Scratch Hardness. I : Relation to Cold-Working

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Scratch Hardness. I
Relation to Cold-Working*

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Synopsis

The scratch hardness was examined with polycrystals and single crystals of several metals. The law similar to the Meyer's in the indentation hardness held good between the load and scratch width. The change in scratch width with cold-working was very small, which was explained as being due to the heat evolved during scratching. Consequently, the scratch hardness, contrary to Tammann's interpretation, be related rather to annealed state than to severely hardened state of a metal.

I. Introduction

Since Mohs(1) proposed the famous scale of the hardness, the scratch hardness has been used in mineralogy, and the method similar to this was devised for metals and alloys, but it has scarcely been used in practice. This is mainly because the nature of the scratch hardness is not so obvious as the indentation hardness besides more or less troublesome procedures. The relation between the scratch hardness and the indentation hardness has been examined(2) extensively, and recently a remarkable regularity(3) has been shown in the indentation hardness of the standard minerals adopted by Mohs. On the other hand, it is generally known that the scratch hardness scarcely changes with the strain-hardening of a metal.

Faust and Tammann(4) showed with polycrystalline zinc, copper and cadmium that the change in the scratch width with cold-working was very small, being of the order of 0.003 mm under a small load. Körber and Wieland(5) reported the results similar to this on polycrystalline brass having various compositions, that is, the change in the scratch width due to the increase of the reduction by cold-rolling was very small, being only 0.002 mm at the maximum reduction of 70 per cent under the load of 5~30 g irrespective of the compositon. From these results, Tammann(6) concluded that the scratch hardness was related to the state of maximum hardening of a metal and so it was not influenced by the previous history of the metal. If this is the case, the scratch hardness may be said to be a mechanical constant of a metal in the extreme state.

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* The 901st report of the Research Institute for Iron, Steel and Other Metals.

(1) F. Mohs *Grundriss der Mineralogy*, Dresden (1822).

(2) H. O'Neill, *The Hardness of Metals and its Measurements*, (1934).

(3) D. Tabor, Proc. Phys. Soc., **B67** (1954), 249.

(4) O. Faust and G. Tammann, Z. phys. Chem., **75** (1911), 108.

(5) F. Körber and P. T. H. Wieland, Mitt. K. W. I. f. Eisenf., **3** (1921), 57.

(6) G. Tammann, *Lehrbuch der Metallkunde*, (1932).

On the other hand, O'Neill(7) investigated the scratch hardness of polycrystalline metals and alloys with his ball sclerometer having a cone of hemispherical diamond, 1 mm in diameter, in place of the conical diamond of Martens' type. The load was very large, ranging from 100 to 1000 g, as compared with that used by Tammann and others. The decrease in the scratch width of polycrystalline aluminium with cold-drawing amounted to 0.038 mm and that of polycrystalline copper and steel was less than 0.01 mm, which were very large compared with the previous results. O'Neill concluded from his results that the scratch handness was quite sensitive to strain-handening, and that it might be used to see the work-hardening capacity of a metal. Later on, Tammann and Tampke(8) carried out the experiment same as their previous works with the load comparatively large but smaller than that used by O'Neill, that is, in the range from 55 to 100 g, and confirmed their previous results which were contrary to those by O'Neill.

The reason for the discrepancy between these results is because the experimental conditions are not all equal to one another; especially, the former works were based almost on polycrystalline metals, and consequently, the grain boundaries might mislead the observation in the case of fine-grained structure.

Such being the case, the present study was carried out mainly with single crystals to see the relation of the scratch hardness to the load together with its dependence on work-hardening.

II. Method of experiment

Metals used were aluminium of 99.99 per cent, electrolytic copper of 99.9 per cent, iron of 99.4 per cent, distilled magnesium of 99.99 per cent and electrolytic zinc of 99.99 per cent in purity. Specimens of single crystals and polycrystals were polished electrolytically, and the Martens' scratch hardness was measured at the load ranging from 3 to 100 g. The microindentation hardness was determined with the specially designed apparatus(9).

In the case of the scratch hardness, the mean of the four readings in one track was taken as its width, and the mean width of four tracks was taken as the scratch width of the metal. The microindentation hardness was determined from the average of five impressions.

Specimens were subjected at room temperature mostly to cold-rolling up to about 90 per cent reduction, and in some cases to tensile elongation.

III. Experimental results

The relation between the scratch width and the load in polycrystalline aluminium, copper, magnesium and zinc is shown in Fig. 1, from which it will be seen first that the order of the scratch hardness is consistent with that of the indentation hardness, and that the curves are all parabolic. The same held good also

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(7) H. O'Neill, Carnegie Schl. Mem., **17** (1926), 109.

(8) G. Tammann and R. Tampke, Z. Metallk., **28** (1936), 360.

(9) T. Hikage, Sci. Rep. RITU, **A5** (1953), 254.

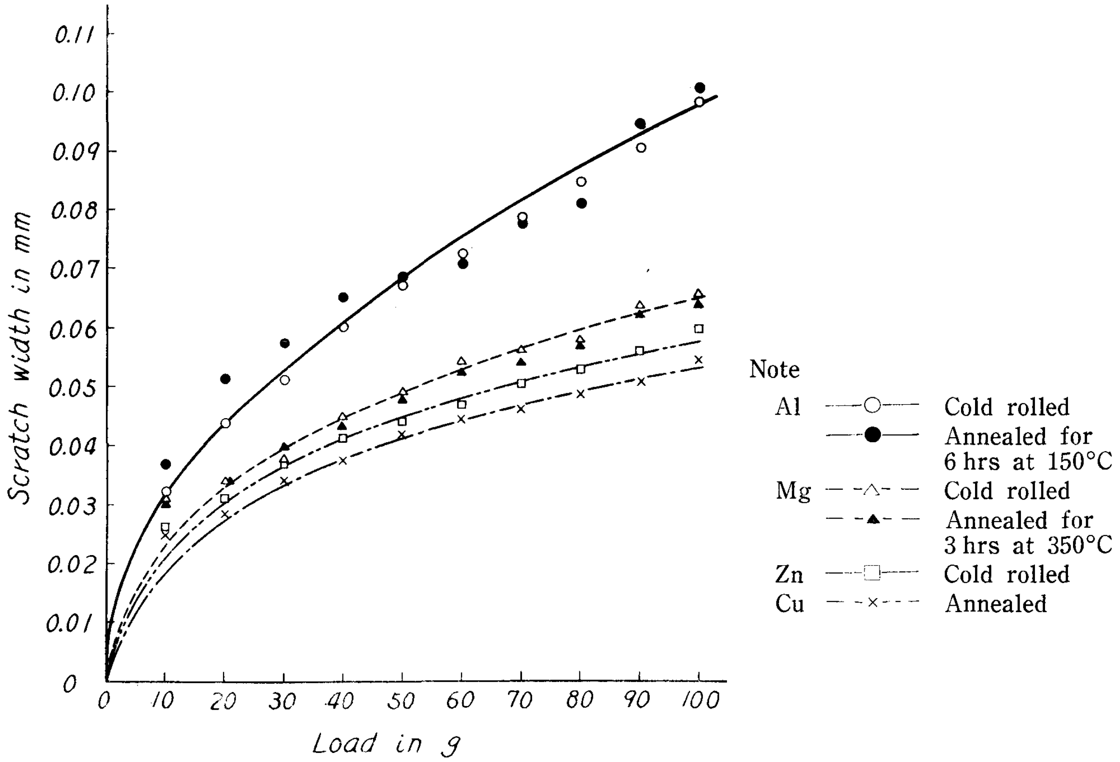


Fig. 1. The load-scratch width relation in polycrystalline metals.

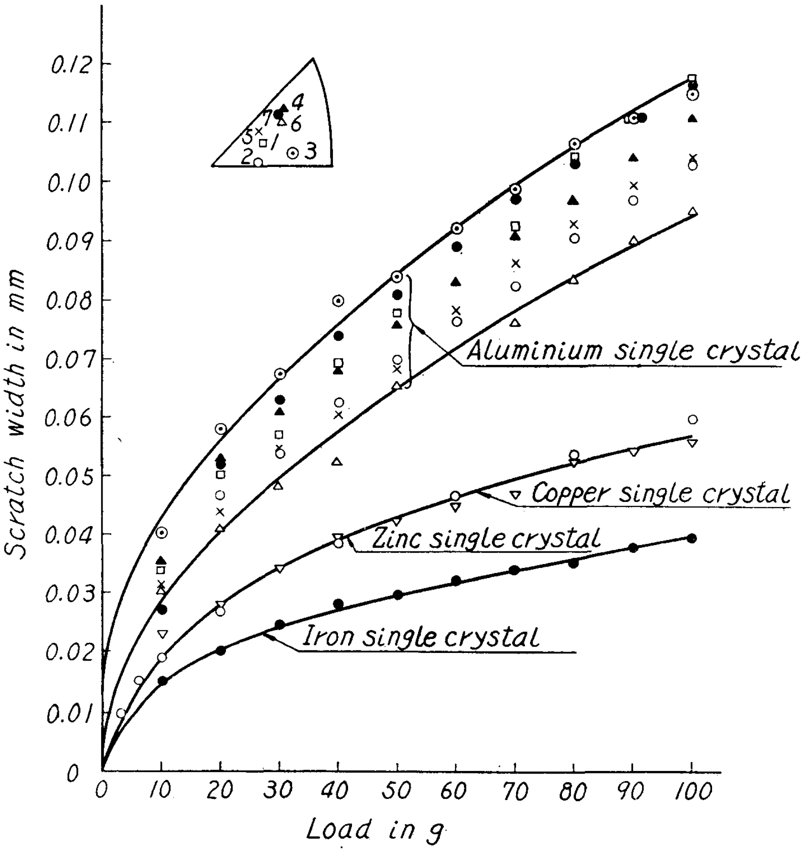


Fig. 2. The load-scratch width relation in single crystals together with the orientation normal to the surface of aluminium single crystal.

in the case of single crystals of these metals as will be seen below. Further, no conspicuous difference in the scratch width was observable between the cold-rolled state and the annealed state in the case of aluminium and magnesium irrespective of the load as shown in the figure. Therefore, the scratch width seemed independent of cold-working, the detailed examination of which will be shown below. The results on single crystals were similar to the above but with minute scattering as shown in Fig. 2. This must be due surely to the absence of grain-boundaries.

As mentioned above, the relation between the load and the scratch width seemed parabolic, and so the logarithmic plotting was made. The results are shown in Fig. 3, in which the result on aluminium crystal is obtained from the specimen 3 in Fig. 2. The relation similar to the Meyer's law in the indentation hardness will be led from this, that is,

$$L = kd^n ,$$

where L is the load, d the scratch width, and k and n the constants. The numerical values of n calculated by the above equation are shown in Table 1 with other remaks. n lies in the range from 1.8 to 2.1 in aluminium single crystal, and is nearly equal to 2.0 in copper, and slightly

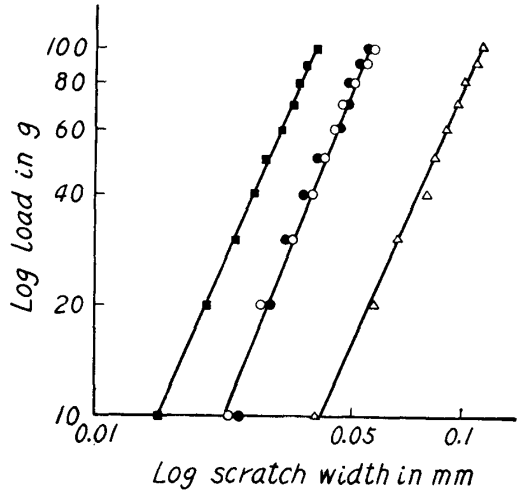


Fig. 3. The log load-log scratch width curves of single crystals shown in Fig. 2.

—■— Iron crystal
—○— Copper crystal
—●— Zinc crystal
—△— Aluminium crystal 3

Table 1

Metal		n		Meyer's constant	Remark
		$n_{\parallel}$	$n_{\perp}$		
Aluminium single crystal	1	1.92	1.91	1.89	
	2	1.85	1.86		
	3	2.14	1.94	1.96	
	4	2.01	1.93		
	5	1.94	1.92		
	6	2.03	1.98	1.89	
	7	2.01	2.01		
	8	1.86			annealed state
	,,	1.86			rolled 90 per cent
Aluminium polycrystal		2.22			
Copper single crystal	1	1.98			
	2	2.05		1.82	
	3	2.04			annealed
	,,	1.93			rolled 70 per cent
Zinc single crystal	1	2.21	2.16		
	2	2.05			
Iron single crystal		2.36		1.93	
Magnesium polycrystal		2.51			rolled
		2.51			annealed 3hrs at 350°C

higher than 2.3 in iron. n is independent of the high strain-hardening in aluminium single crystal and polycrystalline magnesium, though in copper single crystal it varies from 2.04 to 1.93, as shown in the table. It will also be seen in Fig. 2 that the scratch width varies with the orientatin of the crystal, especially conspicuously in aluminium. This relation was observed also by O'Neill(7) with single crystals of aluminium and silicon-iron alloy.

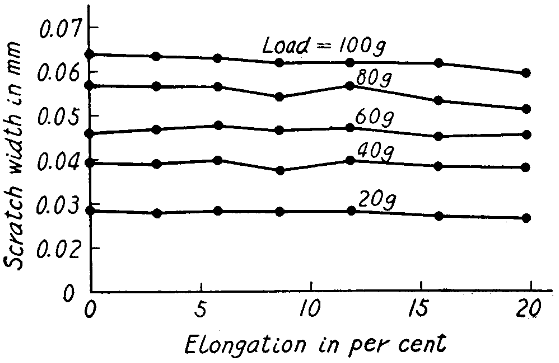


Fig. 4. The change in scratch width with elongation on copper crystall.

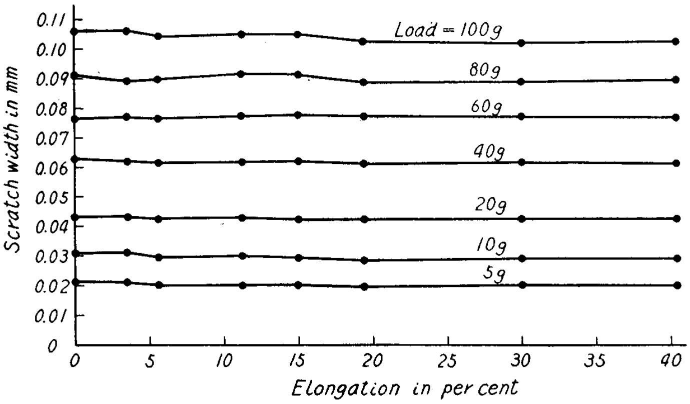


Fig. 5. The change in scratch width with elengation on aluminium single crystal.

Next, the variation of the scratch width with the cold-working was examined. The results on copper and aluminium single crystals subjected to tensile elongation are shown in Figs. 4 and 5, respectively. As seen in these figures, the decrease in the scratch width with increasing deformation is very small irrespective of the load, being at most only a few per cent of the value in the annealed state. The result quite similar to this was also obtained with zinc crystals. To confirm this point further, similar measurements were carried out with the colled-rolled single crystals of aluminium and copper, the results of which are shown respectively in Figs. 6 and 7. No qualitative difference was observable between the changes in the scratch width with the increasing reduction in the two directions parallel and perpendicular to the rolling, and so the mesurements were carried out only in the direction parallel to the rolling. In the case of copper crystal, the width decreased gradually with the increase in the reduction irrespective of the load, as shown in Fig. 6. The widths in the initial and the final states are shown in Table 2, from which the maximum and the minimum decrease of the width were respectively 1.9μ and 1.6μ, when the reduction was approximately 70 per cent. The result for aluminium crystal was quite similar, but with somewhat larger change in width than that for coper, being nearly 4μ, as seen from Table 2. These results are in good agreement with those of Tammann and others on polycrystalline metals. Futher, a comparison was made between the changes in the indentation hardness and the scratch hardness during the course of cold-rolling by using the same load of 20 g. The results for aluminium and copper crystals are

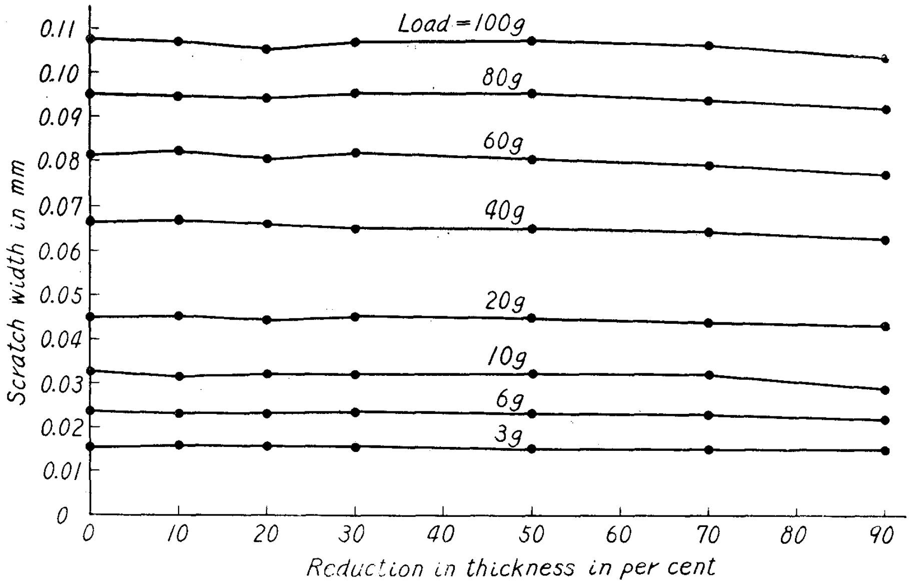


Fig. 6. The change in scratch width with cold-rolling on copper single crystal.

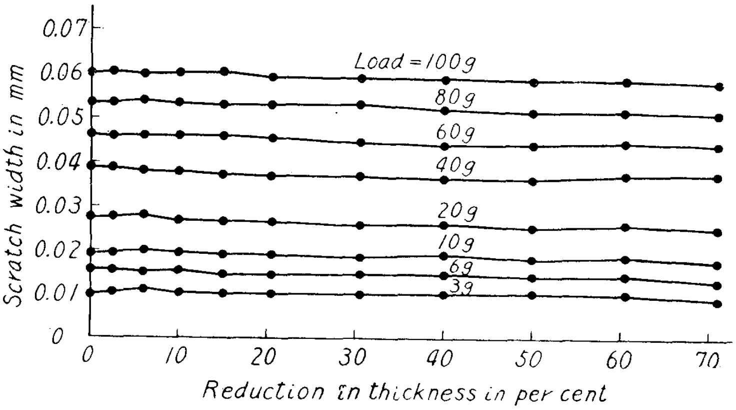


Fig. 7. The change in scratch width with cold-rolling on aluminium singl crystal.

Table 2

Metal	Load (g)	Scratch width (mm)		Difference of width (m)
		initial	final	
Copper			rolled 71%	
	10	0.0194	0.0175	0.0019
	40	0.0390	0.0374	0.0016
	100	0.0600	0.0582	0.0018
Aluminium			rolled 90%	
	10	0.0327	0.0293	0.0034
	40	0.0666	0.0629	0.0037
	100	0.1074	0.1035	0.0039

shown in Figs. 8 and 9, respectively. The change in the scratch width with cold-rolling was quite similar to that mentioned above for both crystals, but the diagonal length of the indentation decreased conspicuously with increasing reduction, that is, the indentation hardness increased from 18.3 to 30.6 kg/mm^2 in aluminium crystal and from 32.9 to 95.6 kg/mm^2 in copper crystal. The scratch hardness, however, did not vary so conspicuously, giving the mean value of 20±1 kg/mm^2 in aluminium crystal and 55±5 kg/mm^2 in copper crystal, respectively, as seen in the figures; in other words, in metallic crystals the change in the scratch hardness with cold-rolling is very small, being of the order of a few per cent even when they are subjected to the severe reduction of 90 per cent.

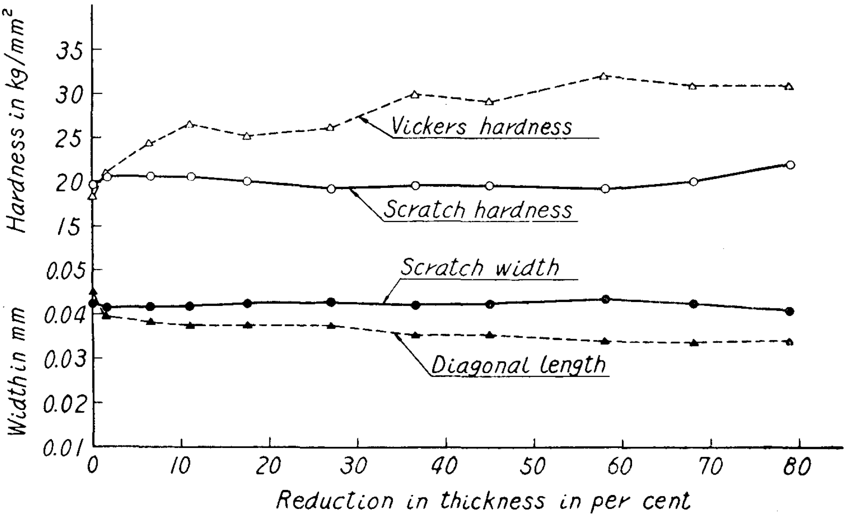


Fig. 8. The changes in width and hardness with cold-rolling on aluminium single crystal.

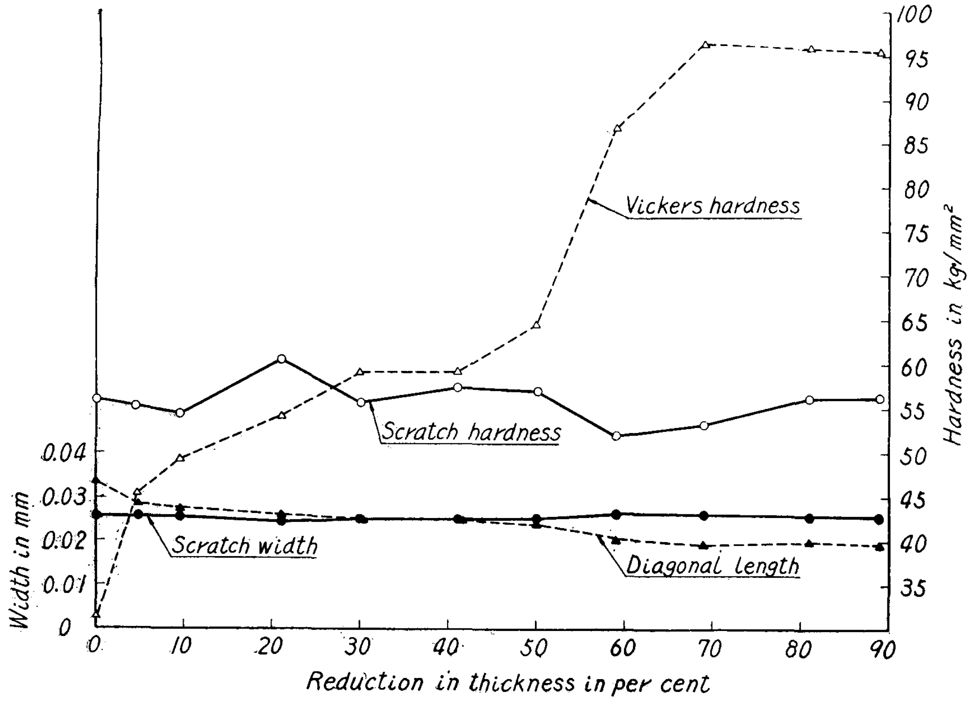


Fig. 9. The changes in width and hardness with cold-rolling on copper single crystal.

Finally, the same experiment was also carried out with polycrystalline metals. As an exmple, the result on copper is shown in Fig. 10. As shown in the figure, the change in width with increasing reduction is quite similar to that in the case of single crystal, and further, it will be seen that the width is of the same order of magnitude as that in single crystal, especially at small load. Therefore, as regards the change in scratch hardness with cold-working, no different feature exists between single crystal and polycrystal of a metal.

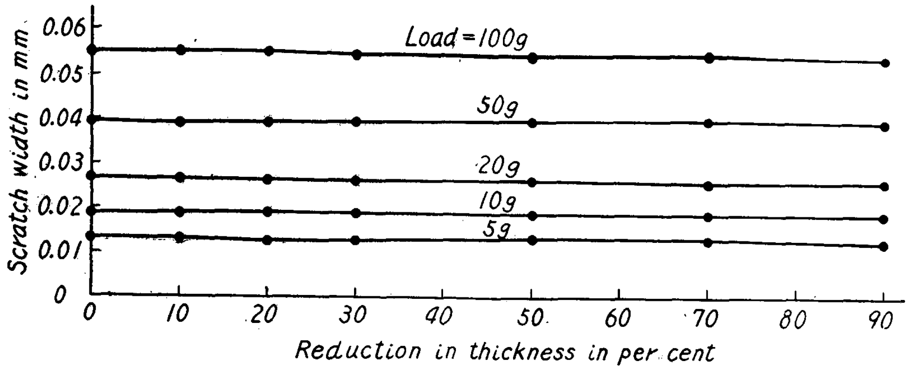


Fig. 10. The change in scratch width with cold-rolling on polycrystalline copper.

The microscopic observations of the scratched track on single crystals will briefly be mentioned below. The microphotographs of the tracks on the single crystals of aluminium, iron, zinc and copper are shown in Photos. 1~4, respectively. The tracks in the directions parallel and perpendicular to the specimen axis are quite different from each other. The slip lines and ripples irregularly develop around the track, which seem dependent on the orientation as clearly observable in these photographs. In aluminium crystals, two types of tracks are observable, in one of which the track edge is nearly straight and the slip lines and ripples develop densely, and in the other, the track edge is serrated and the slip lines and ripples are less dense than the former, as shown in Photos. 1a and 1b. Such an abnormal track was hardly observable in other metals. In zinc crystal, twin traces are clearly observable besides the slip lines and ripples. The changes in the tracks parallel to the specimen axis with increasing reduction are shown in Photos. 5 for copper crystal. It will be seen that the slip lines around the track become less dense with increasing reduction together with a decrease in width.

To see the effect of scratching the matrix, the indentation hardness was measured in the vicinity of the track.

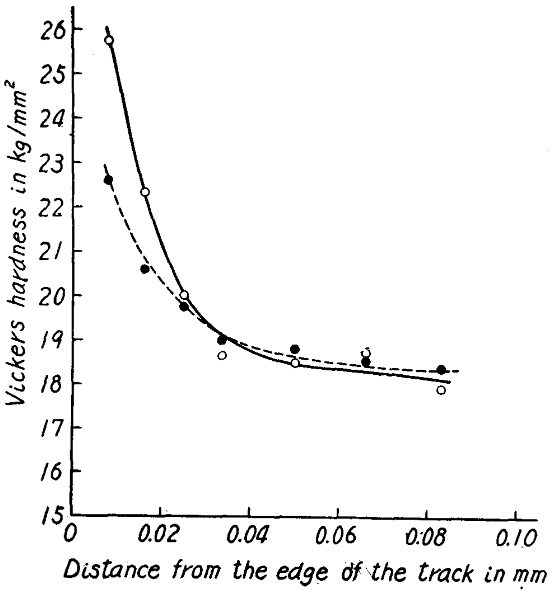


Fig. 11. Variation of the hardness with the distance from the edge of the track.
—○— Perpendicular to the specimen axis,
—●— Parallel to the specimen axis.

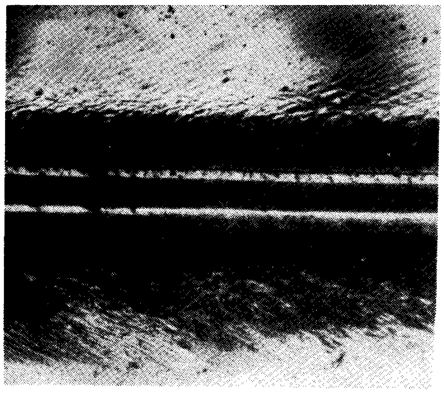
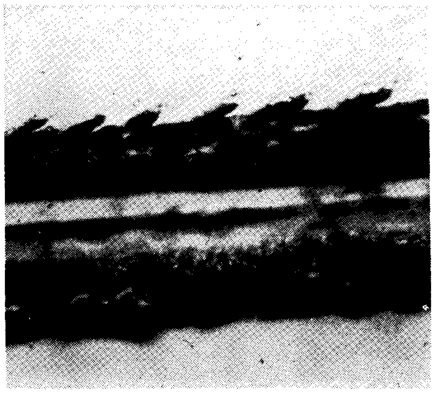

(a)

Photo. 1
Aluminium crystals


(b)

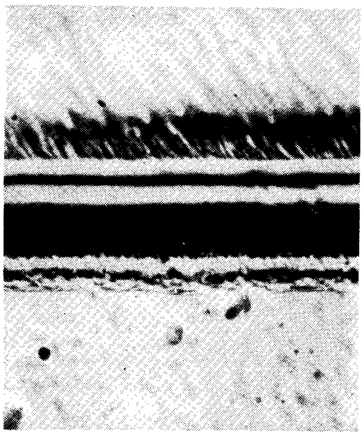
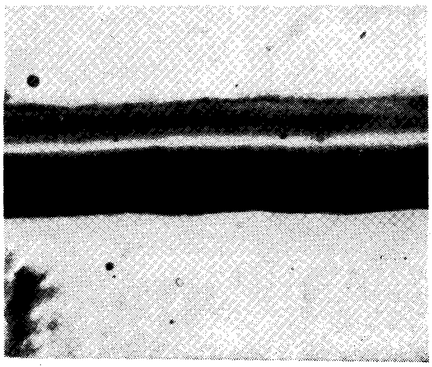
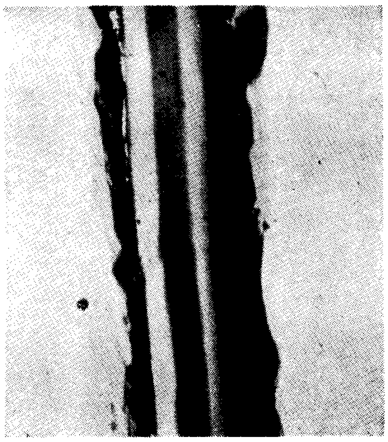

(a)

Photo. 2
Iron crystal


(b)


(a)

Photo. 3
Zinc crystal


(b)

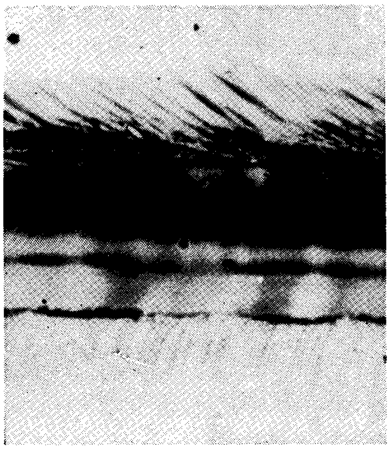
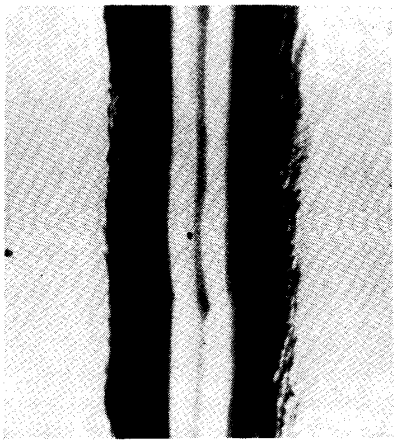
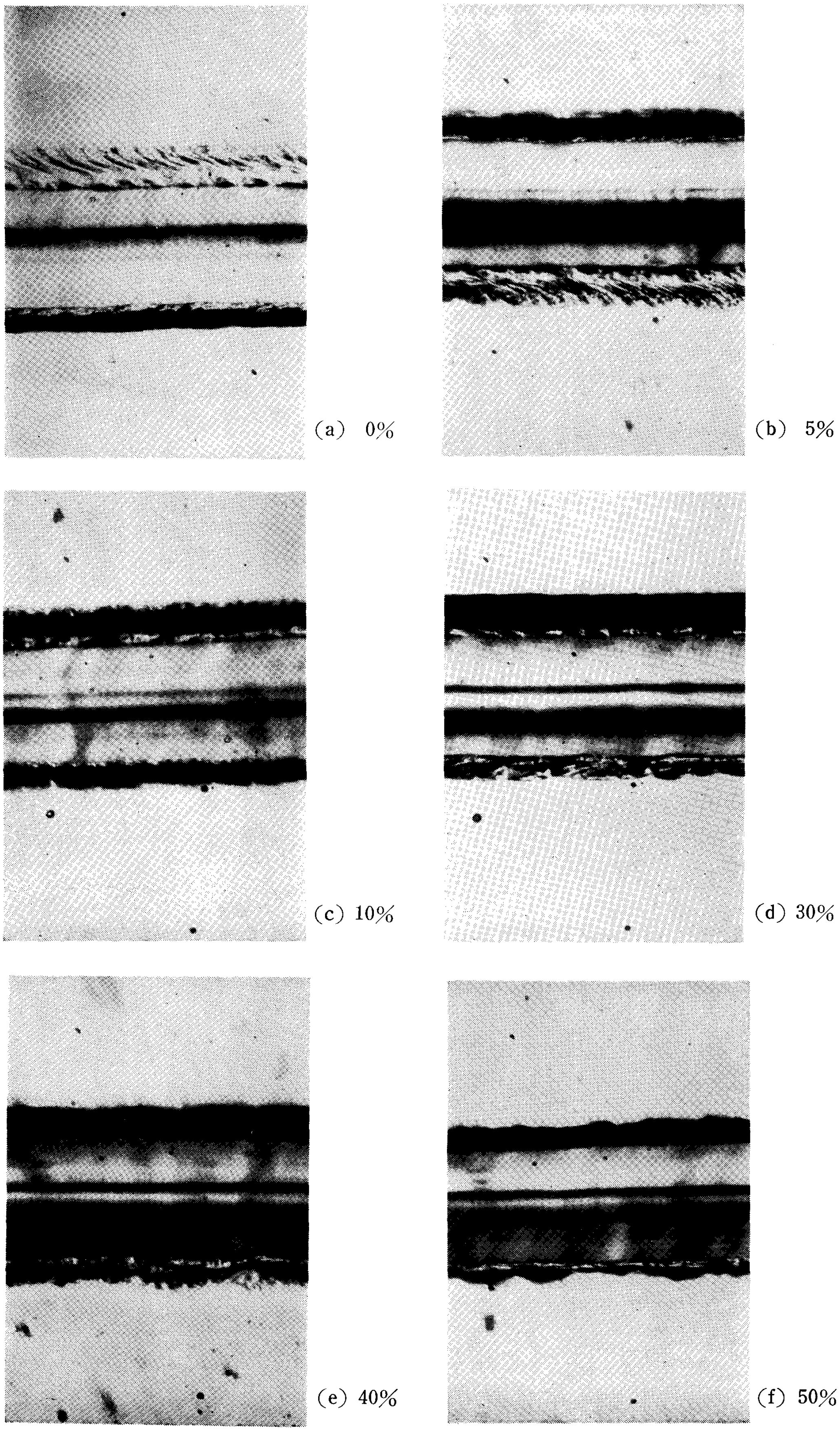

(a)

Photo. 4
Copper crystal


(b)

←———— Direction of scratching

Photos. 1~4. Microphotographs of the track on various metals at the load of 20 g
Magnification ×400



(a) 0%
(b) 5%
(c) 10%
(d) 30%
(e) 40%
(f) 50%

Photo. 5. The change of the track with the reduction in thickness at the load of 40 g
Magnification ×400

The load of scratching was 1 kg, under which the track widths in aluminium single crystal were 0.537 mm and 0.45 mm respectively in perpendicular and in parallel to the specimen axis. The microindentation hardness of this crystal was 17.7 kg/mm^2 in annealed state. The result is shown in Fig. 11. As seen in the figure, the hardness suddenly falls to 19.4 kg/mm^2 at the distance of about 30 μ from the edge of the track, and then gradually decreases to the value of the annealed state. In other words, the effect of the scratching extends only about 0.1 mm from the track, being small compared with the width.

VI. Discussions

When metal single crystals are cold-worked, the indentation hardness shows large increase, but the change in the scratch width is very small as mentioned above. According to Tammann, this is because the track produced by scratching is strained so severely as not to be affected by its previous history; in other words, the scratch hardness is related to the extremely strained state of a metal, and so no remarkable change will be observable even though the metal is subjected to severe working such as cold-rolling. In the present experiment, the change in the scratch width with increasing reduction was about 2 and 4 μ for copper and aluminium crystals, respectively, which is in good agreement with the results on polycrystalline metals by Tammann and co-workers. If Tammann's explanation is correct, the scratch width should be much smaller than the diagonal length of the indentation at the given load and, especially at small degree of cold-working. According to the present results, however, this is not the case, as shown in Figs. 8 and 9.

In the experiments of friction between metals by Bowden and his co-workers(10), a considerable heat evolution is observed at the instant the slider traverses the metal surface, resulting in serious damage of the track due to the adhesion between them by partial melting. In the present expriment, the scratching was carried out at a comparatively slow rate and, consequently, the heat evolved may not be large, but it may be conceivable that the just scratched part is partially annealed by the heat evolved. This process takes placee successively during scratching, resulting in annealing of the track. If such is the case, it may be said that the scratch hardness is related rather to the hardness of a metal in the annealed state. As mentioned in Figs. 8 and 9, the scratch hardness shows only small scattering and the mean value is much smaller than the indentation hardness in a severely cold-rolled state of the metal. It may, therefore, be concluded that the scratch hardness is related rather to annealed state than to extremely worked state.

The effect of scratching on the hardness of surrounding matrix extended only to a small distance from the track as shown in Fig. 11. Recently, King and Tabor(11) measured the change in the hardness of the friction track with increasing depth on the cleavage surface of rock salt crystal, and observed that the hardness suddenly

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(10) F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, (1950).

(11) R. F. King and D. Tabor, Proc. Roy. Soc., **A223** (1954), 225.

changed at the depth of 20 μ from the surface of the track and approached that of the matrix at the depth of 0.2 mm, when the load was 4 kg, and that though the load was reduced, the relation was quite similar to this. From the results of the present study and of King and Tabor, it, therefore, follows that the effect of scratching extends to a very small region around the track, though a very large strain remains in the vicinity of the track. In appearance, the comparatively large hardening in the vicinity of the scratch track will seem inconsistent with the heat evolution due to scratching. This is, however, not necessarily the case, because the evolved heat will be insufficient to give annealing effect to the neighbouring matrix, softening only the track and teared-off material. The validity of this consideration will probably be verified by X-ray analysis, for which preparations are in process.

Summary

(1) The scratch hardness was measured on the single crystals and polycrystals of several metals.

(2) The relation between the load and the scratch width was similar to the Meyer's law in the indentation hardness.

(3) Though the metal was cold-worked, the change in the scratch width was very small, whereas the indentation hardness conspicuously changed.

(4) The scratch hardness was considered to be related rather to annealed state than to extremely worked state of a metal.

Acknowledgement

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