Heat-Resistant Alloy Selection – The Importance of Microstructure Under Cycling Conditions

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The evaluation of heat-resistant alloys often relies on the chemistry and strength levels of the material. Often overlooked is the impact of microstructure on performance. The microstructure of the alloy can greatly impact the service life of bar baskets and other heat-treat fixtures.

Bar frame baskets, corrugated boxes, etc. are commonly fabricated from nickel alloys such as RA330, alloy 600 and others that are commercially available. Chemistries for some common alloys are shown in Table 1. Table 2 provides a guide for what impact these alloy additions have on high-temperature properties.

In the search for the lowest cost, some important details may be overlooked. Although the chemistries may be the same, alloys from different sources may perform much differently in service.

Critical alloy property requirements for most furnace fixtures include strength, resistance to thermal fatigue, oxidation and carburization resistance. These properties are interrelated in impacting the life of alloy fixtures. Strength is normally considered to be defined by the creep or rupture behavior and is improved by coarser grain structures. Thermal-fatigue resistance is also strongly related to grain size, but finer grains are desirable in this case. Finer-grained alloys – typically ASTM 4 or finer – provide superior life in thermal fatigue but with some sacrifice in creep-rupture strength.

In practice, quenching fixtures are not subject to dead loads but rather to a combination of mechanical loads and cyclic thermal strains. Thermal-fatigue damage in a coarse-grained bar can lead to more significant distortion and damage in service than the use of a finer-grained alloy with lesser creep-rupture strength.

Cast and Wrought Structures

Case in point is that cast alloys, which typically have a very coarse grain structure, offer superior structural strength at red heat as compared to a finer-grained wrought product. They do, however, commonly suffer from cracking when subjected to cyclic duty due to their coarse grain structure.

Figures 1-4 compare cast and wrought grids used at a wire processor that provides spheroidized, normalized and annealing services. Traditional cast HT alloy grids were used in their furnaces. Their process involves the heating of steel-rod coils in a nitrogen atmosphere to approximately 1500°F followed by a controlled cooling.

Cast grids typically provided a lifetime

Table 1. Common alloy chemistries

Alloy	Ni	Cr	Fe	Si	Other
446	-	25	73	0.5	
304	8	18	70	0.5	
309	13	23	62	0.8	
310	20	25	52	0.5	
RA 253 MA®	11	21	65	1.7	Ce, N
RA330®	35	19	43	1.25	
RA333®	45	25	18	1.0	Mo,Co,W
Alloy 601	61	21	14	0.2	
RA 602 CA®	63	25	9	0.03	Al,Zr,Ti
Alloy 600	76	15	8	0.2	

Table 2. Guide for impact of alloy additions on high-temperature properties

Alloying Element	Major effects on high-temperature properties	
	Positive	Negative
Nickel	Strength, carburization and molten salt resistance, phase Stability	Cost, sulfidation resistance
Chromium	Primary oxide former, scaling, carburization, and sulfidation resistance	Promotes formation of sigma phase
Silicon	Scaling and carburization resistance	Promotes formation of sigma phase
Aluminum	Scaling resistance	Nitriding resistance
Iron	Basic element in steels	-
Carbon	Strength	Reduced ductility
Nitrogen	Strength	-
Cerium & yttrium	Scaling resistance, strength	-
Molybdenum	Strength	Cost, decreased scaling resistance
Cobalt	Strength	Cost
Tungsten	Strength, carburization resistance	

of 18-24 months until major repairs were required, with cracking becoming visible after about a year of service. At that point, cracks in the castings led to segments breaking away from the trays (Fig. 3). A leading heat-resistant alloy fabricator noted the cracking problems associated with the cast trays and proposed a new fabricated design using RA330 alloy.

In contrast to cast HT, this wrought alloy has a carbon content of 0.05% and is also manufactured to control its grain size, which greatly enhances resistance to cracking from thermal cycling. RA330 is also immune to sigma-phase formation. As a result, even after long-term exposure at 1500°F, RA330 alloy retains its ductility. This allows for life extension through restraightening and/or weld repair. After six years in service, the fabricated grids are still performing well. Good ductility has allowed for occasional restraightening as required.

Grain Size Variation in Wrought Alloys

Over the years, alloy suppliers have looked for ways to reduce the production costs of these heat-resistant alloys by streamlining the production process. While the chemistry remains consistent, altering the mill production process can yield a rod coil product with a wide variety of microstructures. Some of these are suitable for high-temperature quenching, and others are not. Figures 5 and 6 show acceptable and unacceptable microstructures seen throughout the years. Experience shows that both the chemistry and the microstructure are critical to the performance of a wrought fabricated tray as well.

Fig. 1. Cast HT tray

Fig. 2. Fabricated RA330 tray

Fig. 3. Close-up of cast tray after 18 months service prior to weld repair to replace lost segments due to fracture from thermal cycling

Fig. 4. Wrought fabricated tray photo taken after five years in service.

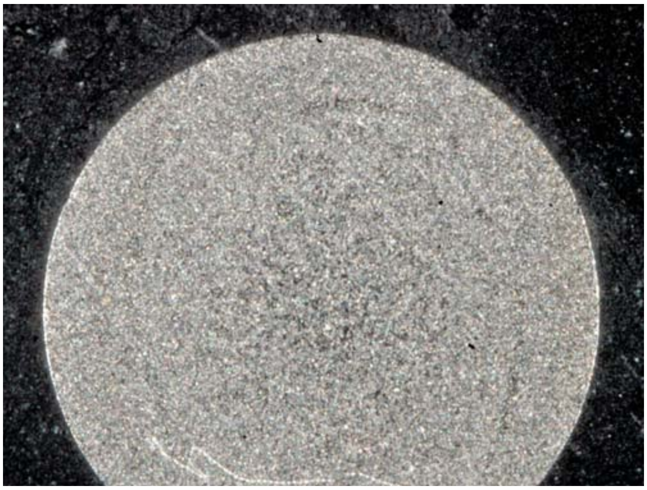

Fig. 5. Acceptable RA330 alloy structure with consistent grain size throughout the cross section of ASTM 7

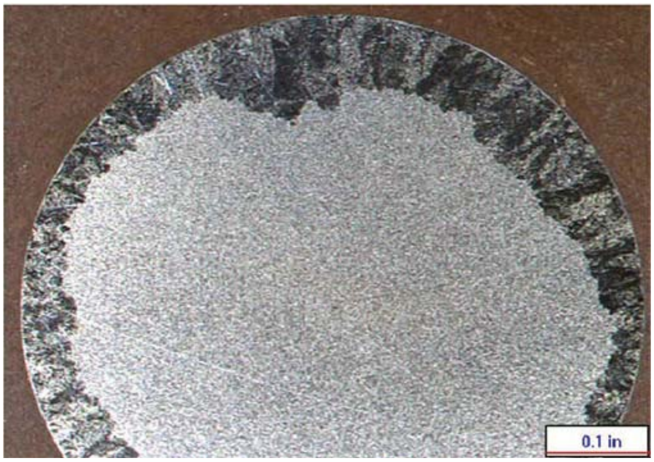

Fig. 6. Unacceptable alloy 330 bar basket structure. Two different grain sizes can be seen – coarse grains (ASTM 1) on the outer surface and fine grains (ASTM 9) at the center.

Case Study – Alloy-600 Bar Baskets

A study done on alloy-600 bar baskets[1] fabricated using a combination of coarse-grained (ASTM 4) and fine-grained (ASTM 8-9) rods also showed the benefit of fine grains in quenching service. In this study, the baskets were evaluated after one year of service in a combination of 50% straight hardening at 1650°F, 30% carburizing at 1650°F and carbonitriding at 1500-1600°F. All cycles included an oil quench. It was found that carburization of the bar baskets was 0.022-0.043 inches deep in the fine-grained bars versus 0.050-0.060 inches in coarse-grained samples. Thermal-fatigue cracks were twice as deep in the coarse bars as the fine-grained bars on average.

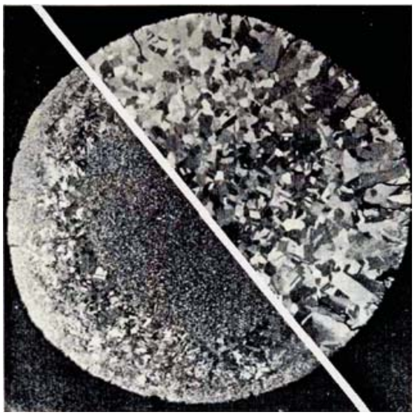

Fig. 7. Photo from a study showing depth of thermal-fatigue cracks in coarse-grained (top right) and fine-grained (bottom left) alloy-600 bar baskets

Case Study – Corrugated Boxes

J.C. Kelly[2] likewise indicates in his experience that grain sizes finer than ASTM 4 are desirable for thermal-fatigue resistance in quenching fixtures. A test was conducted with corrugated boxes where half the box was constructed of material with a grain size of ASTM 4 and the other half was ASTM 00. After 18 months of service in a carbonitriding operation at 1650°F followed by an oil quench, the corners of the box cracked in the coarse-grained product while no cracking was evident in the finer-grained product.

Similar support for the benefit of fine-grained material in quenching service can be derived by considering the markets for two nickel alloys. RA330 at 35% nickel and 19% chromium is fairly similar in chemistry to alloy 800H/AT (32% Ni, 20% Cr). RA330 is common to the heat-treating industry, whereas 800H/AT is commonly used in the petrochemical industry.

The difference between the two involves their processing at the mill level. RA330 is mill annealed at a more moderate temperature – typically around 1900°F – whereas 800H/AT is required to be solution annealed at 2100°F minimum. Higher annealing temperatures yield a coarse grain structure (commonly ASTM 4 or coarser) and maximize creep-rupture strength in the 800H/AT product. RA330 has a typical grain size finer than ASTM 4. As a result, 800H/AT is most suited to structural components of petrochemical furnaces where operation is continuous and temperature cycling is minimal. RA330, with its finer grain structure, is more suitable for the rigors of thermal shock encountered by fixtures in the heat-treat industry.

Table 3. 10,000-hour average stress to rupture, psi

Alloy	1400°F	1600°F	1800°F
800H/AT	7300	3500	1200
RA330	4300	1700	630

Alloy Cost Savings

It would be an unusual heat-treat operation if it has not experienced dramatically rising costs in recent years. The cost of energy and materials has been on the rise. Heat-resistant alloy pricing has risen whether cast or wrought. A significant factor in the higher costs for these alloys is the recent rise of nickel prices. Many heat-treat fixtures are used in applications other than carburizing, nitriding or carbonitriding. In services like annealing, vacuum heat treating, etc., alloys high in nickel (35-76%) such as RA330, HR-120 and alloy 600 are used because nickel alloys are typically stronger than stainless steels, but not necessarily for environmental resistance. RA 253 MA (UNS S30815) is an 11% nickel alloy with added nitrogen. It has been utilized for high-temperature service for more than two decades. Its most significant use has been in steel mills and power-plant applications. It is, however, gaining in popularity in the industrial heat-treat industry because of its low initial cost and high creep strength. The nitrogen provides high strength without the need for a coarse grain structure.

Table 4. 10,000-hour average stress to rupture, psi

Alloy	1600°F	1700°F	1800°F	2000°F
RA 253 MA	2500	1650	1150	680
RA330	1700	1050	630	280

72" x 72" RA 253 MA corrugated boxes made of 11ga sheet with 5/8-inch diameter round-bar grids used for an isothermal heat treatment at 1600°F

Conclusions

While chemistry plays an integral part in the performance of a heat-resistant alloy, the microstructure of a material, as shown here, impacts resistance to thermal fatigue. Understanding both will ensure the proper material and method of manufacture are selected for your application. Before substituting alloys of similar chemistry, it is suggested that you check with your alloy supplier to ensure that the products are designed for similar operating conditions. **IH**

References

1 J. Barry Harland, "How Grain Size Affects Life of Heat Treating Baskets", *Metal Progress* April 1967, p 22-24

2 J.C. Kelly, "Heat Resistant Alloy Performance", *Heat Treating July 1993*

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