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THE TEMPERATURE AND TIME DEPENDENCE OF THE HARDNESS OF IRON AND NICKEL

J. Larsen-Badse

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THE TEMPERATURE AND TIME DEPENDENCE OF THE
HARDNESS OF IRON AND NICKEL

J. Larsen-Badse

JULY 1967

OAK RIDGE NATIONAL LABORATORY
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THE TEMPERATURE AND TIME DEPENDENCE OF THE HARDNESS OF IRON AND NICKEL

J. Larsen-Badse¹

ABSTRACT

Vickers hardness testing was carried out on Armco iron and pure nickel between 400 and 800°C. The load was 1 kg and the time of loading was varied between 15 sec and 1 hr.

The hot-hardness values were shown to be most easily analyzed by considering them to consist of a temperature-dependent and a time-dependent contribution. The temperature-dependent part is intimately related to the flow stress of the material while the time-dependent part is a function of the creep properties. Activation energies for indentation creep as well as the exponent of stress dependence of the creep strain rate at low stresses can be determined rapidly from hot-hardness data.

INTRODUCTION

Tabor² has shown that during Vickers hardness testing at room temperature the material under the indenter deforms until a "representative" strain of 8 to 10% is reached. The pressure in the plastic zone surrounding the indentation increases simultaneously to a value of 2.9 to 3.0 times the flow stress at this strain. These results have been extended by Nunes and Larson³ to cover a range of temperatures around room temperature. When the indenter is applied to the sample over extended periods of time a creep phenomenon, often referred to as indentation creep, will lead to an expansion of the indentation.

Most published hot-hardness data have been obtained from short-time tests, where the duration of loading is in the order of 5 to 100 sec. The hardness values determined in this manner have been found

¹Research participant from the University of Hawaii, Honolulu.

²D. Tabor, The Hardness of Metals, Oxford University Press, London, 1951.

³J. Nunes and F. R. Larson, J. Inst. Metals 91, 114-17 (1962-63).

experimentally to correlate well with the hot tensile strength of the sample material.⁴⁻⁷ In reviewing the literature up until 1953, Westbrook⁷ found the hardness variation with temperature for pure metals to fit a relationship of the type

$$H = Ae^{-BT}, \quad (1)$$

where H is the hardness, T is the absolute temperature, and A and B are material-dependent constants. The similarity between Eq. (1) and the Hollomon-Lubahn equation⁸ for the flow stress at constant strain,

$$\sigma_c = Ae^{-BT}, \quad (2)$$

was taken as showing a fundamental relation between hardness and flow stress at elevated temperature. Since that time it has been customary to represent the hardness-temperature relation according to Eq. (1).

For metals and alloys of the same family the hot-hardness values correlate fairly well with various measures of creep strength.^{4,5,9-11} It would appear that the change in hardness, measured as a function of the duration of loading over extended periods of time, would be a better measure of the creep properties of a material. So far, this aspect of hot-hardness testing has received only limited attention, but the

⁴F. Garofalo, P. R. Malenock, and G. V. Smith, Trans. Am. Soc. Metals 45, 377-96 (1953).

⁵E. R. Petty, Metallurgia 56, 231-36 (1957).

⁶E. R. Petty, Metallurgia 65, 25-26 (1962).

⁷J. H. Westbrook, Trans. Am. Soc. Metals 45, 221-48 (1953).

⁸J. Hollomon and J. Lubahn, Gen. Elec. Rev. 50, 28-32, 44-50 (1947).

⁹E. R. Petty and H. O'Neill, Metallurgia 63, 25-30 (1961).

¹⁰F. P. Bens, Trans. Am. Soc. Metals 38, 505-16 (1947).

¹¹E. E. Underwood, Mater. & Methods 45(4), 127-29 (April 1957).

published data correlate well with creep strength,¹²⁻¹⁴ and more fundamental creep parameters, such as activation energy, have been sought¹⁵⁻¹⁷ from the hardness time relationship. The author^{18,19} has compared the time dependence of the indentation hardness of soft metals at room temperature with data obtained for the same materials undergoing indentation creep under flat punches. It was shown that

$$t \propto H_V^{-y}, \quad (3)$$

where t is the time of loading, H_V is the Vickers hardness, and y is an exponent dependent on the sample material. This relation confirms the results of other investigations,^{15,20} although an exponential relation also has been proposed.¹⁶ Further, the exponent y is given by

$$y = 2n + 1, \quad (4)$$

where n is the exponent of the low-stress relation between creep strain rate and stress

$$\dot{\epsilon} \propto \sigma^n. \quad (5)$$

¹²K. A. Osipov and Tyan De-chen, Izvest. Akad. Nauk SSSR, Otd. Tech. Nauk, Met. i Toplivo 1959(4), 77-81 (July-August).

¹³V. V. Glazova and N. N. Kurnakov, Russian Met. Fuels (English Transl.) 1963(1), 94-102.

¹⁴R. J. Parker, Metallurgia 67, 219-23 (1963).

¹⁵T. O. Mulhearn and D. Tabor, J. Inst. Metals 89, 7-12 (1960-61).

¹⁶R. K. Steele and M. J. Donachie, Trans. Am. Soc. Metals 58, 273-84 (1965).

¹⁷A. G. Atkins, A. Silverio, and D. Tabor, J. Inst. Metals 96, 369-78 (1966).

¹⁸J. Larsen-Badse, Time-Dependent Hardness of Soft Metals, ORNL-TM-1771 (April 1967).

¹⁹J. Larsen-Badse, Indentation Creep of Soft Metals, ORNL-TM-1862 (in press).

²⁰F. Hargreaves, J. Inst. Metals 39, 301-35 (1928).

The present investigation seeks to extend the relations of Eqs. (3) and (4) into the area of hot-hardness testing. Although of limited accuracy, the hot-hardness test has shown itself to be a valuable tool in many initial investigations because of the ease of sample preparation, etc. It was felt that the value of the test would increase considerably if the hardness and its variations could be associated with fundamental properties of the sample material.

EXPERIMENTAL

Hot-hardness tests were carried out using a Vickers-type indenter ground from synthetic sapphire and mounted in a molybdenum holder. The apparatus is shown in Fig. 1 and details of the furnace chamber in Fig. 2. The commercially built apparatus is based on the ORNL design by Hallerman.²¹ The sample is placed on a tantalum metal support that can be rotated in small increments. This rotation combined with sideways movement of the indenter permits a large number of indentations in one run. The furnace is of the cold-wall type, heated by tantalum elements and operated in a vacuum of 10^{-5} torr or better. Load is applied to the indenter by a lever arm housed completely inside the vacuum system. This eliminates any possible influence from sliding friction in vacuum seals on the magnitude of the load. The indenter is lowered slowly towards the metal surface by a motor and removed rapidly at the end of a preset time cycle. The timer is activated by a small electric circuit, which is closed when the indenter touches the metal surface. The size of the indentation produced is measured after cooling to room temperature.

The load used throughout this investigation was 1050 g. Previous work¹⁸ had shown the load to have no discernible influence on the time-dependent hardness of soft metals at room temperature. The time of loading was varied between 15 sec and 1 hr. The temperature was measured with a Chromel vs Alumel thermocouple drilled into a small hole in the sample and was controlled to within $\pm 5^\circ\text{C}$.

²¹G. Hallerman and R. J. Gray, Equipment for Hardness Testing at Elevated Temperatures, ORNL-3448 (July 17, 1963).

Fig. 1. Overall View of the Hot-Hardness Tester. To the left is the control panel for the furnace and the vacuum system. In the right background may be seen the vacuum pumps and the transformer for the furnace. The load for indentation is applied via a lever arm housed in the horizontal cylinder in the upper right corner. The sample and the furnace chamber are housed in the section immediately below this. The small panel that supports the indentation chamber also houses motor and timing devices for applying and removing the indenter.

Fig. 2. Furnace Chamber. The door has been opened to show details of the cold-wall design. The sample support, reflectors, and heaters are constructed of tantalum. The synthetic sapphire indenter is mounted in a molybdenum holder and connected via a long tantalum extension rod to a lever arm located in the horizontal chamber, which is partly visible in the upper portion of the picture. The lever arm is used to apply the load to the indenter and is kept in the same vacuum as the furnace chamber.

Two samples were used. One was Armco iron, the other nickel 270. Nominal composition: Armco iron, 0.12% C, 0.017% Mn, 0.005% P, 0.025% S, bal Fe; Nickel 270, 0.021% C, 0.001 to 0.01% Fe, 0.0001 to 0.001% Cu, 0.001 to 0.01% Si, 0.0001 to 0.001% Mg, remainder 99.95% Ni. Before the start of the investigation the samples were annealed for 2 hr at 850°C, well above the highest temperature used in the later hardness tests, to stabilize the structure. The grain diameter in both cases was approximately 175 μ . The sample surface was finished by wet grinding on silicon carbide papers through grit 600. The distance between indentations was kept large to avoid any interaction between the deformed zones around the holes. Usually two indentations were made for each combination of duration and temperature.

RESULTS

The general appearance of the indentations and the extent to which the surrounding material was deformed is illustrated in Figs. 3 and 4. The measured values of the area of the indentations projected onto the

Fig. 3. Vickers Indentation in Armco Iron at 750°C for a Duration of Loading of 60 sec. Thermal etching, 75x. Oblique light.

Fig. 4. Vickers Indentation in Nickel 270 at 750°C for a Duration of Loading of 2 sec. Slip lines and instances of grain-boundary sliding are evident. Thermal etching, 200x.

sample surface are listed in Tables 1 and 2 in the appendix together with the corresponding hardness values. The hardness is plotted as a function of the time of loading in Figs 5 and 6. As is usually the case for hot-hardness data, there is considerable spread in the values. They do, however, fit nicely to straight lines in a double logarithmic coordinate system for the loading times used here. One line is obtained for each temperature of testing, and the hardness value at any given time and temperature can be considered to be the sum of a "time-dependent" and a "time-independent" (or temperature dependent) contribution. The slopes of the lines were determined, and the values of y , according to the expression

$$t \propto H_v^{-y} \quad (3)$$

are listed in Table 3 in the appendix. The value of y for the nickel remains constant around 45 up to a temperature of approximately 540°C; above that it is 12.5. A similar transition is found for iron at

Fig. 5. Vickers Hardness of Nickel 270 as a Function of Time of Loading and of Temperature.

Fig. 6. Vickers Hardness of Armco Iron as a Function of Time of Loading and of Temperature.

approximately 680°C, where the value of y changes from 10 at the lower temperatures to 7.5. The results do not appear to support the findings by Atkins, Silverio, and Tabor²² that the slope of the $\log H$ - $\log t$ curves gradually decreases with increasing temperature. The hardness values at 15-sec loading time, determined from the curves, are listed in Table 3 in the appendix and plotted semilogarithmically against temperature in Fig. 7 and against $1/T$ in a rectangular plot in Fig. 8. It was decided to use this value as representative of the "time dependent" contribution to the hardness value, rather than to extrapolate back to, for example, 1 sec. It has been shown^{23,24} that the $\log H_v$ - $\log t$ curve is a straight line

²²A. G. Atkins, A. Silverio, and D. Tabor, J. Inst. Metals 96, 369-78 (1966).

²³J. Larsen-Badse, Time-Dependent Hardness of Soft Metals, ORNL-TM-1771 (April 1967).

²⁴F. Hargreaves, J. Inst. Metals 39, 301-35 (1928).

Fig. 7. The Vickers Hardness Obtained at a Loading Time of 15 sec Plotted Semilogarithmically Against the Testing Temperature. For comparison, 0.55 times the absolute melting point of each metal is shown.

Fig. 8. The Vickers Hardness Obtained at a Loading Time of 15 sec Plotted Against the Inverse Absolute Testing Temperature. For comparison, half the absolute melting point of each metal is shown.

only at intermediate values of the time t of loading. For very short times it deviates towards constant hardness. Thus, an extrapolation may easily introduce errors greater than those due to the use of the value at 15-sec loading time.

DISCUSSION

The results of this investigation confirm the relationship of Eq. (3). Steele and Donachie²⁵ have published results for Armco iron that, for short time intervals, appear to fit an exponential expression better. The double logarithmic curve can be expected to deviate from linearity at very short and at very long times.^{23,24} For this reason it does not seem improbable that the two curves can coexist within the spread in hardness values generally encountered, at least for not too long intervals of time.

²⁵R. K. Steele and M. J. Donachie, Trans. Am. Soc. Metals 58, 273-84 (1965).

Values of the exponent n calculated for the present experiments from Eqs. (3) and (4) are: iron below 680°C, $n = 4.5$; iron above 680°C, $n = 3.2$; nickel below 540°C, $n = 22$; and nickel above 540°C, $n = 5.5$. Weertman²⁶ has considered a model for creep in which dislocation loops from sources located on different slip planes expand until their stress fields interact with one another. At high temperatures the leading dislocations can climb and annihilate each other, giving steady-state creep. The rate of creep will be controlled by either the rate of dislocation climb or the rate of dislocation glide. For pure metals there is little impediment to dislocation glide and the rate of climb is considered to be rate controlling. For this case, at low stresses, Weertman derived the expression:

$$\dot{\epsilon} = \frac{3\sqrt{6} \pi^2 \sigma^4 \cdot 5 D}{2^5 b^{0.5} M^{0.5} \mu^{3.5} k T} , \quad (6)$$

where $\dot{\epsilon}$ is the measured creep rate, σ the unresolved applied stress, D the coefficient of self-diffusion, b the length of the Burgers vector, M the density of Frank-Read sources on one slip system, μ the shear modulus, k the Boltzmann constant, and T the absolute temperature.

When a microcreep mechanism controls the creep rate, as might be expected for alloys, the low-stress expression becomes:²⁶

$$\dot{\epsilon} = 0.35 \sigma^3 / \mu^2 A , \quad (7)$$

where the constant A depends on the particular mechanism.

In the present investigation the value of n for iron was found to be 4.5 below 680°C and 3.2 above this temperature. The value of 4.5 correlates nicely with Weertman's expression, Eq. (6), and is in the range of values generally found for commercially pure metals.²⁷ In a recent

²⁶J. Weertman, Trans. Met. Soc. AIME 218, 207-18 (1960).

²⁷F. Garofalo, Fundamentals of Creep and Creep-Rupture in Metals, Macmillan, New York, 1965, pp. 50, 100, 152.

investigation Ishida, Cheng, and Dorn²⁸ found a value of $n = 6.9$ in the temperature range 600 to 750°C. However, the material used in their work was considerably purer than the Armco iron used in the present investigation. The fairly sudden change in n from 4.5 to 3.2 as the temperature increased above 680°C does not appear to have been noted in other investigations. The changes are in the direction expected, a decrease in n with increased temperature.²⁷ It coincides, as also expected,²⁷ with a change in the activation energy, as discussed below. The change in n occurs at approximately half the absolute melting point and indicates a change in creep mechanism, a change from dislocation climb control to control by a microcreep mechanism. That the variation has not been noted by other workers could be due to differences in sample composition and to the fact that most other investigations have been performed under tensile stresses, whereas the deformation around the hardness indenter takes place under compressive stress.

The power relation between stress and strain rate of Eq. (6) breaks down at higher stresses, and the strain rate becomes stress-dependent to a considerably higher degree. For the higher stresses Weertman²⁶ developed the general expression

$$\dot{\epsilon} = \frac{3\pi^2 \sigma^2 D}{2\sqrt{2} \mu^2 b^2} \sinh \left(\frac{\sqrt{3} \sigma^{2.5} b^{1.5}}{8\mu^{1.5} M^{0.5} kT} \right) \quad (8)$$

The low-stress relation of Eq. (6) is valid up to the stress at which the hyperbolic sine in Eq. (8) becomes greater than one. This stress is thus strongly dependent on the modulus μ . For nickel it has been found²⁹ to be of the order of 7×10^8 dyne/cm², at least for the temperature range 400 to 1100°C. A rough estimate of the corresponding hardness value can be obtained by using the concept of Tabor³⁰ that the hardness is three

²⁸Y. Ishida, C.-Y. Cheng, and J. E. Dorn, Trans. Met. Soc. AIME 236, 964-71 (1966).

²⁹J. Weertman and P. Shahinian, Trans. Met. Soc. AIME 206, 1223-26 (1956).

³⁰D. Tabor, The Hardness of Metals, Oxford University Press, London, 1951.

times the yield strength at 8% strain.. This would mean that the power law of Eq. (6) would break down for indentation creep at hardnesses above approximately $3 \times (7 \text{ to } 10) = 21 \text{ to } 30 \text{ kg/mm}^2$. The actual change is noted at hardnesses of 35 to 40 kg/mm^2 in Fig. 5, corresponding to a temperature of approximately 540°C. Below this temperature the n value determined from Eq. (4) is 22 and obviously does not correspond to the values generally met for low-stress creep. Above 540°C a value of 5.5 was obtained for n . This correlates well with published values^{29,31,32} of 4.6, 6, and 5.6 for low-stress creep.

Values of the apparent activation energy for creep derived from this work are:

Temperature range, °C	below 550	550 to 680	above 680
Q for iron, kcal/mole	29.5	49	73.5
Temperature range, °C	below 650	650 to 740	above 740
Q for nickel, kcal/mole	39	47	53.5

They are obtained as follows. The simplified expression for uniaxial creep at constant stress is

$$\dot{\epsilon} \propto e^{-Q/RT} \quad (9)$$

where Q is the activation energy. It has been shown³³ that for time-dependent hardness

$$\dot{\epsilon}/S \propto (\sigma/p)^n, \quad (10)$$

where $\dot{\epsilon}$ and σ are the strain rate and the stress in the uniaxial case and p is the pressure in the hardness indentation; S , which corresponds to a strain rate at a given indentation size, was found to be equal to

³¹J. P. Dennison, R. J. Llewellyn, and B. Wilshire, J. Inst. Metals 94, 130-34 (1966).

³²C. M. Sellars and A. G. Quarrell, J. Inst. Metals 90, 329-36 (1961).

³³J. Larsen-Badse, Time-Dependent Hardness of Soft Metals, ORNL-TM-1771 (April 1967).

$\sqrt{A/t}$, where A is the area of the indentation and t the time of loading. For the case of constant stress σ the corresponding pressure p in the hardness test is constant. In other words, the hardness is constant, and, since the load does not vary, the area is also constant. Then, from Eq. (10) $\dot{\epsilon} \propto S$ and, by substitution into Eq. (9)

$$S \propto \sqrt{1/t} \propto e^{-Q/RT}$$

or,

$$\ln t_1 - \ln t_2 = \frac{2Q}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right). \quad (11)$$

Thus, the activation energies are easily determined by measuring along constant-hardness lines the distance between parallel lines in Figs. 5 and 6. There is considerable scatter in the data. The values listed above are calculated as averages over a range of temperatures. The activation energy found for the indentation creep of iron at the higher temperatures, above 680°C, is 73.5 kcal/mole. This value corresponds well with published data^{28,34} for uniaxial tensile creep, which are in the range 67 to 78 kcal/mole. The lower values obtained at the lower temperatures do not seem to correspond to similar changes for tensile creep.²⁸ However, for indentation hardness Steele and Donachie³⁵ found similar low values at the lower temperatures. The values found in this investigation for the activation energy of indentation creep of nickel, 39 to 53.5 kcal/mole, are also somewhat lower than the values measured^{29,32,34,36} in tensile creep, which are in the range 64 to 67 kcal/mole. An explanation of the difference must await further work on creep under compressive stresses as well as on indentation creep. However, it is clear that an indication of the value of the activation energy can be obtained from hot-hardness measurements at the higher temperatures.

³⁴O. D. Sherby, R. L. Orr, and J. E. Dorn, Trans. Met. Soc. AIME 200, 71-80 (1954).

³⁵R. K. Steele and M. J. Donachie, Trans. Am. Soc. Metals 58, 273-84 (1965).

³⁶P. R. Landon et al., Trans. Am. Soc. Metals 51, 900-10 (1959).

The variation of hardness with temperature has, since the early work by Westbrook,³⁷ customarily been plotted according to Eq. (1). The results of the present investigation fit this expression with the anticipated changes in slope at $T = 0.55T_m$ (Fig. 7) as well as an expression of the type (Fig. 8)

$$H = K_1/T + K_2, \quad (12)$$

where K_1 and K_2 are constants. In the former case the results lend support to the Hollomon-Lubahn flow-stress relation,³⁸ in the latter case to the modified Cottrell-Bilby^{39,40} equation. It is difficult to determine which of the two relations is more closely fitted by the present data. However, the results indicate that other ways of plotting hardness-temperature data than according to Eq. (1) may be profitable and that the temperature-dependent short-time contribution to the hardness is intimately related to the flow stress of the material, even at elevated temperatures.

CONCLUSION

The change in hot hardness can be divided into two parts, one due to the influence of temperature and one due to the influence of the duration of loading. The temperature-dependent part is intimately related to the flow stress of the material. The traditional way of representing the hot hardness as a function of temperature, originally modeled on the Hollomon-Lubahn flow equation, is not the only relation that will fit the data. The time dependence of the hardness can be explained in terms of the creep properties of the material. The hardness varies with time according to $t \propto H_v^{-y}$ where $y = 2n + 1$ and n is the exponent found in low-stress uniaxial creep for the stress dependence of the strain rate.

³⁷J. H. Westbrook, Trans. Am. Soc. Metals 45, 221-48 (1953).

³⁸J. Hollomon and J. Lubahn, Gen. Elec. Rev. 50, 28-32, 44-50 (1947).

³⁹A. H. Cottrell and B. A. Bilby, Proc. Phys. Soc. 62, 49-62 (1949).

⁴⁰J. C. Fisher, Trans. Am. Soc. Metals 47, 451-62 (1955).

It changes values rather suddenly when the hardness passes a certain level that corresponds well with the breakdown stress for the power relation found in uniaxial creep tests. For temperatures above half the absolute melting point, a reasonable estimate of the activation energy for creep can be obtained from the hardness data.

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APPENDIX

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Table 1. Projected Area and Vicker's Hardness for Nickel ^a

Time (sec)	400 °C		440 °C		485 °C		520 °C		565 °C		610 °C		645 °C		680 °C		720 °C		750 °C		815 °C	
	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V
15	0.0243	40.0	0.0239	40.8	0.0235	41.5	0.0232	42.0	0.0251	38.8	0.0307	31.7	0.0354	27.5	0.0378	25.8	0.0458	20.8	0.0454	21.5		
15	0.0214	45.5	0.0236	41.2	0.0210	46.4	0.0269	36.2	0.0242	40.2	0.0261	37.3	0.0276	35.3	0.0419	23.3	0.0454	21.4	0.0553	17.6	0.0600	16.2
30	0.0204	47.6	0.0231	42.1	0.0216	45.1	0.0250	38.9	0.0259	37.6	0.0304	32.0	0.0290	33.6	0.0424	23.0	0.0431	20.2	0.0530	18.3	0.0708	13.8
30	0.0198	49.1	0.0216	45.0	0.0240	40.6	0.0244	39.9	0.0246	39.5	0.0280	34.8	0.0279	34.9	0.0371	26.2	0.0433	20.1	0.0485	20.0	0.0650	15.0
60	0.0197	49.4	0.0240	40.6	0.0238	40.9	0.0254	38.4	0.0277	35.2	0.0313	31.1	0.0348	28.0	0.0400	24.3	0.0472	20.6	0.0539	18.0	0.0628	15.5
60																	0.0492	19.8			0.0628	15.5
120	0.0224	43.5	0.0226	43.0	0.0231	42.1	0.0249	39.1	0.0284	34.3	0.0314	31.0	0.0373	26.1	0.0404	24.2	0.0538	18.1	0.0578	16.8	0.0705	13.8
120																	0.0490	19.9			0.0716	13.6
300	0.0216	45.1	0.0225	43.2	0.0230	42.3	0.0260	37.5	0.0286	34.0	0.0371	26.2	0.0320	30.4	0.0424	23.0	0.0625	15.6	0.0552	17.6	0.0762	12.8
300	0.0216	45.1	0.0228	42.6	0.0234	41.6	0.0246	39.6	0.0271	35.9	0.0350	27.8	0.0370	26.3	0.0488	20.0	0.0587	16.6	0.0638	15.3	0.0762	12.8
600			0.0228	42.6	0.0231	42.1	0.0255	38.2	0.0324	30.0	0.0371	26.2	0.0400	24.3	0.0541	18.0	0.0550	17.7	0.0608	16.0	0.0724	13.5
600																	0.0610	16.0			0.0860	11.3
615	0.0211	46.1																				
1200	0.0221	44.0			0.0244	39.9	0.0271	35.9	0.0356	27.4	0.0418	23.3	0.0410	23.8			0.0621	15.7				
1200																	0.0674	14.4				
1230			0.0226	43.1																		
1250																					0.0822	11.8
2400															0.0592	16.4	0.0642	15.2			0.0970	10.0
2600																					0.0840	11.6
3300	0.0226	43.0																				
3600			0.0217	44.9			0.0290	33.6	0.0395	24.7			0.0445	21.9	0.0638	15.3	0.0640	15.2			0.0827	11.8
3600																	0.0752	12.9			0.1018	9.6
3900											0.0464	21.0							0.0672	14.5		
5300					0.0260	37.4																

^a Applied Load - 1050 g.

Table 2. Projected Area and Vickers Hardness for Armco Iron^a

Time (sec)	400°C		435°C		475°C		510°C		565°C		595°C		620°C		650°C		715°C		750°C		790°C	
	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V	Area (mm ²)	H _V
15	0.0149	65.4	0.0159	61.2	0.0168	58.0	0.0220	44.5	0.0290	33.6	0.0344	28.3	0.0389	25.0	0.0520	18.7	0.0651	15.0	0.0910	10.7	0.1310	7.4
15	0.0149	65.4	0.0152	64.0	0.0177	55.0	0.0239	40.8	0.0285	34.2	0.0348	28.0	0.0392	24.8	0.0496	19.6	0.0630	15.4	0.0882	11.0	0.1192	8.2
30	0.0146	66.6	0.0160	61.0	0.0192	50.7	0.0252	38.7	0.0290	33.6	0.0357	27.3	0.0416	23.4	0.0509	19.2	0.0682	14.3	0.0970	10.1	0.1360	7.2
30	0.0135	72.1	0.0158	61.6	0.0193	50.5	0.0251	38.8	0.0291	33.5	0.0384	25.4	0.0410	23.8	0.0509	19.2	0.0652	14.9	0.0960	10.2	0.1465	6.6
60	0.0144	67.6	0.0173	56.4	0.0199	49.0	0.0260	37.5	0.0315	30.9	0.0425	22.9	0.0418	23.3	0.0528	18.5	0.0748	13.1	0.1018	9.6	0.1532	6.4
60											0.0413	23.6			0.0519	18.5	0.0760	12.8			0.1575	6.2
120	0.0149	65.4	0.0177	55.0	0.0209	46.6	0.0265	36.7	0.0326	29.9	0.0406	24.0	0.0445	21.9	0.0556	17.5	0.0883	11.0	0.1082	9.0	0.1880	5.2
120											0.0395	24.7			0.0570	17.1	0.0768	12.8			0.1950	5.0
300	0.0156	62.4	0.0200	48.6	0.0226	43.1	0.0284	34.5	0.0360	27.1	0.0442	22.1	0.0485	20.1	0.0642	15.2	0.0900	10.8	0.1305	7.5		
300	0.0162	60.1	0.0209	46.6	0.0232	42.0	0.0290	33.6	0.0349	27.9	0.0480	20.3	0.0485	20.1			0.0838	11.6	0.1320	7.4	0.2310	4.2
360															0.0619	15.3						
600	0.0184	53.0	0.0209	46.6	0.0250	39.0	0.0319	30.6	0.0385	25.5	0.0507	19.2	0.0509	19.2	0.0658	14.8	0.0990	9.8	0.1320	7.4	0.2560	3.8
600											0.0527	18.5			0.0665	14.6	0.1010	9.6			0.2450	4.0
1200	0.0188	51.8	0.0229	42.5	0.0274	35.6	0.0342	28.5	0.0412	23.6	0.0580	16.8	0.0600	16.3	0.0702	13.9	0.1070	9.1	0.1635	6.0	0.2710	3.6
1200											0.0570	17.1					0.1105	8.8			0.2690	3.6
1400															0.0713	13.3						
2000																					0.2790	3.5
2400											0.0588	16.6			0.0812	12.0	0.1242	7.8			0.3490	2.8
3300									0.0466	20.5												
3600	0.0195	50.0					0.0390	25.0			0.0610	16.0			0.0816	11.6	0.1135	8.6	0.1870	5.2		
3600											0.0604	16.1			0.0800	12.2						
3900													0.0692	14.1			0.1295	7.5			0.3550	2.7
4800			0.0265	36.8	0.0284	34.5																

^aApplied Load - 1050 g.

Table 3. Exponent y of Relation $t = H_V^{-y}$ and the Vickers Hardness Value at 15-sec Loading for Various Temperatures

Temperature		Nickel		Iron	
°K	°C	y	H_V	y	H_V
673	400	46.0	49.0	11.0	77.0
708	435			10.0	65.5
713	440	43.5	45.8		
748	475			10.0	56.8
758	485	45.5	43.5		
783	510			10.0	44.5
793	520	45.5	40.8		
838	565	12.0	39.2	10.5	35.8
868	595			9.5	28.5
883	610	12.5	34.2		
893	620			10.0	25.1
918	645	12.5	32.3		
923	650			10.5	20.8
953	680	13.0	24.8		
988	715			7.5	15.7
993	720	12.5	22.3		
1023	750	12.0	21.1	7.0	11.2
1063	790			7.5	7.8
1088	815	12.0	16.7		

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