DESIGN

> ***Stresses (compressive, tensile, or shear) due to unequal temperature distribution and non-uniform temperature gradients, cause more failures in high—temperature equipment than all other influences combined amounting . . . to about 90 per cent of the total number of cases. And it is destructive chiefly because the engineer does not include in his design proper allowance for or provision against temperature inequalities or because the operator imposes temperature differentials which cause localized dimensional changes with accompanying stresses greater than the elastic strength of the alloy at the given temperature.***
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> *F. A. Fahrenwald. Some Principals Underlying the Successful Use of Metals at High Temperatures, Proceedings of ASTM, 1924 V. 24*

Nothing has changed in eighty years. High temperature equipment design has certain unique features not commonly found, nor at least emphasized, in mechanical engineering texts.

The first and most important is that **metals expand in volume with heat.** This simple statement is so obvious, yet often dismissed or given but slight consideration in design. If thermal expansion is somehow restrained, the resulting stresses will equal the yield strength of the metal at temperature. One must design to permit free expansion (and contraction) or the metal will bend, buckle or crack.

A corollary to this is that most heat resistant alloys have rather poor thermal conductivity, less than 1/4 that of carbon steel and only 1/30 that of copper. Thermal gradients, hence thermal strains, are the rule and not the exception in high temperature equipment.

Next, one should be aware of the significance, and the limitations, of creep-rupture data. These data are obtained under very closely controlled laboratory conditions of constant temperature and stress. Even so, there is considerable scatter, 15 to 20%, in rupture data, and possibly more in creep. When using published average creep-rupture data for design one must include a safety factor, and be clearly aware of the range over which temperature will be controlled in service. It can be surprising how rapidly mechanical strength drops off with temperature. For example, an increase in service temperature from 1700°F (927°C) to 1800°F (982°C) could drop the life of an RA330 component from 10 years down to only 15 months, under the same load.

In practice, the furnace industry often designs to an allowable stress of one half the stress required for a minimum creep rate of 0.0001% per hour, at the service temperature. The ASME Boiler & Pressure Vessel Code is more conservative, designing to either 100% of the extrapolated 0.00001%/hour minimum creep rate, or 67% of the extrapolated 100,000 hour rupture stress, whichever is lower.

Rotating components, such as kilns, are often designed to much higher stresses than are static components. Kiln failures may be due to hot corrosion, more often to flite design, but rarely, if ever, to fatigue from the rotation.

An item of some minor confusion is elastic modulus. Although modulus data are published at elevated temperatures, the numbers are obtained by a means involving the speed of sound through the material. In practice, above about 1000°F (540°C) stress is no longer proportional to strain. In other words, at red heat these alloys are simply not elastic, and the modulus data has no real meaning. One cannot calculate a simple beam deflection at 1650°F (900°C) using anyone's published modulus data. At such temperatures strain is proportional to both time and stress, and not simply to stress alone.

Thermal Strain

This point is such an important consideration for high temperature equipment design that it must be examined in some detail.

A large portion of the many field failures reported to us happen because the designer or user did not appreciate the significance of thermal expansion. This expansion must be accommodated not only by design but by installation practice as well.

Heat resistant alloys expand a great deal when heated. This expansion is roughly 3/16" to 1/4" for each foot of length (16 mm per meter), when heated from room temperature to 1800°F (982°C). If the metal is not free to expand, it will stretch, bend or warp permanently with each thermal cycle. Eventually, this repeated strain will fatigue the metal and the equipment will break.

It is important to recognize just how large the total expansion can be, in typical heat treat service. A 48" (1220 mm) long RA330 heat treat basket, for example, oil quenched from 1550°F (843°C) will contract 0.692 (17.6 mm)—more than 11/16"—in overall length. Since the bottom of the basket enters the quench while the top frame is still red hot, the bottom members contract before the top does.

A flexible bar frame design may tolerate this. But, a mechanically strong and rigid welded angle frame design may be inclined to crack or distort. This is because this "strong" design cannot accommodate the relative thermal contraction of the bottom versus the top of the frame.

Thermal strain, continued

As temperature goes up the metal not only expands but diminishes rapidly in strength. The short-term yield strength of RA330, for example, averages about 37,200 psi (256 MPa) at room temperature, but only 40% of that figure, or 15,400 psi (106 MPa) at 1600F (871C). The short-term modulus, for whatever that is worth, drops from $28.5x10^{6}$ psi (196 GPa) to $19.5x10^{6}$ psi (134 GPa). The combination of differential thermal expansion/contraction and reduction in strength at heat is why quenched grids or large bar frame baskets tend to bow like a rocking chair, convex to the quench.

In general any piece of metal which is hotter on one side will, when cooled, become concave on what was the hot side. As well as being the cause of distortion in service, this principle may be used to straighten metal parts[1,2].

The equation for calculating thermal stress in the elastic region is:

$$S = \frac{aETK}{1 — ?}$$

a = coefficient of thermal expansion
T = temperature difference
? = Poisson’s ratio
E = elastic modulus
K = restraint coefficient

The formula may be found in S.Timoshenko, Theory of Elasticity, McGraw-Hill, New York, NY 1934

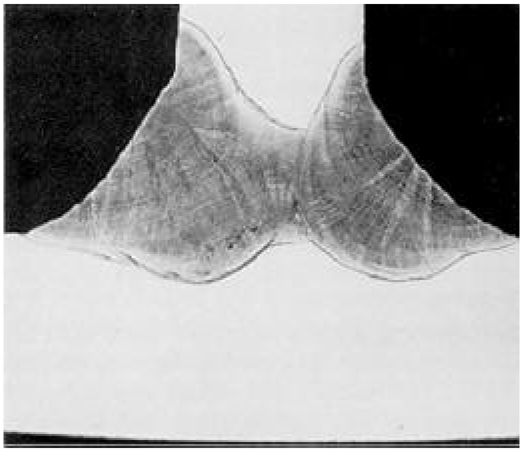
Apply this formula to RA330. Assume a plate 1000F on one side and 800F (538 to 427°C) on the other. $a = 9.3 \times 10^{-6}$ inch/inch°F $E = 23.8 \times 10^{6}$ psi $T = 200$°F $K = 1$? = 0.297

The calculated stress = 62,970 psi. Average 0.2% offset yield strength of RA330 at 1000°F (538°C) is 25,000 psi. So, one may assume that a temperature differential of only 200°F (110°C) in this temperature range would cause permanent plastic deformation. The restraint coefficient in real structures will be some number less than one.

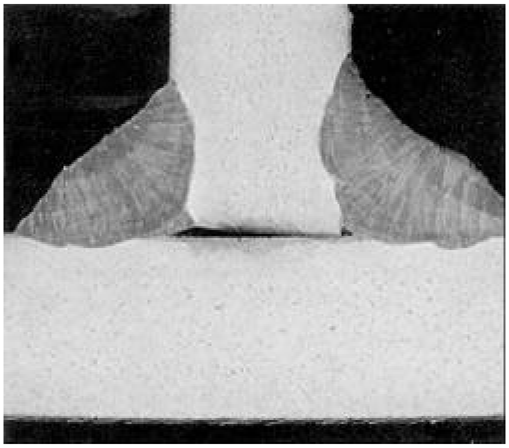
Nevertheless, one rough, but good, rule of thumb is that a 200°F (110°C) temperature differential will yield most austenitic heat resistant alloys.

Weldments

Weldments can fail from repeated thermal cycles. All welds, butt or fillet, must be completely fused. In thermal or mechanical cycling, the unwelded areas behave as large cracks or notches. Repeated thermal strains cause the "crack" to grow outward through the weld bead, a small step each cycle. Since this crack cannot be seen from the outside, there is no warning sign that the part is about to break.



This fully welded joint can
both thermal and
and mechanical fatigue.



The unfused void in this fillet resist
weld acts as a stress riser
may cause premature failure.

Incompletely penetrated weld joints will not tolerate thermal strains and are the most common cause of weldment failure in high temperature service. A couple of examples:

1. Bar frame heat treating baskets. Incompletely fused welds crack a little more each time the basket is quenched. The weld may break in service, or when the basket is straightened. This happens even though the remaining weld metal is still ductile.

2. Furnace fans. Each time the fan starts up, it goes through one fatigue cycle. This is because centrifugal force, gas loading and the temperature differential between blade and hub all stress the blades. Eventually, just starting and stopping the fan will cause low cycle fatigue failure of incompletely penetrated welds. The blades may also flutter or vibrate

Weldments, continued

during operation, which causes more fatigue crack growth. All welds of fan blades to the hub **must** be fully penetrated. A higher strength weld filler such as RA333 may be helpful in resisting mechanical loads. But no weld filler will compensate for inadequate weld joint design. Incidentally, it is more difficult to achieve weld penetration by the arc in nickel alloys than in stainless. A joint design that makes a good fan in 316L stainless (W.Nr. 1.4404) may well not allow adequate weld penetration in RA330. The result can be that the nickel alloy fan fails even though a stainless fan of same design performed well. More root gap may be required to achieve full penetration in a nickel alloy.

Thermal Expansion

A simple way to calculate the thermal expansion of a fixture is to use the chart below. Pick the alloy, read down the column to the operating temperature and read the number, which is how much (in inches) each foot of metal will expand. (Multiply by 83.33 to get how many millimeters each meter of metal will expand) Remember that thermal expansion occurs in all three dimensions. It is really a volume expansion, not just an expansion in one direction. So while the fixture is increasing in length, it is also increasing in width and height. A hole, incidentally, will expand at the same rate as the piece of solid metal that would just fill that hole.

Example: An RA330 D-muffle 36 inches wide and 20 feet long operates at 1800°F. How far will the free end expand? Looking down the RA330 column we find a total expansion of 0.208 inches/foot at 1800°F (982°C). Multiply this figure by the length of the muffle, 0.208 in/ft X 20 ft = 4.16 inches total expansion. How wide will it be in the hottest zone? 36 inches + 0.208 in/ft X 3 ft = 36.624 inches.

Thermal Expansion, continued

Temperature Range **Total Thermal Expansion, inches/foot**

°F	SA-387	RA446	RA321	RA309	RA 253 MA	RA310	RA 353 MA	RA330	RA333	RA601	RA600	RA 602 CA
70-200	0.0104	0.00874	0.0145	0.0137	0.0141	0.0131	0.0134	0.0129	0.0109	0.0119	0.0115	0.0103
-400	0.0281	0.0225	0.0372	0.0356	0.0370	0.0348	0.0345	0.0341	- -	0.0317	0.0305	0.0297
-600	0.0471	- -	0.0604	0.0591	0.0610	0.0569	0.0566	0.0566	- -	0.0516	0.0502	0.0496
-800	- -	0.0526	0.0876	- -	0.0859	0.0806	0.0796	0.0797	- -	0.0727	0.0710	0.0710
-1000	0.870	0.0681	0.115	0.108	0.111	0.106	0.104	0.104	0.0960	0.0949	0.0937	0.0915
-1200	- -	0.0854	0.144	- -	0.137	0.133	0.129	- -	0.122	0.120	0.117	0.115
-1400	- -	0.102	0.174	- -	0.164	0.160	0.154	- -	0.148	0.147	0.142	0.144
-1600	- -	0.123	0.204	0.185	0.193	0.186	0.181	0.180	0.173	0.175	0.167	0.174
-1800	- -	0.152	0.237	- -	0.224	0.214	0.209	0.208	0.201	0.204	0.193	0.201
-2000	- -	- -	- -	- -	- -	0.245	- -	- -	- -	0.236	- -	0.227

The more general way to calculate thermal expansion is to use the mean coefficients of thermal expansion, such as those given on the next page. Multiply the length in inches, times the difference between room temperature and operating temperature, times the expansion coefficient. Note that these coefficients are all multiplied by 10^{-6}, which is the same as dividing by one million. For that 20 ft long RA330 muffle operating 1800°F 982°C) this is:
20 ft X 12 inches/foot X (1800-70F) X 10.0×10^{-6} = 240 inch X 1730F X 10×10^{-6} = 4.152 inches.
To convert these numbers to the metric system, multiply by 83.33 to get millimeters expansion per meter of length

MEAN COEFFICIENTS OF THERMAL EXPANSION

ALLOY	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
304	9.6	--	--	--	9.9	--	--	--	10.2	--	10.4	--	--	--	--	--	--	--	--
316	8.9	--	--	--	9.0	--	--	--	9.7	--	10.3	--	--	11.1	--	--	--	--	--
2205	7.2	7.3	7.5	7.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
RA321	9.3	--	9.4	--	9.5	--	10.0	--	10.3	10.5	10.6	--	10.9	--	11.1	--	11.4	--	--
RA309	8.8	8.9	9.0	9.2	9.3	9.4	--	--	9.7	--	--	--	--	10.0	10.1	--	--	--	--
RA310	8.4	8.6	8.8	--	8.95	--	9.2	--	9.5	--	9.8	--	10.05	--	10.15	--	10.3	--	10.6
SA-387	6.7	--	7.1	--	7.4	--	--	--	7.8	--	--	--	--	--	--	--	--	--	--
RA 253 MA®	9.06	--	9.34	--	9.59	--	9.81	--	9.97	--	10.14	--	10.3	--	10.5	--	10.8	--	--
410	5.5	--	--	--	--	--	--	--	--	--	6.5	--	--	--	--	--	--	--	--
RA330®	8.3	8.4	8.6	8.7	8.9	9.0	--	9.2	9.3	9.4	9.6	--	--	9.7	9.8	9.9	10.0	--	--
HR-120®	7.95	--	8.29	--	8.56	--	8.80	--	8.98	--	9.24	--	9.52	--	9.72	--	9.87	--	--
RA 353 MA®	8.48	--	8.68	--	8.88	--	9.07	--	9.27	--	9.46	--	9.66	--	9.86	--	10.05	--	--
RA800AT	7.9	--	8.8	--	9.0	--	9.2	--	9.4	--	9.6	--	9.9	--	10.2	--	--	--	--
RA446®	5.6	--	5.7	5.8	--	5.9	6.0	--	6.1	--	6.3	--	6.4	--	6.7	6.9	7.3	--	--
RA600	7.4	--	7.7	--	7.9	--	8.1	--	8.4	--	8.6	--	8.9	--	9.1	--	9.3	--	--
RA601	7.6	--	8.01	--	8.11	--	8.3	--	8.5	--	8.87	--	9.19	--	9.51	--	9.82	--	10.18
RA 602 CA	6.6	--	7.5	--	7.8	--	8.1	--	8.2	--	8.5	--	9.0	--	9.5	--	9.7	--	9.8
RA333®	7.0	--	--	8.0	--	--	--	--	8.6	--	9.0	--	9.3	9.3	9.4	9.5	9.7	--	--
HH	--	--	--	--	--	--	--	--	9.5	--	9.7	--	9.9	--	10.2	--	10.5	--	10.7
HK	--	--	--	--	--	--	--	--	9.4	--	9.6	--	9.8	--	10.0	--	10.2	--	10.4
HT	7.9	--	8.14	--	8.37	--	8.61	--	8.85	--	9.09	--	9.33	--	9.56	--	9.8		10.04
HP	--	--	--	--	--	--	--	--	9.2	--	9.5	--	9.8	--	10.0	--	10.3	--	10.6
E-BRITE®	5.17	5.3	5.44	5.56	5.67	--	--	--	--	6.09	6.22	6.4	6.57	6.72	6.85	6.88	7.1	--	--
825	7.8	--	8.3	--	8.5	--	8.7	--	8.8	--	9.1	--	9.5	--	9.7	--	--	--	--
20Cb-3®	8.2	8.3	8.4	--	8.65	--	--	8.9	8.95	--	9.15	--	9.3	9.4	9.5	--	--	--	--
AL-6XN®	7.9	8.3	8.37	8.42	8.6	8.7	8.8	8.85	8.96	--	9.3	--	--	--	--	--	--	--	--
TiGr 2	4.8	--	--	--	5.1	--	--	--	5.4		5.6	--	--	--	--	--	--	--	--

NOTE: All coefficients are reported as inch/inch °F x 10^{-6}, room temp to indicated temp. Multiply by 1.8 for metric units.

Section Size

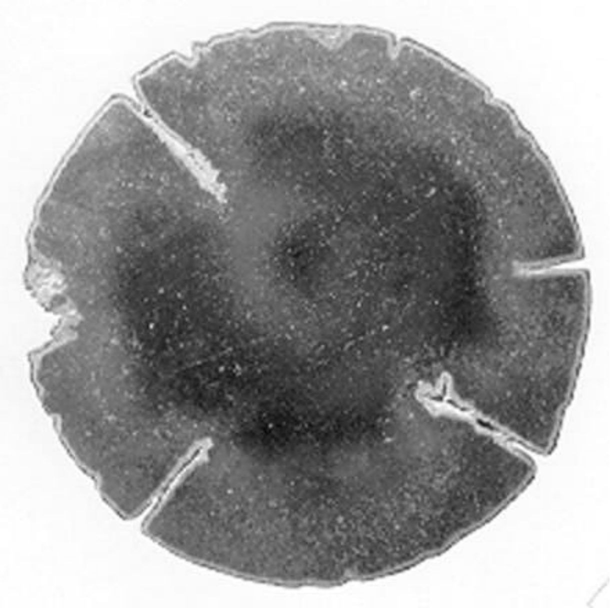
Thin, rather than thick, sections reduce the thermal gradients inherent in heat resistant alloys used under conditions of rapid thermal cycling. Bear in mind that these alloys combine high thermal expansion coefficients with low thermal conductivity.

In quenching service, the effects of repeated thermal shock can be as important as mechanical loading. The lightest possible section size should be used, to permit more uniform heating and cooling. We have seen baskets used for neutral hardening (which see many, many quench cycles) last twice as long when made of 1/2" (12.7 mm) diameter RA330 bar, as when they were constructed of 5/8" (15.9 mm) dia. bar.

A dramatic example of the effect bar diameter has on quench cracking is shown below.

About 4X

1/2" (12.7 mm) dia. RA330,
basket top frame



About 4X

5/8" (15.9 mm) dia. RA330
from same heat treat basket

A 1/2" (12.7 mm) diameter bar, which shows essentially no cracking, was used for the basket's top frame. The basket vertical members were 5/8" (15.9 mm) diameter. One of these is shown in cross-section, on the right. This 5/8" (15.9 mm) dia. bar has cracks extending in depth to one half its radius. Even though this heavier bar should be mechanically stronger, it is clearly weaker in resisting thermal shock.

References

1. John P. Stewart, *Flame Straightening Technology for Welders,* 9773 LaSalle Boulevard, LaSalle, Quebec Canada H8R 2N9, 1981

2. John P. Stewart, *Distortion Control*, 9773 LaSalle Boulevard, LaSalle, Quebec Canada H8R 2N9, 1989