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Total Hemispherical Emittance of Coated and Uncoated Inconel and Types 321 and 430 Stainless Steel

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The total hemispherical emittance of specimens of three alloys, Inconel and types 321 and 430 stainless steel, in six different surface conditions, was evaluated at temperatures in the range 200 to 1,000 °C by a modification of the hot filament method. The surface conditions were (1) polished, (2) sandblasted, (3) polished and then oxidized, (4) sandblasted and then oxidized, (5) coated with NBS coating A–418, and (6) coated with NBS coating N–143.

The total hemispherical emittance was markedly affected by the surface treatment. In general emittance was low for polished specimens, intermediate for sandblasted specimens, and high for oxidized or ceramic-coated specimens of each alloy.

1. Introduction

Total hemispherical emittance is the amount of radiant energy emitted, per unit area and time, expressed as a fraction of that emitted by a blackbody or complete radiator under the same conditions. When this property of a specimen has been measured, the rate of heat dissipation by radiation of the specimen at any temperature for which data are available can be computed.

The total hemispherical emittance of a specimen is affected by its chemical composition, internal structure and surface texture, and if a specimen of a given material is not completely opaque to the emitted radiant energy, its emittance is also a function of its thickness.

The present investigation was undertaken to study the effect of surface treatments, including the application of several thicknesses of ceramic coatings A–418 and N–143, on the total hemispherical emittance of specimens made from three alloys.

2. Description of Material

The three alloys studied were Inconel, type 321 stainless steel, and type 430 stainless steel. Inconel is an austenitic alloy, nominally 80 percent nickel, 14 percent chromium, and 6 percent iron, that is used for those high-temperature applications in which an alloy of good oxidation and corrosion resistance is required, and moderate high-temperature strength is acceptable. Type 321 stainless steel is an austenitic alloy, nominally containing 18 percent chromium and 8 percent nickel, that is stabilized with titanium to inhibit intergranular corrosion at elevated temperatures. Type 430 stainless steel is a ferritic alloy that contains nominally 17 percent chromium.

Two ceramic coatings were used, NBS coatings A–418 and N–143. These have been previously described [1, 2].[1] The frit and batch compositions are given in table 1. Coating A–418 consists of an alkali-free barium borosilicate frit, with a refractory mill addition of chromic oxide. Coating N–143 consists of a boron-free barium beryllium silicate frit with a refractory mill addition of cerium oxide.

TABLE 1

Computed frit compositions

Oxide	Weight percent in frit No.	
	435	332
SiO_2	37.02	37.5
BaO	47.24	44.0
Al_2O_3		1.0
BeO	3.08	
B_2O_3		6.5
CaO	4.15	3.5
ZnO	5.01	5.0
ZnO_2		2.5
P_2O_5	3.50	

Coating mill batch compositions

Material	Parts by weight in coating	
	N–143	A–418
Frit 435	67.5	
Frit 332		70.0
CeO_2	32.5	
Cr_2O_3		30.0
Clay	5.0	5.0
Firing temperature	1,120 °C	1,010 °C

3. Preparation of Specimens

The Inconel and type 321 stainless steel were received in the form of dull-finished sheets approximately 30 in. wide by 8 ft long. The type 430 stainless steel was received in the form of coiled strip, 2 in. wide. The strips had a highly polished surface. Several different thicknesses were used.

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[1] Figures in brackets indicate the liturature references at the end of this paper.

The sheet metal was sheared into strips 20 cm long by 6.35 mm wide (8 by ¼ in.). These strips were then mounted in a special jig, in lots of 20 to 100, and the edges were ground on a surface grinder until the sides were parallel to within ±0.013 mm over the center 10 cm of each strip.

3.1. Polished and Sandblasted Specimens

Polished specimens of Inconel and type 321 stainless steel were prepared by electropolishing; the procedure used is outlined in table 2. Because the type 430 stainless steel was received in the form of highly polished strip, no further polishing was required.

TABLE 2. *Procedure for electropolishing Inconel and type 321 stainless steel*

Electrolyte	600 ml H_3PO_4 (concentrated). 300 ml H_2SO_3 (concentrated) 100 ml H_2O.
Current density [a]	1–2 amp/in.^{2}
Time [a]	5–10 min.
Temperature	80–100° F.
Cathode [b]	Type 321 stainless steel.

[a] Time and current density vary with initial condition of the surface.

[b] Two cathodes, one on each side of specimen.

Sandblasted specimens of each alloy were prepared by blasting with 60-mesh fused alumina grit, at an air pressure of approximately 75 psi. Care was taken in blasting to avoid excessive warpage of the thinner specimens.

Three thermocouples were welded to each uncoated, unoxidized specimen. Very shallow grooves were inscribed perpendicular to the axis of the specimen, one at the midlength of the specimen, and one 13 mm from the midlength on each side. Wires were laid in these grooves in order to position them accurately before welding. The 0.127 mm diam Chromel and Alumel thermocouple wires were separately welded to the specimen by means of an electronic condenser-discharge type of spot welder. The welds forming each thermocouple were about 3 mm apart. The Chromel leads from the outside thermocouples were used as the voltage taps.

3.2. Oxidized Specimens

Eight specimens of each alloy, in the polished and sandblasted condition, respectively, were prepared and marked for identification. The width, length, and thickness of each specimen was accurately measured, and it was weighed to the nearest 0.1 mg. these specimens were then oxidized in air in an electrically heated furnace at a temperature of 1,000±5 °C for times of ½, 1, 3, 5, 10, 20, 40, and 80 hr. One specimen of each alloy in each condition was removed at the end of each period of oxidation. All of the specimens remaining in the test were weighed at the end of each oxidation period.

After oxidation, the oxide layer was removed from both sides by grinding each specimen for a distance of about 25 mm at each end, to ensure good contact with the electrodes. Also, a light scratch was made through the oxide at the three areas where the thermocouples were to be attached. The thermocouple wires were then welded in place, as described above.

3.3. Coated Specimens

The ceramic coatings were applied, by dipping, to sandblasted specimens to which thermocouples had been welded. It was found that when the coated specimens were fired in a furnace to mature the coatings, the thermocouple leads oxidized excessively. To eliminate this difficulty the coated specimens that were used were fired in air, heated by an electric current passed through them.

4. Experimental Procedure

The equipment and procedure for evaluation of total hemispherical emittance has been described in a previous publication [3]. Only a brief summary will be given here.

The specimen was heated in a vacuum of 4×10^{-5} mm of Hg or less by passing a current through it. The test conditions were such that essentially all of the heat dissipation from the area at and near the midlength of the specimen was by radiation. The power input to, and temperature of, a small length (approximately 25 mm) of known dimensions near the midlength of the specimen and the temperature of the walls of the chamber surrounding the hot specimen were measured. The total hemispherical emittance was then computed from these values by means of the following relationship derived from the Stefan-Boltzmann equation:

$$E=\frac{V\cdot I}{A\,\sigma(T_1^4-T_2^4)}$$

in which E=total hemispherical emittance
V=voltage drop between voltage taps
I=current flowing through specimen
A=surface area of specimen between voltage taps
σ=Stefan-Boltzmann constant
T_1=temperature of specimen, °K
T_2=temperature of shell, °K.

In these determinations the specimen was held at one power input only long enough for its temperature to stabilize, and the changes in emittance that occurred on long-time heating in vacuum were not followed. The time that each specimen was held at each power input usually was less than 10 min, and in many cases the time was less than 5 min. While some changes in emittance undoubtedly did occur in these short times, the magnitude of the changes was less than 2 percent, except where noted.

5. Results and Discussion

Data for Inconel are shown in figures 1, 4, and 7; for type 321 stainless steel in figures 2, 5, and 8; and for type 430 stainless steel in figures 3, 6, and 9. In

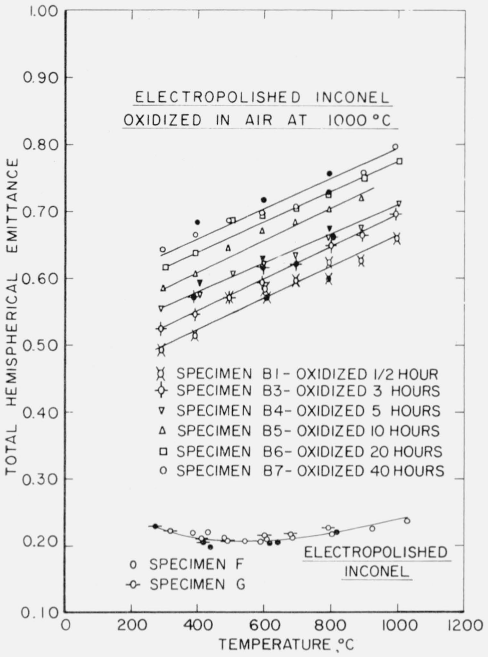

FIGURE 1. *Total hemispherical emittance of Inconel in the electropolished condition, bottom curve, and after oxidation at 1,000 °C for various times subsequent to electropolishing, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

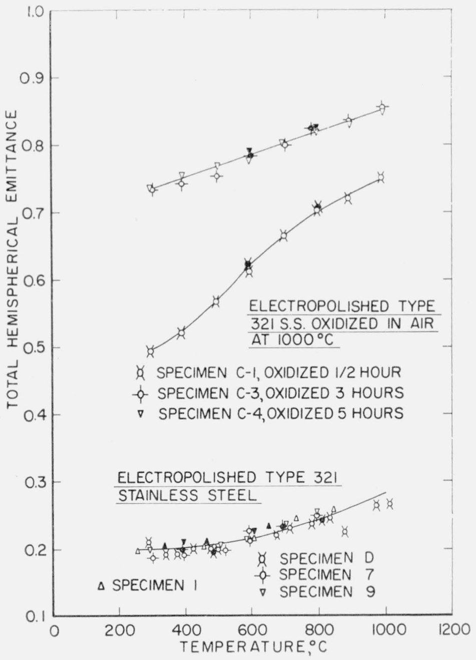

FIGURE 2. *Total hemispherical emittance of type 321 stainless steel specimens in the electropolished condition, bottom curve, and after oxidation in air at 1,000 °C for various times subsequent to electropolishing, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

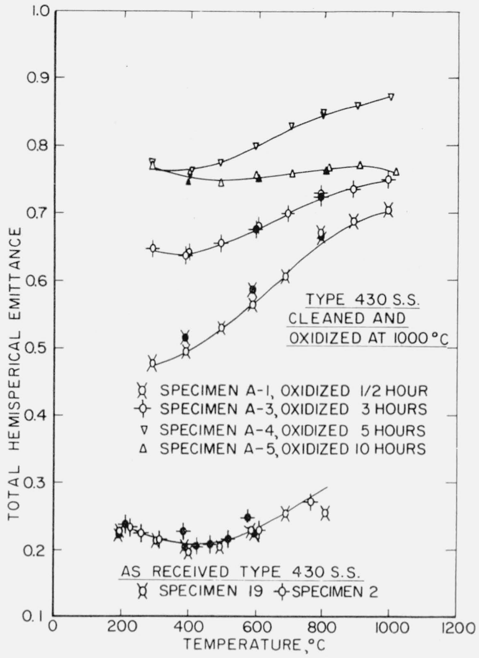

FIGURE 3. *Total hemispherical emittance of type 430 stainless steel in the as-received condition (polished) bottom curve, and after oxidation in air at 1,000 °C for various times, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

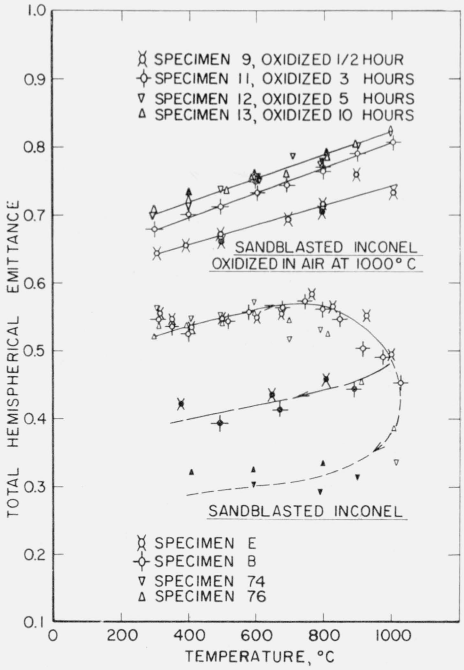

FIGURE 4. *Total hemispherical emittance of Inconel in the sandblasted condition, bottom curves, and after oxidation at 1,000 °C for various times subsequent to sandblasting, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

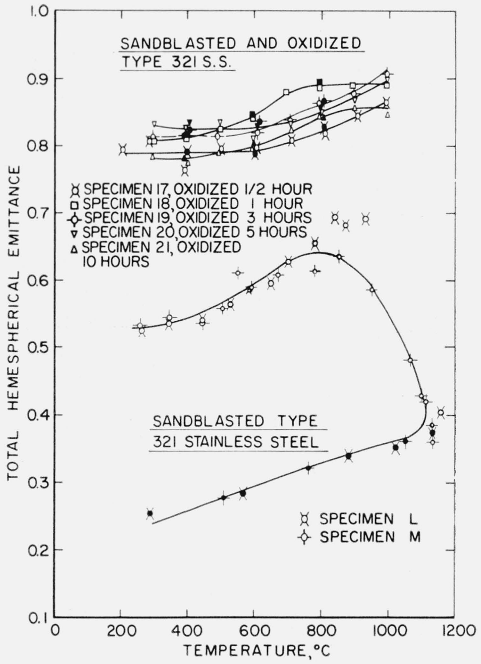

FIGURE 5. *Total hemispherical emittance of type 321 stainless steel specimens in the sandblasted condition, bottom curves, and after oxidation in air at 1,000 °C for various times subsequent to sandblasting, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

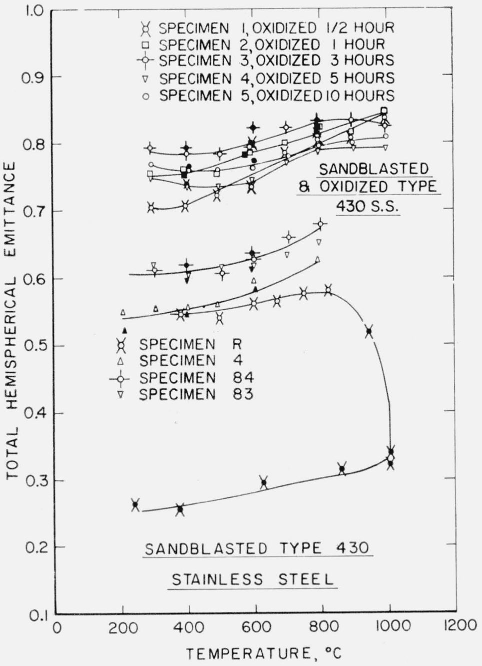

FIGURE 6. *Total hemispherical emittance of type 430 stainless steel in the sandblasted condition, bottom curves, and after oxidation in air at 1,000 °C for various times subsequent to sandblasting, top curves.*

Open points represent values obtained during heating; closed points, during cooling.

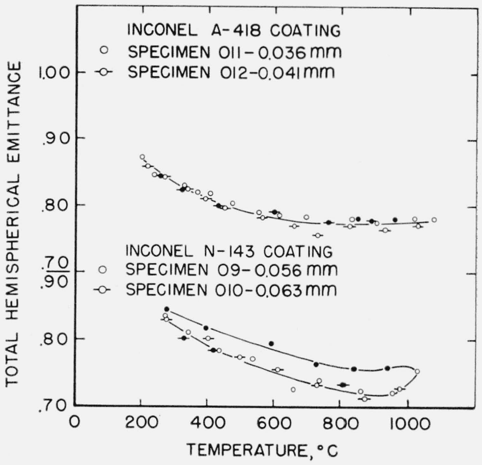

FIGURE 7. *Total hemispherical emittance of composite specimens consisting of Inconel coated with NBS coating A–418, top curve, and NBS coating N–143, bottom curve.*

Open points represent values obtained during heating; closed points, during cooling.

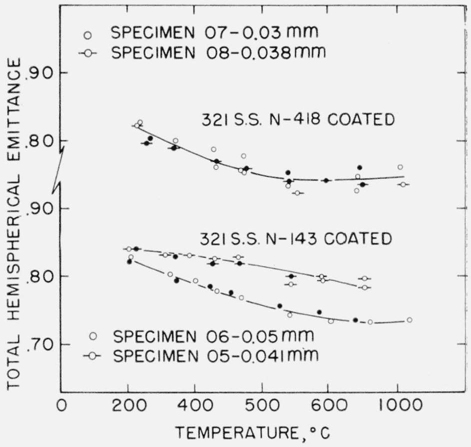

FIGURE 8. *Total hemispherical emittance of composite specimens consisting of type 321 stainless steel coated with NBS ceramic coating A–418, top curves, and NBS ceramic coating N–143, bottom curves.*

Open points represent values obtained during heating; closed points, during cooling.

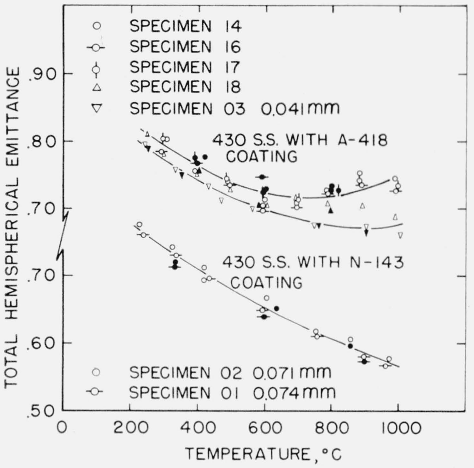

FIGURE 9. *Total hemispherical emittance of composite specimens consisting of type 430 stainless steel coated with NBS ceramic coating A–418, top curves, and NBS ceramic coating N–143, bottom curve.*

Open points represent values obtained during heating; closed points, during cooling.

each case open symbols indicate data points that were obtained during the heating cycle, and filled symbols indicate data points that were obtained during the cooling cycle.

5.1. Polished Specimens

The data for the polished specimens, figures 1, 2, and 3, show that there was very little difference in the emittance of the three alloys in this condition. They all had total hemispherical emittance on the order of 0.20 to 0.28, increased in emittance with an increase in temperature, and showed no evidence of a permanent change in emittance on heating in vacuum for the times required to complete the evaluations. The total hemispherical emittance of the polished Inconel was slightly higher at 400 °C and below, and slightly lower at 600 °C and above, than that of the type 321 and type 430 stainless steel specimens.

5.2. Sandblasted Specimens

The data for the sandblasted specimens are shown in figures 4, 5, and 6. In general there was little difference between the emittances of the different alloys in this condition. They all had total hemispherical emittance on the order of 0.5 to 0.65, and the emittance of each alloy increased with temperature. There was no indication that heating in vacuum at temperatures below 800 °C for the times required to complete the evaluations produced any permanent change in emittance. None of these sandblasted specimens showed any visual evidence of an oxide film formation after completion of the tests.

The total hemispherical emittance of each of the alloys in the sandblasted condition was permanently reduced by heating in vacuum at temperatures above 800 °C, even for the short times required to complete the evaluations. When a time of approximately 10 min elapsed between successive evaluations, as in specimens 74 and 76 in figure 4, specimens L and M in figure 5, and specimen R in figure 6, the total hemispherical emittance was reduced on the order of 0.25 to 0.30. When the time between successive readings was reduced to about 5 min, specimens E and B, figure 4, the amount of the reduction in emittance was on the order of 0.15.

The observed reduction in total hemispherical emittance of sandblasted metal specimens on heating in vacuum was previously reported [3] to be due to volatilization of chromium, which was accompanied by a polishing action on the surface, somewhat similar in appearance to electropolishing. At temperatures below 620 °C, specimens oxidized even at a pressure of 9×10^{-5} mm of mercury and emittance increased; at temperatures of 795 °C or above, the oxide dissociated and chromium volitalized, and the emittance decreased.

5.3. Oxidized Specimens

The data for the specimens that had been polished and then oxidized are shown in figures 1, 2, and 3, and for the specimens that had been sandblasted and then oxidized in figures 4, 5, and 6. In every case the oxidation treatment greatly increased the total hemispherical emittance. Also in every case but one the emittance of each oxidized specimen increased with an increase in temperature.

Apparently the oxide film formed during oxidation at 1,000 °C in air for 30 min was not completely opaque for any of the alloys studied, in either the polished or sandblasted condition. This is indicated by the observation that emittance increased with time of oxidation, at least for the first few hours.

The weight gain, in mg/cm^2, is plotted as a function of oxidation time for Inconel in figure 10, for type 321 stainless steel in figure 11, and for type 430 stainless steel in figure 12. The computed thickness of the oxide layer, in microns, is also indicated on these figures. The computation was made on the following assumptions: (1) The oxide has a density of 5.2g/cm^3.[2] (2) The specimen is flat, i.e., the area of the oxide layer was computed from the measured length, width, and thickness of each specimen, and (3) the oxide layer is of uniform thickness. All of these assumptions are in error, usually in the direction that would tend to give high values for the computed thicknesses, but the computed thicknesses nevertheless serve to give a rough approximation of the thickness of the oxide layers, and a much better approximation of the relative thicknesses of the oxide layers on different specimens of any one alloy in a single surface condition.

In the case of electropolished Inconel, figure 1, the emittance increased with time of oxidation for at

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[2] The exact density of the oxide layer is not easily determined. It may vary with the time of oxidation, and it is probably different for the three alloys used in this investigation. The value of 5.2 was selected as a lower limit on the basis of published values of the densities of oxides that may be present.

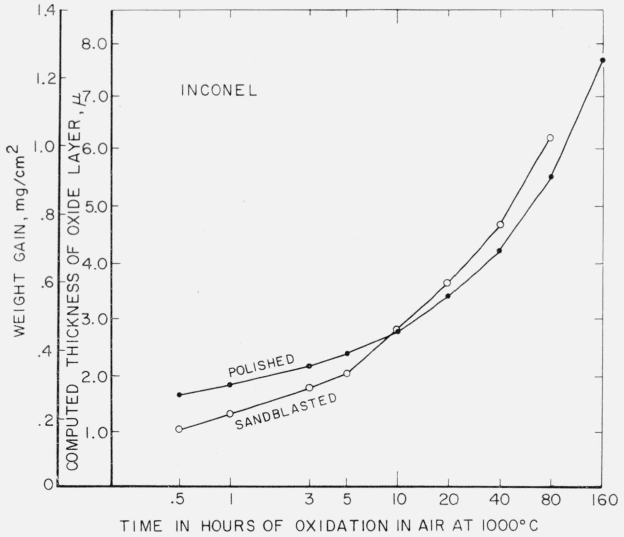

FIGURE 10. *Weight gain, in mg/cm², and computed thickness of the oxide layer, in microns, of specimens of Inconel, in the as-received and sandblasted conditions, plotted as a function of time of oxidation in air at 1,000 °C.*

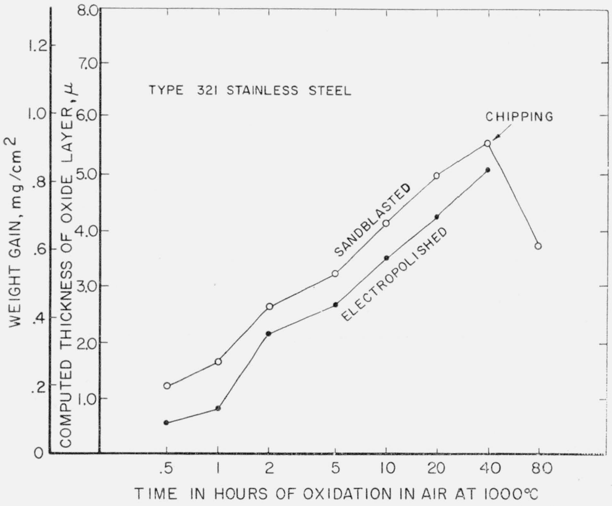

FIGURE 11. *Weight gain, in mg/cm², and computed thickness of the oxide layer, in microns, of specimens of type 321 stainless steel in the electropolished and sandblasted conditions, plotted as a function of time of oxidation in air at 1,000 °C.*

least 40 hr. The emittance of specimens oxidized for times longer than 40 hr was not determined. The computed thickness of the oxide layer produced by oxidation of electropolished Inconel in air at 1,000 °C for 40 hr was slightly over 4 μ.

The increase in emittance with time of oxidation of the electropolished Inconel could be due to the increase in thickness of the oxide layer, to a gradual increase in roughness of the surface and/or a gradual change in the composition, crystal form, or physical condition of the oxide layer. X-ray diffraction patterns were made of the specimens that had been oxidized for periods of ½, 5, 10, and 40 hr. All of the patterns showed the oxide to consist of a nickel-

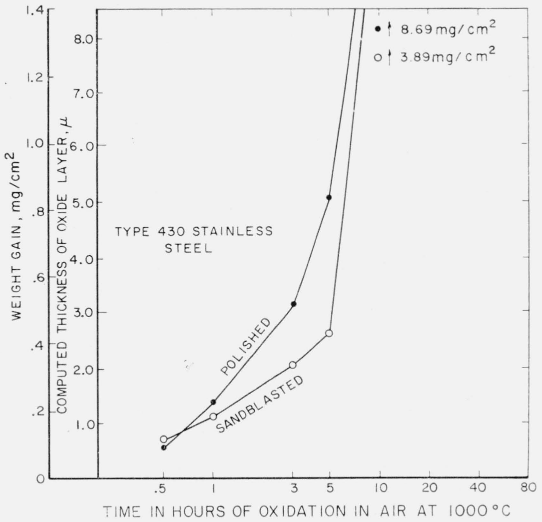

FIGURE 12. *Weight gain, in mg/cm², and computed thickness of the oxide layer, in microns, of specimens of type 430 stainless steel in the as-received and sandblasted conditions, plotted as a function of time of oxidation in air at 1,000 °C.*

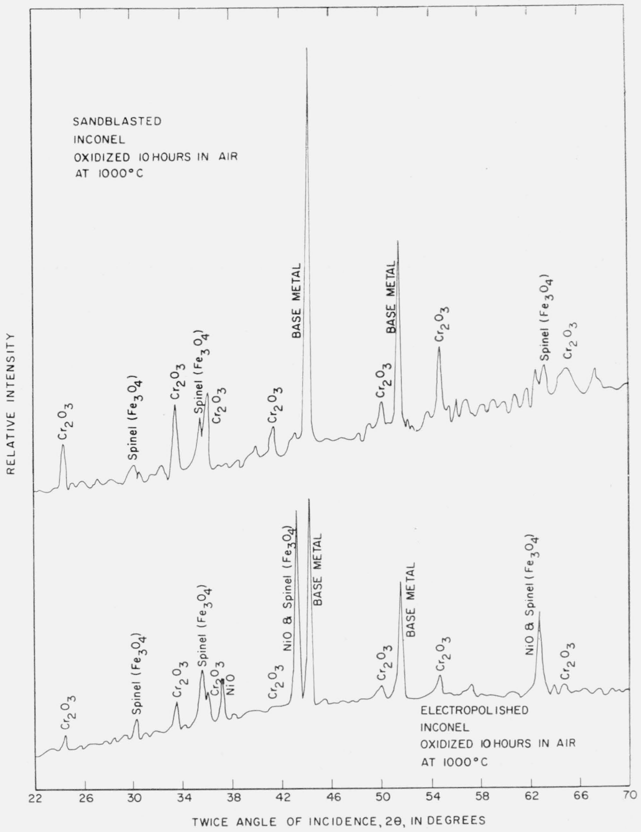

FIGURE 13. *X-ray diffraction patterns of oxidized specimens of electropolished and sandblasted Inconel.*

NiO was found to be a major constituent of the oxide on the electropolished specimen, but was not found in the oxide on the sandblasted specimen.

chrome spinel, NiO, and Cr_2O_3. The X-ray patterns for the spinel and for Fe_3O_4 are practically indistinguishable; however, from thermodynamic considerations, the presence of Fe_3O_4 is unlikely. No significant differences in composition or crystal form were found and no marked increase in roughness was observed; hence it is believed that for electropolished Inconel the increase in emittance with an increase in time of oxidation is due to the increase in thickness of the oxide layer.

In the case of sandblasted Inconel, figure 4, there was an increase in emittance with time of oxidation up to 5 hr, but there was no significant increase in emittance on increasing the time of oxidation from 5 to 10 hr. This difference in behavior of the oxide layers on electropolished and sandblasted Inconel was somewhat puzzling, and called for an explanation.

The weight-gain oxidation data in figure 10 shows that the computed thickness of the oxide layer on the electropolished Inconel that had been oxidized for 40 hr was on the order of 4 μ while that of the sandblasted Inconel that had been oxidized for 5 hr was only about 2 μ. Actually the difference in true layer thickness is much greater than is indicated by these computed values. Measurements made in another study [4] showed that the sandblasting treatment increased the surface area by about 50 percent; hence, on this basis, the average thickness of the oxide layer on the sandblasted specimen would be more nearly 1.3 than 2 μ. Obviously thickness differences do not account for all the observed difference in emittance behavior between specimens that had been electropolished and sandblasted before oxidation. The effect of surface roughness on emittance noted on the unoxidized specimens will, of course, persist in the oxidized specimens.

An X-ray diffraction pattern was made of a specimen of sandblasted Inconel that had been oxidized in air at 1,000 °C for 10 hr. This is compared in figure 13 to a similar pattern from a specimen of electropolished Inconel that had been oxidized in air at 1,000 °C for 10 hr. The curves show that NiO was a major constituent of the oxide layer on the electropolished Inconel, but was not identified as such in the oxide layer on the sandblasted specimen. Similar differences in the NiO content of the respective oxide scales were found in a previous study [5].

It is believed that these observed differences in composition of the oxide formed on sandblasted and polished Inconel satisfactorily account for the observed difference in emittance behavior. Apparently the oxide layer containing NiO as a major constituent requires a much greater thickness to become opaque than does the NiO-free oxide layer.

The data for oxidized type 321 stainless steel suggest that the oxide layer on the electropolished specimens, figure 2, became essentially opaque after 3 hr of oxidation. The total hemispherical emittance of a specimen oxidized for 3 hr was appreciably greater than that of a specimen oxidized for ½ hr, but no difference in emittance was found between specimens oxidized for 3 and 5 hr, respectively.

In the case of the sandblasted type 321 stainless steel, figure 5, the picture becomes more complex. The total hemispherical emittance of all sandblasted oxidized specimens was greater than 0.75. The emittance of the specimen oxidized for 1 hr was appreciably greater than that of the specimen oxidized for ½ hr, but the emittance decreased on continued oxidation until the emittance at some temperatures after 10 hr of oxidation was lower than that after ½ hr of oxidation. In this case there was a change in the appearance of the oxide layer with continued oxidation, which suggests that the composition or structure of the oxide was changing. Small flakes of oxide began chipping from the corners of the specimens after about 3 hr of oxidation, and severe flaking occurred after 40 hr of oxidation. Such a decrease in emittance could also result from a decrease in roughness of the sandblasted surface with continued oxidation, which did occur to some extent.

In the case of type 430 stainless steel rather marked changes in the oxide layer occurred as oxidation progressed. The as-received specimens, figure 3, increased in emittance with time of oxidation up to 5 hr, but the emittance decreased appreciably, especially at the higher temperatures, on further oxidation for an additional 5 hr. It is interesting to note that the total hemispherical emittance of specimen A–5 that had been oxidized in air at 1,000 °C for 10 hr showed very little variation with temperature over the range of 300 to 1,000 °C. The weight-gain oxidation data in figure 12 show that rate of oxidation increased markedly after about 5 hr of oxidation.

The general pattern for the sandblasted specimens of type 430 stainless steel that had been oxidized is similar to that for the as-received specimens, but in this case the maximum emittance was obtained after 3 hr of oxidation. The type of oxidation on both as-received and sandblasted type 430 stainless steel changed after 5 hr of oxidation from uniform attack, with a smooth, dense oxide layer, to a pitting type of attack with tubercle formation in the oxide.

There was no indication in the data that significant changes in emittance of any of the oxidized specimens were produced by heating in vacuum for the times required to complete the evaluations.

5.4. Ceramic-Coated Specimens

The data for the ceramic-coated specimens, figures 7, 8, and 9, show that in every case the total hemispherical emittance of the coated specimens decreased with an increase in temperature, in contrast to that of the unoxidized and oxidized metal specimens. The effect of increasing temperature in increasing total normal emittance of bare and oxidized metal, on the one hand, and decreasing the total normal emittance of ceramic-coated metal on the other hand, has been explained [5] on the basis of the differences in the spectral distribution of the emitted energy. The same explanation applies to the differences observed in the total hemispherical emittance.

The Inconel and type 430 stainless steel specimens coated with A–418 had higher emittances than the corresponding specimens coated with N–143. In the case of the coated type 321 stainless steel specimens, the emittance was nearly the same for specimens 07 and 08 coated with 0.03 and 0.038 mm respectively of A–418 and specimen 06 coated with 0.05 mm of N–143. Specimen 05 coated with 0.041 mm of N–143 had slightly higher emittance than the specimens coated with A–418.

An effect of the base metal on the total hemispherical emittance was to be expected, because the previous report [5] showed that these coatings are partially transparent at thicknesses of less than about 0.13 mm. There was less effect of base metal composition on total hemispherical emittance of specimens coated with A–418 than on those coated with N–143.

Of the specimens coated with A–418, the Inconel specimens had the highest emittance, and the type 430 stainless steel the lowest emittance at each temperature, and the maximum difference was on the order of 10 percent. Of the specimens coated with N–143, emittance was about the same for Inconel and type 321 stainless steel, and appreciably lower for type 430 stainless steel. Also the slope of the curve over the 200 to 600 °C temperature range for the type 430 stainless steel specimens was steeper than that for the other alloys.

There is no evidence that heating in vacuum at temperatures up to 1,040 °C for the time required to complete the determinations produced any appreciable change in emittance of the specimens coated with A–418, or in the type 321 or 430 stainless steel specimens coated with N–143. One specimen of Inconel to which coating N–143 was applied at a thickness of 0.056 mm showed a permanent increase in emittance of 2 to 3 percent after heating in vacuum at 1,015 °C.

6. Comparison of Results With Published Data

Total normal emittance determinations were reported by De Corso and Coit [6] for as-rolled and sandblasted Inconel, both in the initially unoxidized condition and after oxidation in air at 982 °C (1,800 °F) for 15 min, and for Nichrome V coated with NBS ceramic coating A–417. NBS ceramic coatings A–417 and A–418 are similar but not identical in composition. Similar results were reported by Snyder, Gier, and Dunkle [7] for 18–8 stainless steel, type not specified, in the as-received condition and after mechanical polishing, sandblasting and weathering, and "oxidized 1,500 °F and weathered"; and by Wilkes [8] for types 316 and 347 stainless steels, Inconel X and A Nickel in the polished condition. The agreement with the total hemispherical data shown in this paper is only fair in most cases. The differences may be ascribed to (1) inherent differences in normal and hemispherical emittance of materials, and (2) differences in the composition or surface preparation of specimens.

The directional emissivity of a material varies with the angle of emission, due to variations in the transmittance of the material-air interface with angle of incidence. Jakob [9] has computed the theoretical ratio of normal to hemispherical emissivity of dielectrics to vary from 1.00 at a normal emissivity of 0.50 to a low of 0.935 at a normal emissivity of 0.90 and 0.95. He also computed [10] the same ratio for electrical conductors, and found it to vary from a high limit of 1.33 for a normal emissivity approaching zero to 1.055 for a normal emissivity of 0.35. All of these values apply only to completely opaque specimens with optically smooth surfaces, as the term emissivity implies. The trend would be in the same direction for surfaces that are not optically smooth, but it is not possible to compute the ratio for such surfaces, unless the surface contour is known with precision.

The data in figures 1, 2, 3, 4, 5, and 6 show that differences in surface preparation or oxidation treatment can cause appreciable differences in emittance, even for specimens of identical composition. Also, the differences in composition among the three alloys are reflected in differences in emittance. These differences are small for the unoxidized specimens, but become greater after oxidation.

A previous report [5] gave data for total normal emittance computed by integrating normal spectral data obtained on specimens of Inconel and type 321 stainless steel. The data obtained show only fair agreement with the measured values of total hemispherical emittance shown in figures 1, 2, 4, 5, 7, and 8. Bevans, Gier, and Dunkle [11] found appreciable differences in the total normal emittance of supposedly identical specimens obtained (1) by direct measurement, and (2) by computation from spectral data. It is not surprising that even larger differences were found in the present study between (1) the measured total hemispherical emittance and (2) the total normal emittance computed from spectral data.

O'Sullivan and Wade [12] reported data on the total hemispherical emittance of Inconel that had been mechanically polished and then oxidized in air at 1,093 °C (2,000 °F) for 13 min. They measured the directional emittance at angles of 0, 30, 45, and 60° to the normal, corrected the values for the actual area of the specimen viewed, plotted the points in polar coordinates, drew a smooth curve through the points and extrapolated it to 90° to the normal. The total hemispherical emittance was obtained by integrating the resulting curve. Their values were about 0.04 higher than the highest values reported in figure 1 for oxidized Inconel. Later, Wade [13] reported similar data for the total hemispherical emittance of type 347 stainless steel specimens that were mechanically polished and then oxidized in air at 1,093 °C (2,000 °F) for 30 min. His reported values are higher than any of the values for oxidized electropolished type 321 stainless steel shown in figure 2.

The values reported by these authors for the directional emittance of the oxidized Inconel and type 347 stainless steel showed practically no deviation from values that would have been computed from the total normal emittance by the cosine law. Hence, the total hemispherical emittance computed from these values was identical to the total normal emittance. Jakob [5] showed that for dielectric materials appreciable deviations from the cosine law do not occur at angles of 60° or less from the normal The values reported by O'Sullivan and Wade [12] and Wade [13] agree with theory, but their method of computation tends to give high values, because all of their measurements were made at angles at which no appreciable deviation from the cosine law would be expected.

7. Summary and Conclusions

The total hemispherical emittance of Inconel and types 321 and 430 stainless steel specimens in six different surface finishes was evaluated by a modification of the hot-filament method. The six surface finishes were (1) polished, (2) polished and then oxidized, (3) sandblasted, (4) sandblasted and then oxidized, (5) coated with A–418, and (6) coated with N–143. The findings may be summarized briefly as follows:

(1) For the three alloys studied, the surface condition of the metal had much more effect on the total hemispherical emittance of the unoxidized and uncoated specimen than did the composition of the alloys. Each of the polished specimens had total hemispherical emittance in the range 0.20 to 0.28, and the emittance increased with an increase in temperature. Each of the sandblasted specimens had total hemispherical emittance in the range 0.50 to 0.65 and again the emittance increased with an increase in temperature.

(2) Oxidation in air at 1,000 °C greatly increased the total hemispherical emittance of each uncoated specimen tested, and the emittance increased with time of oxidation for at least several hours. The total hemispherical emittance of the oxidized specimens increased with an increase in temperature.

(3) All ceramic-coated specimens evaluated had relatively high total hemispherical emittance at low temperatures, and the emittance decreased with an increase in temperature. The coatings were not opaque, as indicated by the fact that the composition of the substrate metal affected the total hemispherical emittance of the composite specimens. The ceramic-coated specimens of Inconel had the highest total hemispherical emittance and the ceramic-coated type 430 stainless steel specimens had the lowest emittance in each case.

(4) The total hemispherical emittance of Inconel and type 430 stainless steel specimens coated with A–418 was higher than that of similar specimens coated with N–143.

(5) The total hemispherical emittance of sandblasted specimens of all three alloys decreased markedly on heating in vacuum at temperatures above 900 °C, even for the short times required to complete the evaluations. No appreciable changes were noted in the emittance of polished, oxidized or ceramic-coated specimens as a result of heating in vacuum for the times required to complete the evaluations, even at temperatures up to 1,000 °C, except for one specimen of Inconel coated with N–143, that showed a slight increase in emittance on heat in vacuum to 1,015 °C.

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