HEAT RESISTANT ALLOY PERFORMANCE

This evaluation looks at wrought solid solution strengthened NiCrFe alloys used as structural elements or containers in thermal processing industries.

By JAMES KELLY

Heat resistant alloys used in fixturing for the heat treatment industry must have good mechanical properties at red heat as well as resistance to chemical attack by the environment. The requirements vary depending upon the equipment in question and are somewhat different for a quenching fixture than for a muffle operating at 2100°F/1149°C. In addition to metallurgical considerations, design and fabrication practice strongly influence the life of furnace equipment.

Alloy property requirements include strength, resistance to thermal fatigue, oxidation and carburization resistance. These properties are interrelated in practice. Strength is normally considered to be defined by the creep or rupture behavior, which is improved with coarser grains. Thermal fatigue resistance is also strongly related to grain size, but the effect of grain size here is quite opposite the case in creep-rupture. That is, the finer grain alloys, typically ASTM 4 or finer, give superior life in thermal fatigue but have lower creep strength.

In practice, quenching fixtures are not subject to dead weight loads as a creep-rupture bar but rather to a combination of mechanical loads and cyclic thermal strains. Internal thermal fatigue damage in a coarse-grained bar may have a more significant effect on deformation in use than does the lower creep strength of fine-grained metal.

Oxidation resistance is conferred primarily by Cr, Ni, Si, Al and rare earths. Laboratory oxidation data emphasizes uniform attack, usually parabolic in nature. Service failures from oxidation are uncommon. Occasionally, they exhibit complete perforation from local scale breakdown, roughly analogous to pitting failures in aqueous corrosion.

Carburization resistance depends most strongly on Ni, Cr and Si. The degree of embrittlement from carburization is related to grain size and to whether discrete carbides versus continuous networks form.

Both oxidation and carburization behavior is influenced by mechanical or chemical damage to the protective oxide scale. Thermal cycling and creep deformation mechanically damage the scale, and even small amounts of common heat treat salts reduce the protective nature of the scale.

Finally, the performance of very expensive heat resistant alloy equipment is dependent upon knowledgeable design and fabrication practice. Designers should be aware that thermal strains are often more significant than mechanical loads. Fabricators need to pay close attention to weld joint preparation be-

Table I
Common High Temperature Alloys

Grade	UNS	Approximate equivalents: wekstoff	Approximate equivalents: DIN	Cr	Ni	Si	Al	C	Other
RA446	S44600	1.4749*	X 18 CrN 28	25	—	.5	—	.05	.7Mn .1N
RA309	S30908	1.4833	X 7 CrNi23 14	23	13	.8	—	.05	—
RA253MA	S30815	1.4893	X 8 CrNiSiN 21 11	21	11	1.7	—	.08	.04Ce 17N
RA310	S31008	1.4845	X 12 CrNi 25 21	25	20	.5	—	.05	—
314	S31400	1.4841	X 15 CrNiSi 25 20	25	20	2.2	—	.10	—
RA85H	S30615	—	—	18.5	14.5	3.5	1.0	.2	—
RA330	N08330	1.4864	X 12 NiCrSi 36 16	19	35	1.3	—	.05	—
HR-120	—	—	—	25	37	.6	.1	.05	.7C .2N
600	N06600	2.4816	NiCr 15 Fe	15.5	76	.3	.2	.08	.2Ti
601	N06601	2.4851	NiCr 23 Fe	22.5	61.5	.2	1.4	.05	—
RA333	N06333	2.4608	NiCr 26 MoW	25	45	1.3	—	.05	3Co 3W 3Mo

*except carbon 0.12 maximum

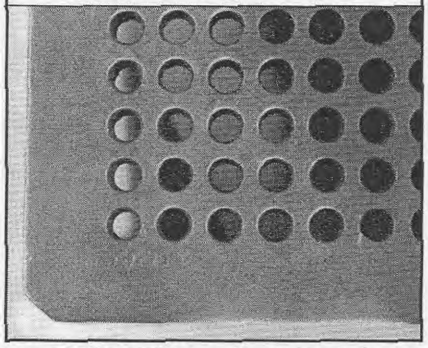
Listed with their chemistries, these alloy grades are commonly used in North America.

Table II
Intergranular Attack in Molten Salt Bath

Grade	Attack Depth, mils
RA85H	4
253MA	7
600	8
309	13
RA330	14

These alloy specimens were exposed for 21 days to 10 to 12 cycles per day. The cycles consisted of preheat salt at 1300°F, transfer to 816°F preheat salt, then to high heat salt at 2200°F, followed by quench in 1100°F salt, then air cooled.

Figure 1
RA85H Drill Fixture



This RA85H drill fixture is used just above salt level in the fumes at a temperature of about 1500°F.

Table III
Oxidation Resistance

Grade	Surface recession, mils
RA333	3
RA330	10
RA85H	19
600	21
310	31

Tests at 2100°F in weekly cycles to 3,000 hours show RA333 subject to only one-third to one-sixth the metal loss of other commonly used heat resistant alloys.

cause incomplete joint penetration is the most common cause of weld failure in service.

The alloys to be addressed in this paper are those wrought solid solution strengthened NiCrFe alloys used as structural elements or containers in the thermal processing industries. Service temperatures range from below 1400°F/760°C to 2300°F/1260°C, atmospheres from vacuum to carburizing, and thermal cycling from furnace cool to brine quench. Corrosive environments can be as benign as air or severe as hot chloride fumes and molten metals.

Alloys

Some of the alloy grades most commonly used in North America are listed in Table I.

The high chromium ferritic RA446 has very low hot strength, about an order of magnitude less than the austenitic grades. RA446 is used primarily for resistance to oxidation, sulfidation or molten copper, for which strength is not a requirement. Large bars (e.g. 2 x 4 in. rectangle) are used for electrodes in neutral salt pots up to 2350°F/1288°C.

Austenitic grades RA309 and RA310 are used primarily for oxidation resistance at 1900°F/1038°C to 2000°F/1093°C. They offer moderate creep strength and, for nickel-bearing alloys, good hot corrosion resistance. RA253MA has exceptionally high strength and oxidation resistance through 2000°F/1093°C and is used in annealing covers, radiant tubes, kilns, hot dampers, cyclones and coal-fired burners. This cerium bearing grade performs best under oxidizing conditions.

The silicon content of 314 provides good oxidation and carburization resistance for use in retorts and muffles. In the United States since the 1960s, type 314 has been supplanted by RA330.

RA85H, RA330, 600, 601 and RA333 have good strength and carburization resistance, with oxidation resistance ranging from very good to excellent.

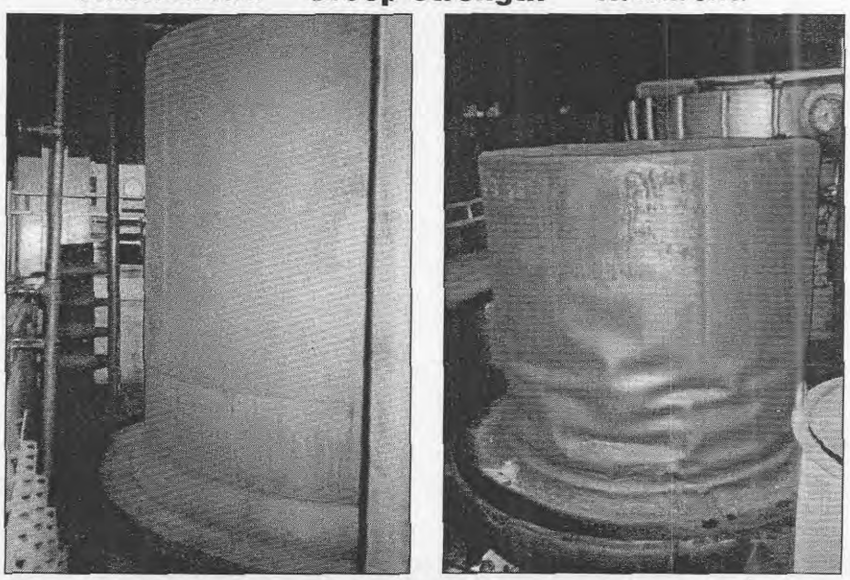
RA85H relies on 3.5 percent Si and 1 percent Al for carburization resistance similar to RA330, with oxidation resistance superior to 309. In addition, this high silicon level provides good resistance to attack by chloride salts. (Table II)

RA85H is used for a variety of salt bath fixturing. The one shown in Figure 1 operates just above the salt in corrosive fumes.

RA333 has perhaps the best combination of strength and oxidation resistance of the commercially available materials. Tests at 2100°F/1149°C show only one-third to one-sixth the metal loss, calculated from weight measurement, of other commonly used heat resistant alloys.[1] (Table III) Cyclic oxidation tests run over 7,500

Figure 2
Creep Strength

a — 253MA Inner Cover | b — 309 Inner Cover



Operating at 1700°F, the nitrogen-cerium strengthened RA253MA in Figure 2a shows no deformation, but the 309 stainless inner cover shows marked creep buckling.

hours at 1900°F/1038°C demonstrate long-time oxidation resistance superior to the aluminum bearing alloy 601.[2] The strength and oxidation resistance of RA333 permit this grade to be used as thin as 11 gauge sheet in copper brazing muffles and gas-fired radiant heating tubes.

Strength

Above 1000°F/538°C, a common definition of strength is the stress to cause a minimum creep rate of 0.0001 percent per hour. The practical effects of creep strength are illustrated in Figures 2a and 2b. At 1700°F/927°C operating temperature, the nitrogen-cerium strengthened RA253MA shows no deformation as compared with marked creep buckling in 309 stainless. Considering that there is a factor of three or four difference in measured creep rate between these two grades, this relative service performance is to be expected.

Table IV
Rupture Strengths

Grade	At 1800°F, stress, psi: Rupture in 10,000 hrs.	At 1800°F, stress, psi: Secondary creep rate, 0.0001% per hr.
RA330	630	500
310	660	280
309	560	220
253MA	1150	890
RA85H	900	700
RA333	1050	880
HR-120	1900	—

It is quite possible for several grades to have similar rupture strengths but vary widely in resistance to creep deformation.

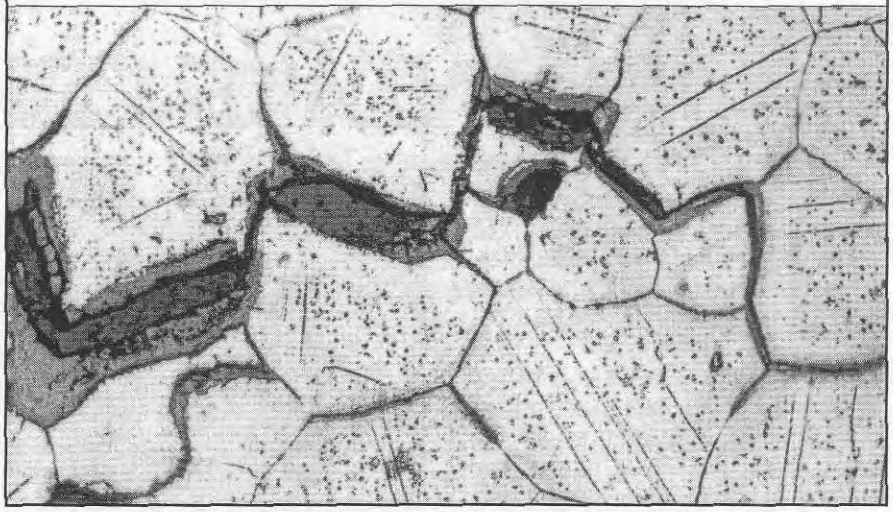
Stress to rupture is another commonly used measure of high temperature strength. However, it does not necessarily predict the relative resistance to deformation among various alloys. It is quite possible for several grades to have similar rupture strengths but vary widely in resistance to creep deformation. For example, in Table IV at 1800°F/982°C, grades 309 and 310 have 90 percent and 105 percent, respectively, of the rupture strength of RA330. But the creep strengths of 309 and 310 are both less than 60 percent that of RA330.

High temperature shear strength is important for the 1/2- to 1-in.-diameter pins used in cast-link furnace belts in North America. For the link design of Figure 3, the pins bear the shearing loads imposed by belt and workload weight and by the force necessary to pull the belt through the furnace.

If the pin lacks shear strength, the failure mode is "crank-shafting," as shown in Figure 4. The most common pin alloy in the United States is RA330HC, a 0.4 percent carbon version of RA330. Requirements for higher strength pins have been met by alloy RA333 and, more recently, by Haynes alloy HR-120.

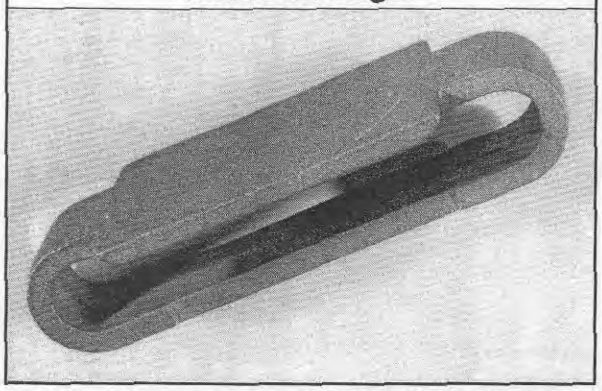
With an interlocking design, the cast link itself bears the shearing stresses, and a high strength pin is not required. In this case, pins of RA330 9/16-in. hexagonal bar provide adequate strength. Hexagonal pins are used to continually scrape away

Figure 5
Thermal Fatigue
100 X



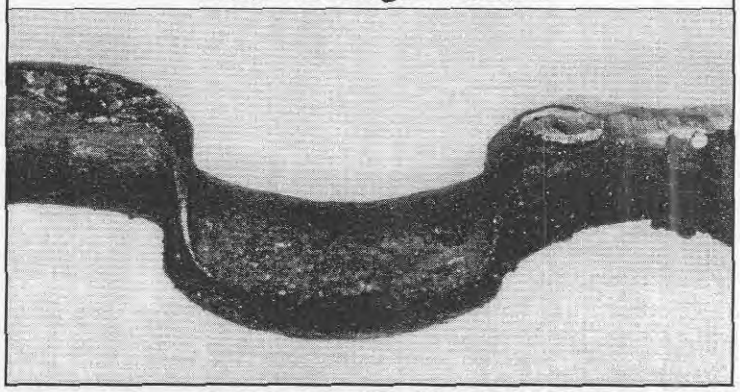
The direction of crack propagation in this 35Ni-19Cr alloy is from left to right.

Figure 3
Shear Strength



High temperature shear strength is important in this pin bearing link cast of 35 Ni 17Cr .4C alloy because as part of a cast-link furnace belt it must bear shearing loads.

Figure 4
Shear Strength Failure



As a consequence of improper annealing, this belt pin lacks shear strength; its failure mode is called crank-shafting.

carbon deposits that would otherwise tend to prevent the belt from flexing over the drive drum.

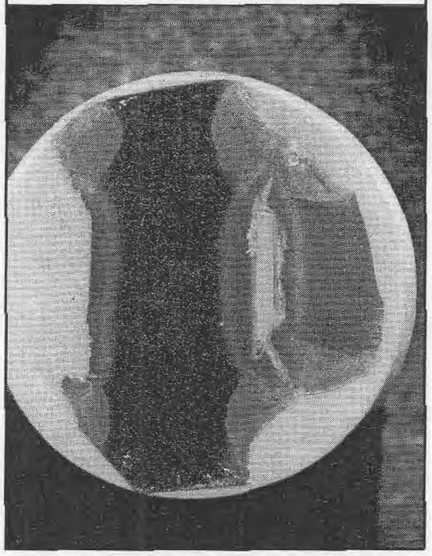
Thermal fatigue problems are far more common than creep-rupture in heat treating furnace equipment. The nature of the business includes thermal shock ranging from air cool to water quench from red heat with alloys that typically expand 0.2-in.-per-foot from 0°F/-18°C to 1800°F/982°C.

Both thermal fatigue and creep-rupture are strongly influenced by the metal's grain size, albeit in opposing manners. It is well known that a high temperature anneal to produce a coarse grain size improves creep-rupture properties. Such processing is required to develop the full strength of grades such as N08810 and N08811. However, in liquid quench applications, coarse grains almost invariably result in short life due to thermal fatigue cracking. Specifically, in bar frame heat treating baskets, a reasonably fine-grained size is required to minimize thermal fatigue damage.[3]

Grain size also affects the life of steel mill annealing covers when rapid cooling is part of the cycle. Covers of RA330 3/16-in. plate, 68-in. diameter by 14-ft. high, have typically lasted in excess of seven years at one North American mill. The maximum cover temperature is reported at 1500°F/816°C, and the product anneal temperature, at 1375°F/746°C. This cover is water-spray cooled from about

Figure 6

Thermal Fatigue in Weld Joints



Incomplete weld penetration, found in this 1/2-in.-bar-frame basket construction, will tend to produce early failure due to thermal fatigue.

900°F/482°C. RA330 is annealed to develop a grain size typically in the range of ASTM 4-7. Other producers of 35%Ni-19Cr alloy prefer to maximize creep strength by a grain-coarsening anneal.

When a cover of such material—grain size ASTM 2—was placed into this same service, it developed severe through-wall cracks within one year.

The microstructure in Figure 5 shows classic thermal fatigue cracks, intergranular and heavily oxidized. It is preferable to avoid the use of deliberately grain-coarsened alloy when the intended service is known to include severe thermal shock.

Incompletely penetrated weld joints tend to fail early in thermal fatigue. The unwelded area functions as a crack and grows outward through the weld during each thermal cycle. Indeed, lack of full penetration is the most common cause of weld joint failure in high temperature service. Figure 6 illustrates an unfortunately common weld joint design used in bar frame basket construction.

While the RA85H bars retained 43 percent tensile elongation at room temperature, the welds broke. Originally a cross, the completely fractured weld is to the left. The initial unwelded condition still may be observed at the right side. This problem could be minimized by cutting a dull chisel point on the bar ends to permit the welder to make a completely penetrated joint. HT

James Kelly is director of technology at Rolled Alloys, Temperance, Mich.

References

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2. A. Roy, F.A. Gagen and J.M. Corwin, "Performance of Heat-Resistant Alloys in Emission-Control Systems," SAE 740093.
3. Gene Rundell, "Evaluation of Heat Resistant Alloys in Composite Fixtures." NACE paper No. 377, 1986.