilization of $CrO_2(OH)_2$. However, the specimen of Fe-20Cr-25Ni+Nb (rolled from NF709 or 20/25Nb) showed increased mass gain during the last 2,000h of testing. The specimen of

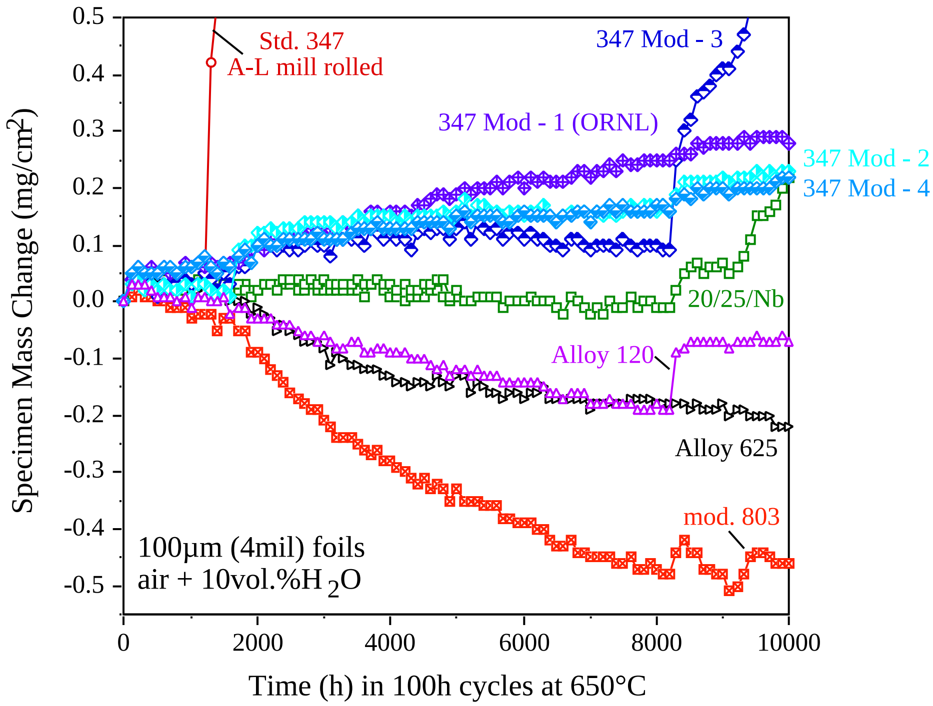

Figure 1. Specimen mass gains for various foil (100µm thick) materials during 100h cycles in humid air at 650°C.

alloy 120 (Fe-25Cr-35Ni) also showed an increase at one point but did not continue to gain afterwards. Specimens of alloy 625 and a modified 803 composition also showed fairly continuous mass losses during the test.

Figure 2 shows specimen mass gain results for foils tested at 700°C for up to 10,000h. Low mass gains and/or mass losses reflect a slow oxidation rate and some evaporation. An increase was noted for 20/25/Nb foil after ≈8,500h. Similar mass change results were found for mill-rolled and ORNL-rolled alloy 120 foils. After a significant incubation period (≈7,500h), a mill-rolled foil specimen of type 347 foil showed AA. The incubation time before AA was much longer than at 650°C. The longer incubation period may be related to the faster scale growth rate at 700°C. A longer period of time may be needed to start AA when a thicker surface oxide forms. Also shown in Figure 2 are results for two specimens of a ORNL-rolled Fe-20Cr-20Ni-4Mn foil. This composition is the first attempt to develop a low-cost creep- and corrosion resistant stainless steel. The higher mass gain for this foil compared to some of the other compositions is not attributed to AA but instead to its higher Mn content (compared to 1-2% in the other alloys). The high Mn content leads to excessive incorporation of Mn in the scale and a faster oxidation rate. As mentioned in prior reports, Mn can be beneficial in preventing AA but in a thin foil, increasing the metal consumption rate can be detrimental to its lifetime.

Figure 3 shows the results for foils tested at 800°C in air + 10%H_2O. Only the foil specimen of alloy 120 was run to 10,000h. This specimen showed a larger mass gain for the last 2,000h of the test. Whether this indicates the onset of AA will be determined by further characterization of the oxide scale and Cr content of this specimen. However, it was a relatively modest increase in mass compared to some of the other specimens. The foil specimen of alloy 625 was stopped at 6,000h for

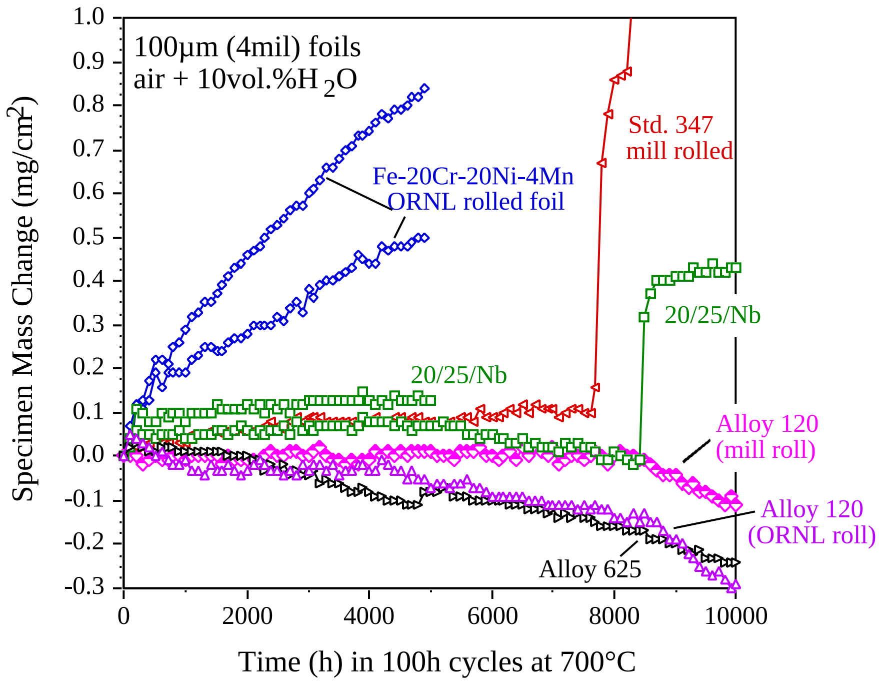

Figure 2. Specimen mass gains for various foil (100µm thick) materials during 100h cycles in humid air at 700°C.

characterization and did not show any signs of AA. The specimens of Fe-20Cr-25Ni+Nb were stopped at 5,000, 6,000 and 7,000h. For this composition, the latter two specimens showed signs of

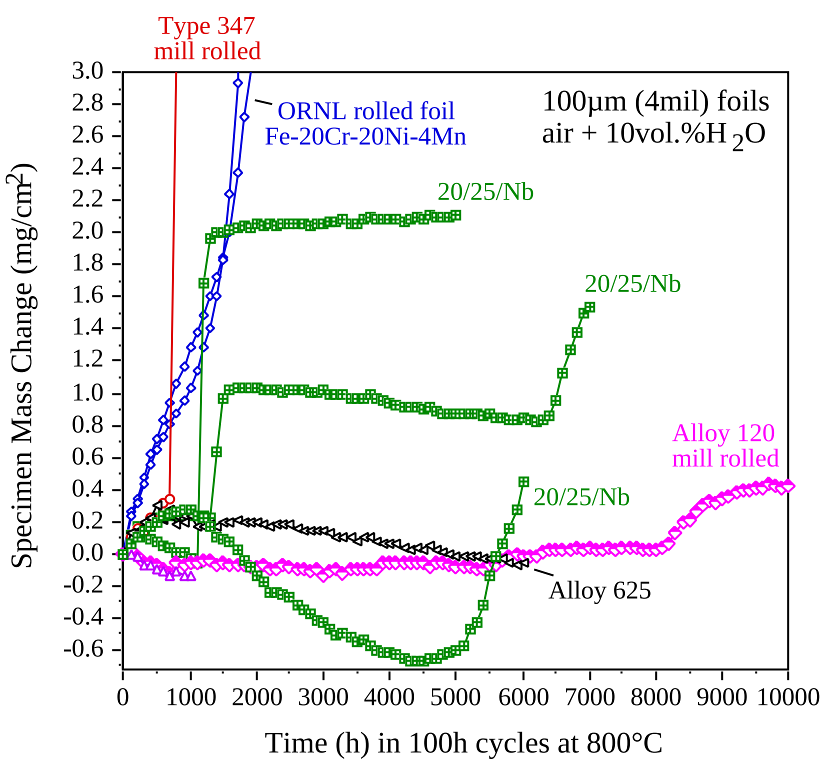

Figure 3. Specimen mass gains for various foil (100µm thick) materials during 100h cycles in humid air at 800°C.

AA when removed from the test due to their rapid mass gains. Foil specimens of Fe-20Cr-20Ni-4Mn were stopped after 2,000h due to excessive mass gain. These specimens outlasted commercial 347 foil which showed AA after less than 1,000h at 800°C, Figure 3. In general, the failure times for the various foils show the benefit of increasing Cr and Ni contents. The Fe-20Cr-25Ni+Nb foil specimens showed AA between 5,000 and 7,000h while alloy 120 only showed a modest increase in mass after 8,000h. The performance of the Fe-20Cr-20Ni-4Mn likely reflects the previously mentioned problem with the high Mn content. New laboratory scale heats with compositions based on Fe-20Cr-20Ni are being fabricated in an attempt to achieve better corrosion resistance.

Collecting data for 10,000h (100, 100h cycles) required more than 2 years. One goal of this program is to develop predictive models requiring less experimental work. However, one important issue that has become clear from these results is that specimen mass gain data is not providing sufficient information for such a model. Figures 4 and 5 illustrate the problem. Figure 4 shows the specimen mass gain data for two foil specimens tested at 800°C in humid air and Figure 5 shows the cross-sections of the oxide scales formed on these specimens. The scale thicknesses observed should have produced a mass gain of ≈0.7mg/cm^2 (marked in Figure 4) assuming that the scale is mostly Cr_2O_3. For alloy 625, a mass loss was measured, while for the Fe-20Cr-25Ni+Nb foil specimen a higher mass gain was observed. Most of the large mass gain occurred during 1 or 2 cycles and is likely due to some AA at the specimen edge or imperfections in the laboratory made foil. In neither case did the mass gain give an accurate reflection of the corrosion product. In general, this is because the specimen mass change is the net result of several general phenomena:

$$\Delta M_{specimen} = \Delta M_{oxide\ growth} - \Delta M_{evaporation} - \Delta M_{spallation} \qquad (1)$$

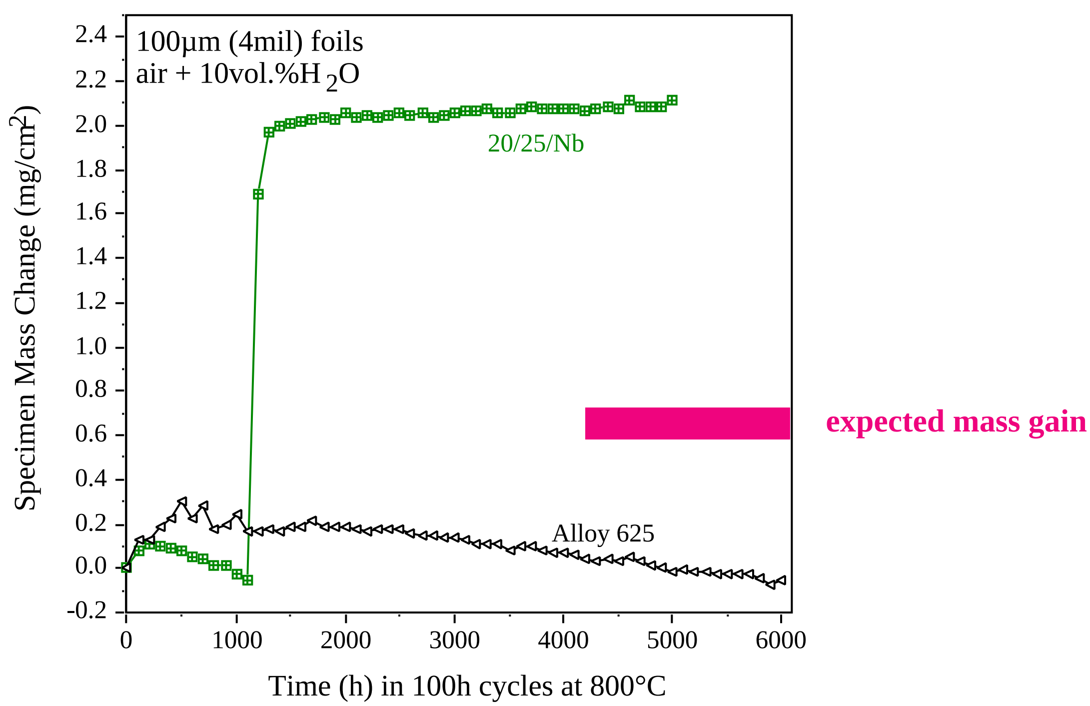

Figure 4. Specimen mass gains for two 100μm thick foil specimens during 100h cycles in humid air at 800°C compared to the predicted mass gain based on the scale thickness after the test.

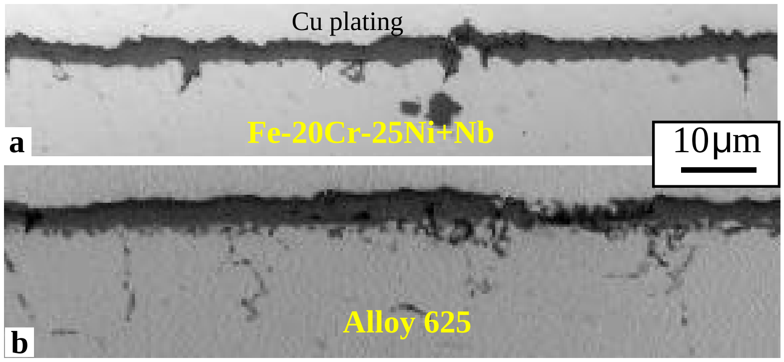

Figure 5. Light microscopy of scale cross-section for the foils in Figure 4 exposed in humid air at 800°C. (a) Fe-20Cr-25Ni+Nb after 5,000h and (b) alloy 625 after 6,000h.

No spallation has been observed from these specimens. Thus, in the case of the alloy 625 foil specimen in Figure 4 and 5b, the mass loss observed is attributed to volatilization of $CrO_2(OH)_2$.and significant Cr depletion in this specimen has been reported previously. A similar explanation would explain the low mass gains or mass losses for the specimens of alloy 625, alloy 120 and Fe-20Cr-25Ni+Nb at lower test temperatures, Figures 1 and 2. Therefore, rather than a model based on mass change, a model is being developed based on Cr consumption which should produce a more accurate lifetime prediction. For new or untested alloys, testing a series of foil specimens for different times over several thousand hours should provide a Cr consumption rate that could then be used to predict long-term behavior. These 10,000h specimens will provide important Cr consumption results for developing this model and the Cr depletion profiles for these specimens will be reported in subsequent reports.

Status of Milestones

Fabricate foil material of two most promising compositions for creep and corrosion testing that simulate conditions in a recuperator.
(March 2004) COMPLETED - fabricated two batches of foil for testing.

Industry Interactions

Discussed oxidation data with W. Matthews of Capstone in January 2004

Discussed materials selection issues with Williams International in March 2004.

Discussed results of NACE conference paper with several members of the audience, March 2004.

Problems Encountered

None.

Publications/Presentations

Presented paper “The Long-Term Performance of Model Austenitic Alloys in Humid Air,” (NACE Paper 04-530, Houston, TX) presented at NACE Corrosion 2004, New Orleans, La, March 2004.

Recuperator Materials Testing and Evaluation

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Objective

The objective of this sub-task is to screen and evaluate candidate materials for the next generation of advanced microturbine recuperators. To attain this objective, a commercially available microturbine was acquired and in coordination and collaboration with its manufacturer, it was modified to operate at recuperator inlet temperatures as high as 843°C. The durability of candidate recuperator materials will be determined by placing test specimens at a location upstream of the recuperator, followed by determination of the evolution of the material's physical and mechanical properties as a function of time of exposure. During exposure tests inside the microturbine, it will be possible to subject test specimens to various levels of mechanical stress by using a specially designed sample holder and pressurized air. The selection of materials to be evaluated in the modified microturbine will be made in coordination and collaboration with other tasks of this program and with manufacturers of microturbines and recuperators.

Highlights

A 500-hr test campaign was completed to evaluate Haynes 120® alloy.

Technical progress

In this document we report the results from the evaluation and characterization of foils of Haynes 120® alloy after a 500-hr test campaign in ORNL's recuperator testing facility. This alloy has been considered a potential candidate material for the manufacture of advanced microturbine recuperators[1] because it "combines excellent high-temperature strength and oxidation resistance[2]". Tables I and II list the composition and tensile properties of Haynes 120®.

Table I. Composition of Haynes 120® alloy (wt. %)[2]

Element	Concentration	Element	Concentration	Element	Concentration
Ni	37	Mo	2.5 (max)	Al	0.1
Cr	25	Mn	0.7	C	0.05
W	2.5 (max)	Si	0.6	Cb	0.7
Co	3 (max)	Fe	33 (balance)	B	0.004
N	0.2				

[1] Omatete, O., O., Maziasz, P. J., Pint, A. B., and Stinton, D. P., "Assessment of Recuperator Materials for Microturbines," ORNL TM-2000/304
[2] Haynes International, Kokomo, IN 46904

Table II. Tensile Properties of Haynes 120® alloy[2]

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
375	735	50

Evaluation of baseline properties of Haynes 120® alloy foils.

The foil materials used in this investigation were supplied by Capstone Turbine Corporation in the form of 20.3-cm wide rolls with thicknesses of 0.089 mm.

Miniature dog-bone shaped test specimens, with their principal axis aligned parallel to the rolling direction, were obtained from the foil rolls by electric discharge machining (Figure 1). The tensile behavior of the miniature test specimens was determined at ambient conditions using a procedure that has been described in detail elsewhere[3]. The tensile tests were carried out at a constant crosshead displacement rate and both the load and crosshead displacement were recorded during the test. Because of the small dimensions of the test specimens it was not possible to measure directly the tensile strain of the test specimens, but values of strain were determined from the crosshead displacement data after applying a correction for the compliance of the load train.

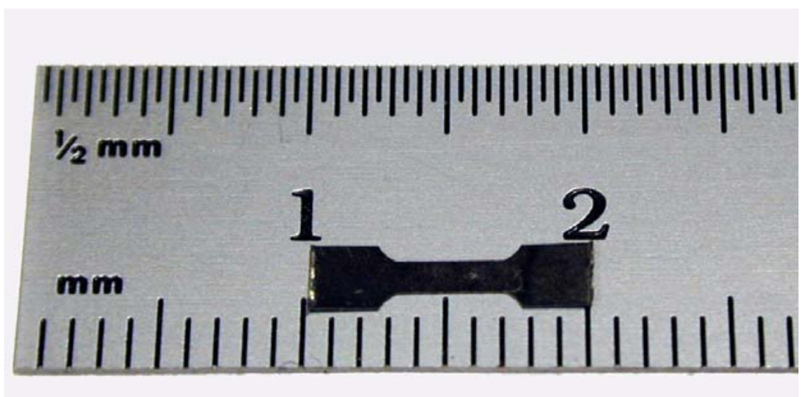

Figure 1. Miniature test specimen used for determination of tensile properties of Haynes 120® alloy.

Figure 2 shows stress versus strain curves obtained from the tensile evaluation of miniature test specimens. The tensile stress-strain curves are characterized by a linear region associated with elastic deformation, a well-defined transition to plastic deformation at a high yield stress and failure strains near 40%.

Table III summarizes the results of these tests and lists values for the 0.2% yield strength, ultimate tensile strength and strain at failure, which are consistent with those reported by the alloy manufacturer[2] (See Table II).

[3] E. Lara-Curzio, "Recuperator Materials Testing and Evaluation" in DER Materials Program Quarterly Report, June-September, 2003

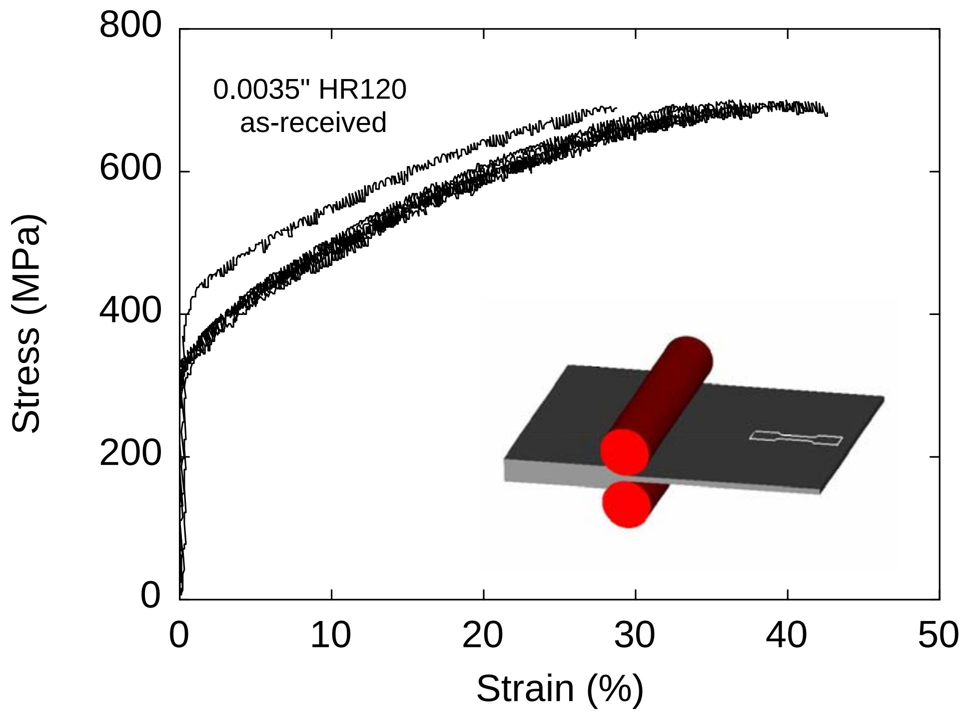

Figure 2. Stress-strain curves obtained from the tensile evaluation of miniature test specimens of 0.089-mm thick specimens of Haynes 120® alloy with their main axis parallel to the rolling direction.

Table III. Summary of tensile results for as-processed 0.089-mm thick foils of Haynes HR-120® alloy.

Haynes 120® alloy	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Failure Strain (%)
‖ to rolling direction	373 ± 31	697 ± 4	37 ± 5

Evaluation of Haynes 120® alloy foils in ORNL's microturbine test facility.
Foil strips 75-mm long and 14-mm wide were e-beam-welded onto a Haynes 230® alloy sample holder as described in detail elsewhere[3]. The diameter of the sample holder onto which the foils were welded was 23.1 mm.

The sample holder was internally pressurized using plant air at 60 psi and subjected to a 500-hour exposure in ORNL's modified microturbine operating with the settings listed in Table IV. The temperature of each foil was monitored during the test using type-K thermocouples that had been placed inside the sample holder.

Table IV. Microturbine settings for 500-hr test.

Engine Speed	45,000 RPM
Turbine Exit Temperature	800°C
Fuel	natural gas

In addition to the magnitude of air pressure inside the sample holder, the temperature of the four foils and the turbine exit temperature were recorded during the test, as illustrated by the temperature history in Figure 3. The maximum and minimum temperatures were 745°C and 632°C, respectively.

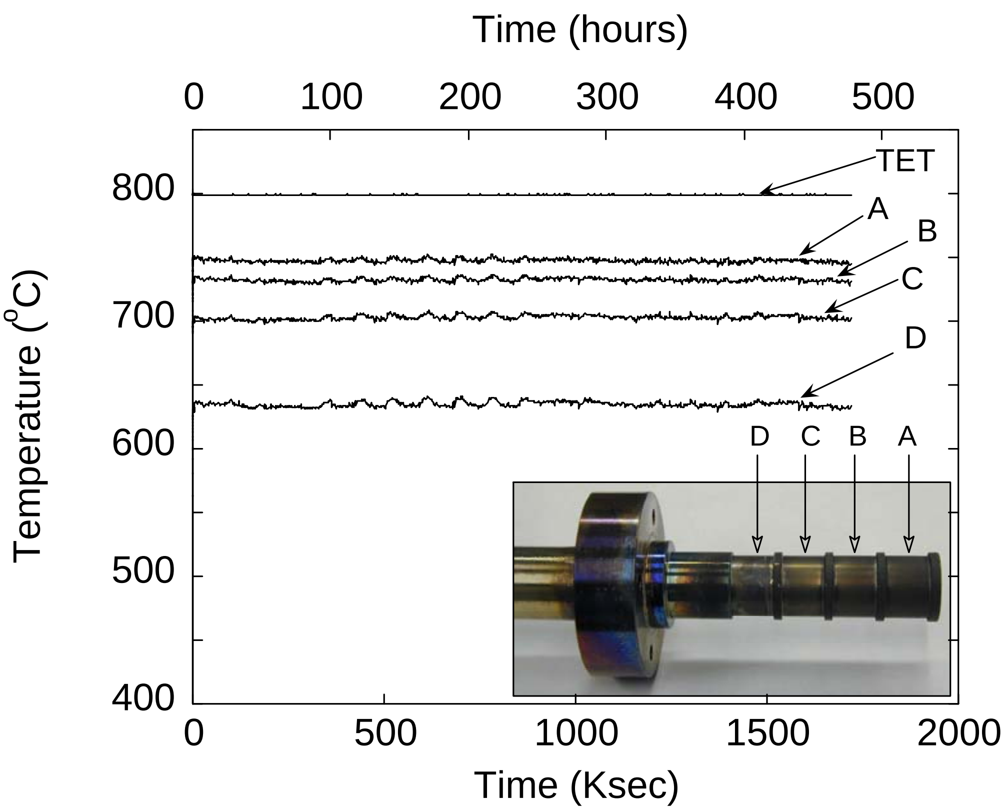

Figure 3. Temperature history for 500-hr test to evaluate the behavior of 0.089-mm thick foils of Haynes 120® alloy.

Post-test analysis

Figure 4 shows the sample holder and Haynes 120® foils at the end of the 500-hr exposure. The foils were removed from the sample holder using a lathe and a diamond tool. About 14 miniature test specimens were obtained from each foil by electric discharge machining for subsequent tensile evaluation and microstructural characterization.

Figure 4. Photographs of sample holder with 0.089-mm thick Haynes 120® foils after 500-hr test at TET=800°C and internal pressure of 60 psi.

Figures 5-8 present the stress versus strain curves obtained from the tensile evaluation of the miniature test specimens. It was found that the ultimate tensile strength and ductility of Haynes 120® alloy decreased by 15% and 50%, respectively, after 500 hours exposure at 745°C. At the lowest exposure temperature of 632°C the ultimate tensile strength and ductility decreased by 10% and 23%, respectively. Table V summarizes the tensile results.

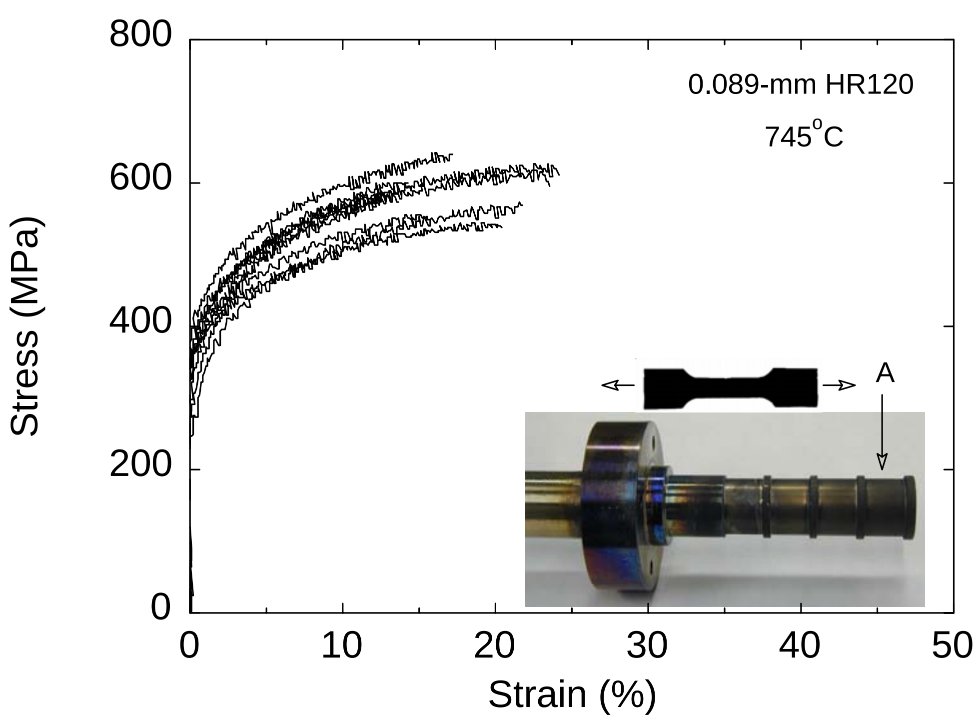

Figure 5. Stress versus strain curves obtained from the tensile evaluation of miniature test specimens obtained from 0.089-mm thick Haynes 120® alloy exposed at 752°C for 500 hours.

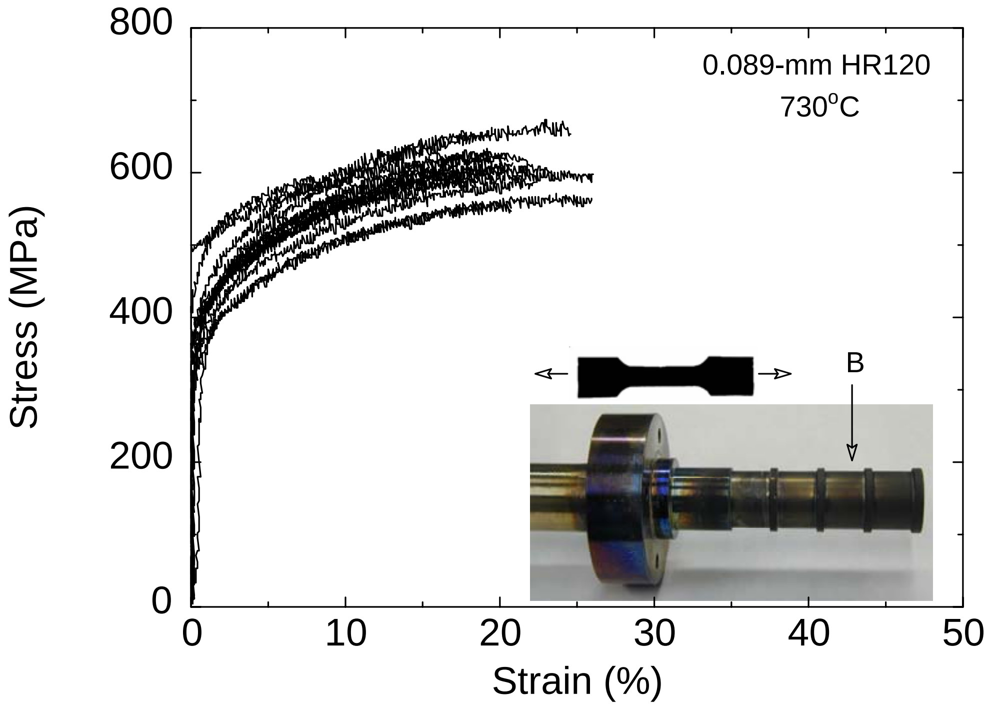

Figure 6. Stress versus strain curves obtained from the tensile evaluation of miniature test specimens obtained from 0.089-mm thick Haynes 120® alloy exposed at 736°C for 500 hours.

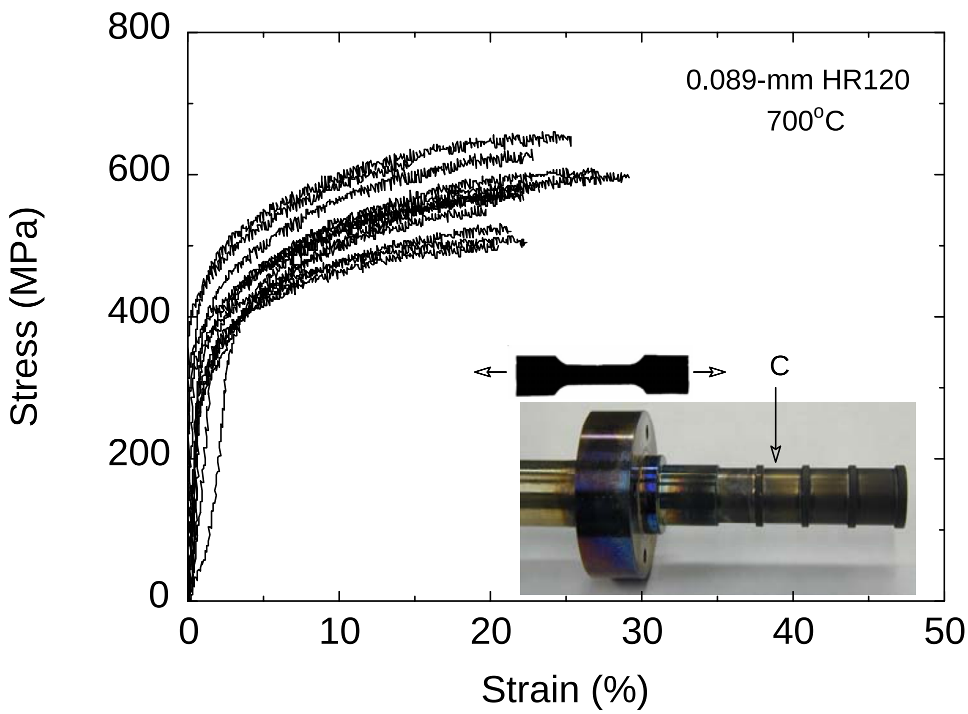

Figure 7. Stress versus strain curves obtained from the tensile evaluation of miniature test specimens obtained from 0.089-mm thick Haynes 120® alloy exposed at 700°C for 500 hours.

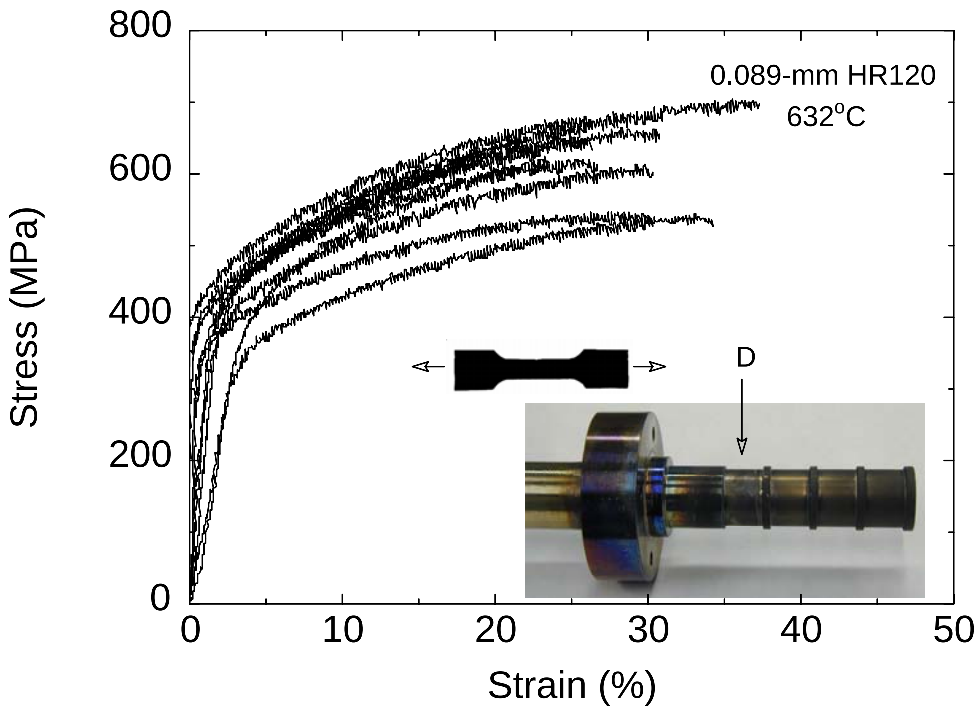

Figure 8. Stress versus strain curves obtained from the tensile evaluation of miniature test specimens obtained from 0.089-mm thick Haynes 120® alloy exposed at 679°C for 500 hours.

Table V. Summary of tensile results for Haynes 120® alloy.

Foil	T (°C)	0.2% σ_y (MPa)	UTS (MPa)	Failure strain (%)
1	745	388 ± 35	594 ± 32	18.0 ± 4.4
2	730	421 ± 37	615 ± 30	21.0 ± 4.4
3	700	408 ± 39	582 ± 48	23.0 ± 4.7
4	632	407 ± 27	631 ± 53	29.0 ± 4.7

Figure 9 shows the normalized ultimate tensile strength of HR120® alloy foils as a function of exposure temperature. The symbols represent the average value of 12-14 tests, while the error bars correspond to one standard deviation with respect to the mean. Also included is a correlation of the form:

HR120® $$\frac{\sigma}{\sigma_o} = \left(1 - \frac{T}{1000}\right)^6 \quad (1)$$

where T is the exposure temperature in degrees Centigrade and σ_o is the tensile strength at 20°C. Figure 10 compares these results with those previously published for 347 stainless steel[3] and HR230®[4].

[4] E. Lara-Curzio, "Recuperator Materials Testing and Evaluation" in DER Materials Program Quarterly Report, October-December, 2003

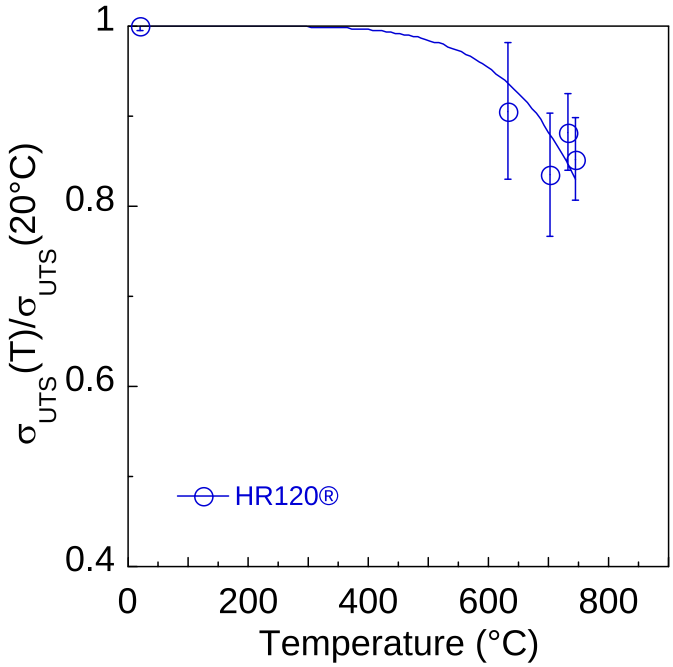

Figure 9. Normalized ultimate tensile strength of HR-122® alloy foils as a function of 500-hr exposure temperature. Error bars correspond to one standard deviation about the mean value.

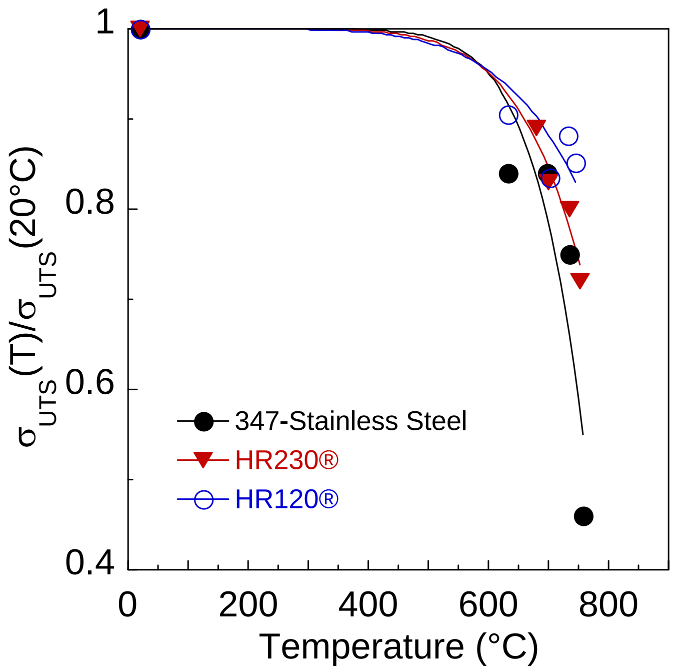

Figure 10. Comparison of ultimate tensile strength of 347-stainless steel, HR-230® alloy and HR-120® alloy foils as a function of temperature for 500-hr exposure.

It was found that among the three alloys, HR120® exhibits the best resistance to exposure to microturbine exhaust gases, followed by HR230® and 347 stainless steel. For the latter two materials, the following correlations were found to provide a good description of the dependence of their ultimate tensile strength with exposure temperature.

HR230® $$\frac{\sigma}{\sigma_o} = \left(1 - \frac{T}{900}\right)^{7.5} \quad (2)$$

347 stainless steel $$\frac{\sigma}{\sigma_o} = \left(1 - \frac{T}{825}\right)^{9.4} \quad (3)$$

While there are no fundamental basis behind the form of these correlations, it is interesting to observe that larger “normalizing temperature” and smaller exponent are associated with increasing resistance to exposure to microturbine exhaust gases.

Figure 11 presents scanning electron micrographs of cross-sections obtained from HR-120®foils after 500-hr microturbine exposure. It was found that only a very thin multilayered oxide scale had formed and that it was thicker on the surface exposed to the exhaust gases. A chemical analysis (Figure 12) revealed that the grain boundaries closest to the surface exposed to the exhaust gases had been depleted of chromium but that they were rich in nickel. The depletion of chromium from grain boundaries close to the metal-oxide interface has been found to be a common feature in all three materials examined to date. In the case of HR120® alloy foils, the oxide scale possesses a multilayered structure consisting of mixed oxides of silicon, chromium and iron.

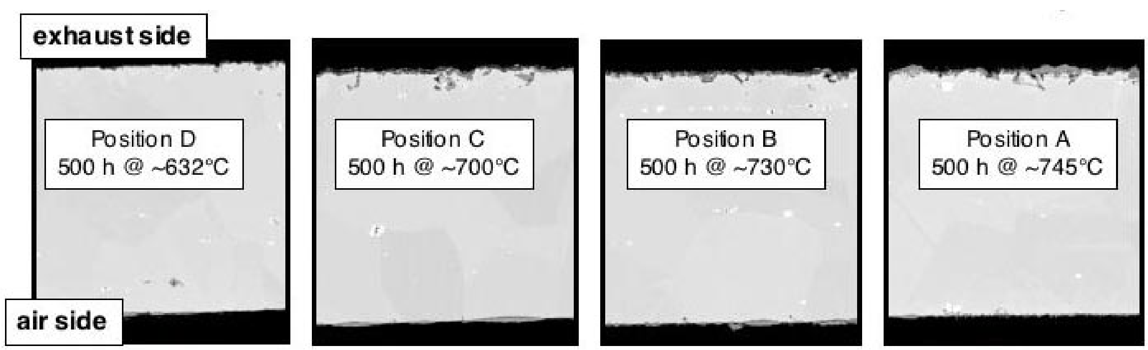

Figure 11. Scanning electron micrograph of cross-section obtained from 0.089-mm thick Haynes 120® alloy foil after 500-hr exposure at 745°C. The lower surface in the micrograph had been exposed to the microturbine exhaust gases.

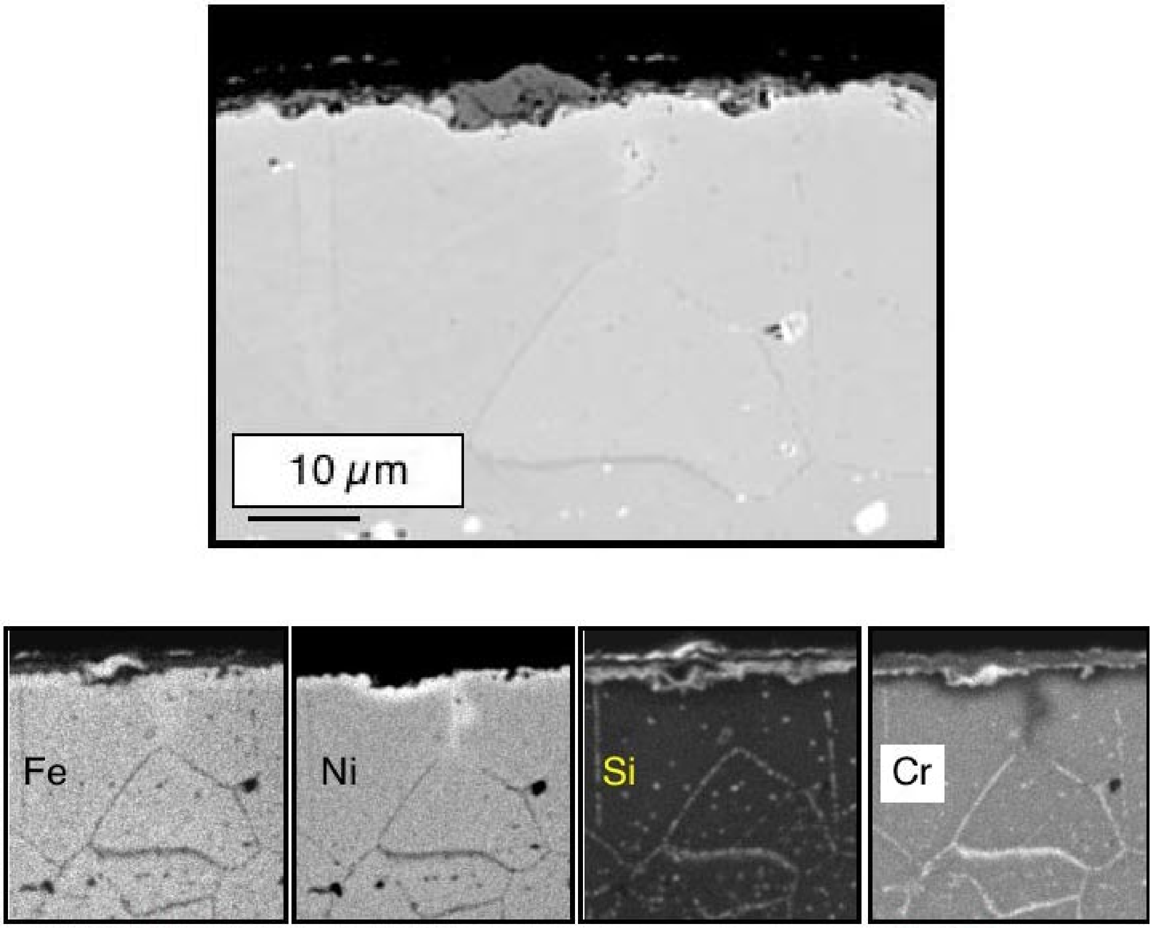

Figure 12. Scanning electron micrograph of cross-sectional area of 0.089-mm thick Haynes 120® alloy foil that had been exposed for 500 hours at 745°C. The upper surface in the micrograph had been exposed to the microturbine exhaust gases. Atomic composition maps of the area in the inset are included.

Analysis of the fracture surfaces of miniature tensile test specimens obtained from foils that had been exposed to the highest temperature (745°C) for 500 hours (Figure 13) revealed intergranular mode of failure. Dimples, which are associated with ductility and plastic deformation and were prevalent on the fracture surface of test specimens of 347 stainless steel and HR230® alloy, were not evident on the fracture surfaces of test specimens of HR120®. However, there was evidence of the existence of sub-micron size particles rich in Fe, Cr and Ni on the fracture surfaces.

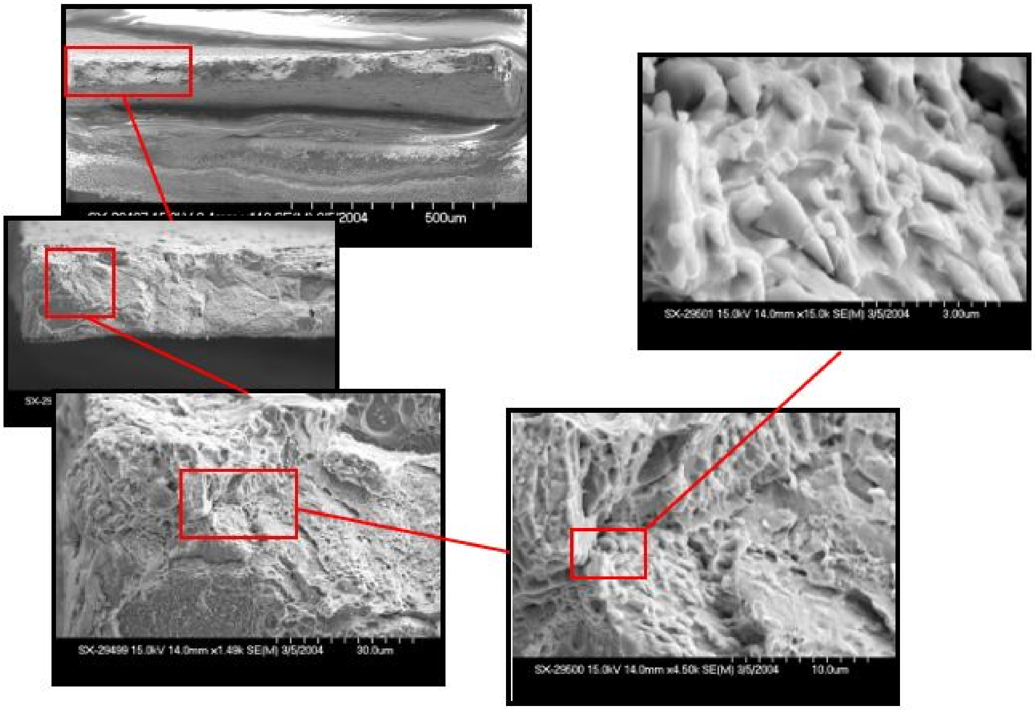

Figure 13. Fracture surface of 0.089-mm thick miniature tensile specimen of HR120® alloy obtained from foil exposed at 745°C for 500 hours. Fracture appears to be intergranular with particulates rich in Cr, Ni and Fe.

Status of Milestones

On schedule

Industry Interactions

Capstone Turbine Corporation provided the foils used in this investigation.

Problems encountered

The Power Distribution Module of the Engine Control Module failed and had to be replaced.

Publications/Presentations

None

Advanced Alloys for High-Temperature Recuperators

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Objective

The main objective of this program is to work with commercial materials suppliers (foil and thin sheet) and recuperator manufacturers to enable manufacture and evaluation of upgraded recuperators from cost effective alloys with improved performance and temperature capability. The near term goal is better performance to or above 704^{o}C (1300^{o}F), and the longer-term goal is reliable performance at 760^{o}C (1400^{o}F) and higher.

Highlights

Materials for use to about 704^{o}C (1300^{o}F)
While severe moisture-enhanced oxidation occurs in standard 347 steel after only 1000-1500h at 650-700^{o}C, new ORNL modified 347 steels with added Mn and N, and the more oxidation-resistant commercial alloys like HR120, NF709 and alloy 625, all show much better resistance to moisture enhanced oxidation after similar testing. A new joint project between ORNL and Allegheny-Ludlum (AL) was initiated this quarter to produce a range of commercial foils and sheet for recuperator manufacturing of their new AL 20-25+Nb stainless alloy with a composition of Fe-20%CR-25%Ni+Nb.

Materials for use to 760^{o}C (1400^{o}F) or higher
Foils of commercial alloys (0.003-0.005 in.) HR120, NF709 and alloy 625 all show good creep rupture resistance at 750^{o}C and 100 MPa. Commercial recuperator sheet (0.010 in.) of alloy 625 was obtained from Ingersoll Rand Energy Systems last quarter, and shows outstanding creep resistance with no rupture after about 2,300 at 750^{o}C. Testing will continue next quarter.

Technical Progress

Recuperator Component Analysis
Different microturbine OEMs have provided pieces of fresh and engine-tested PFR and PSR recuperators made from standard 347 stainless steel for analysis, testing, and characterization, which was completed previously. ORNL continued expanded analysis of PFR recuperator air cells and related manufacturing process specimens with Ingersoll Rand Energy Systems this quarter.
Detailed component analyses data are only reported to each of the OEMs. Collaborative efforts between ORNL and the recuperator makers to provide or characterize advanced

alloys (i.e. HR120, 20-25Nb or alloy 625) with more temperature capability and reliability continued this quarter.

<u>Selection and Commercial Scale-Up of Advanced Recuperator Materials:</u>
<u>a) Materials for use to about 704°C (1300°F)</u>

Testing of standard 347 steel with modified commercial processing for improved creep rupture resistance as sheet and foil was completed by ORNL and Allegheny Ludlum (AL). AL has made this material commercially available as AL347HP, and commercial quantities appropriate for recuperator air cell manufacturing have been supplied to Capstone Turbines and Ingersoll Rand Energy Systems.

Last quarter creep testing of specimens from plate stock was completed to measure improvements of the initial series of ORNL modified 347 stainless steels relative to standard 347 steel. Both the mod. 2 and mod. 4 ORNL modified 347 steels have significantly longer rupture life and lower secondary creep rates than standard 347 stainless steel creep tested previously at 750°C.

Previous oxidation testing in 10% water vapor at 650-750°C continued this quarter. That testing shows a significant benefit for the ORNL modified 347 steels that contain Mn and N additions relative to standard 347 steel, particularly the mod. 4 steel. Detailed microanalysis using analytical electron microscopy of the modified 347 (mod. 4) steel specimen shows complex surface oxides rich in Mn and Cr on top of a thinner chromia layer at the metal-oxide scale interface. There is a clear role of Mn that helps form a protective oxide to resist moisture-enhanced oxidation, in addition to its role in improved creep resistance. Tests at 650°C continued beyond 10,000 h this quarter.

<u>b) Materials for use at 760°C (1400°F) or higher</u>

HR 120 (Fe-25Cr-35Ni) is one of the more promising commercially available materials which has significantly better creep-resistance and corrosion-resistance in this temperature range at 3-4 times the cost of 347 stainless steel. Commercial 3.5 mil foil of HR120 was obtained by ORNL from Elgiloy Specialty Metals (Elgin, IL) and creep-tested at 704°C/152 MPa, and at 750°C/100 MPa. The HR 120 foil lasted 900h at 704°C, and lasted for 3300 h at 750°C, both with good rupture ductility. The creep resistance of HR 120 at 750°C is about 13 times better than standard 347 steel foil with standard commercial processing (Fig. 1). Creep data is also included for NF709 (Fe-20Cr-25Ni, Nb, N), from boiler tubing that was split and rolled into foil at ORNL. The NF709 shows about 50% longer rupture life than HR120. Alloys 625 foil shows roughly similar creep rupture life, but a much lower creep rate.

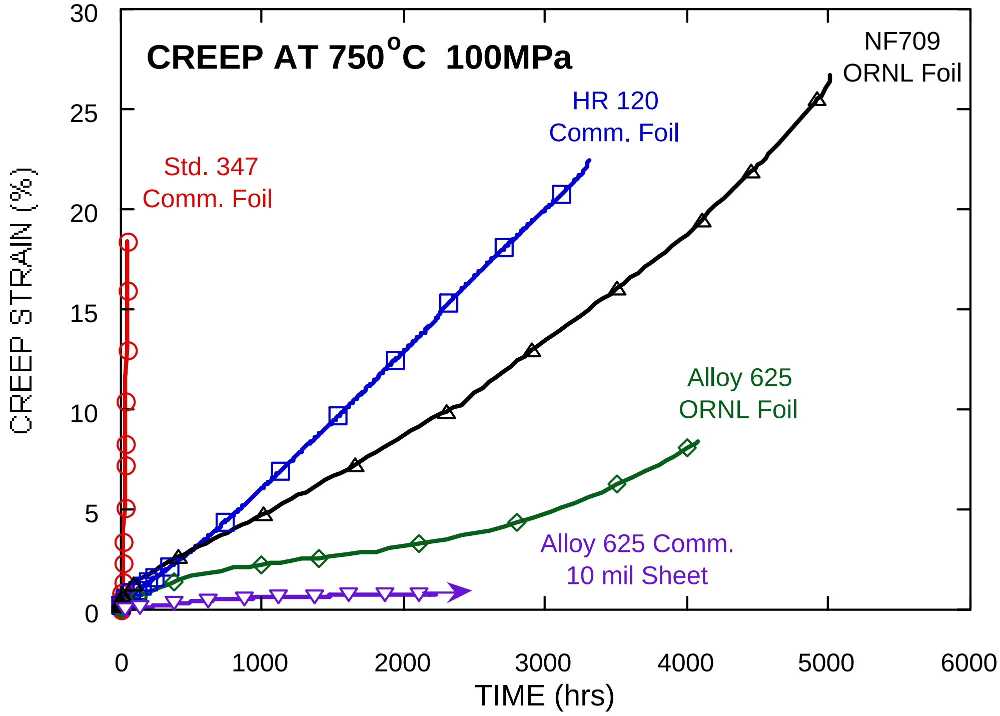

Figure 1 – Comparison of creep rupture curves for testing of commercial or ORNL processing of 4 mil foils of high performance alloys at 750°C and 100 MPa (14.5 ksi). Foils include prior data on commercial HR120, and ORNL processed foils of NF709, alloy 625, and new data on commercial 10 mil sheet of alloy 625.

This quarter, new samples of commercial 10 mil sheet of alloy 625 used for manufacturing PFR recuperator aircells were placed into creep tests at 704 and 750oC, and tests continue to about 2,300 h with no rupture. Fig. 1 shows that the 10 mil sheet shows even better creep resistance than the 4 mil foil, most likely due to difference in grain size and processing. Creep testing will continue next quarter, and microcharacterization will be done after the specimens rupture.

The commercial HR 120 foil and ORNL foils of alloy 625 and NF709 have also been incorporated into the oxidation testing matrix, and at 650-750°C are resistant to water-vapor enhanced oxidation, at least to about 8000 h. Oxidation testing will continue next quarter, and many of these steels and alloys will also be incorporated into the ORNL recuperator testing facility next quarter.

Status of Milestones

FY2004 – In collaboration with Allegheny Ludlum, process a 5000 lb commercial heat of corrosion-resistant 20/25 Nb alloy into foils and sheet for high-temperature recuperators (August 2004). (On-Schedule)

Industry Interactions

Microturbine OEM Ingersoll-Rand Energy Systems sent ORNL a sample of commercial 10 mil sheet of alloy 625, used for PFR aircell manufacturing, for creep and corrosion testing. ORNL and Ingersoll Rand continued the braze alloy studies in support of their advanced PFR recuperator manufacturing efforts. ORNL and AL initiated a new joint project effort to produce the new AL 20-25+Nb stainless alloy that has shown significantly better oxidation and creep resistance relative to standard 347 steel in their preliminary testing. The DOE milestone related to this joint project is on schedule. Tenative agreement was obtained from Capstone Turbines, Inc. and Ingersoll-Rand Energy Systems to participate in this project and take the appropriate commercial foils and sheet of AL 20-25+Nb to assess recuperator aircell manufacturing behavior.

Problems Encountered

None

Publications/Presentations

P. J. Maziasz, P. A. Bint, J. P. Shingledecker, K. L. More, N. D. Evans, and E. Lara-Curzio, “Austenitic Stainless Steels and Alloys with Improved High-Temperature Performance for Advanced Microturbine Recuperators,” paper GT2004-54239 was written and accepted for presentation and publication at the ASME Turbo Expo 2004, to be held 14-17 June, 2004 in Vienna, Austria.