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INDENTATION CREEP OF SOFT METALS

Jorgen Larsen-Badse

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INDENTATION CREEP OF SOFT METALS

Jorgen Larsen-Badse

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

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CONTENTS

	<u>Page</u>
Abstract	1
Introduction	1
Experimental	4
Results	7
Discussion	12
Conclusions	17
Appendix	19

INDENTATION CREEP OF SOFT METALS

Jorgen Larsen-Badse¹

ABSTRACT

The phenomenon of indentation creep found at room temperature when flat punches are pressed under constant load into the surface of soft metals was studied. The depth of penetration D was in all cases proportional to the square root of time: $D = S\sqrt{t}$. The constant S depends upon the metal, the load, and the type of punch used and is related to the punch pressure according to $S \propto p^n$. The exponent n is the same as that found for the low-stress creep relation $\dot{\epsilon} \propto \sigma^n$; S may be considered to represent an "average" strain rate at a given depth of penetration and for a given punch size. The pressure required to obtain a certain S value decreases with an increase of the face area of the punch. This is due to the influence of punch size on the extent of the plastically strained zone and thus on the effective stress of deformation.

INTRODUCTION

Many attempts have been made at relating hot-hardness values of metals with their resistance to creep. For this purpose most investigators have used the hardness data obtained in the conventional short-time tests,²⁻⁶ but some use as a parameter the change in hardness with

¹Research Participant from the University of Hawaii, Honolulu, Hawaii.

²F. Garofalo, P. R. Malenock, and G. V. Smith, "Hardness of Various Steels at Elevated Temperatures," Trans. Am. Soc. Metals 45, 377-96 (1953).

³E. R. Petty, "Relationship Between Hardness and Tensile Properties Over a Wide Range of Temperature for Aluminum Alloys," Metallurgia 65, 25-26 (1962).

⁴F. P. Bens, "Hardness Testing of Metals and Alloys at Elevated Temperatures," Trans. Am. Soc. Metals 38, 505-16 (1947).

⁵E. R. Petty and H. O'Neill, "Hot Hardness Values in Relation to the Physical Properties of Metals," Metallurgia 63, 25-30 (1961).

⁶E. E. Underwood, "Creep Properties from Short Time Tests," Materials & Methods 45(4), 127-29 (1957).

duration of load application.⁷⁻¹⁰ A general empirical relation normally exists in both cases with some spread in values. This spread is smallest when the metals and alloys being compared are closely related and when the times of load application for the two tests are of similar order of magnitude.⁵ For the tensile test, Nunes and Larson¹¹ were able to show that the hardness of some pure metals and some steels, tested in a temperature range around room temperature, is proportional to the flow stress at 8% strain. This is an extension of Tabor's work on room-temperature hardness.¹²

So far, no quantitative analysis of the creep taking place under a hardness indenter has been published. The solution of this problem is difficult because of the complex stress conditions found under the indenter and because of the continuous decrease of the pressure between metal and indenter as the indentation increases in size. To eliminate the latter variable and to simplify the stress conditions as far as possible the present investigation used indenters of constant simple cross section. The simplest shapes in this connection are those having either a circular cross section or a long narrow rectangular one; in the latter case plane strain conditions are approached. No creep data appear to have been published for either of these geometries.

Hill¹³ has presented a slip-line field solution for initiation of frictionless plane-strain indentation showing that yielding will start

⁷C. Rubenstein, "The Influence of Creep on the Measured Hardness of Soft Metals," Proc. Phys. Soc. (London), (B) 67, 563-68 (1954).

⁸T. O. Mulhearn and D. Tabor, "Creep and Hardness of Metals: A Physical Study," J. Inst. Metals 89, 7-12 (1960).

⁹K. A. Osipov and Tyan De-Chen, "Study of the High-Temperature Creep of Nickel Solid-Solutions by the Hot-Hardness Method," Izv. Akad. Nauk SSSR, Otd. Tekhn. Nauk, Met. i Toplivo 1959(4), 77-81.

¹⁰V. V. Glazova and N. N. Kurnakov, "Creep of Titanium-Zirconium-Tin Alloys," Russ. Met. Mining (English Transl.) 1963(1), 94-102.

¹¹J. Nunes and F. R. Larson, "Low-Temperature Hardness and Flow-Stress Relationships of Metals," J. Inst. Metals 91, 114-117 (1962).

¹²D. Tabor, The Hardness of Metals, Oxford University Press, London, 1951.

¹³R. Hill, The Mathematical Theory of Plasticity, pp. 254-62, Oxford University Press, London, 1950.

in a plastic-rigid material when the pressure p under the indenter reaches a value

$$p = 5.14k, \quad (1)$$

where k is the shear strength. This equation has been verified experimentally by Watts and Ford.¹⁴ A solution taking the friction into account has been presented by Nadai,¹⁵ giving Eq. (1) for zero friction and an increase in p with increased coefficient of friction. Shield¹⁶ has calculated the average pressure to initiate yielding under a flat frictionless cylindrical punch pressed into the surface of a plastic-rigid material. He obtains

$$p = 5.69k. \quad (2)$$

Bishop, Hill, and Mott¹⁷ measured the force to deeply press at constant rate a cylindrical punch with a conical head into annealed copper. The force increased until a depth of 4 to 5 times the punch diameter was reached; then it leveled off. The authors attributed this to the confinement of the plastic zone by the elastic matrix. Near the surface the material can escape and form a lip around the hole, but for deep holes a plastic zone of 7 to 17 times the punch diameter is confined around the head of the punch by the elastically strained matrix. The strain associated with indentation has been determined by Atkins and Tabor.¹⁸ They compared indentation pressures for cones of various

¹⁴A. B. Watts and H. Ford, "An Experimental Investigation of the Yielding of Strip Between Smooth Dies," Proc. Inst. Mech. Eng. London (B) 1, 448-68 (1952).

¹⁵A. Nadai, Theory of Flow and Fracture of Solids, Vol. 2, pp. 467-71, McGraw, New York, 1963.

¹⁶R. T. Shield, "On the Plastic Flow of Metals Under Conditions of Axial Symmetry," Proc. Roy. Soc. (London) Ser. A 233, 267-87 (1955).

¹⁷R. F. Bishop, R. Hill, and N. F. Mott, "The Theory of Indentation and Hardness Tests," Proc. Phys. Soc. (London) A57, 147-59 (1945).

¹⁸A. G. Atkins and D. Tabor, "Plastic Indentation in Metals with Cones," J. Mech. Phys. Solids, 13, 149-64 (1965).

angles with stress-strain diagrams and were able to calculate a "representative strain." The value of this "strain" for a flat cylindrical punch is low, of the order of 2 to 3%. No corresponding estimates of any "average strain" associated with deep indentations appear to have been published.

EXPERIMENTAL

An indenter was pressed into the surface of soft metal samples, kept at room temperature, by the application of a constant load. The metal under the indenter moves to the side by creep allowing the indenter to sink slowly into the sample. For small depths - roughly the diameter of the punch - the displaced material forms a lip around the hole as shown in Figs. 1 and 2. The depth of penetration was recorded as a function of time. Figure 3 is a sketch of the experimental setup. To eliminate the influence of elastic deformation, the dial gage was set to zero reading after the load had been applied for 15 sec. The gage was difficult to zero exactly with the simple equipment used,

Fig. 1. Indentation of Cylindrical Punch in Tin. The plastically strained zone around the indentation has recrystallized during hardening of the Araldite mounting medium. 20X. Etchant: $\text{FeCl}_3\text{-HCl}$.

Fig. 2. Indentations on the Surface of a Tin Sample. The lip is clearly visible. Depth of indentations: plane strain indenter (upper row), left to right: 0.12, 0.50, 0.28 mm; cylindrical punch (lower row): 0.15, 0.75, 0.50 mm. Original sample diameter was approximately 25 mm.

Fig. 3. Apparatus Used for Indentation Creep Experiments.

but this does not seem to be important in this connection. The test was discontinued when a depth equal to the punch diameter had been reached, or, for lower loads, after 2 to 3 hr.

The major part of the work was performed with two different indenters. One had a rectangular cross section of 4.2×0.3 mm; the stress and strain conditions around this indenter were expected to be similar to plane strain conditions. The other indenter was a 1.4-mm-diam cylindrical punch. To evaluate the influence of the diameter of the punch, some tests were performed with cylindrical punches of other diameters. The indenters were machined from low-alloy tool steel and the surface was finished by filing. This leaves a rather rough surface, and one can expect full friction between the lower punch surface and the metal. The effect of friction along the vertical sides of the indenter was slight; it was always possible to withdraw an indenter from a hole or to reinsert it.

The applied loads were calculated so that the range of pressures obtained between tool and metal was similar to the range found during long-time hardness testing of the material in question.

The samples 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 paper through grit 600. All measurements for any one metal sample were performed on one side only.

For most of the holes the final lip width was estimated by measuring the width of visibly deformed material around the indentation.

RESULTS

The depth of indentation varies with time as shown in Fig. 4. The curve is a straight line of slope 2 in double logarithmic coordinates for times up to at least 115 hr. For this reason, depth was plotted versus the square root of time for all indentations. This gives a straight line in all cases, corresponding to a relationship

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

where D is the depth, S is the slope of the curve, and t is the duration of load application. The line does not always pass through the origin. Since repeated testing at the same load gives lines of approximately the same slope but different intercepts of the axes, this deviation was attributed to small variations in alignment between sample and indenter and to the previously mentioned difficulties of zeroing the dial gage. Since the slope S is the value of interest in this connection, no attempts were made to diminish the effect. The sample thickness does not influence the results for depths less than 10 to 15% of the thickness;

Fig. 4. Penetration of a 1.45-mm-diam Cylindrical Punch Under a Pressure of 2.45 kg/mm^2 Into Two Lead Samples of Different Thicknesses.

there appears to be a slowing down of the indenter motion for deeper holes. All further tests were performed at depths well below this limit.

Figure 5 shows some examples of the curves. The measured values of D are listed in Tables 1 through 7 and shown in Figs. 12 through 19 in the appendix; the values of the slope S are listed in Tables 8 and 9 also in the appendix. It should be pointed out that the relation described by Eq. (3) is not necessarily the only one that fits the data of this investigation. However, of the many different correlations tried it appears to give the closest fit.

The measured width of material displaced above the metal surface, the lip, is shown in Table 10 in the appendix and plotted in Figs. 6 and 7. The spread of these values is considerable, due to difficulties of determining the transition region between lip and undistorted surface. The data for the plane strain indentations fall around a line

Fig. 5. Examples of Penetration vs Square-Root-of-Time Curves.

Fig. 6. Square Root of Hole Depth vs Width of Lip for Plane Strain Indentations.

Fig. 7. Cube Root of Hole Depth vs Width of Lip for Cylindrical Punches.

$$L = 2.5 \sqrt[3]{D}, \quad (4)$$

where L is the lip width and D is the depth. The corresponding relation for the cylindrical punches is

$$L = 2.5 \sqrt[3]{D}. \quad (5)$$

The spread is too large to allow any determination of a possible influence of punch diameter; the data all seem to fall around the same curve. The deviation near the zero point in both cases may again be due to the zeroing difficulties.

In Fig. 8 the slope S is plotted versus p , the average pressure on the punch. In all cases a relation of the type

$$S \propto p^n \quad (6)$$

Fig. 8. Values of S Related to the Average Pressure on the Indenter Face.

is obtained. The values of n seem to be independent of punch size or shape and to depend only on the metal. The approximate values are 5.9 to 6.0 for indium, 5.5 for lead, and 3.3 for tin. A few values at very low pressures do not follow these relations. However, the data in question are obtained near the lower limit of apparatus capability, and thus do not necessarily signify any changes in the fundamental phenomena. It will be noticed that an increased punch diameter leads to a decrease in the pressure necessary to obtain a given value of S . This is shown in Table 11 (appendix) and in Fig. 9, where for a given S value

$$p = p_0 + C/A, \quad (7)$$

where p_0 and C are constants depending on S , and A is the punch area.

Fig. 9. The Pressure Required to Give Various Values of S for Indentation by Cylindrical Punches in Lead, Plotted as a Function of the Inverse Punch Area.

DISCUSSION

Equation (3) shows that the depth of penetration is proportional to the square root of time, $D \propto \sqrt{t}$, which implies that the rate of penetration is inversely proportional to the depth, $\dot{D} \propto D^{-1}$. This correlation can be explained qualitatively simply on the basis of the increase with depth of the distance that elements of the material must travel between the punch face and the sample surface. A more quantitative explanation

of the two expressions would require a detailed knowledge of the distribution of stress, strain, and strain rate in the region around the indenter.

The relations between lip width and depth of indentation, Eqs. (4) and (5), indicate that, in the range tested, the deformed regions corresponding to various hole depths are geometrically similar. This region is sketched for the plain strain indenter in Fig. 10. If an incremental penetration, dD , leads to the addition of a constant thickness increment $c dL$ to the lip, as sketched, then $dD \propto L dL$, or $L \propto \sqrt{D}$ as found experimentally [Eq. (4)].

Bishop, Hill, and Mott¹⁹ have presented theoretical solutions for the pressure necessary to expand either an infinitely long cylindrical hole or a spherical hole inside a metal. They show that the ratio c/a between the radius of the plastically strained zone and the radius of the hole is given by

$$\frac{c}{a} = \left[\frac{E\sqrt{3}}{2(1+\nu)Y} \right]^{1/2} \quad (8)$$

¹⁹R. F. Bishop, R. Hill, and N. F. Mott, "The Theory of Indentation and Hardness Tests," Proc. Phys. Soc. (London) A57, 147-159 (1945).

Fig. 10. Sketch of the Lip Formation and the Extent of the Plastically Strained Zone During Plane Strain Indentation Creep.

for the cylindrical hole, and

$$\frac{c}{a} = \left[\frac{E}{Y(1 + \nu)} \right]^{1/3} \quad (9)$$

for the spherical hole. In these expressions E is Young's modulus, Y the yield strength, and ν Poisson's ratio. The values of c/a in Eq. (8) are 39 and 52 for lead and tin, respectively; in Eq. (9) the value of c/a for lead is 12, for tin 17.5. The calculations and the data on which they are based are listed in Table 12 (appendix). These expressions are not directly applicable to the present case because the pressure here acts in only one direction and because only relatively shallow indentations are considered. They do, however, have an indirect bearing on the results of this investigation. They show that the strained zone will grow to 40 to 50 times the hole width for the plane strain case and approximately 15 times the hole diameter for the cylindrical punches. The highest values attained in the present investigation are 10 times for the plane strain indenter, at a hole depth of 1.5 times the indenter width, and a visibly deformed zone of 4 times the hole diameter for cylindrical punches at a hole depth of 1 diameter. This is in agreement with the findings by Bishop, Hill, and Mott¹⁹ that the full plastic zone is not attained until the depth of indentation is at least four times the punch diameter.

The factor of main interest in a discussion of creep at constant temperature is the relation between creep rate and stress, generally of the form

$$\dot{\epsilon} \propto \bar{\sigma}^n \quad (10)$$

Unfortunately, the strains around an indentation are not known, except for Tabor's previously mentioned determination of an average value for initial indentation. Thus, an exact determination of the strain rate is impossible for the time being.

The same holds true for the stress distribution under the unlubricated indenter. The relation of Eq. (6) gives values of n equal to those

published for the uniaxial case of Eq. (10). For lead the result of the present investigation is $n = 5.5$, for indium $n = 5.9$ to 6.0 . For uniaxial tests Weertman²⁰ obtained $n = 4.5$ in both cases, while Gifkins²¹ found a value near 6 for lead tested at room temperature. This indicates that S is related to $\dot{\epsilon}$ in a way similar to the relation between p and $\bar{\sigma}$, or

$$\dot{\epsilon}/S \propto \bar{\sigma}^n/p^n. \quad (11)$$

For the sake of simplified discussion one may assume that a hydrostatic pressure of the order of $\bar{\sigma}$ of Eq. (10) is acting throughout the plastic zone. For the plane strain indenter $pd = \bar{\sigma}w$, where d is the indenter width, L is the width of the lip, and $w = 2L + d$ is the width of the plastically strained zone (see Fig. 10). Substituting into Eq. (11):

$$\dot{\epsilon} \propto (d/w)^n S = [d/(2L + d)]^n S. \quad (12)$$

Thus, S represents the strain rate for constant hole depth (i.e. constant L) and for constant indenter size.

By combining Eqs. (11) and (12), one obtains

$$p \propto (2L/d + 1)\bar{\sigma} \quad (13)$$

which, for constant values of L (constant D) and of $\bar{\sigma}$ (approx constant S at constant D), may be written

$$p = p_0 + \text{const}/A, \quad \text{Eq. (7)}$$

where A is the punch area. The experimentally found decrease in the punch pressure necessary to obtain a given value of S with increased

²⁰J. Weertman, "Creep of Indium, Lead, and Some of their Alloys with Various Metals," Trans. Met. Soc. AIME 218, 207-18 (1960).

²¹R. C. Gifkins, discussion of Weertman's paper (ref. 20), ibid., 1128-29.

punch diameter (Fig. 9) is thus due to the influence of punch size on the size of the plastic zone and thereby on the effective stress for deformation.

The relation of penetration rate to strain rate is of some interest. For a constant punch size a given depth of penetration will presumably correspond to a given strain.²² From Eq. (3)

$$\frac{dD}{dt} = \dot{D} = \frac{S}{2\sqrt{t}} = \frac{S^2}{2D} \quad (14)$$

Since $S \propto \dot{\epsilon}$ at constant depth D :

$$\dot{\epsilon} \propto D^{1/2} \quad (15)$$

for constant depth of penetration and constant punch diameter.

A more detailed treatment of the stress-strain rate relations during indentation creep must await further investigation. However, it is apparent that a simple indentation creep test is a useful tool for obtaining preliminary values of n in the low-stress region.

An illustration of the difficulty associated with strain and strain rate determinations is offered by Fig. 11. As mentioned by Hill²³ a cap of dead metal seems attached to the end of the indenter. The flow of metal is very heavy at the end of this cap and around the corners of the punch but apparently quite small in other regions.

²²A. B. Watts and H. Ford, "An Experimental Investigation of the Yielding of Strip Between Smooth Dies," Proc. Inst. Mech. Eng. London (B) 1, 448-68 (1952).

²³R. Hill, The Mathematical Theory of Plasticity, pp. 254-62, Oxford University Press, London, 1950.

Fig. 11. Deformation Lines Around End of Plane Strain Indentation in Tin. 200X. Heavily etched in HF-HNO_3 to reveal the lines.

CONCLUSIONS

1. For shallow indentations produced by creep taking place under a constant load, the depth of penetration D is related to the duration of load application t according to $D = S\sqrt{t}$.
2. The width of the lip around the holes is proportional to $\sqrt{D}$ for plane strain indentation and to $\sqrt[3]{D}$ for indentation by cylindrical punches.
3. The slope S is related to the average pressure on the indenter face according to $S \propto p^n$. The values of n are the same as in the creep relation for uniaxial test, $\dot{\epsilon} \propto \bar{\sigma}^n$. For a given depth of penetration and size of indenter, S is shown to represent $\dot{\epsilon}$. This means that $\dot{\epsilon} \propto \dot{D}^{1/2}$ where $\dot{D}$ is the indentation rate.
4. The pressure to obtain a given value of S decreases with increased area for the cylindrical punches. This effect is due to the influence of punch size on the size of the plastically strained zone.

5. Although a detailed determination of the stresses and strains associated with the indentation is not possible, the results show that the simple indentation test affords a means of rapidly estimating values of stress-strain rate relations.

APPENDIX

- Table 1. Depth vs Time for Plane Strain Indenter in Lead
- Table 2. Depth vs Time for Plane Strain Indenter in Tin
- Table 3. Depth vs Time for Plane Strain Indenter in Indium
- Table 4. Depth vs Time for 1.45-mm-diam Cylindrical Punch in Lead
- Table 5. Depth vs Time for 1.45-mm-diam Cylindrical Punch in Tin
- Table 6. Depth vs Time for 1.45-mm-diam Cylindrical Punch in Indium
- Table 7. Depth vs Time for Cylindrical Punches of Various Diameters in Lead
- Fig. 12. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Lead at 3.2 kg/mm².
- Fig. 13. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Lead.
- Fig. 14. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Tin.
- Fig. 15. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Indium.
- Fig. 16. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Lead.
- Fig. 17. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Tin.
- Fig. 18. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Indium.
- Fig. 19. Depth vs $\sqrt{t}$ for Cylindrical Punch of Various Diameters Indenting Lead.
- Table 8. Slope of Depth-vs-Square-Root-of-Time Curves for the Plain Strain Indenter
- Table 9. Slope of Depth-vs-Square-Root of Time Curves for the Cylindrical Punches
- Table 10. Final Lip Width and Hole Depth
- Table 11. Pressure Required to Give Various Values of S , the Slope of the Penetration-vs-Square-Root-of-Time Curve in Lead.
- Table 12. Calculation of c/a Ratio (Radius of Plastically Strained Zone to Radius of Hole)

Table 1. Depth vs Time for Plane Strain Indenter in Lead

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm^2)											
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 12	Run 10	Run 11	Run 8	Run 9
	3.2	3.2	3.2	3.2	3.2	3.45	3.45	4.90	2.08	2.08	2.66	2.66
1	33	23	25	13	33	13	20	117	5	5	20	30
1.5								150				
2	51	69	47	30	56	56	33	175	25	15	43	43
3	71	84	61	41		79	51	216		18		51
4	84	100				96	81	252			56	
5	96	110	76	59	97	117	100	277	28	19		58
6								308				
7									31		84	
8	127	137	104	76	130	155						
10				85		183	173			24		82
13											100	89
15	201		150	116			232					
18									41			
20	231	223			250		267					
25				160		282	291					
28			220		275							
30	287			178	282	302			46	33		116
35				191								
40										43	166	
45			280									
46									48			145
52			298									
60										46		175
76											205	195
110										52	230	
125									75			

Table 1 (continued)

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm ²)											
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 12	Run 10	Run 11	Run 8	Run 9
	3.2	3.2	3.2	3.2	3.2	3.45	3.45	4.90	2.08	2.08	2.66	2.66
137										54		240
150									80		265	252
170									81		284	
180												276
188										65		
200									84	66	303	

Table 2. Depth vs Time for Plane Strain Indenter in Tin

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm^2)						
	Run 7	Run 6	Run 1	Run 2	Run 3	Run 4	Run 5
	2.08	2.66	3.21	3.21	4.12	4.90	5.70
1	10	10		15	20	10	33
1.5			20				
2		20		25	30	25	61
3	25	25	28	28	40		84
4			30	31		48	104
5		28	33		46		125
7	33	33					
8	43					76	162
10	46		51	51		91	
13						105	208
18	51				97		
20		56		59	102	148	
22							254
26						178	302
35	60					206	
40		76		76			
45	68		98			246	
65		92	112	97	190		
90			127	107			
103	79	105			249		
138	81		150		282		
150		119		145			
160	89		158		306		
175				150			
190	96	126					
200	97		178	170			

Table 3. Depth vs Time for Plane Strain Indenter in Indium

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm^2)							
	Run 8	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
	0.502	0.634	0.634	0.79	0.79	0.95	0.95	1.03
1	3	5	5	8	20	41	31	76
1.5						69		122
2			13	20	38	91	52	145
3		20	18		46	127	64	178
4		23			51	165	99	211
5						204	107	
6								249
7		33	22		71	285		
8							147	287
10				33	82			
12							198	
15		56	27	46	97			
20	20			53			284	
31		75		66				
45	28	81		80	150			
62		89	52	107	174			
71			53	116	180			
80	34	99		130				
106	46	105						
130	47	114		188				
140		122	78		234			
156			81	208				
180	58	131	91		295			
200	68	142	97					
217				267				

Table 4. Depth vs Time for 1.45-mm-diam Cylindrical Punch in Lead

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm^2)						
	Run A	Run C	Run S	Run D	Run E	Run F	Run B
	2.02	2.02	2.25	2.43	2.43	2.73	3.12
1	3	0	3	3		13	8
2		5	8	8		20	25
3	5				28	25	
5			20	25		30	
7	9				53		41
10		5	43	51	61	71	
15	24	5	50			89	
17				74			135
20	31		53			103	170
30			69	104	135	135	
34		13					223
40			76	117	157	165	
57	44		120				398
68		13				188	454
80							482
91		20	142			231	
112	48			226	249		
136				258		298	
152		20	202				
168				286	302		
200		25	249	310			
210	55			312	355		
240					373		
330					426		
450					482		
1140				729			
1260				784			
1380					813		
1500					858		
1620				860			
1740					894		
1860					920		
2580				1020			
2880				1095	1210		
3000					1218		
3090				1148			
3300					1288		
4440					1440		
4620					1470		
6900				1180			

Table 5. Depth vs Time for 1.45-mm-diam Cylindrical
Punch in Tin

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm ²)				
	Run A	Run B	Run C	Run D	Run E
	2.02	3.12	3.54	3.74	4.32
1	5	10	3	13	25
2		20	8		43
3	10	25			53
4			20	38	73
6	20			51	
11	23	44		76	
14	24		41		150
23			51	118	203
40		75	72	163	284
50	29	82	84	185	
73				231	406
100				277	535
112		130			
127			156		
140	50	150		330	
160	51				
191			200		
195					742

Table 6. Depth vs Time for 1.45-mm-diam Cylindrical Punch
in Indium

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm ²)			
	Run C	Run D	Run A	Run B
	0.48	0.60	0.72	0.72
1	3	7	18	15
2	5	4	28	25
3		25		
4			46	
5		30		51
8		46		69
12		53		84
18	29		112	107
24			132	178
30	33	91	159	207
35			165	257
40		125		282
50	46	146		
54			277	
67		165		
70				460
77		178	391	
91		185	482	
100			528	586
115		206		
141	71			
145		231		
155	75			
169	81			
210	86			

Table 7. Depth vs Time for Cylindrical Punches of Various
Diameters in Lead

Time (min)	Depth (μ) of Penetration at Pressure (kg/mm^2)									
	1.12-mm-diam punch			1.92-mm-diam punch			2.43-mm-diam punch			
	Run I	Run H	Run G	Run L	Run K	Run M	Run N	Run O	Run R	Run P
	2.23	2.68	3.41	1.65	2.27	2.70	1.69	2.00	2.40	2.56
1	5	5	28	5	8	5	2	5	10	18
2	8	18	58	13	25	20	2		25	43
5	20	28	107	28	53		4	13	76	94
10	24	38	196	30	79	122		20		175
15	25	53	265		109					231
20	26	56	335		153	228		23		284
25		69		46	181	274			244	
30	28	79			203	325				406
40	30	96	502	50	239	380		25	333	513
50	36	109	561	51	274		31			
60	52	145		52	305	533	34		435	680
80	64			63	376		43	58	530	
100	70			73	440	689	49	76		
120	71			75			51	96		
150	76				530		52	132		
180							53			
200							56

Fig. 12. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Lead at 3.2 kg/mm^2 .

Fig. 13. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Lead.

Fig. 14. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Tin.

Fig. 15. Depth vs $\sqrt{t}$ for Plane Strain Indenter in Indium.

Fig. 16. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Lead.

Fig. 17. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Tin.

Fig. 18. Depth vs $\sqrt{t}$ for Cylindrical Punch, $d = 1.45$ mm, in Indium.

Fig. 19. Depth vs $\sqrt{t}$ for Cylindrical Punch of Various Diameters Indenting Lead.

Table 8. Slope of Depth-vs-Square-Root-of-Time Curves
for the Plane Strain Indenters

Metal	Run	Average Pressure (kg/mm ²)	Slope ($\mu/\text{min}^{1/2}$)
Tin	7	2.08	4.6
	6	2.66	7.5
	1	3.21	10.5
	2	3.21	10.9
	3	4.12	24.3
	4	4.90	41.0
	5	5.70	66.5
Indium	8	0.502	4.7
	1	0.634	7.9
	2	0.634	6.7
	3	0.79	22.9
	4	0.79	21.3
	5	0.95	135.0
	6	0.95	77.5
	7	1.03	127.5
Lead	10	2.08	5.2
	11	2.08	3.9
	8	2.66	19.4
	9	2.66	19.3
	1	3.2	58.9
	2	3.2	49.5
	3	3.2	45.4
	4	3.2	37.7
	5	3.2	56.7
	6	3.45	68.3
	7	3.45	76.6
	12	4.90	129.7

Table 9. Slope of Depth-vs-Square-Root-of-Time Curves
for the Cylindrical Punches

Metal	Run	Punch Diameter (mm)	Average Pressure (kg/mm ²)	Slope ($\mu/\text{min}^{1/2}$)
Tin	A	1.45	2.02	3.5
	B	1.45	3.12	12.0
	C	1.45	3.54	15.0
	D	1.45	3.74	29.8
	E	1.45	4.32	52.0
Indium	C	1.45	0.48	6.2
	D	1.45	0.60	20.9
	A	1.45	0.72	94.3
	B	1.45	0.72	84.7
Lead	A	1.45	2.02	2.4
	C	1.45	2.02	1.8
	S	1.45	2.25	21.1
	D	1.45	2.43	24.3
	E	1.45	2.43	25.3
	F	1.45	2.73	27.3
	B	1.45	3.12	76.1
	I	1.12	2.23	6.5
	H	1.12	2.68	17.2
	G	1.12	3.41	89.8
	L	1.92	1.65	5.5
	K	1.92	2.27	49.1
	M	1.92	2.70	91.0
	N	2.43	1.69	10.1
	O	2.43	2.00	17.0
	R	2.43	2.40	64.5
	P	2.43	2.56	101.0

Table 10. Final Lip Width and Hole Depth^a

Run	Indenter Dimensions	Lead		Tin		Indium	
		Depth	Lip	Depth	Lip	Depth	Lip
1	4.2 × 0.3	0.508		0.178	0.65	0.142	0.65
2		0.480	1.45	0.170	0.75	0.096	0.65
3		0.477		0.335	1.05	0.266	
4		0.340	1.2	0.480	1.45	0.320	1.05
5		0.543	1.35	0.456	2.0	0.53	1.45
6		0.454	1.25	0.126	0.95	0.515	1.45
7		0.529	1.35	0.097	0.5	0.46	1.35
8		0.302	1.35			0.094	0.3
9		0.276	1.05				
10		0.084	0.35				
11		0.066	0.30				
12		0.513	1.7				
X	4.7 × 0.7			0.38	2.5		
Y				0.51	2.65		
Z				0.48	2.8		
A	1.45 diam	0.055	0.40	0.050	0.30	0.530	1.75
B		0.495	1.95	0.150	1.30	0.585	1.65
C		0.025	0.30	0.200	1.55	0.085	0.35
D		1.45	2.35	0.331	1.70		
E		1.45	2.1	0.740	2.10		
S		0.25	1.2				
G	1.12 diam	0.50	1.7				
H		0.17	0.75				
I		0.075	0.60				
K	1.92 diam	0.53	1.75				
L		0.075	0.80				
M		0.83	1.95				
N	2.43 diam	0.055	0.60				
O		0.135	0.90				
P		1.00	1.95				
R		0.53	1.80				

^aAll numerical values are in millimeters.

Table 11. Pressure Required to Give Various Values of S, the Slope of the Penetration-vs-the-Square-Root-of-Time Curve in Lead

Indenter	Pressure (kg/mm ²) to Give Each Slope ($\mu/\text{min}^{1/2}$)		
	1	10	100
Plane strain indenter	1.59	2.40	3.62
1.12-mm-diam punch	1.58	2.38	3.60
1.45-mm-diam punch	1.37	2.10	3.20
1.92-mm-diam punch	1.20	1.82	2.78
2.43-mm-diam punch	1.11	1.72	2.58

Table 12. Calculation of c/a Ratio (Radius of Plastically Strained Zone to Radius of Hole)^a

Quantity	Lead	Tin	Average
Data used	(b)	(c)	
E, psi	2×10^6	6.0 to 6.5×10^6	
ν	0.40 to 0.45	0.33	
Y, psi	800	1500	
Value of c/a			
for cylindrical hole	12.1	17.6	14.6
for spherical hole	39	52	46.5

^aFormulas for c/a: cylindrical, $[E\sqrt{3}/2Y(1 + \nu)]^{1/2}$, Eq. (8); spherical, $[E/Y(1 + \nu)]^{1/3}$, Eq. (9).

^bT. Lyman, ed., Metals Handbook, 1948 Edition, American Society for Metals, Metals Park, Ohio, 1948, p. 961.

^cibid, pp. 1070-72.

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