TABLE 2 COMPOSITION OF TITANIUM ALLOYS

Alloy	H	C	N	O	Fe	Cr	Mn	Mo	Ti
Ti 75A (2)	0.0068	0.06	0.048	0.131	0.07	..	..	..	99.75
Ti 130A	0.0069	0.05	0.034	0.177	0.20	..	6.50	..	93.21
Ti 150A (2)	0.0092	0.05	0.076	0.105	1.40	2.71	..	..	95.65
Rc-55	0.0073	0.08	0.028	0.123	0.12	..	..	..	99.64
Cr-Mo	0.0077	0.02	0.032	0.131	0.13	3.38	..	2.10	96.30

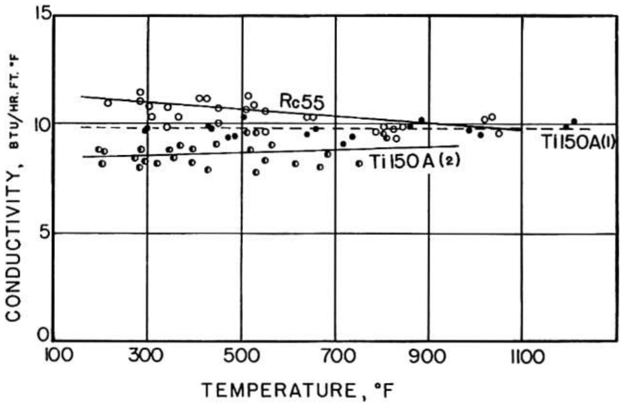

FIG. 5 THERMAL CONDUCTIVITY OF TI 75A, TI 130A, AND CR-MO TITANIUM ALLOYS

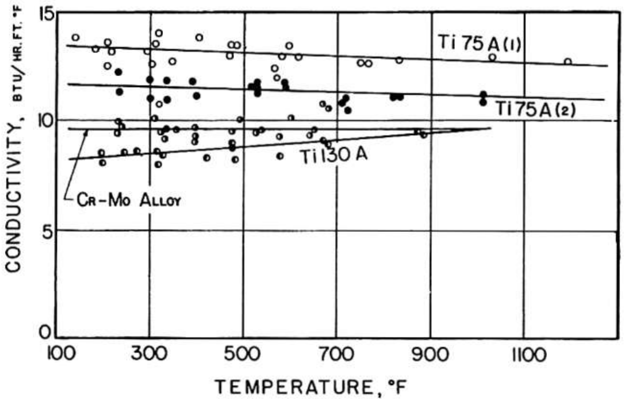

FIG. 6 THERMAL CONDUCTIVITY OF TI 150A AND RC 55 TITANIUM ALLOYS

The specific heat (C_p) of Ti 75A and Ti 150A of nominal composition were found to be

$$\text{Ti 75A:} \quad C_p = 0.125 + 4.8 \times 10^{-8}(\theta - 70)^2 \text{ Btu/lb F}$$
$$\text{Ti 150A:} \quad C_p = 0.130 \times 4.8 \times 10^{-8}(\theta - 70)^2 \text{ Btu/lb F}$$

where θ is the temperature in deg F.

Caution is in order if these equations are to be extrapolated above the maximum temperature of the experiments (1400 F). The values between room temperature and 212 F were checked independently by heating the specimens in steam and dropping them into a water calorimeter. The results so obtained were

$$\text{Ti 75A :} \quad C_p = 0.129 \pm 2 \text{ per cent (at 140 F) Btu/lb F}$$
$$\text{Ti 150A:} \quad C_p = 0.131 \pm 3 \text{ per cent}$$

and agree with the equations just given.

It is obvious that the specific heat of titanium increases rapidly with temperature. This fact was confirmed when the new values were used in conjunction with the analysis given in (1) to calculate the temperatures at the tip of a lathe tool machining titanium. Instead of giving absurdly high values, as the previously published values of C_p had done, the calculated temperatures agree quite well with direct experimental measurement of the cutting temperatures (2).

ACKNOWLEDGMENT

Part of the work reported was sponsored by the Allegheny-Ludlum Steel Company. The same company also furnished machined specimens of CA2 and CA4 carbides and specimens of Ti 75 (1) and Ti 150A (1). Watertown Arsenal furnished the remaining titanium specimens and was responsible for the chemical analysis reported in Table 2. The Kennametal Company furnished the specimens of K6 and K2S. The advice of Prof. L. R. Vianey, formerly of M.I.T., and the assistance of Messrs. R. Gleason, A. Maciulaitis, and A. S. Tweedie in carrying out many of the experiments is gratefully acknowledged.

BIBLIOGRAPHY

1 "On the Analysis of Cutting-Tool Temperatures," by E. G. Loewen and M. C. Shaw, Trans. ASME, vol. 76, 1954, pp. 217–232.

2 "Machining Titanium," by M. C. Shaw and collaborators, published by Machine Tool Division, Mechanical Engineering Department, M.I.T., 1954.

3 "Apparatus for Determining Thermal Conductivity," by J. W. Donaldson, *Metallurgia*, vol. 2, 1930, pp. 150–154.

4 "Apparatus for Measuring Thermal Conductivity of Metals Up to 600 C," by M. S. Van Dusen and S. M. Shelton, *Journal of Research*, NBS, vol. 12, 1934, p. 429.

5 "The Thermal Conductivity of Metals at High Temperature," by C. L. Hogan and R. E. Sawyer, *Journal of Applied Physics*, vol. 23, 1952, pp. 177–180.

6 "Heat Capacity of Sodium," by D. C. Ginnings, T. B. Douglas, and A. F. Ball, NBS Res. Paper RP 2110, vol. 45, 1950, pp. 23–33.

7 NBS Report on "Thermal Conductivity of Armco Iron," prepublication 1953.

Discussion

B. T. CHAO.[3] Since the analytical procedure for estimating metal-cutting temperature was made available, much useful information concerning the mechanism of tool failure has been obtained. One major handicap in applying the analysis is the lack of adequate data of the thermal properties of the tool and work materials. The author is to be congratulated on the fine piece of work reported here. There is at present great need for additional similar work.

In calculating the thermal conductivity of the test specimen from Equation [1] of the paper, the author replaced $d\theta/dx$ by $\Delta\theta/\Delta x$, and stated that the error in doing so was negligible. The Δx used were either 2 or 3 in. No $\Delta\theta$ values were reported. Actually, the error resulting from such a substitution may be small or large depending on (*a*) the rate of change of the thermal conductivity of the specimen material with temperature and (*b*) the range of temperature concerned. For a material whose conductivity does not vary as temperature changes, the temperature-distance relation for the apparatus described will be linear, and, consequently, $d\theta/dx$ and $\Delta\theta/\Delta x$ are identical. However, if the conductivity exhibits a strong temperature dependency, and the temperature difference across the hot and cold end of the specimen is large, such a substitution may introduce appreciable error inasmuch as the Δx selected by the author are relatively coarse. Examination of Fig. 3 shows that the data scatter for CA4 carbide is considerably larger than that of other carbides listed, particularly in the lower-temperature range where the temperature

---

[3] Associate Professor of Mechanical Engineering, University of Illinois, Urbana, Ill.

dependency of its conductivity is stronger. Such observation seems to support the foregoing discussion.

Fig. 4 of the paper gives conductivity values of four different kinds of high-speed steel in the annealed state. It is well known that changes in microstructure of steels oftentimes produce a significant change in their electrical and thermal properties.[4] A quenched medium or high C steel tempered to a high hardness has a lower conductivity than the same steel in the annealed state. It seems, therefore, that the data will be more useful if the conductivity values of high-speed steels were determined from quenched and tempered specimens (corresponding to the condition in service) rather than from the annealed specimens.

Finally, the writer would like to know the technique which the author used to produce 0.05-in-diam holes in cemented-carbide materials.

AUTHOR'S CLOSURE

Professor Chao was too modest in his discussion to point out that he, too, has been measuring thermal properties of important engineering materials. Since he used a different method it is regrettable that we did not happen to choose at least one common material for comparison of results. It is even more regrettable that nobody has yet devised a reliable method for measuring thermal conductivity rapidly. One specimen per week is slow progress.

The writer was able to prove that conductivity curves must have much more curvature than CA-4 (Fig. 3) before the substitution of $\Delta\theta/\Delta x$ for $d\theta/dx$ causes any noticeable errors. The scatter Professor Chao refers to is not explained thereby, but must be ascribed to less refined measurement techniques since this was one of the first materials tested.

Producing small holes (down to 0.010 in.) in carbide is no longer the problem it used to be. Ultrasonic drilling (Raytheon, Cavitron), controlled Arc (Method X), spark (Elox), and others, are all capable of doing the job.

---

[4] "Heat Transfer," by Max Jakob, John Wiley & Sons, Inc., New York, N. Y., vol. 1, 1950, chapter 6.