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Maximizing Performance of Alloy Components in High Temperature Furnaces

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Abstract

Performances of consumable alloy furnace components in a high temperature furnace directly affect the operating cost of that furnace. Extending service life, reducing cost, or improving thermal efficiency of such an alloy component improves that component's performance. The goal of maximizing performance of alloy components is to reduce the overall operating costs for high temperature furnaces.

OPERATING AND FINANCIAL CONCERNS drive the need to maximize performance of alloy components. These concerns include product quality, production rate and furnace operating cost. Muffles, retorts and radiant tubes are alloy components that are responsible for separating products of combustion from the process atmosphere of furnaces. This basic function allows muffles, retorts and radiant tubes to be affected by the most operating variables. Therefore, muffles, retorts and radiant tubes offer the highest potential for reduction in furnace operating cost. The term "alloy components" will refer to muffles, retorts and radiant tubes throughout this article and are the primary focus of this article. Also, for the purpose of this article, high temperature furnaces will include processes that occur between 815°C (1500°F) to 1150°C (2100°F).

This article will examine performance improvements of alloy components resulting from a series of design options including structural design, material selection and fabrication methods. It will also identify seven key costs that affect overall furnace operating cost and show their direct relationship to maximizing performance of alloy components.

Key Furnace Operating Costs

Analyses of high temperature furnace operating costs show that performance of alloy components directly affects seven separate costs. Increasing performance of alloy components reduces or eliminates any or all of these key costs. Although the cost of an individual alloy component may actually increase as the result of an optimized design that maximizes performance, the overall furnace operating costs will reduce.

Figure 1 illustrates average costs during the service life of an alloy component from typical high temperature processes. The seven key costs represent these average costs.

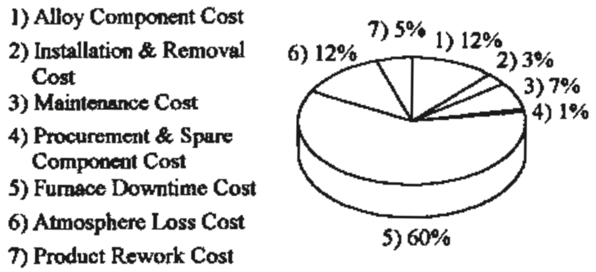

Fig. 1 -- Furnace operating costs related to alloy components.

Service life of an alloy component affects "Installation and Removal Costs" for that alloy component. These amortized costs decrease as service life increases.

Eliminating "Maintenance Costs" is usually impossible, however, minimizing maintenance cost is achievable. The goal of a new alloy component designed to maximize performance may not be to directly increase service life. Rather eliminating or reducing repetitive repairs will reduce maintenance costs during the service life of that component.

Service life of an alloy component affects "Procurement and Spare Component Costs." Procurement is less frequent as service life increases and amortized spare alloy component costs will reduce as service life increases.

Maintenance costs also affect "Furnace Downtime Costs." By reducing or eliminating maintenance requirements for alloy components the furnace will experience more production time. Service lives of alloy components also reduce furnace downtime.

Atmosphere furnaces always incur "Atmosphere Costs." However, an alloy component that .maintains structural integrity with no holes to leak atmosphere into the furnace chamber reduces atmosphere costs. This cost reduction is a direct result of reduced maintenance costs and increased service life.

Increasing performance of alloy components also eliminates or reduces "Product Rework or Scrap Costs."

Structural Design

A number of factors form the basis for structural design of alloy components. These factors typically have included the product work package, process atmosphere, process temperature, material selection and alloy component cost. With the introduction of many new alloys over the years, material selection can be considered a separate design option and will be discussed in the following section.

The goal of enhancing structural design to maximize performance of alloy components is generally to minimize total weight of the component while maintaining its' structural integrity or to minimize deformation of the component. This goal can be achieved by reducing the wall thickness of the component and selecting different fabrication methods such as corrugating walls, applying reinforcing gussets and controlling the shape of the component to maintain or increase strength.

The first design criteria used in the structural design of an alloy component is the product work package, which determines the overall geometry of that component. Figure 2 illustrates the product work package in a muffle for a continuous belt furnace.

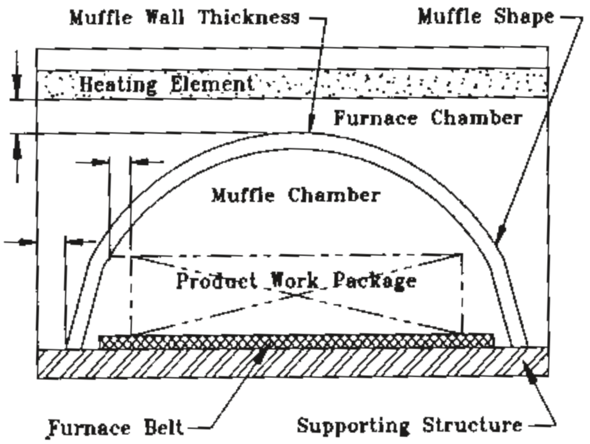

Fig. 2 -- Product Work Package for a continuous belt furnace with muffle

The product work package is the cross-sectional area required to adequately process the product within the alloy component. The product work package is determined using interrelated parameters that include maximum product dimensions and clearances on inner surfaces of the alloy component.

In a new furnace design, once the furnace type is selected, the product work package is established by the end user's product dimensions. This product work package is the controlling factor for alloy component and furnace geometry. However, when retrofitting an existing furnace, the product work package and furnace geometry must be considered to maximize structural strength of an alloy component design. Retrofit alloy components are designed using the product work package and furnace geometry to establish dimensions allowing for clearances between the product fixturing (or furnace belt) and the inside of the alloy component. Clearances would then be maintained between the outside of the alloy component and the inside of the furnace chamber, including all thermocouple wells, atmosphere piping and heating elements. The retrofit alloy component design could then be determined between the minimum and maximum allowable dimensions to achieve the optimum structural strength.

Process atmosphere and process temperature affect material selection and the relative strength of the selected material. Process atmosphere and temperature affects on material selection will be discussed in the following section. An alloy material's strength decreases with respect to time and temperature. Because of this physical relationship an alloy component that will be exposure to high temperatures should be designed using the creep strength or average stress to rupture values as the allowable stress value for the designed service temperature. Both creep strength and stress to rupture are represented as stress (force per unit area) with respect to time and are commonly expressed in units of megapascals (MPa) or kilopounds per square inch (Ksi). Creep strength values are lower than stress to rupture values for the same temperature and time relationship, therefore, using creep strength as a design criteria is a more conservative approach. Table I illustrates creep strength versus average stress to rupture values for type 330 alloy (UNS N08330).

Table I. Secondary creep strength versus average stress to rupture for RA-330 Alloy. All data from Rolled Alloys, Inc. (1)

Temperature °C (°F)	Secondary Creep Strength 0.0001%/hr MPa (Ksi)	Average Stress to Rupture 10,000 hr MPa (Ksi)
538 (1000)	145.00 (21.0)	200.00 (29.00)
648 (1200)	52.40(7.6)	75.80 (11.00)
760 (1400)	24.80 (3.6)	29.60 (4.30)
871 (1600)	14.50 (2.1)	11.70 (1.70)
981 (1800)	3.45 (0.5)	4.34 (0.63)

Using 1.0% secondary creep strength in 10,000 hours as an allowable design stress, a comparison can be made at different service temperatures for the cross-section of a hypothetical alloy component fabricated from type 330 alloy. The cross-section could develop a stress of 145.00 MPa (21.0 Ksi) at 538°C (1000°F) prior to failure. However, the same cross-section could only develop a stress of 14.50 MPa (2.1 Ksi) at 871°C (1600°F) prior to failure. Therefore, the same cross-section operating at 871°C (1600°F) could only carry 10% of the load it could carry operating at 538°C (1000°F).

Significant differences in allowable stresses with respect to temperature as shown in Table I provides a problem to the alloy component designer. The designer must compensate for the loss of material strength at elevated temperatures. This can be accomplished by increasing the material thickness, increasing cross-sectional area using fabricating methods or upgrading to a higher strength material. Figure 3 compares four different cross-sectional designs with respect to moment of inertia. The area moment of inertia is a characteristic of a cross-sectional (plane) area that relates the ability of that cross-sectional area to resist bending. In figure 3 the moment of inertia of each design is compared to the moment of inertia of plate number 1. This comparison yields a factor that can be called a relative moment of inertia.

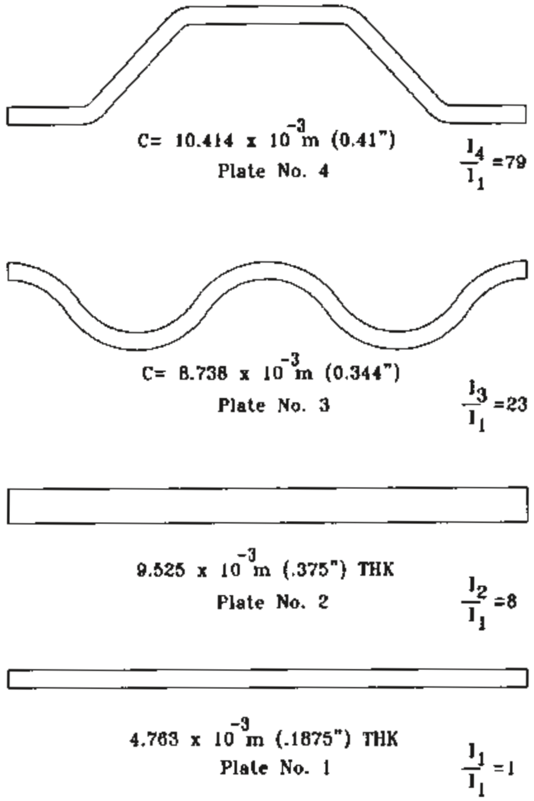

Fig. 3 -- Comparison of moment of inertia of four plate designs where I=Moment of Inertia and Ia/Ib=Relative Moment of Inertia.

Figure 3 shows four separate metal plates with different. designs. All plates are 15.24 x 10(-2) m (6") wide type 330 alloy and are assumed to be similarly loaded with a concentrated load at the centerpoint and simply supported on both ends. Also assume all plates are exposed to a temperature of 871°C (1600°F) and the allowable stress of the design is determined using the 1% secondary creep stress in 10,000 hours from Table I. Using the data from Table I and Figure 3, Equation (1) can be solved to determine the load factor for each plate design.

Eq. (1) Bending stress (2)

$$\sigma = M c / I$$

Where: σ= bending stress

M=bending moment

c=distance from neutral axis

I=moment of inertia

The allowable bending stress for each plate design is the same and a relative moment of inertia has been established in Figure 3 for each plate with respect to the original flat plate design (flat plate number one) of 4.763 x 10(-3) m (0.1875") thick. Since the allowable bending stress is the same for any two plate designs, the equations for bending stress can be set equal to each other and solved in terms of M. The relative moment of inertia from Figure 3 should be substituted in the equation for the actual moment of inertia. The resultant value is the load factor, a comparative number for bending strength based on the original flat plate design of 4.763 x 10(-3) m (0.1875") thick. Table II shows results of calculations in terms of load factor.

Eq. (2) Solving for Load Factor in terms of M where I_{rel} equals relative moment of inertia.

$$\{Mc / I_{rel}\}_{\text{Plate No. 1}} = \{Mc / I_{rel}\}_{\text{Plate No. 2}}$$

$$\{2.3815 \times 10(-3)\, M / 1\} = \{4.763 \times 10(-3)\, M / 8\}$$

Load Factor of Plate No. 2 = 4

Table II. Load calculations in terms of load factor.

Plate Design (Fig. 3)	Load Factor
Flat Plate No. 1	1
Flat Plate No. 2	4
Corrugated Plate No. 3	6
Corrugated Plate No. 4	12

Load factor calculations show that doubling the flat plate thickness will increase section strength by a factor of four. While this is a significant gain it requires twice the material, which means twice the material costs, to achieve the results. This design option is not economical when compared to corrugated plate designs. The corrugated plate number four, with no increase in material thickness, increased the strength by a factor of 12. Although slightly more material is required to develop the corrugation and still maintain the specified overall length and labor costs are added to form the corrugations, the design significantly increases strength with marginal increases in cost.

The budget a user of alloy components has will also affect the structural design. Traditionally this budget has only considered the one-time cost of an alloy component. This method of establishing budgets limits innovative design options. However, a more effective way to maximize the performance and design of the alloy component is to apply the "Seven Key Costs" model and use a system approach to the design. The goal of a design using this model is to reduce the overall operating costs associated with the alloy component. This goal gives the designer flexibility in terms of cost considerations. Optimizing the structural design of an alloy component may increase the one-time cost of that component. The cost may increase by adding more material, adding labor to corrugate or strengthen surfaces or upgrading material, however, the overall furnace operating costs can be reduced, justifying the design.

Material Selection

Material selection is a critical design option that can independently determine the success of an alloy component . However, the goal for material selection should be to maximize the alloy's strength while at the same time minimizing overall material cost. To achieve this goal the selected alloy must meet minimum material requirements that include temperature and atmosphere resistance.

The first concern when selecting a material for an alloy component should be matching alloy specifications with the temperature range and atmosphere of the applicable process. Due to the introduction of many new alloys, for most applications there are at least two alloys available from different manufacture's that will satisfy design parameters. These parameters include factors such as creep or rupture strength, carburization resistance, oxidation resistance and sulfidation resistance to name a few.

Secondly, alloy selection should be considered in conjunction with structural design options. Assume a material upgrade is added to the example shown in the Structural Design section. A corrugated 4.763 x 10(-3)m (0.1875") type 330 alloy plate operating at 871°C (1600°

F) has 12 times more strength than a flat plate of equivalent material and width. However the 1% secondary creep strength in 10,000 hours of Haynes® Alloy No. 230 (UNS N06230) is 30 MPa (4.4 Ksi) (3). This material is over two times stronger than type 330 alloy for this temperature range. Combined with the corrugated structural design the strength of an alloy component can be increased 24 times compared to the strength of flat plate number one.

Certainly not every design needs to increase strength by a factor of 24. Most budgets, regardless of calculation method, can not absorb the additional material costs for this type of material upgrade unless the application required the change. Cost justification is an important part of material selection. Using the type 330 alloy versus Haynes® Alloy No. 230 example, the Haynes® Alloy No. 230 is twice as strong as type 330 alloy based on creep strength. However, Haynes® Alloy No. 230 costs approximately three times as much as type 330 alloy. A Haynes® Alloy No. 230 component would require a service life approximately 1.5 times greater than the type 330 alloy to justify the increased material cost.

Good material selection will account for all factors that impact the design. Selecting the material that meets all minimum operating specifications and also reduces cost will justify itself.

Fabrication Methods

A number of fabricating methods can be used to maximize alloy component performance. These methods typically impact alloy component strength, quality and resistance to process atmosphere.

Weld joint design is the most basic fabrication method that impacts strength or service life of alloy components. Proper weld joint design will consider the size and strength of welds and the welding process. Weld joint location is an important consideration to minimize stress risers and weld crack propagation. Weld joint design should consider joint preparation and joint fit-up. Fabrication tolerances should be specified to assure proper fit of the finished alloy component into the furnace. Fabrication tolerances can also help reduce distortion of the alloy component in service because they control final dimensions.

After an alloy component has been fully designed, perhaps the most important fabrication method is the proper use of quality assurance. A great deal of resources will be wasted on the design of an alloy component and the cost of material if the proper welding procedures, in process inspection checkpoints and final inspection specifications are not followed.

A simple quality assurance plan should: verify material type; inspect weld joint preparation and joint fit of the alloy component for dimensional accuracy; verify weld process and filler metal; inspect final dimensions; provide at least one test to assure the alloy component is gas tight; provide documentation for all inspection points.

Conclusion

Understanding and identifying furnace operating costs that apply to alloy components is the key to maximizing the performance of an alloy component in a high temperature furnace. After identifying these costs, applying a system approach for the alloy component design allows the design to exploit the strengths of the process while improving the weaknesses.

A process that identifies key furnace operating costs and reduces these costs through the application of structural design enhancements, material selection and well-monitored fabrication methods will ultimately maximize the performance of alloy components and reduce furnace operating costs.

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