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NATIONAL BUREAU OF STANDARDS REPORT

3483

ANALYSIS OF TOOL HEATING PROBLEM

By

William F. Roeser

To

Materials Division
Structures Research Department
U. S. Naval Civil Engineering Research & Development Laboratory
Construction Battalion Center
Port Hueneme, California

NBS

U. S. DEPARTMENT OF COMMERCE
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1. INTRODUCTION

Our ideas of hotness and coldness are fundamentally derived from our sensations; and though, in some instances, we may have cause to distrust the information which we obtain through these channels, it does not follow that we should, even were it possible, discard entirely these foundations for our knowledge of the phenomena connected with the tool heating problem. For example, if various objects in a room are touched successively, it will be found that the metal objects feel cooler than the other objects, even though they are all at essentially the same temperature. The reason for this is that the sense of touch does not inform us directly of the temperature of an object, but of the rate at which an area of our skin gains or loses heat. Thus to control the hotness or coldness of metallic objects we must seek means of controlling the rate of heat exchange between the object and the sensitive portion of the skin.

Although we are not able to give an exact solution because of uncertainties in effects due to callous skin, perspiration, contact pressure, etc., we can give some of the more important factors that govern the rate of heat transfer.

2. TOOLS WITH SOLID HANDLES OF ONE MATERIAL

Assume that we have two semi-infinite solids A and B at uniform temperatures T_A and T_B, respectively. Let C_A, P_A, and K_A be the heat capacity per unit mass, the density, and the thermal conductivity, respectively, of material A; and C_B, P_B, and K_B be the values for the corresponding properties of material B. (Any set of units may be used, provided they are consistent.)

It can be shown mathematically that, if these two bodies are suddenly brought into intimate thermal contact, the temperature (T_S) of the interface is given by

$$T_S = \frac{T_B\sqrt{C_B \; P_B \; K_B} + T_A\sqrt{C_A \; P_A \; K_A}}{\sqrt{C_B \; P_B \; K_B} + \sqrt{C_A \; P_A \; K_A}} \qquad (1)$$

$$= T_B + \frac{(T_A - T_B)\sqrt{C_A \; P_A \; K_A}}{\sqrt{C_B \; P_B \; K_B} + \sqrt{C_A \; P_A \; K_A}}$$

It should be noted that the temperature of the interface is independent of time.

The above problem is given in Section 42 of "Modern Operational Mathematics in Engineering" by R. V. Churchill.

In the handling of implements, we are concerned with a material of finite size and the human hand. It is true that neither of these is a semi-infinite solid, but for short periods of time they may be considered

as such. Thus, if an implement with a handle of material A at a uniform temperature T_A is firmly gripped by the hand (material B), the temperature of the surface of the skin will come to a temperature T_S.

The rate of heat transfer from the surface of the skin to the temperature and pain receptors below the skin should be very closely proportional to $(T_S - T_B)$.

A few simple experiments were made to determine if the above relationship held, approximately, for the gripping of implements of different materials with the hand. The implements were heated in an oven to various temperatures, and the maximum temperatures at which two observers agreed that they could handle them without undue discomfort were established. These values are given in the second column of the following table. The third column gives approximate values of the ratio

$$\frac{\sqrt{C_A \quad P_A \quad K_A}}{\sqrt{C_B \, P_B \, K_B} + \sqrt{C_A \, P_A \, K_A}} = R$$

for the different materials and the fourth column gives the calculated values of the skin temperature.

Material	T_A °F	R.	Skin Temp. °F
Carbon Steel	119	0.89	116.8
Plastic (Used for tool handles)	158	0.30	116.4
" " " " "	160	0.29	116.4
Hardwood (sp.gr. = 0.82)	169	0.24	115.5
Softwood (sp.gr. = 0.5)	183	0.16	112.1
	Considered average		116.

In the above calculations, T_B was taken as 98.6°F, and the values of C_B, P_B, and K_B for the body were taken to be the same as those of water.

Even though the temperatures of the implement handles ranged from 119° to 183°F, the temperature of the skin came to approximately the same value in each instance, indicating that the rate of heat transfer was nearly the same in each case.

According to the above relationship, the human tongue should stick to steel at any temperature below 23.8°F.

Equation (1) can be rearranged to read

$$T_A = T_S + \frac{(T_S - T_B)\sqrt{C_B\ P_B\ K_B}}{\sqrt{C_A\ P_A\ K_A}} \qquad (2)$$

Substituting for T_S, 116°, the maximum temperature of the surface of the skin that can be tolerated and for T_B, C_B, P_B, and K_B, the values for the body, we have

$$T_A = 116 + \frac{0.66}{\sqrt{C_A\ P_A\ K_A}} \qquad (3)$$

where T_A is in °F and C_A, P_A, and K_A are in Cal, Cm, Gram, °C and Sec units.

This equation gives the maximum temperature, T_A, at which an implement can be handled in terms of C_A, P_A, and K_A.

Even though the above relationship is based upon the assumption that the two bodies considered are semi-infinite solids (which they are not), and even though no account was taken of the amount of moisture or

callousness of the hands, it gives a basis for the selection of materials which we believe to be in general agreement with experience.

3. TOOLS WITH COATED HANDLES

With different thicknesses of clear coatings of Plastisol R-2101 (a vinyl chloride) on steel rods, we found that the maximum temperature at which the coated rods could be handled varied with the thickness as shown in Figure 1. Apparently a 1/16-inch coating was just as effective as one of infinite thickness.

We can now set up the following relationship for steady-state heat transfer

$$q/a = \frac{K\,(T - T_s)}{D} = \frac{K_A\,(T_A - T_s)}{D_A} \qquad (4)$$

where q/a is the heat transfer per unit area from a steel rod, through a coating, and to the skin, K and K_A are the thermal conductivities of the plastisol used and of any similar material that might be used, respectively, and D and D_A are the corresponding minimum thicknesses of coating that will permit the implement to be handled at the maximum tolerable temperatures of T and T_A, respectively. Substituting the known values for K, T, T_s, and D in equation (4), we have

$$\frac{0.11\, D_A \text{ (in cm)}}{K_A} = (T_A - T_s) \qquad (5)$$

From equation (3) $$T_A - T_s = \frac{0.66}{\sqrt{C_A\, P_A\, K_A}} \qquad (6)$$

$\frac{1}{2}$" STEEL RODS COATED WITH PLASTI~~C~~SOL R-2101

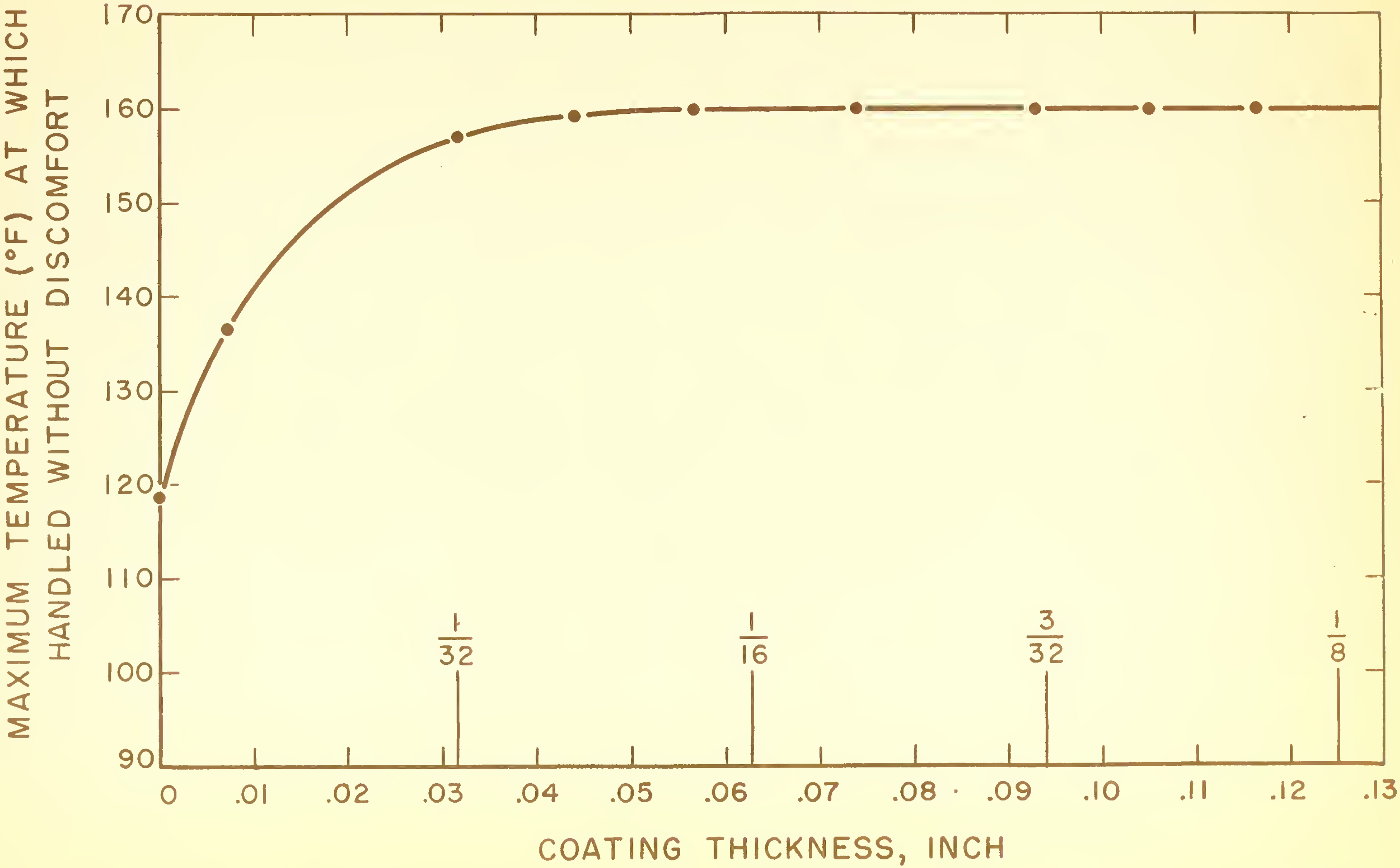

FIG. 1

Eliminating $(T_A - T_s)$ and collecting terms, we have

$$D_A \text{ (in cm)} = 6.0 \sqrt{\frac{K_A}{C_A \, P_A}} \qquad (7)$$

$$D_A \text{ (in inches)} = 2.36 \sqrt{\frac{K_A}{C_A \, P_A}} \qquad (8)$$

(C_A, P_A, & K_A in Cal., Cm, G, ^oC, Sec)

It is seen from equations (6) and (8) that any reduction in the values of C_A and P_A of the coating material will increase both the maximum temperature at which the implement can be handled and the minimum thickness necessary to permit the implement to be handled at the maximum temperature. As an example, if K_A is maintained constant and the product, $C_A \, P_A$, reduced by a factor of 4, both $(T_A - T_s)$ and D_A are increased by a factor of 2. Any reduction in the value of K_A will increase the maximum temperature at which the implement can be handled and will decrease the minimum thickness of the coating necessary to permit the implement to be handled at the maximum temperature. As an example, if C_A and P_A are maintained constant and K_A reduced by a factor of 4, $(T_A - T_s)$ is increased by a factor of 2 and D_A is decreased by a factor of 2. All this means is that the rate of heat transfer through the coating (q/a in equation 4) has been maintained constant.

The maximum temperature, 160^{o}F, at which we could handle the plastics used in our experiments is so near the temperatures that tool handles might

attain when exposed to the sun that consideration should be given to any means of reducing their temperature. In some experiments which we made in the period June 22, to July 1, 1954, 1/2-inch steel rods coated with 1/16 inch of plastic and painted black attained a temperature of 60°F above the ambient, 90°F, when exposed to the sun. Under the same conditions, similar specimens painted white attained a temperature of 42.5°F above the ambient, while those without any paint attained a temperature of 57.5°F above the ambient.

The maximum temperature rise attained by any of the specimens was that of the one with a plastic coating painted black. If we express this temperature rise as 100 per cent, the following table gives the corresponding increase in temperature of other specimens exposed under similar conditions. All the temperatures measured were that of 1/2-inch steel rods to which the coatings were applied.

Coating	Relative Temperature Rise Above Ambient, Expressed in Per Cent
1/16 in. plastic, painted black	100
No plastic, painted black	97.5
1/16 in. clear plastic, no paint	96
None, cleaned	95
1/16 in. plastic, painted white	71
No plastic, painted white	69

From these data, it would appear advisable to consider adding a white filler to the plastic. This would not only aid in keeping the handle cooler, but also should reduce the cost of the plastic coating as well as making it more stable. We believe that the use of metallic powders as a filler should be avoided, since these would probably increase the conductivity of the coating material and would not aid in keeping the handle cool.

In the selection of a plastic with the desired thermal characteristics, such properties as the resistance to abrasion, greases, cleaning solvents, etc., should not be overlooked.

If any use is made of the above analysis, it is hoped that the limitations of the mathematical analysis due to assumptions involved and of the results based upon only a few simple experiments, are borne in mind. If they are not, someone might get his fingers burnt, literally.

THE NATIONAL BUREAU OF STANDARDS

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The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

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Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.00). Information on calibration services and fees can be found in NBS Circular 483, Testing by the National Bureau of Standards (25 cents). Both are available from the Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

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