

# EMISSIVITY OF POWDER BEDS

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## Abstract

A simple model for estimating the emissivity of the surface of a powder bed from knowledge only of the bed porosity and solid emissivity is presented. Estimates by this model are compared with experimental measurements for powder beds of alumina, silicon carbide, and iron. Agreement within the uncertainty of the measurements,  $\pm 10\%$ , is obtained.

## Introduction

Thermal models for the Selective Laser Sintering (SLS) process have been developed that can predict the sintering depth as a function of the energy received by the surface (1,2). The Energy Density, given by

$$\text{Energy Density} = \frac{P}{V * SCSP} \quad (1)$$

has been found useful for correlating sintering depth to SLS operating parameters such as laser beam power,  $P$ , beam scan velocity,  $V$ , and scan spacing,  $SCSP$ , for a particular powder that is processed in a particular geometry (2,3). Equation (1) can not, however, be relied upon to predict the behavior of a new powder bed, nor can it predict fusion depth when the scan length is greatly altered. One of the reasons for this behavior is the use of beam power,  $P$ , instead of "power received",  $P'$ , as heat by the powder bed.  $P'$  is related to  $P$  via,

$$P' = \alpha P - \varepsilon \sigma (T_s^4 - T_a^4) \quad (2)$$

Its use requires knowledge of the emissivity,  $\varepsilon$ , and absorptivity,  $\alpha$ , of the powder bed, as well as the surface and ambient temperatures,  $T_s$  and  $T_a$ , respectively, and is obviously more complex to implement. Part of this problem can be solved by the emissivity model presented and verified below.

## Predictive Model

We begin with the usual assumption that most bodies are considered to be "gray" with no transmission of radiation. This leads to the assumption that  $\alpha = \varepsilon$ . The emission of radiation to ambient from a hot porous surface, such as the powder bed, can be assumed

to be caused by emission from the heated particles and emission from the cavities in the powder bed, all at the same temperature. Although the walls of the cavities are made by the same particles, the emissivity of the hole is a function of its geometry, particularly the fraction,  $f$ , of total cavity surface that is cut away by the emitting hole (4,5),

$$\varepsilon_H = \frac{\varepsilon_s}{\varepsilon_s + f(1 - \varepsilon_s)} \quad (3)$$

where  $\varepsilon_s$  is the emissivity of the solid particle and  $\varepsilon_H$  is that of the hole. Equation (3) suggests that the hole emissivity is always higher than that of the material comprising the cavity and may even approach 1.0, the emissivity of a black body radiator, as  $f$  becomes small. Consequently, we expect that emissivity of the powder to be somewhat higher than that of the solid, and to follow the expression,

$$\varepsilon = A_H \varepsilon_H + (1 - A_H) \varepsilon_s \quad (4)$$

where  $A_H$  is the area fraction of the surface that is occupied by the radiation emitting holes. This expectation is experimentally met, see below.

The general problem remains to describe the parameters  $A_H$  and  $f$  in Equation (4) for a powder bed. German (6) provides a relationship that describes the mean pore diameter,  $d$ , as a function of the particle size,  $D$ , and the fractional packing density,  $\rho$ , for a powder bed comprised of randomly packed, single-sized spheres,

$$d = \frac{2}{3} \frac{D(1 - \rho)}{\rho} \quad \text{or} \\ d = \frac{2}{3} \frac{D\varphi}{1 - \varphi} \quad (5)$$

where  $\varphi$  is the fractional porosity of the bed, and  $\varphi = 1 - \rho$ . German (7) also estimates that there are approximately 2.92 pores per sphere in the randomly packed bed. The surface of the randomly packed bed should have  $(2.92)^{2/3}$  or 2.043 pores per sphere in the plane.

The area fraction,  $A_H$ , occupied by the pores is then,

$$A_H = \frac{2.043 \frac{\pi d^2}{4}}{2.043 \frac{\pi d^2}{4} + \frac{\pi D^2}{4}} \quad (6)$$

Substitution of Equation (5) into Equation (6) yields,

$$A_H = \frac{0.908 \varphi^2}{1.908 \varphi^2 - 2\varphi + 1} \quad (7)$$

We estimate  $f$  by considering each pore to be a cylinder of length,  $L$ , so that

$$f = \frac{\pi \frac{d^2}{4}}{2\pi \frac{d^2}{4} + \pi d L} = \frac{1}{2 + \frac{4L}{d}} \quad (8)$$

The Length,  $L$ , can be determined from the definition of porosity,  $\varphi$ ,

$$\varphi = \frac{2.92 \frac{\pi}{4} d^2 L}{2.92 \frac{\pi}{4} d^2 L + \frac{1}{6} \pi D^3} \quad (9)$$

by transposing and substituting Equation (5) to yield,

$$L = 0.514 D \frac{1 - \varphi}{\varphi} \quad (10)$$

Substitution of Equations (10) and (5) into Equation (8) yields,

$$f = \frac{\left(\frac{\varphi}{1 - \varphi}\right)^2}{2\left(\frac{\varphi}{1 - \varphi}\right)^2 + 3.082} \quad (11)$$

and substitution of Equation (11) into Equation (3) leads to,

$$\varepsilon_H = \frac{\varepsilon_s \left[ 2 + 3.082 \left(\frac{1 - \varphi}{\varphi}\right)^2 \right]}{\varepsilon_s \left[ 1 + 3.082 \left(\frac{1 - \varphi}{\varphi}\right)^2 \right] + 1} \quad (12)$$

Equation (12) suggests that the emissivity of the hole is independent of particle diameter and a function only of solid emissivity and the bed porosity. As shown in Figure 1, the calculated emissivity of the hole decreases slightly as the bed porosity increases and also increases as the emissivity of the solid increases. The first trend occurs because  $f$  increases with increasing porosity, see Equation (11), causing the hole to become a less perfect radiator. The second trend simply notes the importance of the solid emissivity in determining the emissivity of the powder bed.

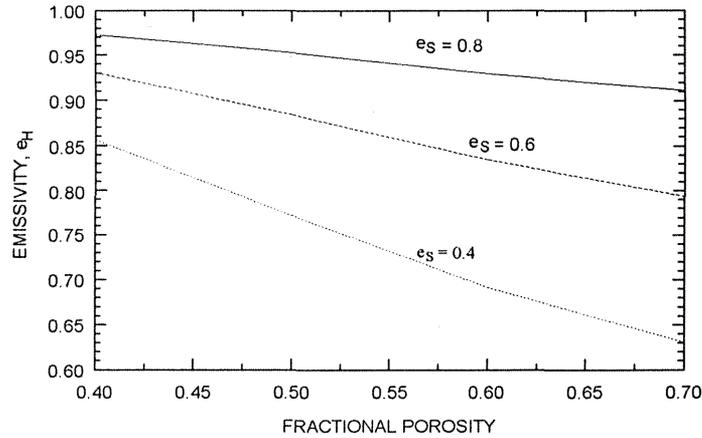


Figure 1. Calculated Hole Emissivity

### Comparison with Experimental Measurements

Experimental emissivities were obtained for three refractory powders, 15  $\mu\text{m}$  Alumina (Norton), 7  $\mu\text{m}$  Silicon Carbide (Norton/Lanxide), 4.6  $\mu\text{m}$  Silicon Carbide (Norton/Lanxide), and  $<45$   $\mu\text{m}$  Iron (Hoeganaes). These materials have measured bulk densities of 1.94, 1.54, 1.06, and 3.44  $\text{g}/\text{cm}^3$ , respectively, with corresponding fractional porosities of 0.512, 0.521, 0.670, and 0.563.

The experimental apparatus has been described previously (8) and is shown schematically in Figure 2. The powder is contained in a thermally-guarded tube that heats the bed to the desired experimental temperature. The powder is then to  $\text{CO}_2$  laser radiation at its top surface.

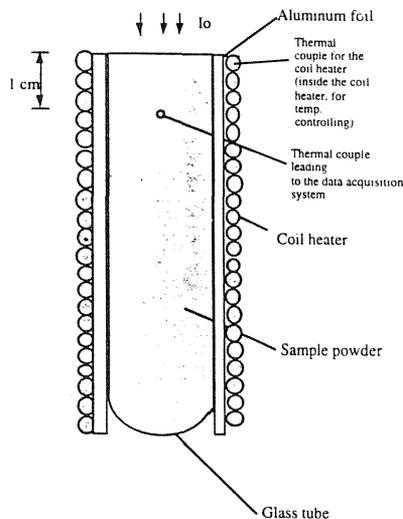


Figure 2. Schematic of Apparatus

A thermocouple is mounted 1 cm below the surface to record the temperature. Per experimental bed temperature, the temperature rise is limited to less than 10°C to permit thermal analysis that is based on constant thermal properties. Surface absorbance,  $\alpha$ , assumed to be equal to surface emissivity,  $\epsilon$ , is measured by noting differences in the thermal rise behavior of the powder bed between exposure, at the same laser power, of the natural surface and the same powder surface covered with a thin layer of carbon black powder, assumed to have  $\epsilon_R = \alpha_R = 1.0$ . The thermal rise rate is measured in the linear region of the thermal rise curve in both measurements, and the bed heat capacity is assumed constant. Consequently, the governing equation is

$$\epsilon = \epsilon_R \frac{(dT/dt)}{(dT/dt)_R} \quad (13)$$

Errors in this method are primarily those associated with determining the rise rates. We estimate relative errors in the range of  $\pm 10\%$ .

Comparison between Equation (5) and experiment is shown in Figures 3-6 for the materials tested. Generally, agreement lies within the experimental error band for all cases studied. The model depends strongly on the emissivity of the solid, and generally this is a function of temperature that must be selected with some care from other sources. The references to solid emissivities employed in this study are (9) for alumina and silicon carbide and (10) for iron (wrought).

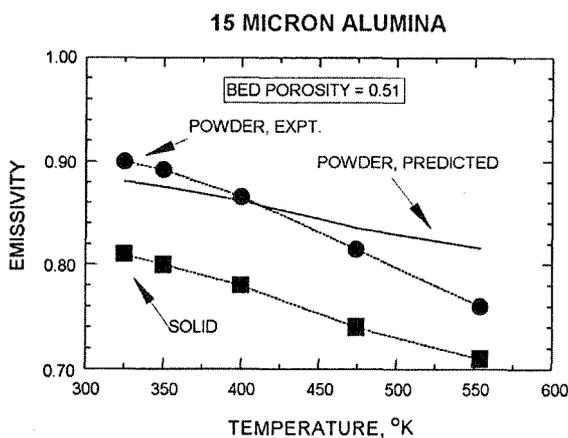


Figure 3. Comparison of Predicted and Measured Emissivity for 15  $\mu\text{m}$  Alumina.

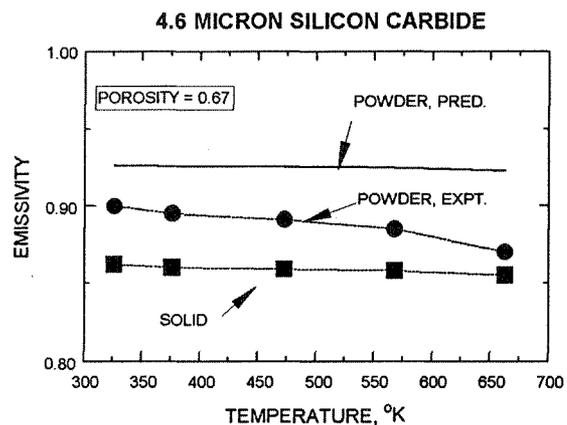


Figure 4. Comparison of Predicted and Measured Emissivity for 4.6  $\mu\text{m}$  Silicon Carbide

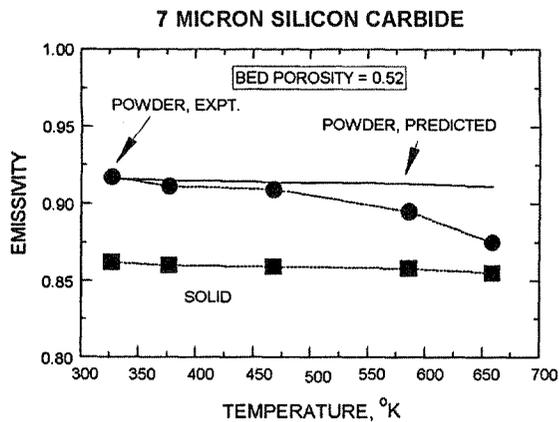


Figure 5. Comparison of Predicted and Measured Emissivity for 7  $\mu\text{m}$  Silicon Carbide.

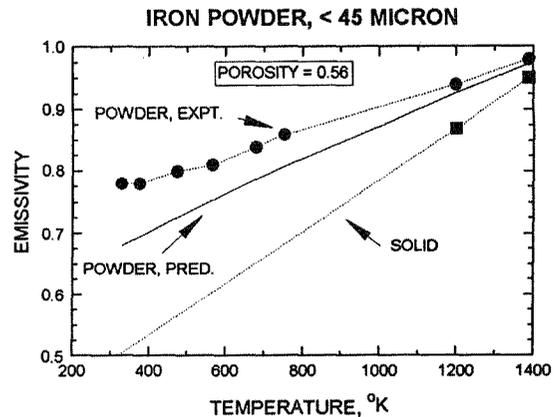


Figure 6. Comparison of Predicted and Measured Emissivity for Iron Powder.

## Conclusions

The simple model for calculating the emissivity of a powder bed, presented here, seems to do an adequate job of predicting the effects of the emissivity of the solid and of the bed porosity. Obviously, more testing is necessary to prove the relationships presented, however these initial comparisons with experiment suggest that the model should provide good estimates that are accurate to within 10% by the proper consideration of just two parameters, the solid emissivity and the bed porosity. These relationships should prove useful for better understanding and controlling SLS operating parameters.

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