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Technical Information

RELIABILITY AND LONGEVITY OF FURNACE COMPONENTS AS INFLUENCED BY ALLOY OF CONSTRUCTION

by

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The productivity and cost-effectiveness of furnace operations in heat treating or thermal processing are very dependent upon the reliability and longevity of furnace components and fixtures. Selecting the correct alloy of construction for these can be a critical choice for economic furnace operation. It can result in minimizing of repair, replacement and down-time costs, and it can lead to optimizing of loading factors, throughput rates and cycle times. The performance capabilities of a large group of commercial heat-resistant alloys will be reviewed. These will be compared with selected component requirements with the intent of establishing a basis for matching alloys to specific components and operating conditions.

To appreciate the factors that enter into selecting materials of construction for furnace hardware and consumables, it is first necessary to understand why such components fail. Overlooking general abuse and mishandling, which unfortunately are not insignificant causes of failure, the most common ways by which failure occurs are: (1) distortion from overload or thermal cycling; (2) thermal or environment-induced embrittlement; and (3) loss of section thickness due to oxidation or dissolution by molten salts. Any or all of these may be contributing factors in a given instance depending upon the nature of the service exposure.

Regardless of the mode of component failure, the practical cure for the problem generally lies in the selection of the "appropriate" material of construction. As there are numerous choices of materials available for furnace components, many of which are shown in Table I, it is important to consider both performance and financial criteria in determining which are "appropriate" materials. A list of what are perceived to be the main criteria in both categories is presented in Table II.

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In the context of the reliability and longevity of furnace components, it should be recognized that initial component material costs can often be of secondary importance when compared with the consequences of downtime, product losses, liability and maintenance charges. Life cycle cost analyses for specific applications often reveal that components made with materials which are more costly to procure are, in fact, less expensive than those made with lower-cost materials over the life of the component. As it is inappropriate to generalize such considerations, we will not deal with "cost-effectiveness" of the various materials discussed, but rather will confine ourselves to comparing their relative performance characteristics.

Resisting Component Distortion

Distortion of high-temperature furnace parts such as retorts, muffles, baskets, grates, etc. is a very common occurrence. The source of the distortion can normally be traced to either an overloading condition or to the imposition of severe thermal stresses during heating and/or cooling. In the first case, the use of thicker component section size, a higher strength material, or even reduction of the load on the component are all effective means for addressing the problem. In the latter case, the issue is a bit more complex. Thermal stresses arise when different parts of a component expand or contract at different rates during heating or cooling. Presuming only one material of construction is involved (this is always desirable), the source of such differential expansion or contraction can be either a variation in component section thickness or a variation in actual heating or cooling rate. Uniformity in component section thickness is virtually always a good design doctrine. Uniformity in component heating and cooling is something certainly to be sought after, but very difficult to achieve in actual practice.

Regardless of whether the issue is distortion from overloading or from thermal stresses, the material solution to the problem calls for higher strength. There are two strength characteristics which are important: yield strength, and creep or stress rupture strength. The former gauges resistance to deformation under short-term transient stresses, such as thermal stresses developed in the component during heating and cooling cycles. The latter relates more to resisting long-term stresses, such as those developed at temperature from supporting the weight of parts being heat-treated, or from supporting the weight of the component itself.

The yield strength properties of the various heat-resistant furnace materials are given in Table III. Solid-solution-strengthened alloys such as 230™ alloy and 556™ alloy exhibit significant strength advantages over the less alloyed Ni-Fe-Cr and Fe-Ni-Cr materials. The 214™ alloy, which develops precipitation hardening below 1700°F, exhibits even higher strengths at the lower temperatures, and strength roughly equivalent to the Ni-Fe-Cr alloys at higher temperatures.

Among the more common heat-resistant alloys. alloys 601 and 253MA appear to rank the highest, although they possess only about half of the strength of 230 and 556 alloys above 1600°F. Next in line are the Fe-Ni-Cr materials RA330 alloy and alloy 800H, followed by alloy 600, the austenitic stainless steels, and lastly the ferritic stainless Type 446. The overall range of yield strength capabilities exhibited is quite large, with nearly a factor of ten between the strongest and weakest alloys at the higher temperatures.

The stress rupture strength properties of these same alloys are illustrated in Figure 1 for temperatures between 1400°F and 2000°F. Once again, the advantage of the 230 alloy, 556 alloy and 214 alloy materials is evident for these 100-hour-to-rupture strength comparisons, although the coarse grain size of the alloy 601 and alloy 800H materials make them compare somewhat more favorably than in the yield strength comparison. It is also a bit difficult to appreciate the significance of the differences in expected life from these bar charts. A better perspective can be gained by examining the data presented in Table IV, which relate the expected life for each alloy under arbitrarily selected conditions of temperature and stress. Here the differences between the stronger and weaker alloys is shown to vary by many orders of magnitude as a consequence of the sometimes small difference in actual strength.

Another factor which is relevant to dealing with distortion arising from thermal stresses is a material's thermal expansion characteristics. The lower these are, the less potential there is for the generation of thermal stresses due to differential expansion or contraction during heating and cooling. Typical expansion characteristics for various heat-resistant alloys are shown in Figure 2. The lowest expansion behavior is exhibited by 230 alloy as a consequence of its nickel base and high tungsten content. Closest to 230 alloy are the other high-nickel alloys. The highest expansion characteristics are exhibited by the iron-base materials and austenitic stainless steels.

Resisting Embrittlement

Thermal and environment-induced embrittlement of furnace parts are important causes of failure. Few of the common heat-resistant stainless steels and alloys suffer environment-induced embrittlement in air or combustion environments that are not reducing, as long as the temperature of operation is not excessive. Many of these same materials, however, have intrinsic susceptibility to thermal embrittlement. Austenitic stainless steels, for example, will embrittle from sigma phase formation when exposed for prolonged times at intermediate temperatures. Most of the higher nickel iron-nickel-chromium and nickel-base materials such as RA330, 800H, 600, 601, and 230 alloys do not exhibit such problems.

One exception to the absence of environment-induced embrittlement in air or combustion environments does bear mentioning. In some cases, if the temperatures are high enough, coarse grain size in the material (either as-supplied or as a result of grain growth in service) can allow for embrittlement to occur as a consequence of grain boundary oxidation. This should be of particular concern if the alloy being employed in component construction will see temperatures in excess of its annealing or solution treatment temperature. Under such circumstances, even if the material is put into service with a reasonable grain size, the grain size can grow in service, rendering the material particularly sensitive to grain boundary oxidation.

Data relating grain size, annealing temperature and grain growth behavior are presented for typical alloys in Table V. Materials with stable primary carbides, such as 230 alloy, resist grain coarsening to very high temperatures. Less alloyed materials, such as 601, 800H and 600 alloys, are susceptible to carbide dissolution and attendant grain growth in service at these temperatures. Grain boundary oxidation along these coarsened grain boundaries can product severe cracking problems in service, particularly under cyclic conditions.

Coarse grain size in the material aside, the two more common modes of environment-induced embrittlement relate to failures in carburizing and nitriding environments. Exposed to the same environments being used to treat parts, furnace hardware will eventually crack due to cumulative carburizing or nitriding coupled with loading or thermal-cycling-induced stresses. The only real choice to preclude short-term failure here is to select materials for the exposed components which resist the embrittlement in addition to meeting all other component performance requirements.

Carburization-resistance and nitriding-resistance properties for typical heat-resistant alloys are presented in Tables VI and VII, respectively. Carburization tests were performed by exposing samples to a mixed gas composition consisting of Ar-5%H_2-5%CO-5%CH_4 at 980°C for 55 hours (unit carbon activity, oxygen partial pressure below that required for chromium oxide scales to form). Although not a commercial carburizing environment test, this procedure is very useful for clearly ranking resistance to carbon absorption, which relates directly to the degree of embrittlement.

The results shown in Table VI, which are expressed in terms of the weight of carbon absorption per unit area, reveal that both RA330 alloy and 214 alloy exhibit excellent resistance to carburization. The resistance of the former relates particularly to its high silicon content, while the latter's resistance is attributable to the formation of an effective aluminum oxide scale barrier to carbon ingress, even under these very low oxygen partial pressure conditions. Next best to these are alloy 800H and 556 alloy, which contain strong carbide formers such as titanium and tantalum. Nickel-base materials such as 230 alloy and alloy 600 are reasonably resistant to carburization, but others, such as 601 alloy, exhibit apparently greater carbon absorptions. Not shown are the austenitic stainless steels, whose resistance to carburization can be significantly affected by variation in silicon content within the wide range of levels typically produced.

Nitriding tests were conducted similarly to the carburization tests. Here, samples were exposed to pure ammonia at 1200°F for a period of 168 hours. Results presented in Table VII are again expressed in terms of weight of nitrogen absorption per unit area. As classical experience would predict, the nickel-base alloys are significantly superior to the iron-base materials. Best in the tests were 230 alloy and alloy 600, the latter being known as the best material for such service for many years. Closely following are alloy 601 and 214 alloy. Among the iron-base alloys, those with the higher nickel or nickel plus cobalt contents, alloy 800H and 556 alloy, are demonstrably better than the lower-nickel, austenitic stainless steels.

Resisting Loss of Section Thickness

As previously mentioned, the third common means of component failure is by loss of section thickness from either oxidation or dissolution by molten salts. Section thinning usually proceeds until either a perforation-type failure occurs in, say a retort or salt pot, or the thinning of a structural member causes an overload failure, as in a basket. Again, the only choices to avoid short service life are to use a thicker section size, or select a material with superior resistance to the cause of the thinning.

In selecting materials for resisting oxidizing environments, the type of test data considered can materially affect the selection process. Oxidation is often equated only with scaling of materials. Indeed, steels and stainless steels are normally characterized by "scaling rates", which rank weight change per unit area per unit time. This is not a good way to judge performance of materials, since it does not address the issue of internal attack. Oxidation-resistance measurements that include evaluation of internal damage (which does serve to reduce effective metal thickness) can be quite damning to what otherwise might be considered very resistant alloys. Also, cyclic combustion environments prove to be much more severe than would be predicted from simple flowing air tests.

Accordingly, tests have been run by exposing samples to 1800°F high-speed combustion gases produced by burning a mixture of No. 1 and No. 2 fuel oils at an air:fuel ratio of about 50:1, and cycling the samples to under 500°F every 30 minutes by air blast. Exposures were continued for 1,000 hours. Results are presented in Figure 3 for both metal loss (thickness reduction) and internal penetration, the latter determined from post-exposure metallographic evaluation.

Under these conditions, ordinary stainless steels, such as Types 304 and 316, were consumed very quickly. Alloy 601, while exhibiting reasonable resistance to thinning, displays a significant amount of internal penetration and void formation, with consequent loss of load-bearing capability. The best resistance is exhibited by the aluminum oxide scale forming 214 alloy, with about 1/3 the damage sustained by 230 alloy, the best chromium oxide forming alloy. The 230 alloy, in turn, is twice as good as 556 alloy, which is about twice as good as RA330 alloy. Alloys 800H and 600 fall thereafter.

For components designed for service in molten chloride salt environments, such as pots or baskets, material selection is obviously influenced by resistance to dissolution by the molten salt. Comprehensive data for such environments has not been generated; however, limited data from the field have been obtained for a 700-hour exposure in 1550°F equimolar BaCl-KCl-NaCl salts. These data are given in Table VIII. The best results were obtained for 556 alloy, which was generally 2-3 times better than the other alloys.

Typical Component Service Requirements

Thus far we have described the various material properties which are generally important for heat-resistant alloy performance. What remains is to tie these properties to the performance requirements for specific components in service. Some of these are outlined in Table IX for examples of a few important furnace applications.

Furnace retorts and muffles are usually the largest components posing alloy selection choices, thus making the choice all the more critical. Retorts are subject to thermal cycling by nature of their use, and therefore are subject to distortion from thermal stresses as well as from deforming at the service temperature under their own weight. The serviceability of a retort is often highly dependent upon its maintaining shape, so resisting distortion is of paramount concern. This is particularly true for sand seal types.

In most cases, retorts will see oxidizing conditions outside with either inert or process environments on the inside. Oxidation-resistance is thus another major consideration, with resistance to carburization or nitriding of equal importance when these processes are involved. Also of importance is resistance to grain growth, since grain boundary embrittlement can produce sudden cracking on cycling which can cause leaks leading to contamination of the environments.

A review of the alloy performance capabilities in the context of these requirements indicates that 230 alloy provides the best balance of properties for retort service other than carburizing furnaces. For carburizing retort applications, RA330 alloy exhibits the best process environment-resistance, but is inferior to both 214 and 556 alloys in strength and oxidation-resistance to a significant degree. On balance, 214 and 556 alloys would appear to be better choices.

The considerations relative to furnace muffles differ somewhat from those for retorts. Thermal cycling is normally not a factor as operation is usually continuous. Resisting distortion is still an issue, but secondary in many respects to resisting the environment. Generally speaking, selecting an alloy for muffle service on the basis of resistance to oxidation and process environment will lead to superior if not optimum service.

Furnace grids, trays, baskets and grates all have to deal with the same basic service conditions. Their function, one way or another, is to support the load of parts being treated, so resisting deformation is of key importance. In other ways, the service requirements for these kinds of furnace internals are similar to those for retorts, with two exceptions. For trays, grates and baskets subject to quenching after thermal exposure, the resistance to distortion and cracking from the severe thermal stresses generated puts a premium on high yield strength, fine grain size, and low expansion characteristics. The second exception also relates to quenching. In both conventional quenching, and in vacuum furnace forced gas quenching, the mass of fixturing can have a significant influence upon quench time for the parts. This puts a premium upon creep and stress-rupture strength, so fixturing can be designed to minimize mass.

Once again, a review of the data reveals that 230 alloy is best suited for this type of component service in all cases excepting carburizing furnaces. It particularly well addresses the two exceptions just mentioned. Good second choices are 556 and 214 alloys, which again are best suited for the carburizing furnace service.

High speed furnace fans, used mainly in combustion gas atmosphere and carburizing furnaces, are particularly demanding components. Often rotating at extremely high speeds, these fans experience very high stresses. Common heat-resistant alloys are not strong enough for use here. Many fans utilize ACI cast alloy parts, and solid-solution-strengthened wrought alloys are also used, particularly for blades. The only alloys of those discussed here which have sufficient strength for this use are 230 and 556 alloys, both of which are actually in service. The former is best suited for non-carburizing atmosphere furnaces, while the latter, once again, is superior for carburizing process equipment.

Salt bath furnaces have been widely used for a variety of heat treatment operations for many years. Salt pots, baskets, chains and hooks are all exposed to the molten salt environment, and are subject to the corrosive attack of the salt at elevated temperature. Resistance to section thinning by the salt is obviously of primary concern. Based upon our limited test data in chloride salts, and field experience with actual basket components, 556 alloy appears to be well suited to this service. Its high strength and apparent resistance to service-related cracking are also considerable in this judgement.

The final component example we shall consider is radiant tubes. These are static parts, operated rather continuously, and usually well supported within the furnace. Although resistance to distortion is an issue, it usually arises as a consequence of tube wall thinning allowing a bulge to develop. Resistance to oxidation is a paramount concern, since tube walls are relatively thin to promote effective heat transfer. On the process side, the resistance to carburization, in relevant facilities, is of equal importance.

From the data, 214 alloy is indicated to be the best overall choice for all facilities. RA330 alloy has somewhat better carburization-resistance, but 214 alloy is significantly better in oxidation-resistance. The 556 alloy would also be a reasonable choice for carburizing furnaces, and 230 alloy for the combustion gas or air atmosphere facilities.

Summary and Conclusions

The performance capabilities of a large group of commercial heat-resistant alloys typically employed for furnace component service has been reviewed. Data have been presented to characterize elevated temperature strength, thermal expansion properties, grain size stability, oxidation-resistance, carburization-resistance, nitriding-resistance, and molten salt-resistance of these materials. These data have been related to the service requirements for a number of important example component groups in terms of the typical modes of failure experienced. It was determined that, in many cases, newer wrought materials such as 230 alloy, 556 alloy and 214 alloy have the potential to provide significant performance and component life advantages over the more common materials in general use.

Table I

NOMINAL COMPOSITION OF ALLOYS

	Ni	Fe	Co	Cr	Mo	W	Mn	Si	Al	N	C	Other
HAYNES® alloy 230	Bal.	3*	5*	22	2	14	.5	.4	.3	-	.10	.02 La
HAYNES alloy 214	Bal.	3	-	16	-	-	-	-	4.5	-	.05	.01 Y
HAYNES alloy 556	20	Bal.	18	22	3	2.5	1	.4	.2	.2	.10	.6 Ta .02 La .02 Zr
Alloy 601	Bal.	15	-	23	-	-	1*	.5*	1.4	-	.10*	-
Alloy 600	Bal.	8	-	15	-	-	1*	.5*	.4*	-	.08*	-
RA330® alloy	35	Bal.	-	19	-	-	1.5	1.3	-	-	.05	-
Alloy 800H	33	Bal.	-	21	-	-	1.5*	1*	.4	-	.07	.4 Ti
Type 304	9	Bal.	-	19	-	-	2*	1*	-	-	.08*	-
Type 316	12	Bal.	-	18	3	-	2*	1*	-	-	.08*	-
Type 446	-	Bal.	-	26	-	-	1.5*	1*	-	-	.15*	-
253MA® Alloy	11	Bal.	-	21	-	-	.8*	1.7	-	.17	.07	.05 Ce

* Maximum

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RA330 is a registered trademark of Rolled Alloys, Inc.
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Table II

CRITERIA FOR SELECTING MATERIALS

Financial Criteria	Performance Criteria
· Material Procurement Cost	· Yield Strength
· Fabrication Cost	· Creep or Stress Rupture Strength
· Maintenance Cost	· Tensile Ductility
· Downtime	· Thermal Stability
	· Thermal Expansion Characteristics
· Product Losses	· Oxidation-Resistance
· Liability	· Carburization-Resistance
	· Nitriding-Resistance

Table III

0.2% YIELD STRENGTH FOR MATERIALS AT ELEVATED TEMPERATURE

Material	0.2% Yield Strength (Ksi) at Temperature Shown, °F						
	70	1000	1200	1400	1600	1800	2000
230 alloy	57	40	41	43	37	21.0	11.0
556 alloy	55	31	31	29	28	18.9	9.0
Alloy 601	35	23	26	27	19	10.0	4.9
RA330 alloy	37	26	22	19	16	9.0	-
214 alloy	82	72	76	73	50	8.4	4.2
Alloy 800H	35	19	18	17	17	8.0	3.0
253MA alloy	51	25	24	22	18	-	-
Alloy 600	51	39	35	26	12	7.0	3.0
Type 316	38	22	20	18	11	-	-
Type 304	37	19	17	14	7	-	-
Type 446	51	35	14	6	-	-	-

Table IV

RUPTURE LIFE FOR CONSTANT TEST CONDITIONS

Material	Estimated Stress Rupture Life (Hours)		
	1400°F/15Ksi	1600°F/4.5Ksi	1800°F/2Ksi
230 alloy	8,200	65,000	5,000
556 alloy	3,000	21,000	10,000
214 alloy	6,000	20,000	550
Alloy 800H	130	1,200	920
Alloy 601	50	1,200	1,000
253MA alloy	140	900	720
Alloy 600	15	280	580
Type 316	100	240	130
RA330 alloy	30	230	130
Type 304	10	100	72
Type 446	<1	<1	<1

Table V

ALLOY GRAIN SIZE BEHAVIOR

Material	Typical Annealing Temperature °F	Typical Supplied ASTM Grain Size	ASTM Grain Size Typical After Long-Term Exposure at 2200°F
230 alloy	2250	4 - 6	4 - 6
alloy 601	2050	1-1/2 - 3	00 - 1-1/2
alloy 800H	2100	2 - 4	0 - 3
alloy 600	1850	7 - 9	00 - 1-1/2

Table VI

CARBURIZATION-RESISTANCE
AT 1800°F

Material	Carbon Absorption For 55 Hour Exposure in Ar-5%H_2-5%CO-5%CH_4 (Mg/CM^2)
RA330 Alloy	<0.5
214 Alloy	0.6
Alloy 800H	1.0
556 Alloy	1.3
230 Alloy	2.5
Alloy 600	2.8
Alloy 601	4.8

Table VII

NITRIDING-RESISTANCE AT 1200°F

Material	Nitrogen Absorption for 168 Hour Exposure in Ammonia (Mg/cm^2)
230 Alloy	0.7
Alloy 600	0.8
Alloy 601	1.1
214 Alloy	1.3
Alloy 800H	4.3
556 Alloy	4.9
Type 316	6.9
Type 304	9.7

Table VIII

RESISTANCE TO MOLTEN MIXED CHLORIDE SALTS AT 1550°F

Material	Metal Loss Plus Internal Penetration for 700 Hour Exposure in Equimolar BaCl-KCl-NaCl (mils)
556 alloy	43
214 alloy	71
Type 304	75
Alloy 600	94
Alloy 601	114

Table IX

COMPONENT SERVICE REQUIREMENTS MATCHED WITH ALLOYS

Component	Typical Environment	Typical Maximum Temp. (°F)	Component Performance Criteria	Alloy Ranking (Best Given First)
Furnace Retorts and Muffles	Inert Inside; Air or Combustion Gas Outside	2300	(1) Resist Distortion	230, 556, 214, 253MA, 601
			(2) Resist Oxidation	214, 230, 556, RA330, 800H
			(3) Resist Grain Growth	230
	Carburizing Inside	1900	(4) Resist Carburization	RA330, 214, 800H, 556, 230
	Nitriding Inside	1200	(4) Resist Nitriding	230, 600, 601, 214
Furnace, Grids, Trays, Baskets, and Grates	Vacuum/Inert	2300	(1) Resist Distortion	230, 556, 214, 253MA, 601
			(2) Resist Grain Growth	230
	Air or Combustion	2000	(3) Resist Quench Distortion and Cracking	230, 556, 601, 214
			(4) Resist Oxidation	214, 230, 556, RA330, 800H
	Carburizing	1900	(4) Resist Carburization	RA330, 214, 800H, 556, 230
	Nitriding	1200	(4) Resist Nitriding	230, 600, 601, 214
High Speed Furnace Fans	Combustion Gas	2000	(1) Very High Loads and Severe Thermal Cycle	230, 556
			(2) Resist Oxidation	230, 556
	Carburizing	1900	(2) Resist Carburization	556, 230
Salt Pots & Baskets, Chains, Hooks	Molten Chloride Salt	1750	(1) Resist Distortion and Cracking	556, 214, 601, 600, 304
			(2) Resist Molten Salt	556, 214, 304, 600, 601
Radiant Tubes	Combustion Gas/Air	2200	(1) Resist Oxidation	214, 230, 556, RA330, 800H
			(2) Resist Distortion	230, 556, 214, 253MA, 601
	Combustion Gas/ Carburizing	1900	(3) Resist Carburization	RA330, 214, 800H, 556, 230

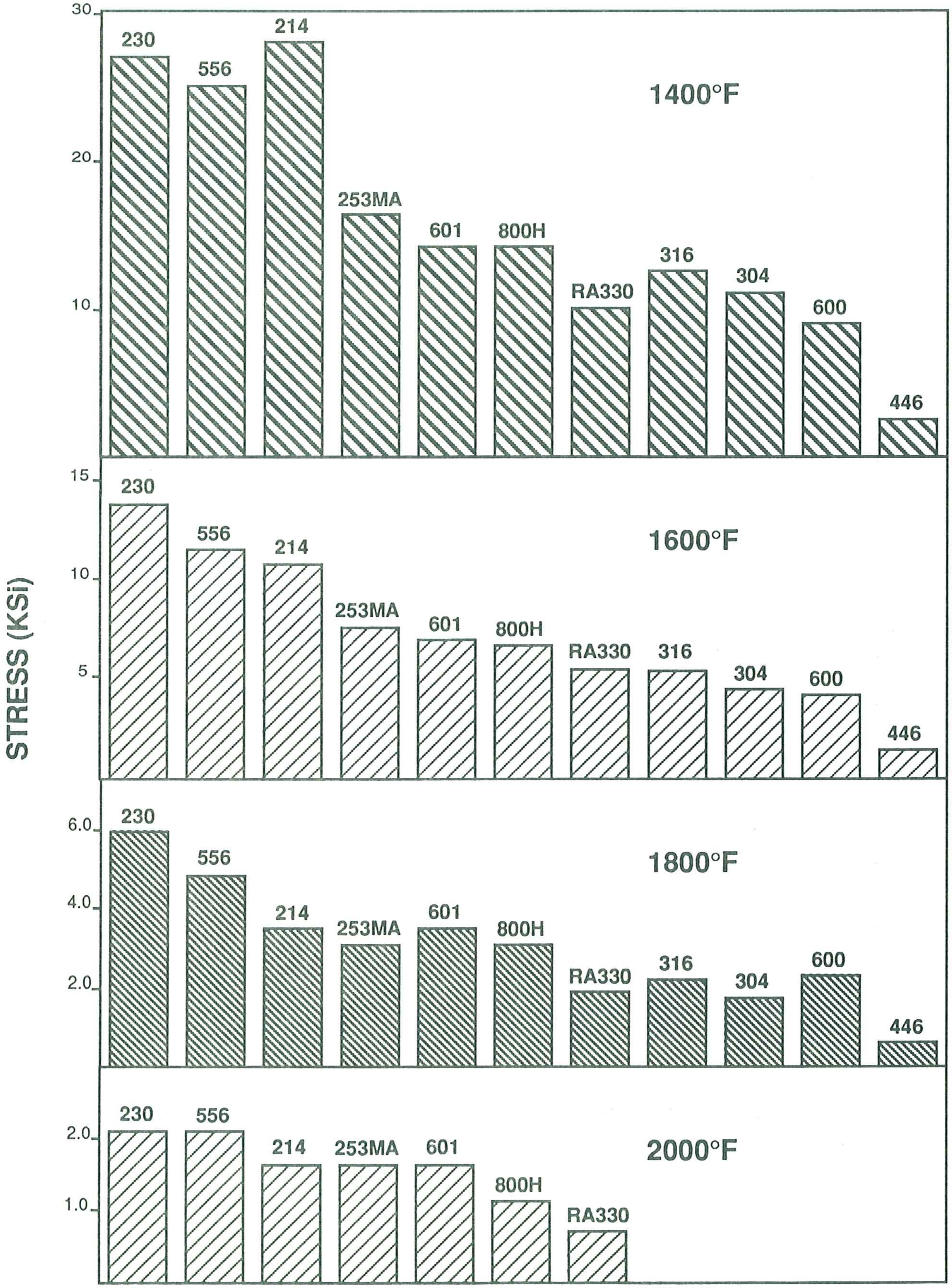

Figure 1: Elevated temperature 100-hour stress rupture strengths for various heat-resistant alloys.

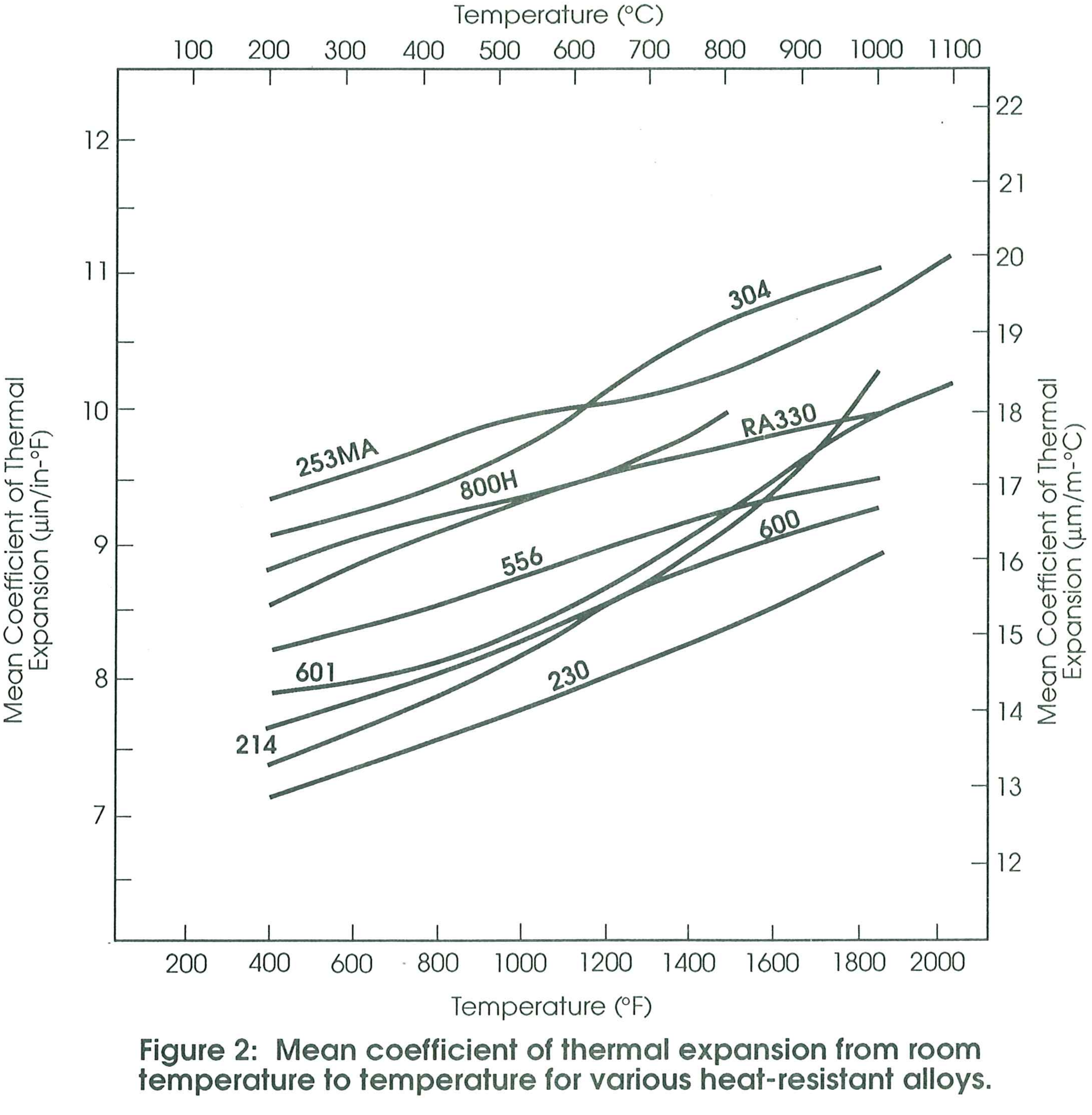

Figure 2: Mean coefficient of thermal expansion from room temperature to temperature for various heat-resistant alloys.

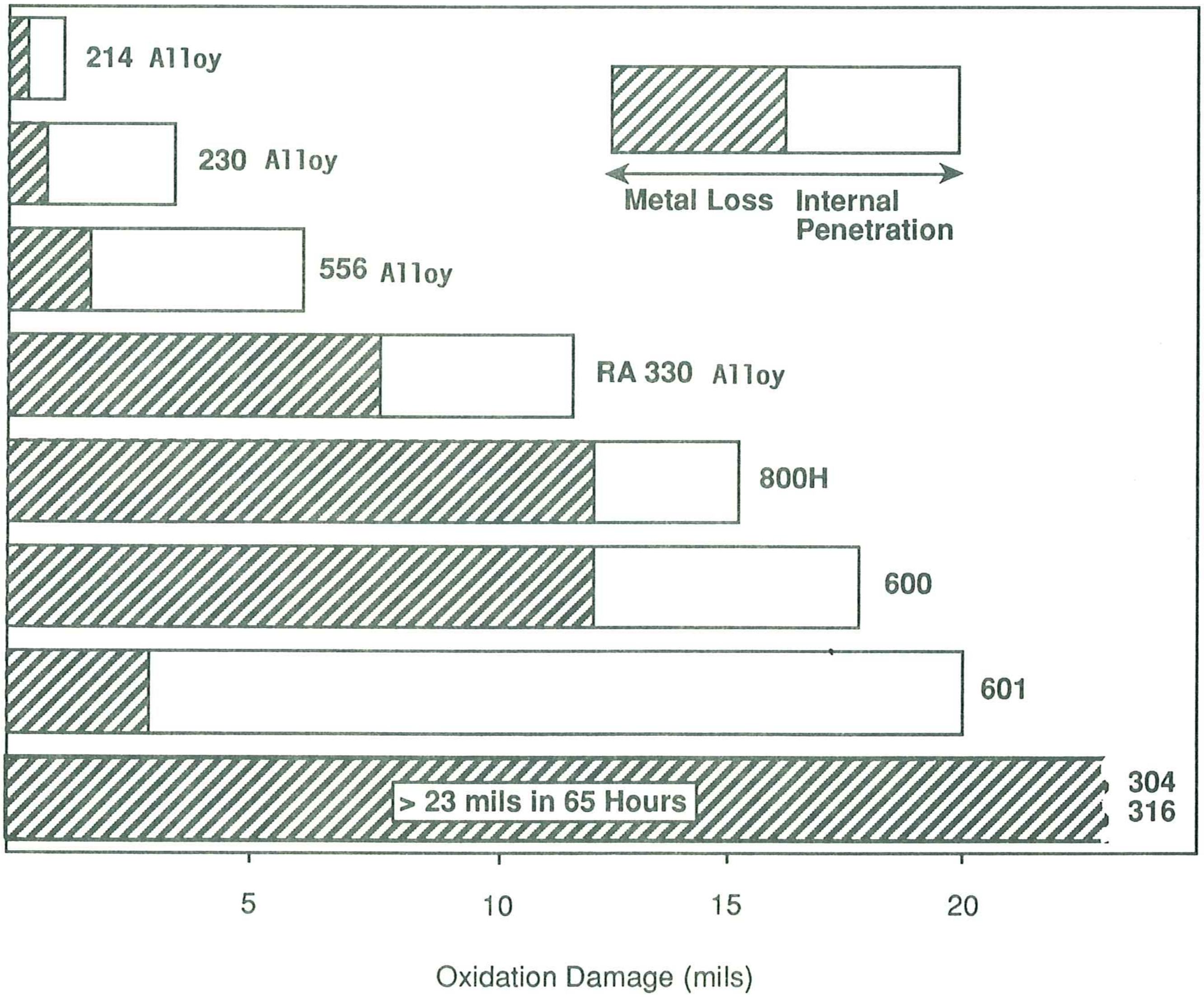

Figure 3: Oxidation damage measured after 1,000 hour exposure to 1800°F combustion gases with severe thermal cycling.

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