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Hardness of steel and thermal contact resistance

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Experiments on steel samples are reported for a new type of hardness tester based on the measurement of thermal contact resistance. These experiments have been carried out using a machine-mounted probe and a newer hand-held double-probe. It is shown that, by using the double-probe, errors due to the sample not having reached ambient temperature can be avoided. Although, ideally, the thermal conductivity of the sample should be much greater than that of the probe tip, it is found that it is simple to apply a correction to the apparent hardness number if this condition is not met. The standard deviation in the Vickers hardness number H, that is yielded by the hand-held probe ranges from 10% to 14% as H changes from 150 to 850 kg mm^{-2}, but the observations with the machine-mounted probe indicate that a much higher accuracy than this is possible.

1. Introduction

We have recently described a technique for determining the hardness of materials through the measurement of thermal contact resistance [1]*. In this method, a heated probe with a hard, pointed tip is brought down, with a fixed force, on to the surface of the sample to be tested. The lowering of the temperature of the tip, which is found by means of a thermocouple, enables a relative value for the contact resistance to be evaluated. This resistance is known to be given by $(1/\lambda_1 + 1/\lambda_2)/4r$, where λ_1 and λ_2 are the thermal conductivities of the tip and the sample respectively and r is the effective radius of contact [2]. Our previous observations on a wide range of materials showed that the radius, r, determined in this way is closely related to the size of the indentation produced by a conventional hardness tester.

The main purpose of the experiments, to be described here, was to determine the accuracy that could be achieved with the new hardness tester. Since most hardness measurements are performed on steel, it is this material that has been adopted for the present investigations. Studies have been made using the original probe, which was mounted in place of the diamond indenter in a Zwick hardness testing machine, and also with a new hand-held probe (or, rather, as we shall see, double-probe). We describe the methods that we have adopted for taking account of variations in the thermal conductivity, λ_2, and for eliminating errors due to the sample not being at the ambient temperature.

2. Experiments with the machine-mounted probe

Details of the machine-mounted probe have been given previously [1]. It consists essentially of a vertical constantan rod of 1.25 mm diameter and about 15 mm length, with copper wires of 0.35 mm diameter attached near each end. A small 10 Ω resistive heater, fed from a 2.0 V source of e. m. f., was fixed near the centre of the constantan rod with Araldite resin. A conical ruby tip, of 50° half-angle, was cemented to one end of the rod, while the other end was held in a perspex cylinder. A foamed-polystyrene heat shield was provided so as to minimize thermal losses.

In order to test the reproducibility of measurements made with this probe, sets of 20 measure-

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TABLE I Analysis of data from repeated tests using Zwick indenter and maching-held thermal comparator

Sample	Mean Vickers hardness (kg mm^{-2})	Standard deviations, 20 measurements (%)		
		Zwick indenter	Thermal hardness tester	
		1 kg load	300 g load	800 g load
Inhomogeneous Steel	638	16	19	14
Homogeneous Steel	152	3		2

ments were carried out, with loads of 300 g and 800 g respectively, on a polished specimen of hard steel. A similar set of 20 measurements was performed on the same specimen using a diamond indenter in the Zwick hardness testing machine at a load of 1 kg. We were disappointed that, as shown in Table I, the standard deviations in the Vickers hardness number predicted by the thermal probe were 19% and 14% respectively, but, since the standard deviation for the diamond indentation test was no less than 16%, it was clear that the variability was due to inhomogeneity of the sample rather than to faults in either of the testing methods. When similar sets of 20 measurements were performed on a more uniform sample (Z1 of Table II) the standard deviations in the hardness number became much lower, i.e. 3% for the Zwick indenter and 2% for the thermal probe. Thus, provided that the thermal probe is rigidly held and brought down in a controlled manner (as it is when mounted in the hardness testing machine) the results seem to show very little random error.

The above experiments were carried out on samples that had been allowed plenty of time to reach the temperature of the surroundings. We also carried out some measurements on a uniform sample of steel (Z3 of Table II) which was deliberately heated above the ambient temperature. We observed the output from the probe when no power was supplied to the heater (cold probe) and when the usual source of e.m.f. was connected (heated probe) and, in Fig. 1, we plot the output from the heated probe against that of the cold probe. We note that the plot is close to linear with a slope of -1. Similar results have been obtained for other heated samples. We conclude, therefore, that the sum of the outputs from the hot probe and the cold probe is constant and equal to the output from the heated probe when the sample is at the temperature of the surroundings.

3. Effect of variations in the thermal conductivity of the test specimen

We should, of course, prefer the output of the device to be independent of the thermal conductivity of the sample. Since the expression for the contact resistance tends to $1/4r\lambda_1$ when the thermal conductivity λ_2 of the sample is much greater than than λ_1 of the tip, it appears that we should make λ_1 as small as possible. However, if λ_1 is very small, the heat losses around the tip become predominant and the measurements become less sensitive. The choice of ruby (λ_1 equal to $35\,W\,m^{-1}\,K^{-1}$ as the tip material was, therefore a compromise between two conflicting requirements. For specimens made from, say,

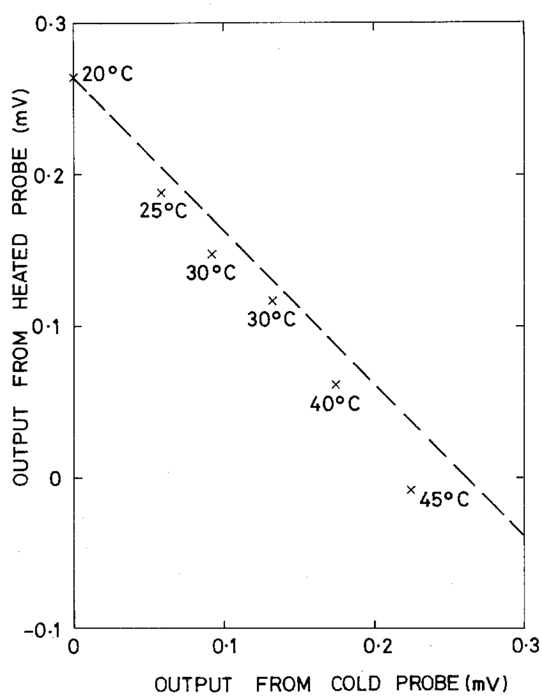

Figure 1 Plot of output from the heated probe against output from the probe when cold for various sample temperatures. The broken line has a slope of — 1.

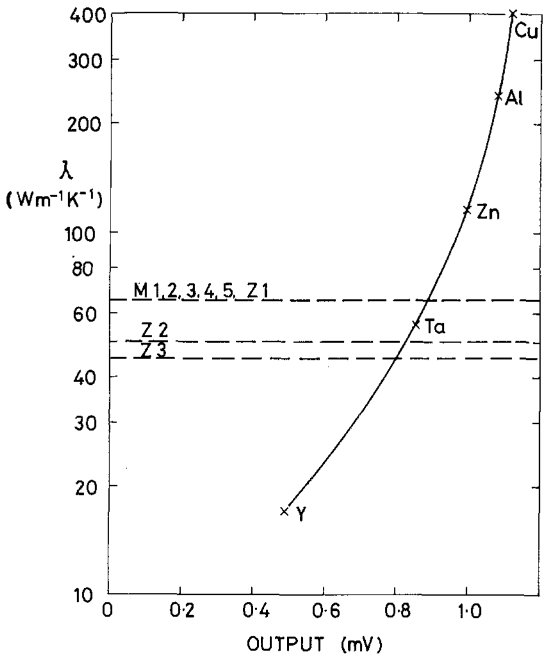

Figure 2 Plot of thermal conductivity against probe output for the tin-tipped thermal comparator.

copper or aluminium λ_2 is equal to some hundreds of $W m^{-1} K^{-1}$ and the condition $\lambda_2 \gg \lambda_1$ is satisfied but, for steel samples, λ_2 is typically equal to only about $50 W m^{-1} K^{-1}$. For the latter then, it is necessary to determine the value of the thermal conductivity and to apply a correction in assessing the hardness number.

The thermal conductivity can be found with sufficient accuracy using a probe of the type that has been developed for tests on gemstones. This particular probe was provided with a tin tip so that it could be used on relatively soft metals like aluminium; otherwise its construction and method of use are as described previously [3]. Fig. 2 shows how the output of the tin-tipped probe was found to vary with thermal conductivity of the test sample, covering the range 17 to $400 W m^{-1} K^{-1}$.

In our previous work on the thermal hardness tester [1] we applied an empirical correction to the output voltage, based on the ratio λ_1/λ_2. However, it now appears to us that it is better to apply a correction to the hardness number, H. Let us suppose that the effective radius of contact, r, is proportional to width of the indentation made by a conventional hardness testing machine and, therefore, inversely proportional to $H^{1/2}$. Then the contact resistance measurement yields an apparent hardness number H' such that

$$H' = (1 + \lambda_1/\lambda_2)^2 H \qquad (1)$$

(i.e. the contact resistance is proportional to $(1 + \lambda_1/\lambda_2)H^{1/2}$). In other words, when the thermal probe is employed for testing the hardness of materials that have a relatively low thermal conductivity, the apparent hardness number must be divided by $(1 + \lambda_1/\lambda_2)^2$ to give the true value of H. We have checked that this procedure yields results that are consistent with those obtained using the previous empirical correction factor.

4. Experiments with the hand-held probe

4.1. Description of apparatus

The attraction of the new thermal technique is clearly that it should enable rapid hardness measurements to be carried out in the field. Obviously, then, a hand-held version of the device is most desirable. Our prototype hand-held model is illustrated in Fig. 3.

As will be seen, the apparatus actually consists of two probes, cemented together, that are identical except that one incorporates a resistive heater and the other does not. Both probes contain constantan rods of 1.25 mm diameter and about 20 mm length with ruby tips cemented to their lower ends with Araldite. The rods are held in perspex cylinders that slide in brass tubes against springs that are permanently in compression and which each yield a force of 5 N when the tips are pressed against a flat specimen. All the electrical connections within the tubes are made using copper wires of 0.15 mm diameter. Wires 1 and 2 lead respectively to the tip and base ends of the unheated rod so as to form a thermocouple. In a similar way Wires 3 and 4 form a thermocouple with the heated rod. Wires 5 and 6 are the leads to the 12 Ω resistive heater that is cemented with Araldite near the centre of the left-hand rod, the resistor being connected to a regulated 2.1 V source of e.m.f. Wires 2 and 4 are connected together so that the output from Wires 1 and 3 becomes the sum of the e.m.f.'s from the hot and cold probes. As was shown in Section 2, this sum is independent of any difference in temperature that might exist between the sample and its surroundings.

4.2. Measurements on steel samples

Measurements were carried out using the hand-held apparatus on eight steel samples having a wide range of hardness values. Details of the

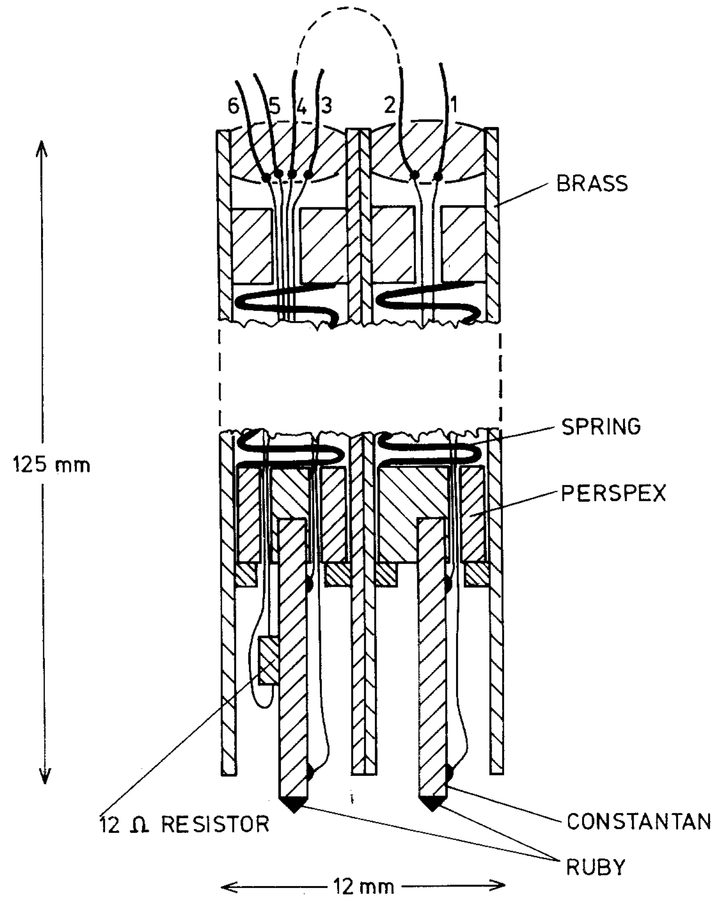

Figure 3 Hand-held double-probe.

samples are given in Table II. All were highly homogeneous, as indicated by conventional hardness measurements, and had polished surfaces.

Eight measurements were made on each sample. In each of these tests the double-probe was pressed down, with the tips fully retracted, for 30 sec, whereupon the output e.m.f., V, was read, and then the apparatus was allowed to recover for 60 sec before another test was attempted. In actual fact, V is measured with respect to a standing e.m.f. that exists before contact is made.

The thermal conductivities of all specimens were found with the tin-tipped probe and the results are indicated in Fig. 2 by the horizontal broken lines. It was, therefore, possible to specify values for the apparent hardness number H' equal to $(1 + \lambda_1/\lambda_2)^2 H$. Fig. 4 shows the mean output e.m.f. of the double probe for each sample plotted against H'. The significance of the broken and solid curves is discussed below.

4.3. Discussion of results

The theory of thermal comparators of the kind that have been used in this work has been presented already [3]. This theory can be simplified for the samples of reasonably high thermal con-

TABLE II Samples used in hardness tests with hand-held comparator

Sample	Source	Treatment	Vickers hardness, H(kg mm^{-2})
M1	Tool steel from School of Metallurgy,	Tempered for 1 h at 480° C	298
M2	University of New South Wales	Tempered for 1 h at 440° C	349
M3		Tempered for 1 h at 360° C	388
M4		Tempered for 1 h at 320° C	515
M5		Tempered for 1 h at 280° C	552
Z1	Standard Test Samples from		152
Z2	Zwick and Co.		661
Z3			839

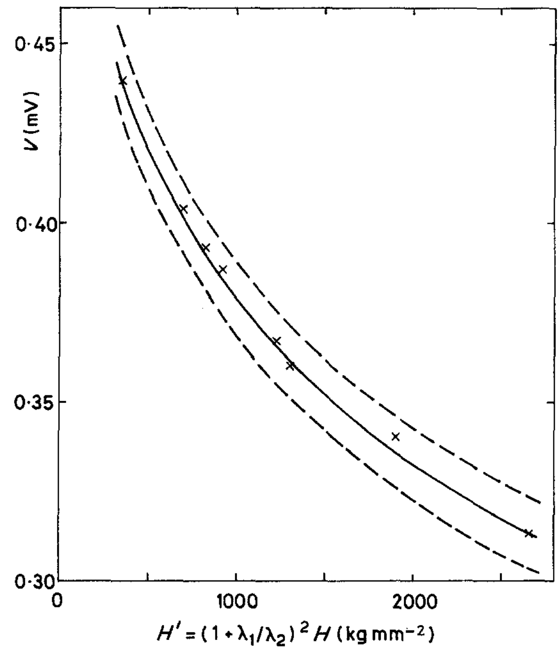

Figure 4 Plot of thermocouple output V against apparent hardness number for steel samples using the hand-held double-probe. The solid curve corresponds to the linear plot of Fig. 5 and the broken curves indicate the standard deviations for individual measurements.

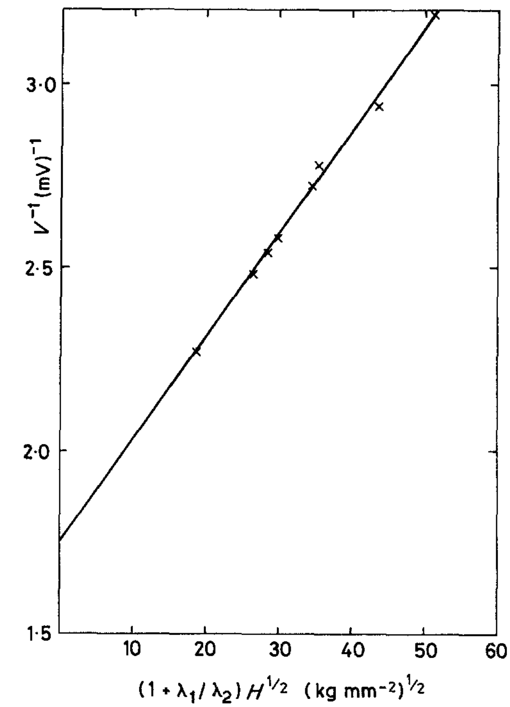

Figure 5 Plot of reciprocal of thermocouple output against apparent hardness number for steel samples using the double-probe.

ductivity that we have employed here. The resultant expression is

$$\frac{V}{V_0 - V} = \frac{4rR_0}{1/\lambda_1 + 1/\lambda_2}, \qquad (2)$$

where V_0 is the output e.m.f. that would exist if the tip were cooled to the ambient temperature and R_0 is the thermal resistance of constantan rod. We can rearrange Equation 2 in the form

$$\frac{V_0}{V} - 1 = (1/\lambda_1 + 1/\lambda_2)/4rR_0$$
$$\propto (1/\lambda_1 + 1/\lambda_2)H^{1/2}. \qquad (3)$$

Thus we expect a plot of $1/V$ against the square root of the apparent hardness number to be a straight line and, as shown in Fig. 5, this is indeed the case. The intercept with the ordinate axis indicates a value for V_0 of 0.57 mV which is close to the output that we observed when applying a soft metal heat sink near the lower thermocouple junction of the heated probe. The solid curve in Fig. 4 corresponds to the straight-line plot in Fig. 5.

We have carried out a statistical analysis of the data from the 64 measurements and have thence been able to determine standard deviations for individual readings. The standard deviations from the mean curve are indicated by the two broken lines in Fig. 4. It appears that the standard deviation is 10% of the hardness number for the softer steels and 14% of the hardness number for the hardest steel.

5. Conclusions

It has been shown that a hand-held thermal probe can be used to determine the hardness of steel samples having Vickers hardness numbers in the range 150 to 850 kg mm^{-2}. In its present form the hardness number is given with a standard deviation of 10% to 14% but measurements with a machine-held probe indicate that, if required, a considerably greater accuracy than this can be achieved. It has also been demonstrated that the double-probe gives results that are not dependent on the sample being at the ambient temperature.

References

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