Thermal Diffusivity of Stainless Steel from 20° to 1000° C.

R. J. JENKINS and R. W. WESTOVER
U. S. Naval Radiological Defense Laboratory, San Francisco 24, Calif.

INCREASED applications where materials are exposed to high temperatures for a time so short that thermal equilibrium is not attained has led to a considerable interest in thermal diffusivity measurements. The stainless steels are among the most useful structural materials for temperatures up to 1000° C., but little data are available on their thermal diffusivities over this temperature range. A series of such measurements on several types of stainless steel is reported here.

Data on these steels were obtained using a method developed at NRDL and described in detail (*3*). Briefly, this method consists of irradiating the front surface of a sample with a very short pulse of thermal energy and measuring the resultant back surface temperature history on a recording device with a suitably rapid response rate.

In the ideal case of a perfectly insulated sample uniformly irradiated with a pulse of thermal energy which is short compared with the time required for heat to flow through the sample, the back surface temperature history is given by

$$\frac{T(L,t)}{T_m} = 1 + 2\sum_{n=1}^{\infty}(-1)^n \exp(-n^2\pi^2\alpha t/L^2) \qquad (1)$$

In the equation $T(L,t)$ represents the instantaneous back surface temperature rise at time t, T_m is the maximum back surface temperature rise, α is the thermal diffusivity, L is the sample thickness, and n takes, successively, the values 1, 2, 3, ... At the time $t_{1/2}$ where $T(L,t) = 0.5T_m$ this equation reduces to

$$\alpha = \frac{1.38L^2}{\pi^2 t_{1/2}} \qquad (2)$$

and the thermal diffusivity can be determined from the sample thickness and the time required for the back surface temperature to rise to one half its final value.

EXPERIMENTAL

The steels tested were all provided by the Crucible Steel Co. of America, and are listed by number in Table I, along with their approximate composition. These compositions (*2*) were taken without further analysis. With the exception of No. 416 stainless steel all samples were cut from No. 2 finish, cold rolled sheet and were used without further surface preparation. No. 416 sample was cut from a ½-inch diameter rod and had surfaces polished on a metal polishing lap. All the samples were one-half inch in diameter.

The furnace used to heat the specimens consisted of Kanthal resistance wire wound on a ceramic core, mounted in a stainless steel shield inside a double-walled stainless steel housing. A flat water-cooled end supported a removable 3-inch diameter round quartz window. The samples were held by the core with the front sample face parallel to and as close as practical to the window. To minimize oxidation of the samples, argon gas from an inlet tube flowed over the sample, through the ceramic core, and out of the housing through a small hole in the rear of the furnace. Ordinary tank argon was used without purification and some darkening of the samples occurred, presumably from traces of oxygen in the argon. This darkening did not affect the measurements since the calculations do not depend on a knowledge of the energy absorbed by the sample.

The thermocouple measuring both the sample back surface temperature rise and the sample temperature came into the furnace housing through the argon exhaust hole, passed through a small hole in the center of the ceramic furnace core, and was pressed against the back of the sample under slight spring pressure. The thermocouple was a Chromel-Alumel couple, of No. 20 B and S gage wires, insulated with small ceramic tubes and sharpened to a point. The thermocouple wires were separated by about

Table I. Composition of Stainless Steel Specimens[a]

AISI No.[b]	Thickness, Cm.	Structure	Cr	Ni	Mn	C	P	S	Other
202	0.065	Austenitic	17/9	4/6	7.5/10	0.15[c]	0.06[c]	0.06[c]	N-0.25[c]
301	0.097	Austenitic	16/18	6/8	2[c]	0.15[c]	0.045[c]	0.03[c]	
302	0.096	Austenitic	17/19	8/10	2[c]	0.15[c]	0.045[c]	0.03[c]	
304	0.080	Austenitic	18/20	8/12	2[c]	0.08[c]	0.045[c]	0.03[c]	
309	0.198	Austenitic	22/24	12/15	2[c]	0.20[c]	0.045[c]	0.03[c]	
316	0.136	Austenitic	16/18	10/14	2[c]	0.1[c]	0.045[c]	0.03[c]	Mo-2/3
321	0.082	Austenitic	17/19	9/12	2[c]	0.08[c]	0.045[c]	0.03[c]	Ti-0.4[d]
347	0.114	Austenitic	17/19	9/12	2[c]	0.08[c]	0.04[c]	0.03[c]	Nb-0.8[d]
410	0.065	Martensitic	11.5/13.5	...	1[c]	0.15[c]	0.04[c]	0.03[c]	Mo-0.6
416	0.177	Martensitic	12/14	...	1.25[c]	0.15[c]	0.06[c]	0.15	Mo-0.6 Zr-0.6
430	0.089	Martensitic	14/18	...	1[c]	0.12	0.04[c]	0.03[c]	
446	0.178	Martensitic	23/27	...	1.5[c]	0.2	0.04[c]	0.03[c]	N-0.25

[a] All numbers are percentage values. All steels also contained up to 1% silicon. All samples except No. 416 cut from No. 2 finish cold-rolled sheet steel of thickness indicated. No. 416 cut from 1.27 cm. diameter rod. Composition values (*2*). [b] Am. Iron and Steel Inst. [c] Maximum value. [d] Minimum.

2 mm. where the points touched the sample, so that the electrical measuring circuit included part of the sample. With a homogeneous sample and essentially no temperature gradients between the two wires, this method of mounting the thermocouple insured that the temperature measured was actually that of the back sample surface. The thermocouple wires were brought out to an air-cooled connection block, mounted off the rear surface of the furnace housing, which served as a cold junction.

Shielded leads connected the cold junctions to a switch box, where the thermocouple output could be switched to a microammeter calibrated in ° C. for a Chromel-Alumel couple or to a preamplifier-oscilloscope combination for measuring the back surface temperature rise. The oscilloscope traces were photographed by a standard oscilloscope camera with a Polaroid-Land back. The time required for the thermocouple to reach half its maximum voltage was determined from the photograph. The oscilloscope was carefully calibrated both as to the accuracy and linearity of the internal time base and the linearity of the vertical amplifiers.

The thermal pulses were supplied by a General Electric Type 524 xenon flash tube which was mounted as close as possible to the quartz window. The lamp, cooled by a blower, dissipated 700 joules of energy in slightly under 600 μsec. This flash time was sufficiently short compared to the back surface temperature rise time ($t_{1/2}$ = 20,000 μsec. in the shortest case) that the conditions of Equation 1 were met. Only a small portion of the 700 joules dissipated actually reached the sample. In most cases, the final back surface temperature rise was approximately 1° C. corresponding to an output signal of about 40 μv., which was too low for any of the oscilloscopes available. The commercial amplifiers available proved unsatisfactory as preamplifiers because of excessive noise in their outputs, so that a two-stage, transistorized, battery-operated differential preamplifier with a maximum gain of 350 was designed and built. The pass band was from DC to 1000 cp. with the upper end deliberately limited to the lowest frequency that would pass the signal without distortion to minimize noise. Pickup noise from the thermocouple leads made the differential feature necessary. The 40 μv. signal from the thermocouple was superimposed on a steady state level as high as 40,000 μv. at the higher temperature ranges. This steady state level was canceled out by a low impedance bucking circuit before the signal went to the preamplifier. The bucking circuit was automatically disconnected when the thermocouple was switched to the microammeter. A pictorial schematic of the entire apparatus is shown in Figure 1.

RESULTS AND CONCLUSIONS

The results for 12 specimens, cut from the various types of steel and subjected to a minimum of working, are presented in graphs. The No. 2 finish on most specimens was very smooth, but not a mirror finish. The samples were not subjected to any type of heating before the test runs.

Precisions of the method is estimated at ±5%. For maximum accuracy the sample dimensions and the design of the sample holder were chosen to minimize the deviations from the boundary conditions required for Equation 1. This method has been shown (*3*) to give results within 10% of other available published data for the pure metals and a number of alloys. Furthermore, a corresponding variation exists in the data of these other sources. Because of these limits to the precision, only one curve is drawn through the points for both the increasing and decreasing temperatures for all the curves except those for Types 202 and 430 steel, although it is quite probable that some of the scatter represents an actual change in the structure of the steel as it is heat treated after being cold worked during the rolling of the sheets.

There is a clear difference in the behavior of the thermal diffusivities of the austenitic (Types 202, 301, 302, 304, 309, 321, and 347) and the martensitic (Types 410, 416, 430, and 446) steels as the metals are heated. The decrease in diffusivity to a minimum at about 700° C. for the latter types is similar to that reported previously for a low carbon steel and two alloy steels and is near the curie point (*1*). The nonmagnetic 200 and 300 series stainless steels do not exhibit this abrupt minimum. The heavy alloying of the stainless steels considerably reduces the room temperature thermal diffusivity below that of the pure iron (0.19 cm.^{2}/

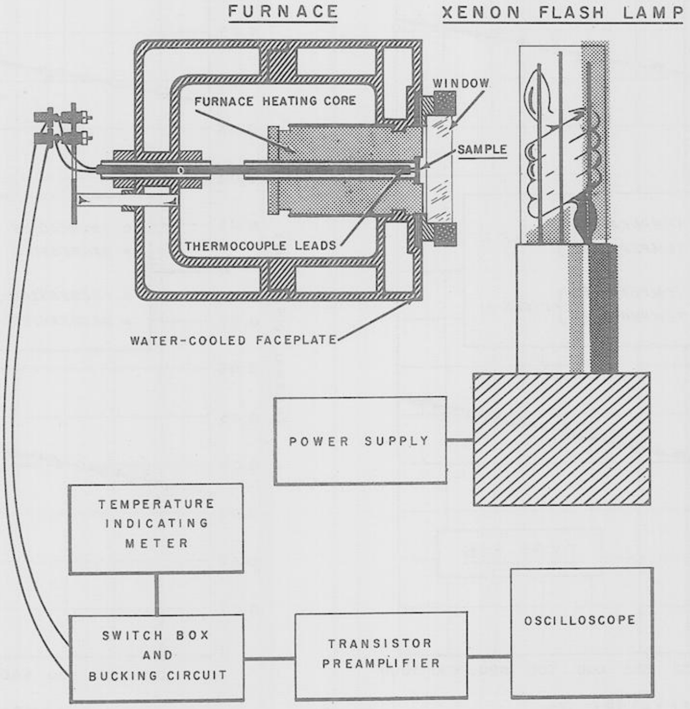
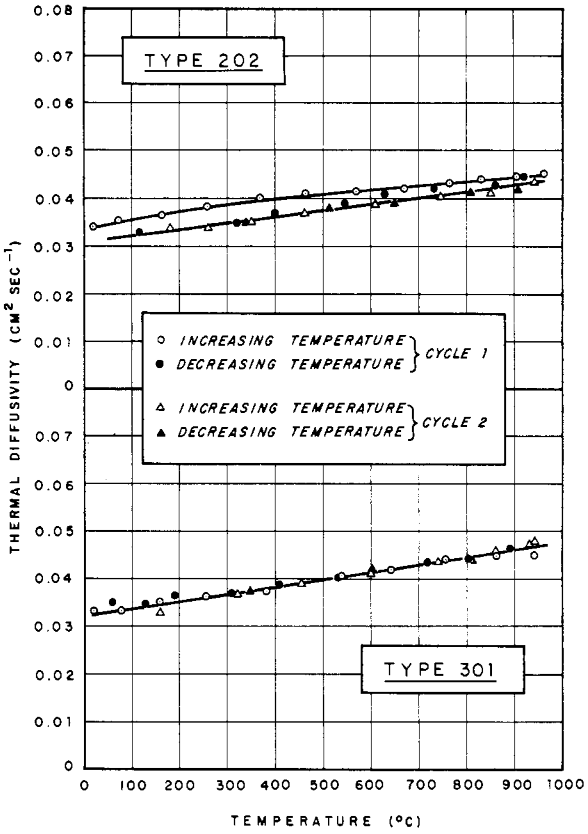
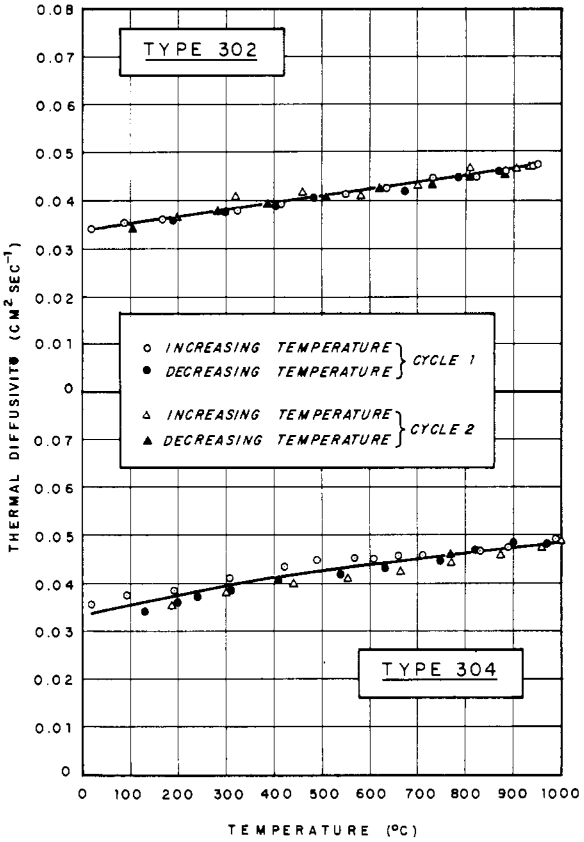
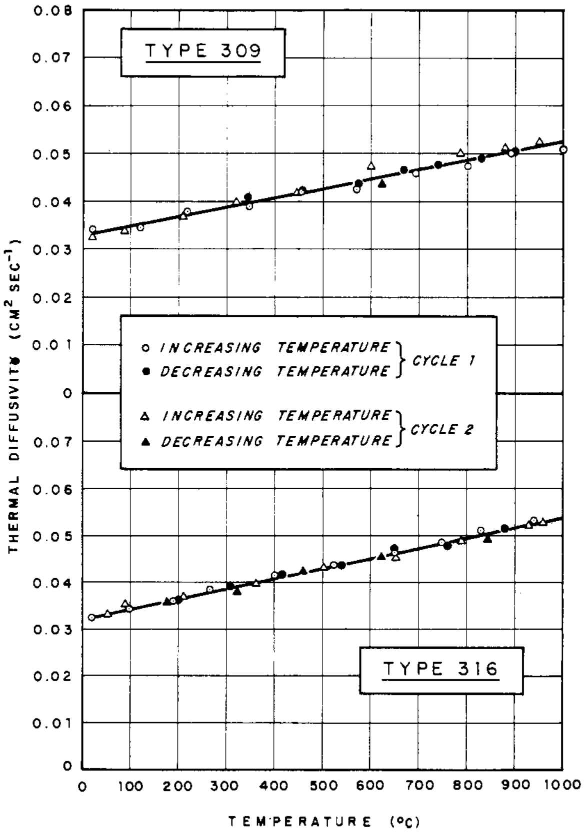


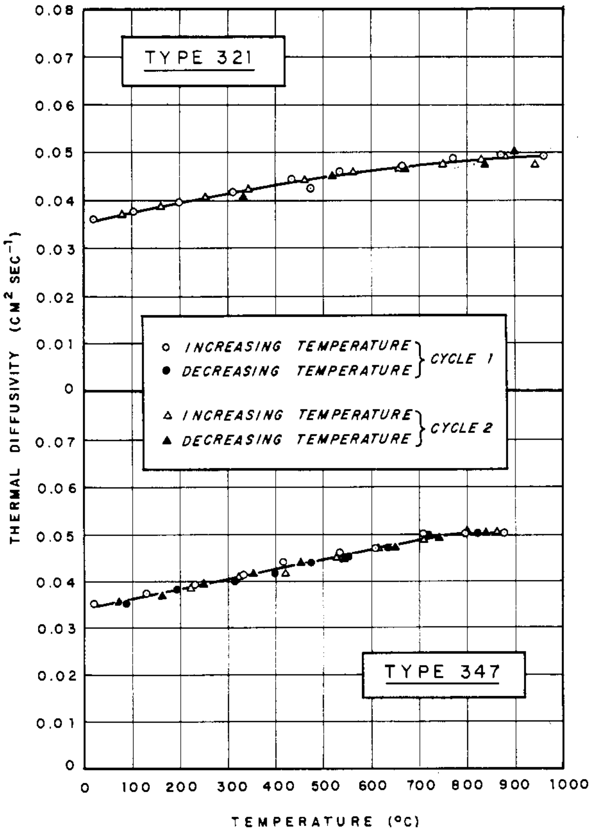
Figure 1. Diagram of test setup

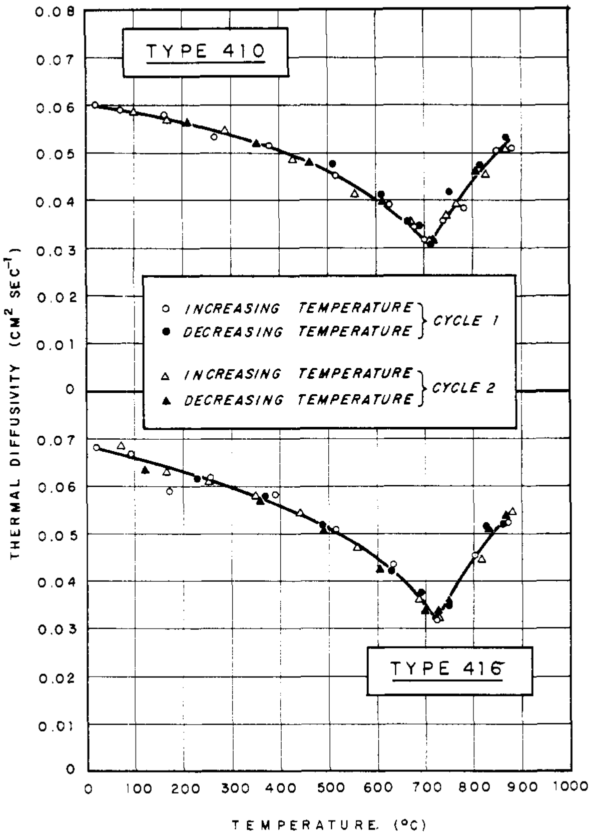
Thermal Diffusivity of Austenitic Stainless Steel Types

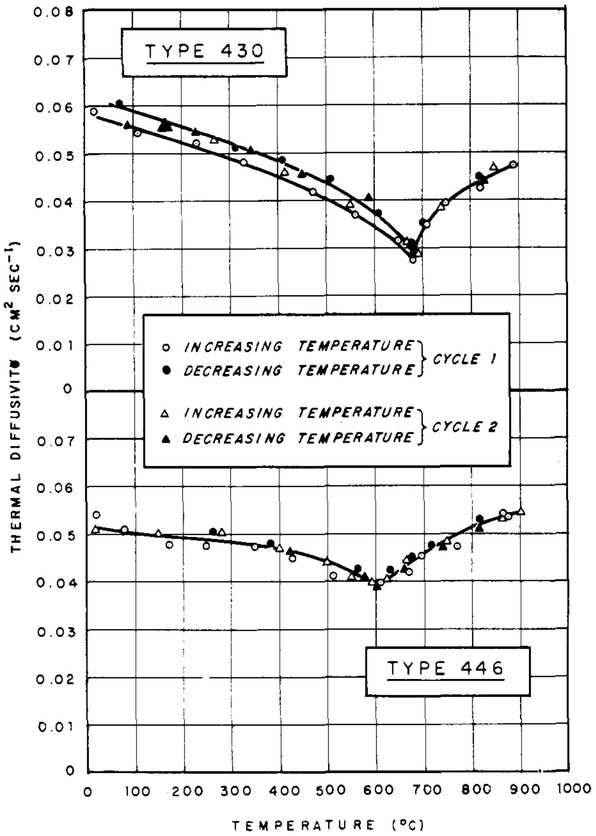












sec.) or low carbon steel (0.16 cm.^{2}/sec.) although this difference decreases as the temperature increases and becomes very small near 700° C.

Points recorded for the measurements were very stable and did not change with time. Samples of both Type 410 and 430 steel were held at 400°, 600°, 700°, and 750° C. on both increasing and decreasing temperatures for several hours, each with no change in the thermal diffusivity greater than the experimental error. Since 3 to 10 minutes were required to change the temperature of the furnace 100° C., nothing can be said about the very short time changes. There were no large differences in the curves on successive heating cycles, nor did the direction of temperature change appear to make much difference in the diffusivity at a specific temperature. In steel Types 202 and 430, however, there was enough difference between the curves obtained on the first heating and the curves obtained on the following coolings and heatings to warrent drawing a separate curve for the increasing temperature part of the first heating cycle.

LITERATURE CITED

(1) Butler, C.P., Inn, E.C.Y., "Thermal Diffusivity of Metals at Elevated Temperatures," Thermodynamic and Transport Properties of Gases, Liquids, and solids, Am. Soc. Mech. Engrs., 29 W. 39th St., New York.

(2) Crucible Steel Co. of America, *Crucible Data Book*, Oliver Building, Mellon Square, Pittsburgh, Pa.

(3) Parker, W.J., Jenkins, R.J., Butler, C.P., Abbott, G.L., *J. Appl. Phys.* **32**, 1679 (1961).

RECEIVED for review November 27, 1961. Accepted March 19, 1962. Research sponsored by the Aeronautical Systems Division of the Air Research and Development Command, U. S. Air Force, under contract.

CORRECTION

The article, "Density and Viscosity of Anhydrous Hydrazine at Elevated Temperatures," by R.C. Ahlert, G.L. Bauerle, and J.V. Lecce [J. CHEM. ENG. DATA **7**, 158 (1962)], should be changed as follows:

On page 159, Equation 2, the first quantity after the equal sign should read

$$\rho = 1.2474 - 0.07226\,(T/100) - 0.003191\,(T/100)^2$$
