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MATERIALS SELECTION FOR GAS TURBINE SEAL RING APPLICATIONS

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ABSTRACT

Many alloys are available to designers for seal ring applications in aircraft and industrial gas turbines. In this paper, the capabilities of a number of alloys are reviewed. Emphasis is placed on thermal expansion, density, environmental resistance, high-temperature strength, microstructural stability after exposure to elevated temperatures, weldability, and brazability. Among the alloys considered, the Ni-Cr-Mo HASTELLOY® alloy S offers a potentially useful combination of properties for seal ring applications.

INTRODUCTION

In a gas turbine engine, a seal ring is installed for each turbine stage in such a manner that the tips of the blades rotate in close proximity to the seal ring. The primary function of a seal ring is to minimize the loss in pressure of the gas stream between the blades and the casing and thus maintain engine efficiency.

Typical exposure temperatures of the seal rings during engine operation are in the range of 650°C to 980°C (1200°F to 1800°F). Gas turbine engine seals are fabricated into hoops from a variety of wrought alloy stock such as hot-rolled and annealed plate and bar products which are subsequently butt welded into rings. A newer manufacturing process in developmental stages is to directly hot roll rings from electroslag remelted hollow ingots. Many seal rings are designed as part of a brazed assembly, e.g., the brazed honeycomb design where abradable materials are brazed to the seal rings.

This paper presents a review of the capabilities of various seal ring alloys in terms of the characteristics relevant to such applications. The objective is to aid the designer in making the proper alloy selection.

MATERIALS REQUIREMENTS FOR SEAL RING APPLICATIONS

A primary material requirement for seal ring applications is a low coefficient of thermal expansion, particularly at elevated temperatures. This serves two important purposes:

(1) It allows for a reduced clearance between the blades and the ring; therefore, less gas can bypass the blades. Thus the engine efficiency is improved.
(2) It reduces the susceptibility to thermal fatigue failure which arises from the rapid thermal cycling encountered during engine operation.

Another important requirement is the brazability.

Materials for seal ring applications must also possess a combination of low density, environmental resistance, high-temperature strength, microstructural stability, and good weldability. Of course, cost is a critical factor, but it is excluded from this review as actual prices vary from time to time. A proper alloy selection must, therefore, involve the best compromise among the above properties.

There are various types of materials which can be considered for seal ring applications. Table 1 lists these materials and their pertinent characteristics. Among those materials, it can be seen that nickel-base alloys are characterized by a useful combination of properties which render them potential candidates for seal ring applications. Alloys which are essentially free of strategic elements, particularly cobalt, are most attractive. Specific alloys in this category include HASTELLOY alloys X, C-276, C, N, W, and S. All of these alloys are solid solution and carbide strengthened; their nominal chemical compositions are given in Table 2.

CHARACTERISTIC PROPERTIES OF SEAL RING ALLOYS

In this section, we present the properties of the alloys listed in Table 2 as they relate to seal ring applications. All the data presented in this paper has been obtained in Cabot's laboratory.

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Table 1

Materials For Seal Ring Applications and Their Characteristics

Material	Thermal Expansion Characteristics	Other Characteristics
INVAR®, SuperInvar, Elinvar, NiSpan, Vibralloy, and Iso-Elastic Alloys	Low coefficient of thermal expansion up to a temperature of only about 275°K (390°F)	-
Iron-Base Alloys	High coefficient of thermal expansion at elevated temperatures	Low mechanical strength and poor oxidation resistance
Cobalt-Base Alloys	High coefficient of thermal expansion at elevated temperatures	Relatively high density and high cost
Nickel-Base Alloys	Relatively low coefficient of thermal expansion at elevated temperatures	Lower density and cost as compared to cobalt-base alloys, adequate mechanical strength and oxidation resistance

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Table 2

Nominal Chemical Compositions of Possible Seal Ring Alloys (Wt. %)

	Alloy					
Element	X	C-276	C	N	W	S
Ni	Bal	Bal	Bal	Bal	Bal	Bal
Co	1.50	2.50*	2.50*	0.20*	2.50*	2.0*
Cr	22.0	14.5-16.5	15.50	7.0	5.0	16.0
Mo	9.0	15-17	16.0	17.0	24.0	15.0
W	0.60	3-4.5	3.75	0.50*	-	1.0*
Fe	19.0	4-7	5.50	5.0*	6.0	3.0*
C	0.10	0.01*	0.08*	0.06*	0.12*	0.02*
Other	-	V=0.35* P=0.025* S=0.010*	V=0.35* P=0.040* S=0.030*	Al+Ti=0.50* B=0.010* Cu=0.35	V=0.60*	Al=0.20 La=0.02 B=0.009

* Maximum

Physical Properties

The physical properties of primary concern in seal ring applications are thermal expansion and density. Table 3 lists the mean linear coefficients of thermal expansion over the temperature ranges of 20°C to 760°C (70°F to 1400°F) and 20°C to 870°C (70°F to 1600°F). The densities of the alloys are given in Table 4.

Environmental Resistance

A measure of environmental resistance (oxidation and hot corrosion) is the "total-metal-affected." This reflects both the surface attack and local penetration. The total-metal-affected can be determined from:

$$\text{Total-Metal-Affected} = [(\frac{A - B}{2}) + C]$$

Table 3

Mean Linear Coefficients of Thermal Expansion (α) of Various Seal Ring Alloys

Alloy	$\alpha \times 10^6$ (20-760°C) m/m/K (in/in°F)	$\alpha \times 10^6$ (20-980°C) m/m/K (in/in/°F)
W	13.59 (7.55)	14.76 (8.20)
N	14.13 (7.85)	15.30 (8.50)
S	14.45 (8.03)	15.39 (8.55)
C-276	14.33 (7.96)	15.44 (8.58)
C	14.49 (8.05)	15.53 (8.63)
X	15.86 (8.81)	16.56 (9.20)

where, A is the original thickness of the test sample, B is its thickness after the test, and C is the depth of penetration which is determined metallographically.

The test conditions for the cyclic oxidation and hot corrosion data presented below are given in Table 5. Table 6 shows the total metal affected in cyclic oxidations and hot corrosion tests.

High-Temperature Strength

Figure 1 shows the 0.2% yield strengths of the alloys as functions of temperature in the range of 20°C to 980°C (70°F to 1800°F).

A comparison between the creep rupture strengths of alloys X and S is given in Table 7.

Microstructural Stability

Alloys such as those discussed in this paper are usually supplied by the manufacturer as wrought products in the mill-annealed condition. In this condition, each alloy consists of an essentially single phase solid solution having a face centered cubic structure. Typical optical microstructures of some alloys are shown in Figure 2. Exposure to elevated temperatures, however, can cause precipitation of additional phases which influence the properties. This is demonstrated by Figure 3, which shows the room-temperature tensile elongations after 1,000 hours of exposure to various temperatures. The variations in the retained room-temperature tensile elongation is attributed to differences in the microstructural stability. As an example, Figure 4 shows transmission electron micrographs derived from thin foils of alloys S, X, and C-276 after 1,000 hours of exposure to 760°C (1400°F). Under these exposure conditions, alloy X precipitates sigma phase, and alloy C-276 precipitates mu phase. These phases are characterized by being hard and brittle, and, therefore, they reduce the tensile elongation of the alloys. Also, because they deplete the matrix in such elements as chromium and molybdenum, the chemical stability of these alloys may be degraded in certain environments. In contrast, the compositional limits of alloy S do not permit the precipitation of these detrimental phases.

Table 4

Densities of Seal Ring Alloys

Alloy	Density gm/cm^3 (lb/in^3)
X	8.22 (0.297)
S	8.76 (0.316)
N	8.86 (0.320)
C-276	8.89 (0.321)
C	8.94 (0.323)
W	9.03 (0.325)

Weldability and Brazability

Alloy X has long been known for its good weldability among the nickel-base alloys. Therefore, the weldability of alloy S is compared to that of alloy X. A measure of weldability is the hot crack susceptibility of a weld heat-affected-zone. This can be determined from the TIG-A-MA-JIG test. Figure 5 shows a comparison between the hot crack susceptibilities of alloys X and S. A significant feature of all the alloys discussed in this paper is their capability to be brazed to other materials. This can be attributed in part to the absence of significant amounts of aluminum and titanium. Oxidation of these elements is hard to control, and in most furnace brazing operations, these oxides inhibit braze alloy wetting.

DISCUSSION

On the basis of thermal expansion characteristics (Table 3) and elevated temperature yield strength (Figure 1), alloy W ranks the first among the alloys considered. However, as indicated in Table 6, alloy W has a poor oxidation resistance. This is also the case for alloy N, which has a fairly low coefficient of thermal expansion. Although alloy X has an adequate mechanical strength and oxidation resistance, it exhibits a large thermal expansion at elevated temperatures. Both alloys C and C-276 have poor microstructural stabilities. All of the above alloys are characterized by good brazability.

Alloy S, however, combines a fairly low coefficient of thermal expansion, low density, adequate oxidation resistance and high-temperature strength, excellent microstructural stability, and good brazability and good weldability. Such a combination of useful properties makes alloy S a highly favorable choice for seal ring applications.

CONCLUSION

The characteristic properties of a number of nickel-base alloys are reviewed in terms of their usefulness as gas turbine seal ring materials. It is concluded that HASTELLOY alloy S possesses a useful combination of properties for seal ring applications. Such a combination is not possessed by any of the other alloys considered.

ACKNOWLEDGEMENT

The authors appreciate the reviewers' comments on the brazability of the alloys discussed.

Table 5

Cyclic Oxidation and Hot Corrosion Test Conditions

Test	Peak Temperature	Thermal Shock Frequency	Duration	Medium	Air/Fuel Ratio
Cyclic Oxidation	1145°K (1600°F)	2/Hour	100 Hours	No. 2 Fuel Oil (0.3 - 0.45% S)	45:1 to 55:1
Hot Corrosion	1170°K (1650°F)	1/Hour	200 Hours	5 ppm Salt with No. 2 Fuel Oil	30:1

Table 6

Cyclic Oxidation and Hot Corrosion Properties of Seal Ring Alloys

Alloy	Cyclic Oxidation 870°C (1600°F), 100 Hours Total Metal Affected µm/side (mils/side)	Hot Corrosion 900°C (1650°F), 200 Hours Total Metal Affected µm/side (mils/side)
C	0.020 (0.52)	0.15 (3.80)
X	0.026 (0.67)	0.13 (3.30)
C-276	0.028 (0.74)	0.32 (8.26)
S	0.052 (1.33)	0.11 (2.72)
N	Poor	-
W	Poor	-

Table 7

A Comparison Between the Creep Rupture Strength of HASTELLOY alloys S and X

Alloy	Temperature °C (°F)	Stress to Cause 0.50% Creep Strain in 1000 Hours MPa (KSI)	Stress to Cause Rupture in 1000 Hours MPa (KSI)
S	760 (1400)	50 (7.1)	115 (16.2)
X		45 (6.5)	110 (15.8)
S	870 (1600)	15 (2.4)	45 (6.4)
X		20 (3.1)	45 (6.5)

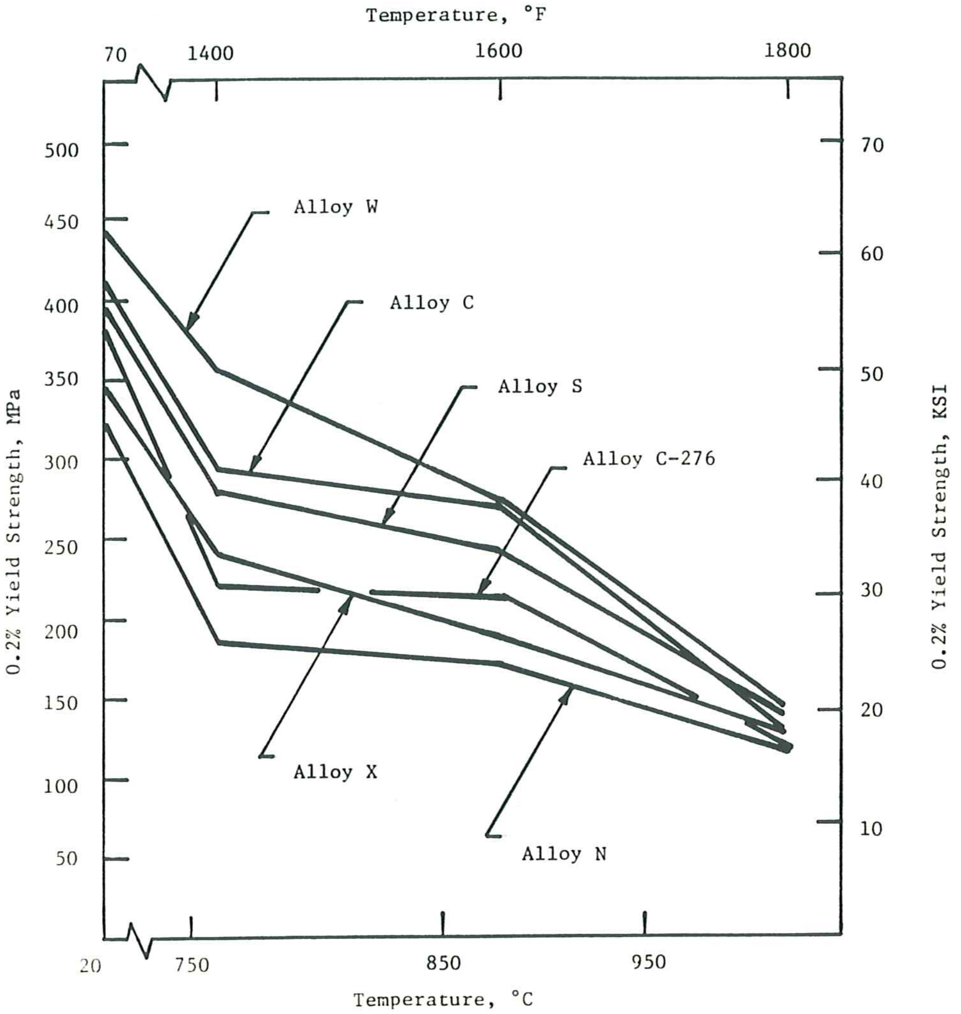

Figure 1: Effect of temperature on the 0.2 percent yield strength of various seal ring alloys.

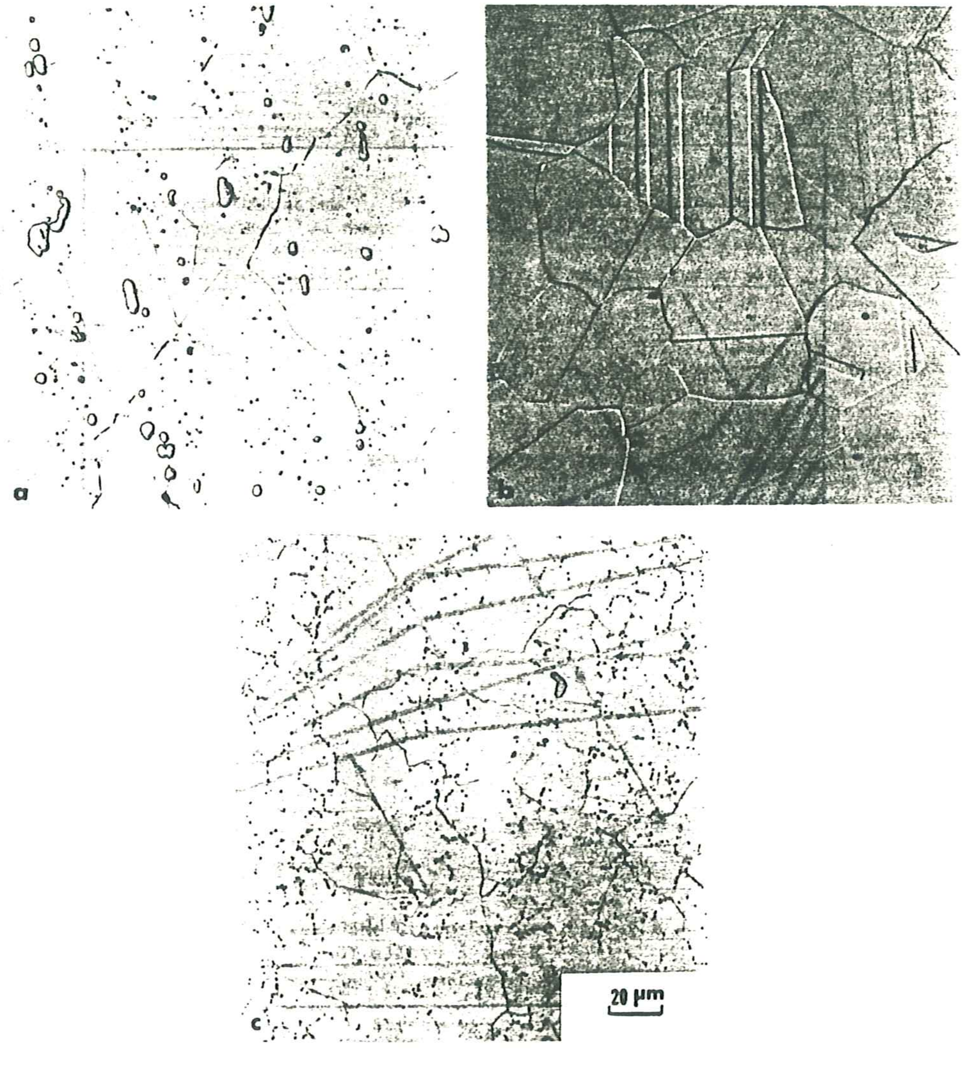

Figure 2: Characteristic optical microstructures of seal ring alloys in the annealed condition.
(a) HASTELLOY alloy X
(b) HASTELLOY alloy C-276
(c) HASTELLOY alloy S

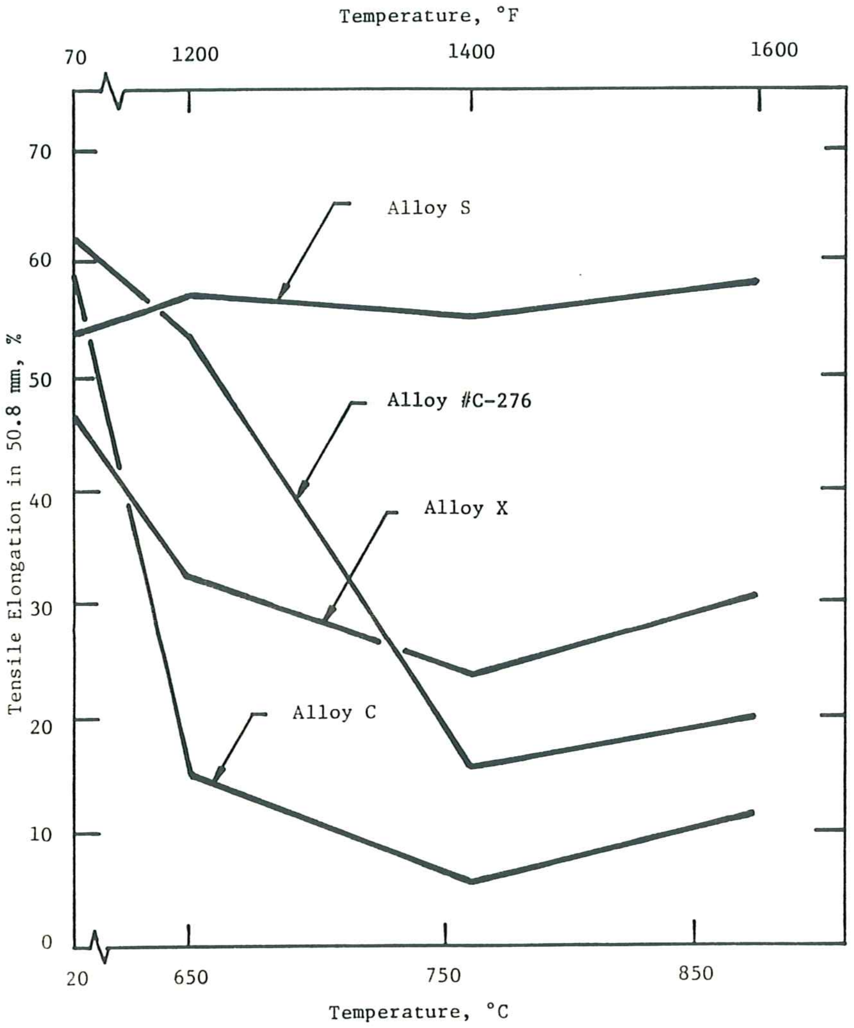

Figure 3: Effect of 1,000-hour exposure at various temperatures on the room-temperature tensile elongation of various seal ring alloys.

Figure 4: Bright field TEM micrographs showing typical microstructures of seal ring alloys after 1,000 hours of exposure at 760°C (1400°F).

(a) HASTELLOY alloy X (a mixture of sigma phase and $M_{23}C_6$ carbide)

(b) HASTELLOY alloy C-276 (mu phase)

(c) HASTELLOY alloy C (only M_6C carbide which was initially present in the annealed condition)

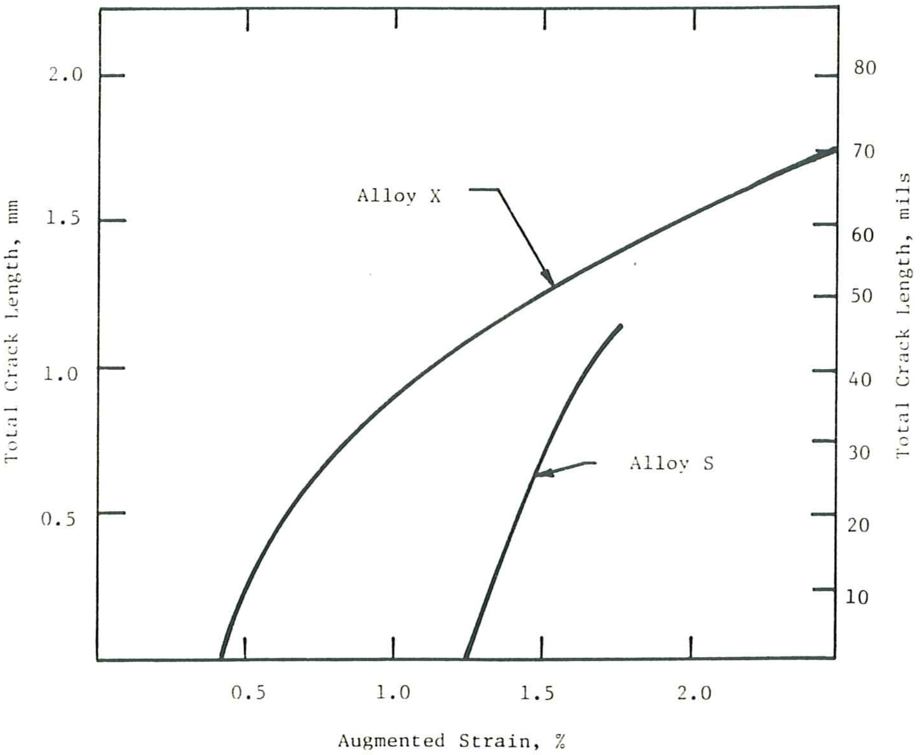

Figure 5: Comparison of TIG-A-MA-JIG weldability data of HASTELLOY alloys S and X.