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High Temperature Radiator Materials for Applications in the Low Earth Orbital Environment

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SUMMARY

Radiators must be constructed of materials which have high emittance in order to efficiently radiate heat from high temperature space power systems. In addition, if these radiators are to be used for applications in the low Earth orbital environment, they must not be detrimentally affected by exposure to atomic oxygen. Four materials selected as candidate radiator materials (304 stainless steel, copper, titanium-6% aluminum-4% vanadium (Ti-6%Al-4%V), and niobium-1% zirconium (Nb-1%Zr)) were surface modified by acid etching, heat treating, abrading, sputter texturing, electrochemical etching, and combinations of the above in order to improve their emittance. Combination treatment techniques with heat treating as the second treatment provided about a factor of two improvement in emittance for 304 stainless steel, Ti-6%Al-4%V, and Nb-1%Zr. A factor of three improvement in emittance occurred for discharge chamber sputter textured copper. Exposure to atomic oxygen in RF plasma asher did not significantly change the emittance of those samples that had been heat treated as part of their texturing process. An evaluation of oxygen penetration is needed to understand how oxidation affects the mechanical properties of these materials when heat treated.

INTRODUCTION

Research to produce radiators which can emit waste heat efficiently, and can operate at high temperatures has become increasingly important with the development of high power systems for use in space. Currently there are three major applications for radiators: (1) space nuclear power systems such as SP-100 for high power Earth orbital space systems; (2) solar dynamic power module for space station; and (3) advanced solar dynamic systems for growth versions of the space station and other applications where the means of producing power through solar driven systems is available (ref. 1). Each application requires different operating temperatures, power levels, environmental concerns, and operational goals (refs. 2 and 3)(table I). Therefore, each radiator must be durable in the environmental and operational ranges specific to its application.

Radiators that operate in the low Earth orbital (LEO) environment must be resistant to attack by atomic oxygen, the predominant species in LEO. Even though the probable altitude (700 km) for the initial SP-100 flight is such that the concentration of atomic oxygen is very low (ref. 4), some change in surface properties could occur, because atomic oxygen degradation is predominantly a surface effect. Although polymers undergo a change in surface morphology when exposed to atomic oxygen (refs. 5 and 6), little is known about the change in the surface morphology or chemistry of metals as a result of their interaction with atomic oxygen at elevated temperatures. It is possible that exposure to atomic oxygen could alter the surface of a metallic radiator enough to reduce its ability to dissipate waste heat.

Radiators must have high emittance values for efficient heat dissipation. In order to improve a material's emittance, the surface morphology can be changed by adding a thin or thick coating to the surface, or texturing the surface by a variety of techniques. Thick coatings are undesirable because they may spall due to differential thermal stresses between the coating and substrate. These stresses could be increased during the temperature extremes of thermal cycling. If spalling occured while in low Earth orbit, the emittance would be reduced because of the removal of the coating, and atomic oxygen could attack the underlying surface.

Both thin film coatings and surface texturing have potential as emittance altering techniques for radiators. This paper concentrates on the alteration of emittance through surface texturing. The substates that were textured were space nuclear reactor radiator materials, as well as one Space Station Solar Dynamic Power Module radiator material.

APPARATUS AND PROCEDURE

Selection of Radiator Materials

Four metals were selected as potential radiator materials for initial texturing research: niobium-1% zirconium (Nb-1%Zr), titanium-6% aluminum-4% vanadium (Ti-6%Al-4%V), 304 stainless steel, and copper. The first three materials were chosen as candidate materials for space nuclear power system radiators based on their density, thermal conductivity, melting temperature, strength at elevated temperatures, atomic oxygen durability, ease of fabrication and compatibility with sodium and potassium (this becomes of importance only if the potassium or sodium containing heat pipe is used as a radiator). The fourth material, a copper-graphite metal matrix composite was selected as one possible candidate for Space Station Solar Dynamic Power Module radiators based on density, thermal conductivity, melting temperature, atomic oxygen durability, and ease of fabrication. Texturing of copper should yield similar results to those for the copper-graphite metal matrix composite, because the composite has a copper clad surface of greater than 0.1 mm and texturing is a surface phenomenon.

Surface Texturing Techniques

Surface texturing was achieved by using a variety of treatments including acid etching, heat treating, abrading, electrochemical etching, and ion

texturing. Combinations of these texturing techniques were also used in order to improve the emittance.

Acid etching. - For alteration of the surface texture of the four radiator materials, three different acids were used: nitric acid (HNO_3), hydrochloric acid (HCl), and hydrofluoric acid (HF). Concentrated acid was used in all cases. For HNO_3 and HCl, room temperature and boiling acid solutions were evaluated. In the case of HF, only room temperature acid exposure was evaluated. Stainless steel (type 304) was exposed to boiling 1.8 M and 18 M sulfuric acid solutions to study the effect of acid concentration on the emittance. Duration of acid exposure varied depending on the material being exposed, and exposure was terminated when no further visual change to the surface was observed.

Heat treating. - Two methods of heat treating were used to alter the emittance of the radiator surfaces. The first method was to place samples in a preheated atmospheric muffle furnace (Sybron: Thermolyne 1400) at temperatures of 1255 K for Nb-1%Zr, stainless steel, and copper; and at 1089 K for Ti-6%Al-4%V. Exposure temperature was varied for stainless steel to determine if there was an effect of exposure temperature on emittance for a given exposure time of 1 hr. The second method of heat treating involved exposing the sample to the hottest part of the flame of a propane torch while moving the torch back and forth across the sample in order to achieve a uniform exposure.

Abrasion. - Texturing by abrasion was performed by either sandblasting with spherical glass beads 27 μm in diameter or sanding in a crosshatching manner with number 320 grit silicon carbide paper. Sandblasting for Nb-1%Zr, Ti-6%Al-4%V, and copper was performed at an operating pressure of 10 psi for lengths of time that varied with the material being textured. Pressures used for texturing 304 stainless steel varied. A pressure of 80 psi was used for samples that were sandblasted, and those with a combination treatment of hydrochloric acid exposure and sandblasting. Eighty psi was found to deform the 304 stainless steel, so the pressure was reduced for the remainder of the samples textured. Forty psi was used for samples with a combination treatment of sanding and sandblasting. All remaining stainless steel samples were sandblasted at a pressure of 20 psi.

Electro-chemical etching. - All surfaces textured electrochemically were immersed in a solution of 1M ferric chloride ($FeCl_3$) and 1M hydrochloric acid (HCl) with iron as the counter electrode. For copper, the electrochemical reaction was self initiating, and no external bias was needed. With Nb-1%Zr, 304 stainless steel, and Ti-6%Al-4%V a current of 1 A was applied.

Ion texturing. - Three methods of ion texturing were used for altering the emittance of the radiator materials: natural texturing, seed texturing, and discharge chamber sputter texturing. Natural texturing results when a high energy ion beam (~1000 eV) bombards a nonhomogeneous surface (ref. 7). The varying sputter yields due to dissimilar materials or variations in microstructure lead to preferential etching of the surface giving it a textured appearance (ref. 7). Seed texturing is a technique similar to natural texturing, but is used when the material to be textured is homogeneous with no surface variation in the sputter yield (ref. 7). For this technique a seed target is placed so that a small amount of the seed material lands on the surface being sputter etched (ref. 7). Typically, the seed material has a lower

sputter yield than the substrate to be textured, so texturing occurs by virtue of an artificially created nonhomogeneous surface (ref. 7). Discharge chamber texturing utilizes a triode system in which the substrate to be seed textured is biased to a certain potential (ref. 8). The ions in the plasma surrounding the substrate are attracted to the substrate by the potential difference, and the impact of the ions results in sputter texturing (ref. 8). For all of the discharge chamber results reported, a Ta seed target was used; and it was biased at the same potential as the substrate (ref. 8). Details of this technique are discussed further in the reference by Mirtich et al. (ref. 8).

Emittance Measuring Techniques

The emittance of the textured surfaces was measured using several types of instrumentation. A room temperature emissometer (Devices and Services Co.) was used to measure the spectral emittance at a wavelength of 8.16 μm which corresponds to 355 K. This is in the range needed for the Space Station solar dynamic radiator surfaces. A Perkin Elmer Lambda-9 UV-Visible-Near IR spectrophotometer was used to measure the spectral emittance at a wavelength of 2.5 μm corresponding to 1159 K. This is near the temperature range of the SP-100 radiator surfaces. The total emittance of a few selected samples was obtained with a Hohlraum Reflectometer (Perkin Elmer). The wavelength range of this apparatus is 1.5 to 15 μm. The total emittance was obtained from reflectance data normalized to 700 and 900 K blackbodies.

Environmental Exposure Techniques

Radiator materials that had been textured and had attained the highest values of emittance were exposed to an atomic oxygen environment in an RF plasma asher. The asher produced an air plasma at a frequency of 13.56 MHz. Pressures ranged from approximately 30 to 100 μm during exposure.

RESULTS AND DISCUSSION

Texturing

The texturing techniques described in the previous section were used either singly or in combination in an attempt to increase the emittance of each material tested. The goal was to increase the emittance of the material so that it fell within the desired range for its application as shown in table I. The results obtained for each radiator material will be discussed individually.

Due to the large number of treatment techniques and combinations of treatments possible, a matrix chart was developed for each material in order to organize the emittance results. Figures 1, 7, 8, and 9 contain the matrices for the four metals evaluated. The numbers in the table represent the spectral emittance at 2.5 and 8.2 μm as well as the total emittance at 700 and 900 K for each texturing treatment or combination. The numbers along the diagonal represent the highest emittances obtained for single treatments, and the remainder of the field represents the highest emittances obtained for the combination treatments. Each matrix represents over 50 tests for each material

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in which the vertical columns are the first treatment technique and the horizontal rows are the second treatment technique. Emittance data listed with an asterisk represent those samples that have been exposed in a plasma asher after texturing.

Stainless steel (type 304). - Figure 1 contains the matrix for 304 stainless steel. The spectral emittance at 2.5 μm was used as a selection guide for this material because it is in the temperature range of SP-100. Of the single treatments, the highest spectral emittance was obtained by heat treating the stainless steel using a furnace. The emittance at 2.5 μm varied with the furnace temperature used. This is illustrated in figure 2 for stainless steel samples that were exposed in the furnace at a fixed temperature for 1 hr. Above 1311 K for 304 stainless steel the emittance no longer changes as rapidly and may even be leveling off. Higher temperatures may play no additional role in surface oxidation. The time it takes to develop a fully oxidized surface is shown in figure 3 where the emittance versus furnace exposure time at 1311 K for 304 stainless steel is plotted. At this temperature, complete oxidation of the surface occurs after approximately 90 min of exposure. Spectral emittances at 2.5 μm varying between 0.91 and 0.93 can be obtained by this technique. This is well above the emittance goal for the SP 100 space nuclear reactor. One disadvantage to this technique is that it requires a conversion of some of the surface material into an oxide. If the penetration of oxidation is deep into the material, it could cause a detrimental change in the bulk mechanical properties.

Discharge chamber sputter texturing provided the second highest single texturing result for spectral emittance. Spectral values near 0.82 at 2.5 μm were obtained using this technique (ref. 8). This is slightly below the desired emittance value for SP-100, but is still a reasonable value. The total emittance at 700 and 900 K is the highest measured to date for stainless steel. The technique of discharge chamber sputter texturing may also have the advantaqe that it may have no effect on the surface or bulk chemistry of the material. These results are discussed in greater detail in reference 8.

Ion beam texturing (both natural and seed texturing), electrochemical texturing, abrasion, propane heating, and exposure to HCl and HNO_3 had little to no effect on the spectral emittance at 2.5 μm. Exposure to sulfuric acid provided the best spectral emittance of these remaining techniques. A spectral emittance at 2.5 μm of 0.69 was obtained with a 1.8 molar solution of H_2SO_4. It would be expected that the higher the concentration of acid in aqueous solution, the higher would be the amount of surface texturing caused by corrosion. For stainless steel in sulfuric acid, this was not the case. More texturing or corrosion actually occured at lower concentrations of acid than for concentrated acid as shown in figure 4. This result is typical of that obtained by corrosion engineers for stainless steel in sulfuric acid. These results can be explained by the polarization curve shown in figure 5. At low concentrations of acid, the corrosion rate increases with acid concentration (ref. 9). At some concentration of H_2SO_4, the oxidizing power of the solution becomes high enough that when a piece of stainless steel is immersed in it, the stainless steel oxidizes to form a very thin film of Fe_3O_4 which protects the surface from further corrosion (ref. 9). The corrosion rate at acid concentrations high enough for this passivating coating to form is very low (ref. 9). As the oxidizing power is increased, eventually a point will be reached where the coating will be removed from the surface (ref. 9). It is interesting to note that the measured emittance of the sample exposed to the concentrated

acid solution is actually lower than that of the untreated sample. The altera-
tion of the surface by the very thin oxide coating may be the cause for the
decreased emittance.

Multiple treatments can improve the emittance of a surface over that which
can be obtained by using single treatments. The spectral emittance at 8.2 μm
illustrates this the best as shown in figure 6. At this wavelength the spec-
tral emittance of 304 stainless steel has been improved by approximately a fac-
tor of three over untreated stainless steel by heat treating in air at 1255 K.
Exposure in concentrated HCl improves the spectral emittance by approximately
a factor of 6. The emittance of stainless steel exposed to HCl followed by
heat treating is improved by more than a factor of 8. This illustrates the
increase in emittance obtained by multiple texturing treatments. Figure 6
also illustrates the surface morphology changes that take place upon texturing
to produce a highly emitting surface. The spectral emittance at 2.5 μm for
stainless steel was not as greatly affected by multiple treatment texturing.

Copper. - For this solar dynamic radiator material, the most important
values of spectral emittance occur at 8.2 μm. Figure 7 shows the texturing
matrix for copper. The single surface treatments for copper were obtained by
heat treating in a furnace (ε = 0.62) and discharge chamber sputter texturing
(ε = 0.57). Abrasion, heat treating with a propane torch, exposure to HNO_3,
and electrochemical texturing also improved the emittance; however, the
improvement was not as great as that for heat treatment and discharge chamber
sputter texturing. Combination treatments involving heat treating in a fur-
nace as the first or second treatment provided the best improvements in the
spectral emittance at 8.2 μm to date. Ion beam texturing following heat treat-
ing increased the spectral emittance to approximately 0.72. These are very
large improvements in emittance when compared to the untreated copper spectral
emittance of 0.01 at 8.2 μm. At 2.5 μm discharge chamber sputter texturing
gave the highest emittance (ε = 0.88). This is approximately a factor of 4
increase over the untreated copper emittance of 0.28. Total emittance at 700
and 900 K is also high for this technique and is above the goal listed for
space station solar dynamic radiators. Values obtained to date are 0.978 at
700 K and 0.983 at 900 K.

Titanium-6% aluminum-4% vanadium. - For Ti-6%Al-4%V, the single texturing
technique that produced the highest value of emittance was heat treating. Fig-
ure 8 shows the emittance values obtained for this material. This technique
increased the spectral emittance from 0.52 to 0.74 at 2.5 μm. Discharge cham-
ber sputter texturing also proved to be an effective technique for improving
the emittance by increasing the spectral emittance of this material to 0.72 at
2.5 μm.

Combination treatments involving heat treating as either a first or sec-
ond treatment were also effective in increasing the emittance of Ti-6%Al-4%V.
Values of spectral emittance for this combination of treatments ranged from
0.75 to 0.82 at 2.5 μm. However, no values for this material were above the
desired goal for SP-100.

Niobium-1% zirconium. - The emittance data obtained from various textur-
ing treatments on Nb-1%Zr are shown in figure 9. The single treatment that
produces the highest spectral emittance at 2.5 μm is heat treating in a fur-
nace. Spectral emittance increased from 0.46 to 0.89 at 2.5 μm. Heating with

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a propane torch produced the second highest value of spectral emittance (ε = 0.72). The total emittance at 700 and 900 K doubled for furnace heat treated Nb-1%Zr from 0.25 to 0.48 at 700 K and from 0.28 to 0.50 at 900 K.

Multiple treatments involving heat treating and abrasion produced higher values of emittance than the single texturing treatment techniques as illustrated in figure 10. While the measured spectral emittance for sandblasted Nb-1%Zr is lower than that for the original untreated material, the sandblasting when combined with furnace heat treatment yields an increase in the emittance greater than that produced by heat treatment alone. Exposure to atomic oxygen in a plasma asher appears to increase the emittance of the treated sample further. For Nb-1%Zr, it is possible that the oxide formed during heat treatment may be porous or loosely attached so that further oxidation can take place in the air plasma. Figure 10 also illustrates the change in surface morphology that takes place upon texturing. Exposure to a 5 percent aqueous solution of NaOH followed by heat treating produced the highest value of spectral emittance at 2.5 μm. It provided an increase from 0.46 to 0.95. This technique is impractical, however, because the reaction rate is slow. Approximately two months of exposure in the base was required for a change in the surface to occur.

For most of the heat treating and abrading techniques used, regardless of which was the first or second treatment, the spectral emittance and total emittance at 700 and 900 K doubled. The spectral emittance at 2.5 μm was above the desired goal for SP-100. Oxidation of tne surface seems to produce a substantial increase in the emittance of Nb-1%Zr, however there are some drawbacks to this technique. Oxygen probably penetrates deep into the Nb-1%Zr leading to embrittlement of the material. Much more information about the depth of penetration and the mechanical properties after texturing is needed.

Environmental Exposure

All testing for durability to the low Earth orbital environment involved exposure to atomic oxygen in a plasma asher. The samples exhibiting the highest values of emittance after treatment were tested. Figure 11 illustrates some of the results obtained. For Nb-1%Zr, the emittance with ashing time did not vary substantially for the heat treated sample. Perhaps a continuous and nonporous oxide layer formed on this surface during heat treatment could provide a protective barrier to further oxidation.

Table II provides a summary of the emittance enhancement results for the four metals tested showing the best treatment technique and values of emittance before and after texturing. This table also shows the resulting emittance after exposing these textured surfaces to atomic oxygen in a plasma asher. For stainless steel that had been exposed to hydrochloric acid then heat treated, there was no noticeable change in emittance. Mirtich et al. have reported a decrease in emittance for stainless steel that had been discharge chamber sputter textured and then exposed to atomic oxygen. This indicates that atomic oxygen may alter the surface enough to detrimentally affect the emittance of some materials. The effect is highly dependent on the material and the texturing technique. Emittance did not change for Nb-1%Zr that had been propane torch heat treated and then furnace heat treated, and also for Ti-6%Al-4%V that had been sandblasted and then furnace heat treated. Copper that had been discharge chamber sputter textured appeared to increase

slightly in emittance upon exposure to atomic oxygen. The reason for this difference may be that it was textured by a technique that did not involve oxidation. Evaluation of more surfaces roughened by various types of techniques may shed more light on this.

CONCLUSION

Multiple texturing techniques involving heat treating in a furnace as the second treatment provided the best values of emittance for 304 stainless steel, Ti-6%Al-4%V, and Nb-1%Zr. Emittances increased by almost a factor of two for these metals upon texturing, and changed very little upon exposure to atomic oxygen. Oxidation of the surface during heat treating may explain this. For copper, the single treatment of discharge chamber sputter texturing provided the best value of emittance, increasing the emittance by over a factor of three. Exposure to atomic oxygen increased the emittance further. The emittance can be positively or negatively affected by exposure to atomic oxygen depending on the material and the texturing technique. Evaluation of the effect of oxidation on the mechanical properties of these materials would be of great importance.

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TABLE I. - RADIATOR OPERATING PARAMETERS AND GOALS

Radiator	Operating temperature, K	Emittance goal	Desired lifetime, years
SP-100	500 to 950	0.85	15
Space Station SDPS	333 to 422	.90	20
Advanced SDPS	450	.85	5 to 15

TABLE II. - SUMMARY OF EMITTANCE ENHANCEMENT RESULTS

[All emittance measurements are at 2.5 μm which corresponds to 1159 K.]

Material	Emittance before texturing	Emittance after texturing	Emittance after texturing and ashing	Surface treatment
304 Stainless steel	0.47±0.02	0.93±0.02	0.93±0.02 (Ashed ≈72 hr)	HCl Etching then furnace heating
Copper	0.28±0.02	0.88±0.02	0.92±0.02 (Ashed ≈72 hr)	Discharge chamber sputter etching
Ti-6%Al-4%V	0.52±0.02	0.83±0.2	0.81±0.02 (Ashed ≈160 hr)	Sand blasting, then furnace heating
Nb-1%Zr	0.46≅0.02	0.91±0.02	0.93±0.02 (Ashed ≈100 hr)	Propane heating then furnace heating

FIRST TREATMENT

SECOND TREATMENT	UNTREATED	HNO₃	HCl	H₂SO₄	FURNACE HEATING	PROPANE TORCH HEATING	SAND BLASTING	EMERY PAPER	NATURAL TEXTURING	SEED TEXTURING	DISCHARGE CHAMBER TEXTURING	ELECTRO CHEMICAL
UNTREATED	0.47 0.11											
HNO₃		0.43 0.13										
HCl			0.50 0.56		0.49 0.71		0.56 0.54	0.46 0.63				
H₂SO₄				0.69								
FURNACE HEATING			0.93* 0.85*		0.92 0.33 0.41 0.43		0.79 0.56	0.85* 0.42 0.42* 0.46*	0.84 0.27	0.77 0.53		
PROPANE TORCH HEATING						0.51 0.12						
SAND BLASTING			0.53 0.38		0.62 0.39		0.54 0.32	0.50 0.34				
EMERY PAPER			0.50 0.49		0.76 0.43		0.58 0.37	0.17				
NATURAL TEXTURING			0.53 0.41		0.89* 0.29		0.49 0.26	0.46 0.18	0.48 0.14			
SEED TEXTURING					0.88 0.26		0.49 0.25			0.36 0.13		
DISCHARGE CHAMBER TEXTURING			0.83* 0.59 0.89 0.89								0.82 0.42 0.79* 0.81*	
ELECTRO CHEMICAL												0.54 0.20

KEY

A	B
C	D

A SPECTRAL EMITTANCE AT PEAK OF 1159 K (2.5 μM)
B TOTAL EMITTANCE AT PEAK OF 355 K (8.2 μM)
C TOTAL EMITTANCE AT 700 K (PEAKS AT 4.14 μM)
D TOTAL EMITTANCE AT 900 K (PEAKS AT 3.21 μM)
* MEASUREMENT MADE AFTER RF PLASMA ATOMIC OXYGEN EXPOSURE

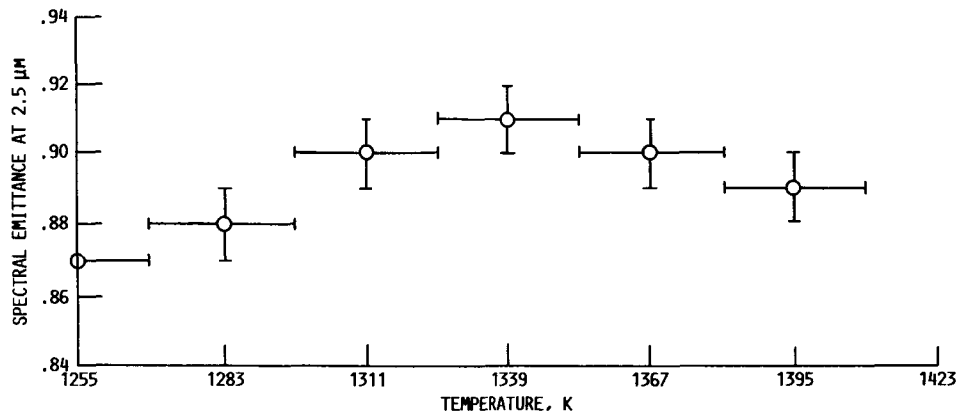FIGURE 1. - EMITTANCE MATRIX FOR 304 STAINLESS STEEL.

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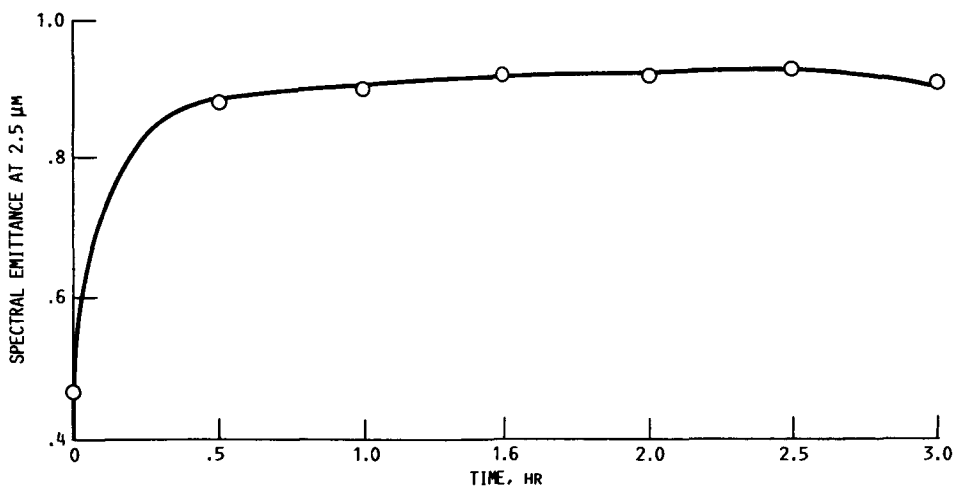FIGURE 2. - EMITTANCE VERSUS TEMPERATURE FOR 304 STAINLESS STEEL HELD AT TEMPERATURE FOR 1 HR.

FIGURE 3. - EMITTANCE VERSUS TIME IN FURNACE AT 1311 K FOR 304 STAINLESS STEEL.
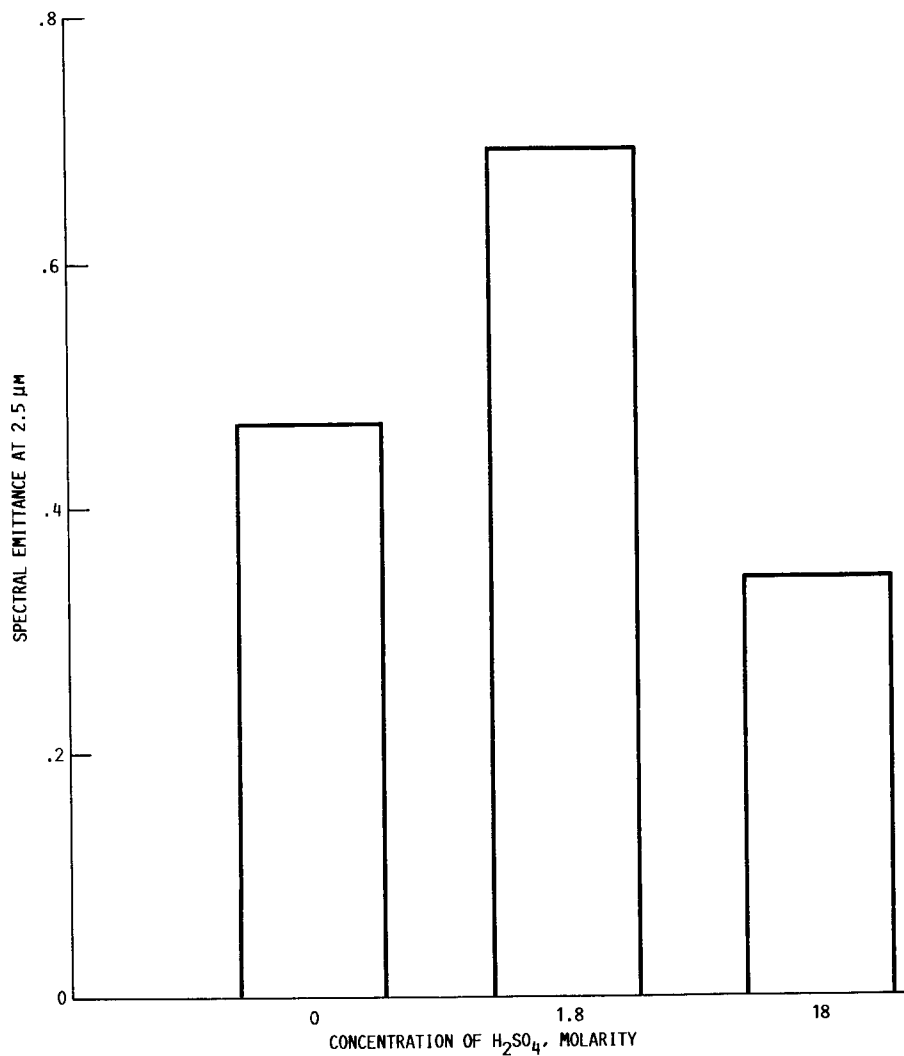
FIGURE 4. - EMITTANCE VERSUS H_2SO_4 CONCENTRATION FOR 304 STAINLESS STEEL.
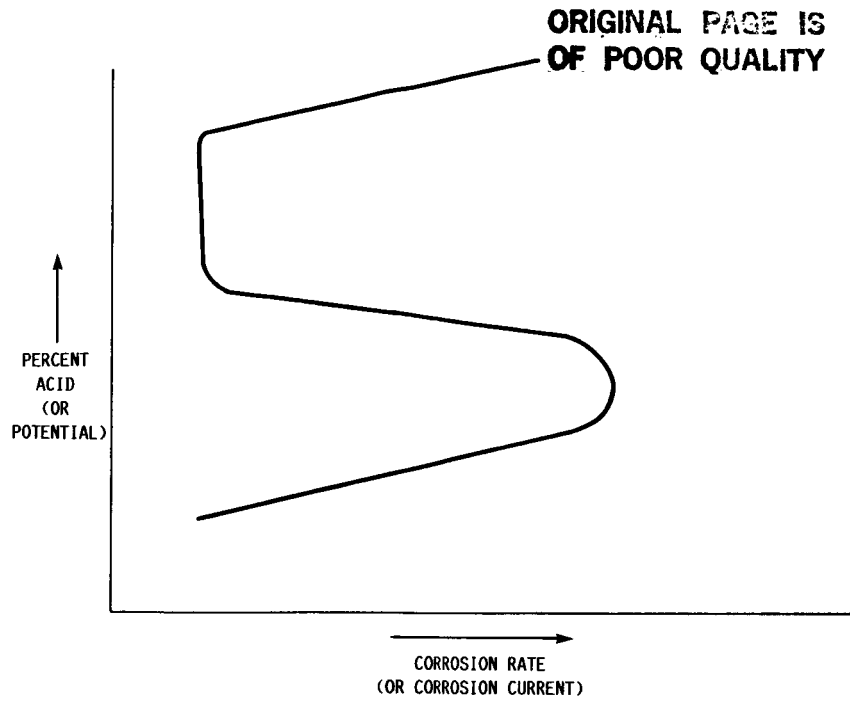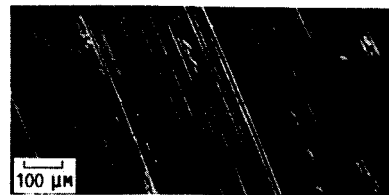
PERCENT
ACID
(OR
POTENTIAL)

CORROSION RATE
(OR CORROSION CURRENT)

FIGURE 5. - POLARIZATION CURVE FOR CORROSION IN ACID. (FROM REF. 9.)

100 µM

UNTREATED

100 µM

HCI AND HEAT TREATED

CD-86-20834

ROOM TEMPERATURE EMITTANCE

1.0

.8

.6

.4

.2

0

UNTREATED

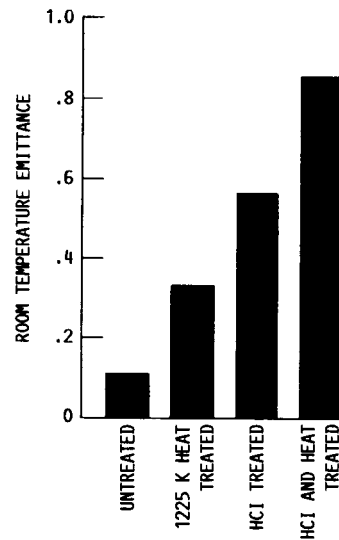1225 K HEAT TREATED

HCI TREATED

HCI AND HEAT TREATED

FIGURE 6. - EMITTANCE WITH VARYING SURFACE TREATMENTS FOR 304 STAINLESS STEEL.

FIRST TREATMENT

SECOND TREATMENT	UNTREATED	HNO₃	HCl	HF	FURNACE HEATING	PROPANE TORCH HEATING	SAND BLASTING	EMERY PAPER	NATURAL TEXTURING	SEED TEXTURING	DISCHARGE CHAMBER TEXTURING	ELECTRO CHEMICAL
UNTREATED	0.28 0.01											
HNO₃		0.62 0.28			0.43 0.69	0.64 0.38	0.73 0.50	0.62 0.41				0.72 0.29
HCl			0.22 0.02									
HF												
FURNACE HEATING		0.20 0.68			0.48 0.62	0.34 0.63	0.25 0.58	0.31 0.63	0.33 0.61			0.31 0.69
PROPANE TORCH HEATING		0.28 0.25			0.39 0.66	0.25 0.18	0.31 0.16	0.28 0.29				0.24 0.18
SAND BLASTING		0.62 0.36			0.41 0.64	0.49 0.25	0.31 0.16	0.32 0.17				0.40 0.19
EMERY PAPER		0.68 0.40			0.40 0.65	0.50 0.28	0.35 0.17	0.28 0.13				0.24 0.10
NATURAL TEXTURING		0.59 0.43			0.60 0.72	0.36 0.15	0.41 0.21	0.28 0.18	0.29 0.02			
SEED TEXTURING		0.61 0.16			0.49 0.46					0.22 0.01		
DISCHARGE CHAMBER TEXTURING											0.92* 0.57 / 0.978* 0.983*	
ELECTRO CHEMICAL		0.26 0.15			0.27 0.58	0.22 0.19	0.24 0.25	0.31 0.36				0.31 0.10

KEY

A	B
C	D

A   SPECTRAL EMITTANCE AT PEAK OF 1169 K (2.5 μm)
B   TOTAL EMITTANCE AT PEAK OF 355 K (8.2 μm)
C   TOTAL EMITTANCE AT 700 K (PEAKS AT 4.14 μm)
D   TOTAL EMITTANCE AT 900 K (PEAKS AT 3.21 μm)
*   MEASUREMENT MADE AFTER RF PLASMA ATOMIC OXYGEN EXPOSURE

FIGURE 7. – EMITTANCE MATRIX FOR COPPER.

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FIRST TREATMENT

SECOND TREATMENT	UNTREATED	HNO₃	HCl	HF	FURNACE HEATING	PROPANE TORCH HEATING	SAND BLASTING	EMERY PAPER	NATURAL TEXTURING	SEED TEXTURING	DISCHARGE CHAMBER TEXTURING	ELECTRO CHEMICAL
UNTREATED	0.52 / 0.24											
HNO₃		0.24										
HCl			0.53 / 0.25									
HF				0.53	0.59 / 0.38							
FURNACE HEATING				0.81 / 0.72	0.74 / 0.64	0.77 / 0.65	0.81* / 0.68*	0.77 / 0.64	0.75 / 0.65	0.82 / 0.65		0.49 / 0.80
PROPANE TORCH HEATING					0.80 / 0.69	0.61 / 0.29	0.61 / 0.36	0.59 / 0.31				
SAND BLASTING				0.59 / 0.40	0.80 / 0.64	0.59 / 0.28	0.58 / 0.37	0.62 / 0.40				
EMERY PAPER					0.78 / 0.66	0.59 / 0.30	0.60 / 0.37	0.56 / 0.32				
NATURAL TEXTURING					0.79 / 0.64				0.52 / 0.24			
SEED TEXTURING					0.81 / 0.67	0.51 / 0.23				0.52 / 0.23		
DISCHARGE CHAMBER TEXTURING											0.72 / 0.36	
ELECTRO CHEMICAL												0.54

KEY

A	B
C	D

A SPECTRAL EMITTANCE AT PEAK OF 1159 K (2.5 μm)
B TOTAL EMITTANCE AT PEAK OF 355 K (8.2 μm)
C TOTAL EMITTANCE AT 700 K (PEAKS AT 4.14 μm)
D TOTAL EMITTANCE AT 900 K (PEAKS AT 3.21 μm)
* MEASUREMENT MADE AFTER RF PLASMA ATOMIC OXYGEN EXPOSURE

FIGURE 8. – EMITTANCE MATRIX FOR Ti-6%Al-4%Y.

FIRST TREATMENT

FIGURE 9. – EMITTANCE MATRIX FOR Nb-1%Zr.

KEY

A	B
C	D

A SPECTRAL EMITTANCE AT PEAK OF 1159 K (2.5 μm)
B TOTAL EMITTANCE AT PEAK OF 355 K (8.2 μm)
B TOTAL EMITTANCE AT 700 K (PEAKS AT 4.14 μm)
D TOTAL EMITTANCE AT 900 K (PEAKS AT 3.21 μm)
* MEASUREMENT MADE AFTER RF PLASMA ATOMIC OXYGEN EXPOSURE

(Each cell is a 2×2 key: top row = A, B; bottom row = C, D)

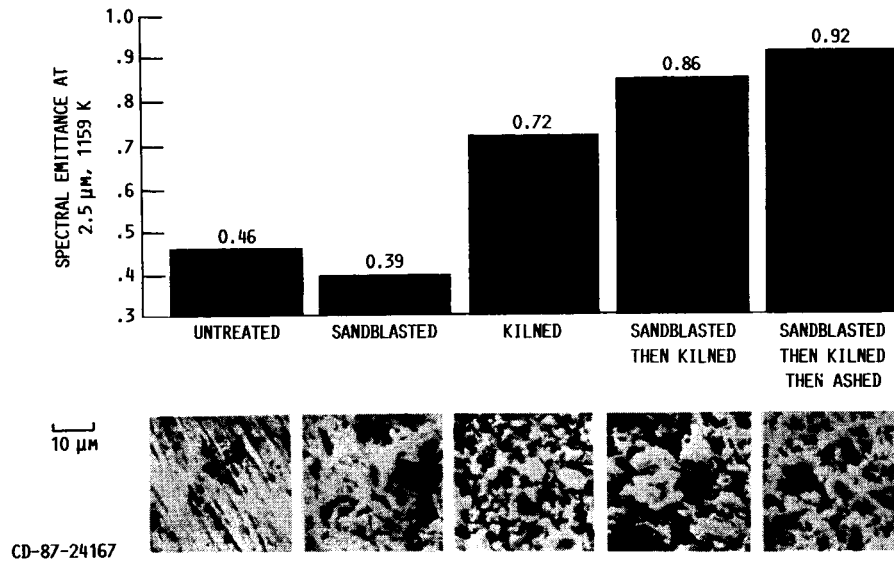| SECOND TREATMENT \ FIRST TREATMENT	UNTREATED	HNO₃	HCl	HF	FURNACE HEATING	PROPANE TORCH HEATING	SAND BLASTING	EMERY PAPER	5% NaOH	SEED TEXTURING	DISCHARGE CHAMBER TEXTURING	ELECTRO CHEMICAL
UNTREATED	0.46; 0.25, 0.28											
HNO₃												
HCl												
HF												
FURNACE HEATING					0.89*; 0.48*, 0.50*	0.93*, 0.54*; 0.63*, 0.66*	0.92*, 0.47*; 0.66*, 0.69*	0.87*, 0.50*; 0.64*, 0.67*	0.95*, 0.57*; 0.67*, 0.70*			0.66, 0.55
PROPANE TORCH HEATING					0.82*, 0.52*; 0.67*, 0.70*	0.72	0.60	0.63				
SAND BLASTING					0.90*; 0.49*, 0.52*	0.77	0.39	0.36				
EMERY PAPER					0.82*, 0.44*; 0.69*, 0.71*	0.70	0.52	0.44				
5% NaOH												
SEED TEXTURING												
DISCHARGE CHAMBER TEXTURING											0.352*, 0.376*	
ELECTRO CHEMICAL												0.47, 0.17

FIGURE 10. - EMITTANCE WITH VARYING SURFACE TREATMENTS FOR Nb-1% Zr.
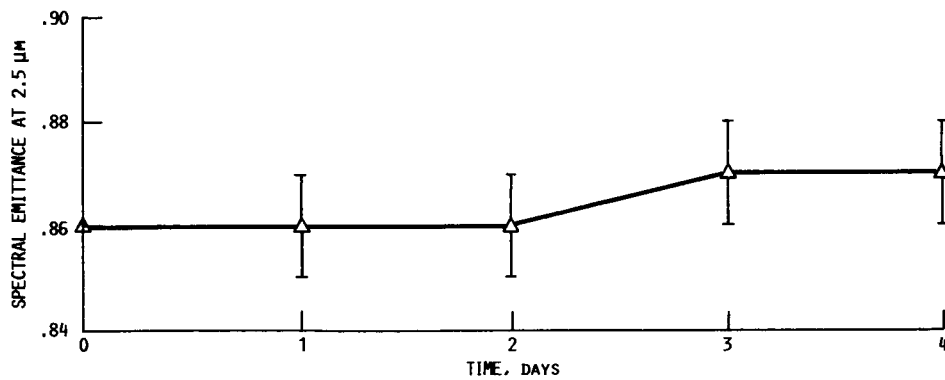
FIGURE 11. - EMITTANCE VERSUS ASHING TIME FOR HEAT TREATED Nb-1%Zr.

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15. Supplementary Notes

16. Abstract

Radiators must be constructed of materials which have high emittance in order to efficiently radiate heat from high temperature space power systems. In addition, if these radiators are to be used for applications in the low Earth orbital environment, they must not be detrimentally affected by exposure to atomic oxygen. Four materials selected as candidate radiator materials (304 stainless steel, copper, titanium-6% aluminum-4% vanadium (Ti-6%Al-4%V), and niobium-1% zirconium (Nb-1%Zr)) were surface modified by acid etching, heat treating, abrading, sputter texturing, electrochemical etching, and combinations of the above in order to improve their emittance. Combination treatment techniques with heat treating as the second treatment provided about a factor of two improvement in emittance for 304 stainless steel, Ti-6%Al-4%V, and Nb-1%Zr. A factor of three improvement in emittance occurred for discharge chamber sputter textured copper. Exposure to atomic oxygen in an RF plasma asher did not significantly change the emittance of those samples that had been heat treated as part of their texturing process. An evaluation of oxygen penetration is needed to understand how oxidation affects the mechanical properties of these materials when heat treated.

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