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TIME-DEPENDENT HARDNESS OF SOFT METALS

Jorgen Larsen-Badse

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Jorgen Larsen-Badse

Paper presented at the Annual Meeting of the American Institute of Mining, Metallurgical and Petroleum Engineers, Los Angeles, California, February 19-23, 1967

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TIME-DEPENDENT HARDNESS OF SOFT METALS

Jorgen Larsen-Badse¹

ABSTRACT

Room-temperature Vickers hardness tests were carried out on indium, tin, and lead for times of loading between 1 and 60,000 sec and with applied loads in the range 500 to 1600 g. The applied load is shown to have no influence on the time-hardness relation within a wide time range. The hardness decreases with increased time of loading according to $t \propto H_V^{-y}$. For long times of loading the hardness deviates from this relation towards lower values.

The results are explained on the basis of previous experiments on creep under flat punches for the same materials. It is shown that $y = 2n + 1$, where n is the exponent of the uniaxial creep relation $\dot{\epsilon} \propto \sigma^n$.

INTRODUCTION

When a hard indenter is pressed into the surface of a metal over extended periods of time, creep will take place in the material leading to a gradual increase in the size of the indentation. For metals of low melting point, this effect influences the hardness values determined at room temperature. The first investigation of the phenomenon was published in 1909 by Kürth.² He found empirically that the indentation diameter increased very rapidly during the first few minutes of loading, more slowly later on. These results were confirmed by Hargreaves,³ who investigated a series of soft metals and alloys. His data fit the expression

$$d = c \cdot t^z \quad (1)$$

¹Research Participant from the University of Hawaii, Honolulu.

²A. Kürth, Z. Ver. deut. Ing. 53, 85-92, 209-16 (1909).

³F. Hargreaves, J. Inst. of Metals 39, 301-35 (1928).

where d is the diameter of the indentation, t the time of loading, and c and z constants related to material and temperature. For long times of loading he noticed in some cases a deviation from this relation, towards larger values of d . Other investigators have published relations similar to Eq. (1) for room-temperature indentation creep of soft metals⁴ as well as for data obtained for harder metals by hot-hardness testing at elevated temperatures.⁵⁻⁹ A few investigations have yielded data that appear to fit an exponential relation better.^{10, 11}

A good general correlation exists for metals between the time-dependent hardness and the creep properties determined in uniaxial tests.⁵⁻⁹ However, attempts^{4, 12} to relate quantitatively the values of z of Eq. (1) to the value of n of the uniaxial creep relation between strain rate and stress

$$\dot{\epsilon} \propto \sigma^n \quad (2)$$

have shown the z values to be several times larger than expected. The main difficulty in this case is to determine a value of the strain rate during indentation creep. It has been proposed to use $\dot{d}$ (Refs 4, 12), $\dot{d}/d$ (Refs 5, 9), or as a strain d^2/d_0^2 (Ref 13). Since the stress and strain conditions under the indenter are complicated (and unknown), even an estimate of a representative strain is difficult to obtain where

⁴T. O. Mulhearn and D. Tabor, J. Inst. of Metals 89, 7-12 (1960-61).

⁵K. A. Osipov and Tyan De-Chen, Izv. Akad. Nauk SSSR, Otd. Tekhn. Nauk Met. i Toplivo 1959(4), 77-81 (July-August).

⁶E. E. Underwood, J. Inst. of Metals 88, 266-71 (1959-60).

⁷T. Pomey, A. Royez, and J. P. Georges, Mem. Sci. Rev. Met. 56, 215-28 (1959).

⁸J. W. Goffard and R. G. Wheeler, Trans. Met. Soc. AIME 215, 902-04 (1959).

⁹V. V. Glazova and N. N. Kurnakov, Russ. Met. Mining (English Transl.) 1963(1), 94-102.

¹⁰A. C. Moore and D. Tabor, Brit. J. Appl. Phys. 3, 299-301 (1952).

¹¹R. K. Steele and M. J. Donachie, Trans. Am. Soc. Metals 58, 273-84 (1965).

¹²H. D. Merchant, Trans. Met. Soc. AIME 230, 1206-08 (1964).

¹³C. Rubenstein, Proc. Phys. Soc. (London) B 67, 563-68 (1954).

indentation creep is superimposed on the plastic flow occurring during initial indentation.

The author¹⁴ has shown for indentation creep under flat indenters of constant cross section that the penetration D is related to the time of loading, t , according to

$$D = S\sqrt{t} \quad , \quad (3)$$

and that S of this expression is related to the punch pressure, p , according to

$$S \propto p^n \quad . \quad (4)$$

The exponent n of Eq. (4) has the same value as the exponent n of Eq. (2).

In the absence of a more fundamental treatment of indentation creep, it was decided to undertake the present investigation in order to test the applicability of Eq. (4) to the case of creep under a hardness indenter.

EXPERIMENTAL

The samples used were the same as those used for the indentation investigations.¹⁴ They were cut from ingots cast from raw materials of the following purity:

Lead (certified reagent granules), > 99.999%

Tin (mossy tin metal), > 99.90%

Indium (indium metal foil), not determined

The surface was finished by wet grinding on abrasive papers through grit 600. All measurements for any one metal were performed on the same sample, without any intermediate repolishing.

A Vickers indenter was pressed into the sample surface under loads in the 500 to 1600-g range and for times up to 1 hr except for a few tests lasting up to 17 hr. The tests were performed at room temperature in a hot-hardness tester. The reason for using this equipment was the ease with which time and load could be varied in it. The indenter was

¹⁴J. Larsen-Badse, Indentation Creep of Soft Metals, report to be published.

a synthetic sapphire ground to the conventional dimensions of the Vickers diamond and mounted in a molybdenum holder.

RESULTS

The influence of time of loading on the indentation size is illustrated in Fig. 1. For each test the area of the indentation projected onto the sample surface and the Vickers hardness number were determined. The data are listed in Tables A-1 and A-2 in the Appendix and plotted in Figs. 2-5.

Tabor¹⁵ has shown that the average vertical pressure in the metal is a more fundamental property than the hardness. The latter is calculated by dividing the applied load by the total, pyramidal surface area of the indentation, whereas the average vertical pressure is equal to

¹⁵D. Tabor, The Hardness of Metals, Oxford University Press, London, 1951.

Fig. 1. Microstructure Showing Hardness Indentations in a Tin Sample. Indenter was pressed into the sample surface under a 530-g load for times of 1/2 min, 8 hr, and 24 hr, respectively. 40X.

Fig. 2. The Projected Indentation Area for Indium, Lead, and Tin as a Function of the Duration of Loading.

Fig. 3. The Projected Indentation Area for Tin as a Function of the Duration of Loading for Various Loads.

Fig. 4. Vickers Hardness Variation with Time of Loading for Indium, Lead, and Tin Tested Under a Load of 1050 g.

Fig. 5. Variation of Hardness and Projected Area for Tin Tested for Extended Periods of Time.

the applied load divided by the area of the base of the pyramid - the area of the projection of the indentation onto the sample surface. For the geometrically similar indentations obtained with the Vickers indenter the hardness number is directly proportional to the average vertical pressure.¹⁵ For this reason, and since hardness data have gained wide acceptance, it was preferred to list the pyramid hardness numbers in the present investigation.

As expected, the spread in values is larger for the softer metals and at the lower loads. It is sufficiently large to mask any small variations in the area-time relation with a change in load. Since no such variation was expected nor indicated by the results, parallel lines were drawn through the data for each metal. When one includes values obtained for very short and for very long times of loading (Fig. 5), it is seen that the curve actually is not a straight line in double logarithmic coordinates. There is, as noted by Hargreaves,¹⁶ a deviation towards larger indentations for long times of loading. It is noted that the curves for different loads are still parallel and coincide in the case of the hardness values. For the region between approximately 20 sec and 1 hr of loading the curves are well represented by straight lines. For this time interval one may write

$$t \propto A^x \quad (5)$$

and

$$t \propto H_v^{-y} \quad (6)$$

where A is the projected area, t the time of loading, H_v the hardness, and x and y the slopes of the lines.

Since H_v is proportional to A^{-1} , x should be equal to y . The values of x and y determined from Figs. 2-4 are listed in Table 1. The values correspond well with data published by other investigators.^{16, 17, 18}

¹⁶F. Hargreaves, J. Inst. of Metals 39, 301-35 (1928).

¹⁷T. O. Mulhearn and D. Tabor, J. Inst. of Metals 89, 7-12 (1960-61).

¹⁸V. P. Shishokin and L. N. Basilevskii, Phys. Metals Metallog. USSR (English Trans.) 11(6), 114-15 (1961).

Table 1. Measured Values of the Exponents

Metal	Exponents			
	x	y	n	2n + 1
Indium	12.3	13.0	5.9-6.0	13
Lead	11.5	12.5	5.5	12
Tin	8.0	8.2	3.3	7.6

Also listed in Table 1 are the values of the exponent n determined by the author¹⁹ according to Eq. (4) for the same samples deforming by creep under indenters of constant cross section. These values correspond well with data for the exponent n of Eq. (2) for uniaxial testing obtained by Weertman²⁰ for lead and indium and by Gifkins²¹ for lead.

The results are explained in the following way. If one assumes that, for not too wide ranges of time, a relation similar to that of Eq. (3) is applicable to the indenting Vickers pyramid, it would seem reasonable to expect also Eq. (4) to hold. The depth of penetration, D , is related to the area, A , by $D \propto \sqrt{A}$, and the pressure is $p \propto 1/A$. Equation (4) may be written

$$S = \frac{D}{\sqrt{t}} \propto p^n$$

Substitution of the values for p and D for the Vickers indenter gives

$$\frac{\sqrt{A}}{\sqrt{t}} \propto \left(\frac{1}{A}\right)^n, \quad (7)$$

or

$$t \propto A^{2n+1} \quad (8)$$

¹⁹J. Larsen-Badse, Indentation Creep of Soft Metals, report to be published.

²⁰J. Weertman, Trans. Met. Soc. AIME 218, 207-18 (1960).

²¹R. C. Gifkins, discussion of Weertman's paper, Ref. 20, Trans. Met. Soc. AIME 218, 1128-29 (1960).

A comparison of the values for x and y with $2n + 1$ show excellent agreement.

The comparison of indentation creep taking place under a 136° Vickers pyramid with that found for flat indenters of constant cross section appears to be valid when the time intervals involved are short. In both cases the total plastically strained volume is considerably (10 or more times) larger than the indentation itself. The resistance to expansion of this zone, as the indenter sinks into the material, must be a major contribution to the creep resistance. Thus, similarity is expected between the two cases, as long as the change of indentation size is relatively small. For longer times the influence of the growth of the Vickers indentation in the horizontal direction will be felt. This would correspond to increasing the cross-sectional area of the flat punch. It was shown¹⁹ that an increased punch area leads to a decrease in the pressure necessary to maintain a constant value of S in Eq. (3). Thus, one would expect that the decrease in hardness values with time for very long times would be larger than predicted from a direct comparison of the two types of indentation (i.e., larger than predicted from a straight line in double logarithmic coordinates). This is confirmed by the results.

CONCLUSIONS

It has been shown for soft metals tested at room temperature that the variation of indentation hardness with time of load application is described by a relation of the type $t \propto H_V^{-y}$, for times between approximately 20 sec and 1 hr. For longer times the hardness deviates towards lower values than predicted from this expression. The relationship and the deviation are both explained on the basis of previous work on the creep under flat indenters of constant cross section. It is shown that $y = 2n + 1$, where n is the exponent from the creep relation $\dot{\epsilon} \propto \sigma^n$. This is confirmed by the experimental data.

APPENDIX

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Table A-1. Projected Area and Vickers Hardness for Various
Times of Loading

Time (sec)	Indium				Lead				Tin	
	1050-g Load		530-g Load		1050-g Load		1600-g Load		1050-g Load	
	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	1.07	0.91	0.231	2.12	0.339	2.88	0.444	3.35	0.194	5.02
15	1.20	0.81	0.204	2.41	0.323	3.01	0.484	3.07	0.192	5.08
30	1.12	0.87	0.240	2.05	0.293	3.33	0.453	3.28	0.189	5.15
30	1.25	0.78	0.230	2.14	0.307	3.18	0.439	3.39	0.187	5.21
60	1.41	0.69	0.243	2.02	0.360	2.71	0.500	2.97	0.192	5.08
60	1.35	0.72	0.235	2.09	0.331	2.94	0.484	3.07	0.210	4.65
120	1.32	0.74	0.238	2.06	0.410	2.38	0.500	2.97	0.224	4.35
120	1.55	0.63	0.241	2.04			0.550	2.70		
130								2.47	0.201	4.85
300	1.43	0.68	0.233	2.11	0.431	2.26	0.601	2.47	0.234	4.35
300	1.46	0.67	0.238	2.06	0.442	2.20	0.635	1.58	0.254	3.84
600	1.53	0.64	0.276	1.78	0.440	2.21	0.736	2.02	0.280	3.48
600	1.47	0.66	0.267	1.84	0.399	2.44	0.716	2.08	0.263	3.70
1200	1.48	0.66	0.295	1.67	0.452	2.16	0.712	2.09	0.284	3.43
1200	1.54	0.63	0.259	1.90	0.409	2.39	0.696	2.14	0.286	3.41
2100	1.33	0.73								
2400			0.281	1.75	0.434	2.25	0.801	1.86	0.327	2.98
3000	1.42	0.68								
3600			0.265	1.85	0.514	1.90	0.866	1.72	0.343	2.84
3600					0.518	1.88	0.798	1.86		
3800									0.350	2.78
3900			0.288	1.70						
4300	1.74	0.56	0.295	1.66						

Table A-2. Projected Area and Vickers Hardness for Various Times of Loading and for Various Loads

Time (sec)	Tin											
	530-g Load		740-g Load		950-g Load		1160-g Load		1380-g Load		1600-g Load	
	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
1					0.148	5.95					0.235	6.31
2					0.152	5.80					0.230	6.45
3					0.162	5.44					0.239	6.21
4					0.152	5.80					0.248	5.98
6					0.161	5.46					0.261	5.69
8					0.164	5.37					0.241	6.16
10					0.153	5.76					0.258	5.75
12					0.168	5.24					0.256	5.80
15					0.159	5.54					0.273	5.44
15	0.087	5.65	0.126	5.43	0.162	5.44	0.195	5.42	0.248	5.16	0.297	5.00
15	0.090	5.45	0.129	5.30	0.162	5.44	0.195	5.42	0.235	5.44	0.318	4.66
30	0.096	5.11	0.129	5.30	0.177	4.98	0.224	4.80	0.241	5.31	0.305	4.87
30	0.096	5.11			0.176	5.00	0.208	5.18	0.251	5.10	0.303	4.90
60	0.102	4.81	0.142	4.82	0.188	4.69	0.242	4.45	0.280	4.57	0.310	4.77
120	0.107	4.60	0.154	4.45	0.194	4.54	0.249	4.31	0.294	4.35	0.342	4.34
300	0.113	4.35	0.168	4.07	0.234	3.76	0.265	4.06	0.338	3.79	0.367	4.04
300	0.121	4.06	0.166	4.13	0.235	3.75	0.277	3.89	0.345	3.71		
600	0.127	3.87	0.189	3.63	0.264	3.33	0.310	3.47	0.349	3.67	0.396	3.75
1200	0.143	3.43	0.213	3.22	0.264	3.33	0.337	3.19	0.395	3.24	0.470	3.15
3300									0.458	2.80		
3600	0.172	2.85	0.240	2.86	0.304	2.90	0.391	2.75				
3900											0.548	2.71
62000					0.525	1.68					0.830	1.79

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