CREEP AND RUPTURE PROPERTIES AT 2000° AND 2100°F OF ALLOYS RA330, RA333, AND RAonel

RA330 and RA333 alloys are widely used for applications where the service temperatures are as high as 2000° and 2100°F. This investigation was undertaken to obtain data which could be used to define the potential value of the alloys in new applications, particularly the aircraft and missile industry. It appeared that this requirement could best be met by determining stress-rupture time and 1-percent creep deformation curves at 2000° and 2100°F. These two values are those most widely used in the applications of interest for comparing the strength of alloys and designing parts to be made from them.

Only RA330 and RA333 alloys were originally included in the program. The research was undertaken as a joint endeavor by Rolled Alloys, Inc. and Simonds Saw and Steel Co. Rolled Alloys, Inc. contracted for the research at 2100°F under ORA Project 04576. The research at 2000°F was supported by Simonds Saw and Steel Company under Project 04556.

Due to certain problems in testing, these alloys at these temperatures, Rolled Alloys supported a few additional tests at both temperatures. They also extended the research to include RAonel alloy at both temperatures.

Because the research was a joint undertaking by Rolled Alloys, Inc. and Simonds Saw and Steel Co., the same text is being used in the reports to both companies. The two organizations jointly decided that the data for the alloys was needed and agreed to share costs by each supporting part of the work.

CONCLUSIONS

For RA330 and RA333 alloys at 2000° and 2100°F, the stress for 1-percent creep as a function of time resulted in a useful evaluation of strength at high temperatures. These data showed that RA333 alloy is considerably stronger for short time periods than the other two alloys; and definitely weaker at long time periods. There was no marked difference in this 1-percent creep strength for RA330 and RAonel alloys.

This characteristic of RA333 alloy would be expected to result in better ability to withstand repeated heating to 2000° to 2100°F with the time at these temperatures kept to short time periods.

RA330 and RA333 alloys underwent marked extension by cracking in the rupture tests, particularly the longer time tests. By reaction with the air, strengthening occurred after large amounts of extension which exaggerated rupture strength. The cracking, however, made the materials so brittle that such strengthening could not be used in an engineering sense.

Unusual creep characteristics prevented useful creep strengths from being established for RA330 and RA333 at 2000° and 2100°F.

RAonel was not subject to the cracking but did have extremely high elongations and reduction of area in the rupture tests at 2000° and 2100°F. This resulted in high rupture strength in comparison to the 1-percent creep strength. Its long time rupture strength was also high compared to the other two alloys.

EXPERIMENTAL MATERIALS

Chemical compositions and processing conditions for the RA330 and RA333 materials used for the investigation were reported to be as given in the tabulation which follows. The type of information was not supplied for the RAonel material, although it was known to have a nominal composition of 76% Ni, 16% Cr, 7% Fe. All three materials had been processed to 3/16-inch thick sheet by hot rolling, annealing, pickling, and light roller leveling.

	RA330 Heat 5441	RA333 Heat 5584	RAonel Heat 7051
C	0.06	0.07	
P	0.011	0.011	
S	0.016	0.016	
Si	1.00	1.27	
Mn	1.74	1.52	
Ni	34.90	44.85	
Cr	18.08	24.68	
W	0.12	3.10	
Mo	0.20	3.08	
Co	0.31	3.09	
Cu	0.08	0.06	
Pb	0.001	0.001	
Al	0.02	-----	
Rolling Temp, °F	2120	2130	
Annealing Temp, °F	2025	2200	
ASTM Grain Size Spread	6 to 2x1	2 to 5x1	coarse-grained
ASTM Grain Size Spread*	1	1+	
Hardness, RB	72-73	79-82	

* Average value

Specimen Preparation

Specimen blanks 1 inch wide x 22 inches long in the rolling direction were furnished with three or four blanks having been sheared from each 2-foot length of the sheet to secure a random sampling along the length and across the 3-foot width of the original RA330 and RA333 sheets. The

RAonel blanks were taken from a piece 24 inches wide x 48 inches long.

A simple fixture held the specimen blanks during machining, to insure that the ½-inch wide gage section at the mid-length of the specimen was accurately aligned between ⅜-inch diameter pull holes drilled about 1 inch in from either end of the strip. Rough machining was done in a milling machine, with alternate cuts taken from the two edges of the specimen blank. The gage section was finished to uniform width by hand draw-filing, producing edges relatively free from residual cold work of machining and with 0.001 inch or less taper in a 2-inch straight length. Fillets between the gage section and the specimen shank had a 1-inch radius of curvature.

No material was removed from the original sheet surface. The minor variation in specimen thickness from point to point as it was produced was accepted in order to preserve surface conditions in the specimen approximately the same as those of the material as it is used in service.

EXPERIMENTAL PROCEDURES

The tests were conducted in accordance with the ASTM Recommended Practices E139 for Creep and Rupture Tests.

Creep was measured by a mechanical-optical extensometer system. Two pairs of extension rods were attached to the lower and upper extremity of the gage section. As creep occurred, the rods in each pair moved relative to one another rotating a round bar mounted between them. A mirror mounted on the end of each bar permitted magnification of the rotation through an optical beam. Changes in specimen length of 0.000010 inch could be measured. Two pairs of rods and two mirrors mounted on each side of the specimen were used. Because it is almost impossible to obtain perfect alignment of the specimens, averaging the two readings avoids erroneous effects from eccentricity.

The extension rods were attached to the upper and lower shoulder of the specimens. A correction for the creep in the shoulders of the specimens was applied. RA333 pins through the specimens shoulder were successful for attaching extensometers for tests at 2000°F. For tests at 2100°F, it was necessary to use ceramic pins (hard fired Aluminia rod). Some difficulty was encountered from oxide particles flaking off the specimen or extension rods and lodging between the extension bars and the mirror stem during tests at 2100°F. When this occurred, erratic extension readings resulted.

Individual automatically-controlled electric resistance furnaces were used to heat the specimens. A control thermocouple inserted in the windings of the furnace responded fast enough to avoid "overshoot" and "undershoot" in specimen temperature. The actual temperature of the specimen was measured by three thermocouples attached to the gage length. Calibration drift occurred in chromel-alumel thermocouples. This problem was solved in two ways. Arrangements were made so that a new thermocouple could be inserted through the furnace wall to the gage length of the specimen. This enabled periodic measurements and temperature corrections with a fresh couple still correct in calibration. The other solution was to use a noble metal thermocouple known as "Platinel" which has about the same emf-temperature characteristics as chromel-alumel. These couples showed no drift in calibration in 1000 hours at 2000°F and at most a few degrees at 2100°F.

Due to the low stresses for the tests, most of the specimens were applied by direct-dead weight. This results in better load control than the usual beam system for magnifying the effects of weights.

RA330 Alloy

Of the three ways used to measure the strength of RA330 alloy at 2000° and 2100°F, the stress for 1-percent creep as a function of time (Fig. 3) appeared to be the most useful and reliable. It was not subject to the uncertainties and abnormal test behaviors influencing the rupture strengths and the stress for a creep rate of 0.0001 percent per hour to be discussed later. Moreover, 1-percent creep strain is an excellent basis for design and selection of materials in most applications.

Creep had virtually stopped for the specimens under 700 psi at 2000°F and 400 psi at 2100°F when the tests were discontinued. Fracture appeared to be far in the future. Both, however, exhibited about 28-percent elongation. The gage lengths were extensively cracked. Evidently, a strengthening mechanism operated to virtually stop creep after a large amount of creep and extensive cracking. These specimens were extremely brittle; the 400 psi specimen could be easily broken by a slight bend by hand. The prolongation of rupture life by a mechanism operating at such large creep strains and accompanied by severe embrittlement exaggerated the rupture strength for engineering purposes. A large proportion of the elongation occurred as a result of extension by crack initiation and growth. Evidently, as judged by the 700 psi test at 2000°F, the strengthening accompanying cracking increased with time for rupture. The exaggeration of rupture strength is indicated on Figures 1 and 3 by making the curves dashed at the longer times at 2000°F and for all tests at 2100°F.

A limited metallographic examination indicated that the cracking was accompanied by reaction with oxygen and/or nitrogen of the air to cause the strengthening. Also, recrystallization occurred throughout the tests at 2000°F, a probable weakening reaction. Recrystallization was complete in a short time at 2100°F and the resulting lack of continued weakening from this cause in comparison to 2000°F also helped to raise the level of the curve for 2100°F close to that for 2000°F.

The stresses for a creep rate of 0.0001 percent per hour (1-percent per 10,000 hours) indicated by Figure 1 indicate a higher creep strength at 2100°F than at 2000°F. The value at 2100°F is not considered reliable. It was evidently high due to the strengthening accompanying cracking, and the low creep rates were attained only after extensive "primary" creep (Figs. 6 and 7). The creep strength indicated for 2000°F is probably reliable. Its determination was, however, clouded by a volume shrinkage (Fig. 5) which offset creep during the first few hundred hours of testing. The data suggested that when the structural changes causing the volume shrinkage were completed, normal creep occurred with an apparent minimum at a normal amount of creep strain. Probably cracking did not occur at the small creep strains and consequently did not produce exaggeration of creep resistance as it probably did at 2100°F.

RA333 Alloy

The curves of Figure 2 for stress versus time for 1-percent creep are considered the most reliable evaluation of strength at 2000° and 2100°F derived from the tests on RA333 alloy. The reasons are the same as those discussed for RA330 alloy.

The longer duration tests were subject to extension by cracking and an associated strengthening from reaction with air was a major factor in the longer-time rupture tests. Note that the test at 2100°F under 500 psi had not ruptured in 2578 hours when it was discontinued, even though the time was much longer than the rupture time suggested by higher-stress tests. It had stretched 32 percent even though the reduction of area was only 2.5 percent. Most of the extension was by extensive cracking and crack growth. This embrittled the material to the point that it broke during cooling after the test was discontinued. The creep data for this test indicated that it virtually stopped creeping by the time it was discontinued.

Several features of the data made the creep strength for 0.001 percent per hour at 2000°F indicated by the data (Fig. 2) open to question. The data at 2100°F could not be used to indicate a creep strength.

At 2000°F, the rupture tests indicated no primary creep and only a brief period before creep rates increased rapidly. The rapid increase was apparently associated with cracking. Lower-stress tests were complicated by a volume shrinkage which apparently would persist to very long time periods at low stresses. Thus, a test approaching a true minimum creep rate of 0.0001 percent per hour would apparently have to be many thousands of hours in duration. At 2100°F, all of the tests had only a brief period of constant creep rate early in the tests. Increasing creep rates occurred after only a very short time period. The measured minimum rates were nearly independent of the stresses (Fig. 2). Obviously, the structural instabilities or cracking leading to early and rapid increasing creep rates prevented determination of true minimum creep rates. As was pointed out earlier, strengthening associated with extensive cracking caused creep to nearly stop in the lower stress-rupture tests after large strains from cracking.

The point at 2100°F for 200 psi related to the 1-percent creep curve was for a test in which the creep measuring extensometer did not operate properly. The over-all extension at the time the test was discontinued was about 2 percent. This supports the belief that the curve as drawn for 1-percent creep was probably correct.

RAonel Alloy

The creep-rupture test data (Fig. 10) for RAonel did not exhibit the anomalies previously described for RA330 and RA333 alloys. The time-elongation curves were accordingly normal (Figs. 11, 12 and 13).

The investigation was limited to rupture tests at 2000° and 2100°F and to determination of stress versus time for 1-percent creep strain at 1800°, 2000°, and 2100°F. Both types of results were apparently normal and reliable for use.

In the rupture tests, the reduction of area was very high. In a number of tests, the specimens reduced down to such a fine point that the reduction could not be measured accurately. In this case, the elongations being higher than the reduction of area was due to the extremely high ductility in contrast to the cracking for RA330 and RA333 alloys. The curves of stress versus time for 1-percent creep were well below those for rupture due to the extensive primary creep. In the tests on RA330 and RA333 alloys, the rupture and 1-percent creep curves were closer together due to the structural changes limiting primary creep.

DISCUSSION OF RESULTS

The stress for 1-percent creep definitely was the best way to evaluate the strength of the RA330 and RA333 alloys. The rupture and creep strengths were subject to the several uncertainties presented with the results. On the basis of the stresses for 1-percent creep in definite time periods defined by Figures 2, 3 and 10, the three alloys had the comparative strengths given in Table 4.

These data show the following:

(1) RA333 is very much more creep resistant than RA330 and RAonel alloys for time periods up to considerably more than 1000 hours at 2000°F and to somewhat more than 100 hours at 2100°F. In applications where the actual service time at the temperature is no longer than these time periods, the RA333 alloy should have considerably better load carrying ability than the other two alloys. This would be very useful in those cases where the operating cycle involved repeated heating to 2000° to 2100°F for brief periods.

(2) It will be noted that the data indicate that RA333 is unstable at 2100°F and inferior to the other two alloys for time periods longer than a few hundred hours. For the same reason, it is no better for long time periods at 2000°F.

(3) There was no real difference in the strength for 1-percent creep between RA330 and RAonel. Variations between lots and heats within each alloy would generally be expected to be more than the differences observed.

(4) RAonel did have a real superiority in rupture strength over the other two alloys at 2000° and 2100°F for long-time periods. The prolongation of life due to its very high ductility was probably mainly responsible for the superior long-time rupture strength.

Limitation of Results

It is to be recognized that only one lot of each alloy with one heat treatment was investigated. It is to be expected that some variations in properties would be expected between heats of the alloys and when production procedures and heat treatments were varied.

The structural examinations carried out prior to and after testing were too limited to be definite. All specimens were forwarded to Mr. Emery of Simonds Saw for a more complete examination.

Table 1

TEST RESULTS FOR RA330 ALLOY

Temp (°F)	Stress (psi)	Time (hrs) for Indicated Creep (%)					Rupture Time (hrs)	Elong. (%/2 in.)	RA (%)
		0.25	0.50	0.75	1.0	1.25			
2000	5000	---	---	---	---	---	0.2	71	47
2000	2000	---	---	---	---	---	12.4	38	30
2000	1200	---	---	---	---	---	197.2	45	20
2000	1000	2	4	6	8	9	227.5	26	16
2000	700	8	15	25	38	48	(Discontinued at 3112 hrs.)	>28	>15
2000	400	125	310	500	660	845	---	--	--
2000	250	[a] (1500)	---	---	[a] (3550)	---	---	--	--
2100	1200	---	---	---	---	---	51.7	52	33
2100	900	---	---	---	2	---	254.0	55	32
2100	600	3	8	13	19	25	1666	32	21
2100	400	---	---	---	---	---	(Discontinued at 2573 hrs.)	>27.5	>15
2100	300	60	135	215	330	530	---	--	--

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[a] Extrapolation

Table 2

TEST RESULTS FOR RA333 ALLOY

Temp	Stress	Time (hrs) for Indicated Creep (%)					Rupture	Elong.	RA
(°F)	(psi)	0.25	0.50	0.75	1.0	1.25	Time (hrs)	(%/2 in.)	(%)
2000	5000	---	---	---	---	---	2.4	12	15.5
2000	2000	65	81	90	95	100	120.5	7.5	6.5
2000	1150	100	240	290	340	370	545.2	12	3
2000	1000	100	240	340	450	530	963.9	23	2.5
2000	600	1450	---	---	[a](2400)	---	(Discontinued at 1729 hrs.)		
2000	400	1460	---	---	[a](3900)	---	---	--	--
2100	1250	---	---	---	---	---	77.0	5	4.5
2100	1000	60	93	111	126	139	178.1	9.5	6.5
2100	650	---	---	---	---	---	505.5	10.5	2.
2100	500	114	208	279	337	[a](388)	(Discontinued at 2778 hrs.)	(32)	(2.5)
2100	350	150	298	440	562	662	---	--	--
2100	200	(Approx. 2% plastic strain when discontinued at 1941 hrs.)							

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[a] Extrapolation

Table 3

TEST RESULTS FOR RAonel ALLOY

Temp	Stress	Time (hrs) for Indicated Creep (%)					Rupture	Elong.	RA
(°F)	(psi)	0.25	0.50	0.75	1.0	1.25	Time (hrs)	(%/2 in.)	(%)
1800	1200	127	205	264	314	360	---	---	--
1800	1000	165	279	382	478	549	---	---	--
2000	2000	---	---	---	---	---	21.0	93	--
2000	1750	---	---	---	---	---	35.0	85	--
2000	1500	---	---	---	---	---	90.8	86	--
2000	1200	---	---	---	---	---	984.2	130	(36)
2000	500	30	80	146	226	(318)	---	---	--
2000	400	71	196	390	646	---	---	---	--
2000	350	210	695	1430	2350	---	---	---	--
2100	1350	---	---	---	---	---	38.0	103	--
2100	1200	---	---	---	---	---	132.5	90	--
2100	1050	---	---	---	---	---	523.4	143	--
2100	980	---	---	---	---	---	1044.	176	51
2100	545	3.5	8	15	25	38	---	---	--
2100	400	17	49	92	142	209	---	---	--
2100	300	58	149	271	460	---	---	---	--

Table 4

COMPARATIVE STRENGTHS OF ALLOYS RA330, RA333, AND RAonel FOR 1-PERCENT CREEP IN STATED TIME PERIODS

	Stress for 1-Percent Creep Deformation in		
Alloy	100 hrs.	1000 hrs.	10,000 hrs.
		2000°F	
RA330	600	370	230
RA333	1950	740	280
RAonel	600	390	260
		2100°F	
RA330	420	250	160
RA333	1100	235	(45)
RAonel	430	280	190