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Relation between Surface Appearance and Coefficient of Friction in Compressive Deformation of Metals*

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Synopsis

The compression test was performed on aluminium, copper, mild steel, stainless steel and aluminium single crystal by using various lubricants. The following results were obtained from the relationship between the microscope pattern of the compressed surface and the frictional coefficient:

(1) The surface pattern of the plate after rolling is similar to that of the specimen after compression.

(2) In the case of a large frictional coefficient, a glossy surface appears in the specimen in which a greater part of the surface is in contact with tools. In the case of a small frictional coefficient, a dull face having a rugged surface of a few microns in depth appears. It seems likely that there is a fluid film in the sinks.

(3) In the 60% deformation of the various materials by using palm oil as a lubricant, the ratio of the surface covered by the fluid film to the total friction surface is 75∼85% for aluminium or copper and about 10% for stainless steel.

(4) From the compression test it is conceivable that there are deformation bands in the rugged surface of the dull face, which the lubricants fill. This phenomenon may be one of the great differences between the sliding friction and the compression deformation.

I. Introduction

A simple method for evaluating lubricants used in the workings of metals should be developed because the results obtained by the usual friction testers are unsatisfactory in practice.

R.D. Guminski(1) reported that the lubricity of rolling oils could be readily examined by compressing steel plates with tools shaped into knife-edge. L.H. Butler(2)-(5) also compared the results obtained by compressing both cylindrical and plate specimens with those obtained in rolling and in drawing.

The effectiveness of lubricants has been examined in the compression test of cylindrical pieces or in the cold rolling and a close relation has been found between

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* The 202nd report of the Research Institute for Iron, Steel and Other Metals. Reported in Japanese in the Journal of the Japan Institute of Metals, 28 (1964), 282.

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(1) R.D. Guminski, J. Inst. Metals, **88** (1959/60), 481.

(2) L.H. Butler, J. Inst. Petroleum, **40** (1954), 337.

(3) L.H. Butler, Sheet Metal Ind., **33** (1956), 647.

(4) L.H. Butler, J. Inst. Metals, **88** (1959/60), 337.

(5) L.H. Butler, ibid., **89** (1960/61), 116; 449.

the surface irregularities and the coefficients of friction in each metal working.(6),(7)

In the present study, the surface figures formed by compressive deformation or by rolling were microscopically observed and the relation between the mechanism of the formation of the figure and that of lubrication was discussed.

II. Experimental procedure

1. Lubricant

Table 1 shows lubricants used in the present experiment.

Table 1. Lubricants used in the experiment.

Lubricant	Type
3# spindle oil	mineral oil
120# machine oil	mineral oil
palm oil	vegetable oil
chlorinated paraffine	EP-lubricant
potassium stearate	soap

2. Specimen

Sizes and annealing conditions of specimens are shown in Table 2, and the optical micrographs of original materials are shown in Phot. 1. Aluminium single crystal 1 mm in thickness and 10 mm in diameter was also used to observe the deformed surface in detail. The compressed surface was nearly (111).

Universal testing machine of 50-ton capacity was used and the rate of the deformation was 0.5mm/min.

Table 2. Properties of materials used in the experiment.

Material	Dia. × Height	Annealing condition
99.7% Al	10 mm × 4 mm	370°C × 1 hour
99.98 Tough pitch copper	〃	500 〃 〃
0.13 C Mild steel	〃	800 〃 〃
18-8 Stainles steel	9.5 mm × 4 mm	900 〃 〃

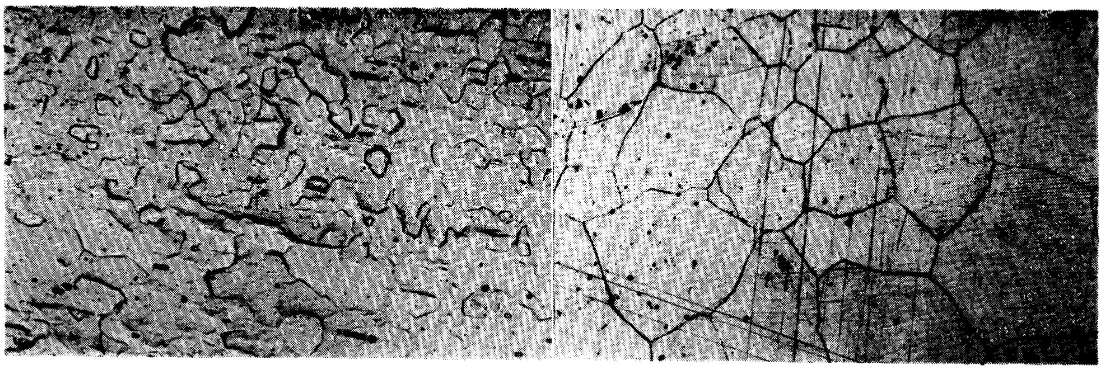
3. Observation of the deformed surface

The surface of the deformed specimen was observed with an optical microscope and its surface irregularities were measured by a dial gage with a microscope.

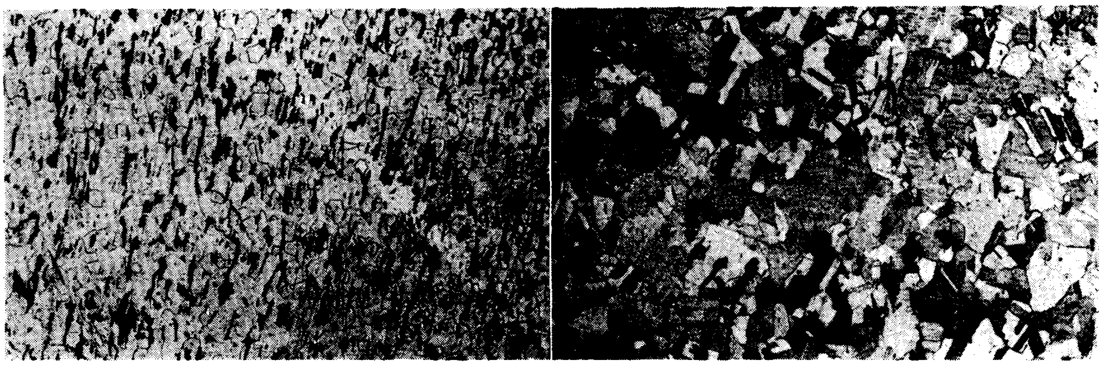
III. Experimental results

Phot. 2 shows the specimen surfaces deformed by using various lubricants, in which (a), (b), (c) and (d) refer to the rolling, and (e), (f), (g) and (h) to the compression.

(6) E. Tanaka, T. Yoshiki and T. Fukuda, J. Japan Soc. Tech. Plasticity, **1** (1960), 3.
(7) E. Tanaka, S. Semoto and Y. Suzuki, J. Japan Inst. Metals, **28** (1964), 228: Sci. Rep. RITU, **A 17** (1965), 193.



Aluminium Copper (×84×3/2)



Mild steel Stainless steel

Phot. 1. Micro structure of original materials. (×84)

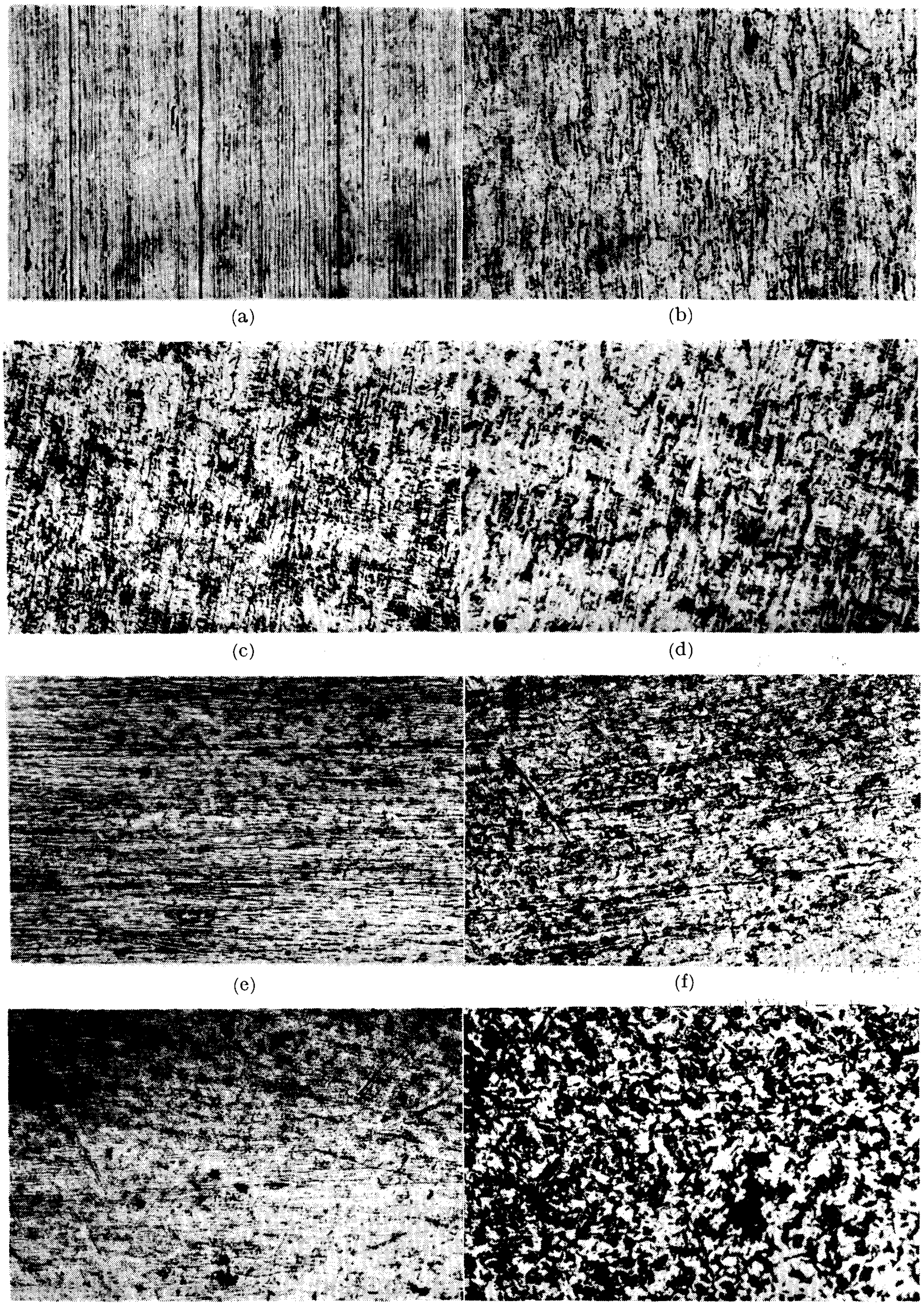
In both cases (a) and (e) without lubricant, the deformed surfaces have long scratches in the direction parallel to metal flow and are bright. By using 3♯ spindle oil, 120♯ machine oil and palm oil in order, the coefficients of friction gradually decreased and the brightness of their surfaces became gradually dull. These facts agreed well with the increase of grooves or skins observed under the microscope as shown in Phots. (b), (c), (d), (f), (g) and (h). It was also found that the surface figures formed by both working methods were considerably similar to each other.

The parts seen as black spots or bands in Phot. 2 are deeper than elsewhere, their depths being in the range from a few to ten odd microns. An example of the diagrams of the surface irregularities obtained with palm oil is shown in Fig. 1.

As shown in Phots. 2 (a) and (e), when no lubricant was used, the whole surfaces of the specimens were almost in direct contact with the tools, had long scratches formed in the direction along the metal flow, and were bright. However, their coefficients of friction were considerably high.

As shown in Phots. 2 (d) and (h) and Fig. 1, when palm oil was used, the direct contact area of the specimen and the tools was small and most of them were in contact with tools through lubricants existing in their hollows. Thus, such surfaces became dull owing to the diffused reflection of light on metal surface.

Generally speaking, the coefficients of friction obtained in the plastic deforma-



Phot. 2. Effect of lubrication on surface figure during cold-rolling (a, b, c, d) and compression (e, f, g, h) of mild steel. ($\times 84$)
(a), (e); without lubricant. (b), (f); lubricated with 3# spindle oil. (c), (g); lubricated with 120# machine oil. (d), (h); lubricated with palm oil.

tion show lower values than those by four ball tester or other friction testers[8]. It may conceivable as a part of causes that true contact area is remarkably smaller than the apparent one as described above.

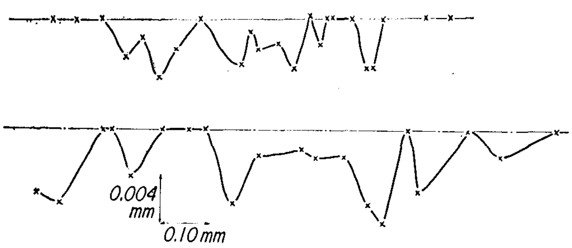


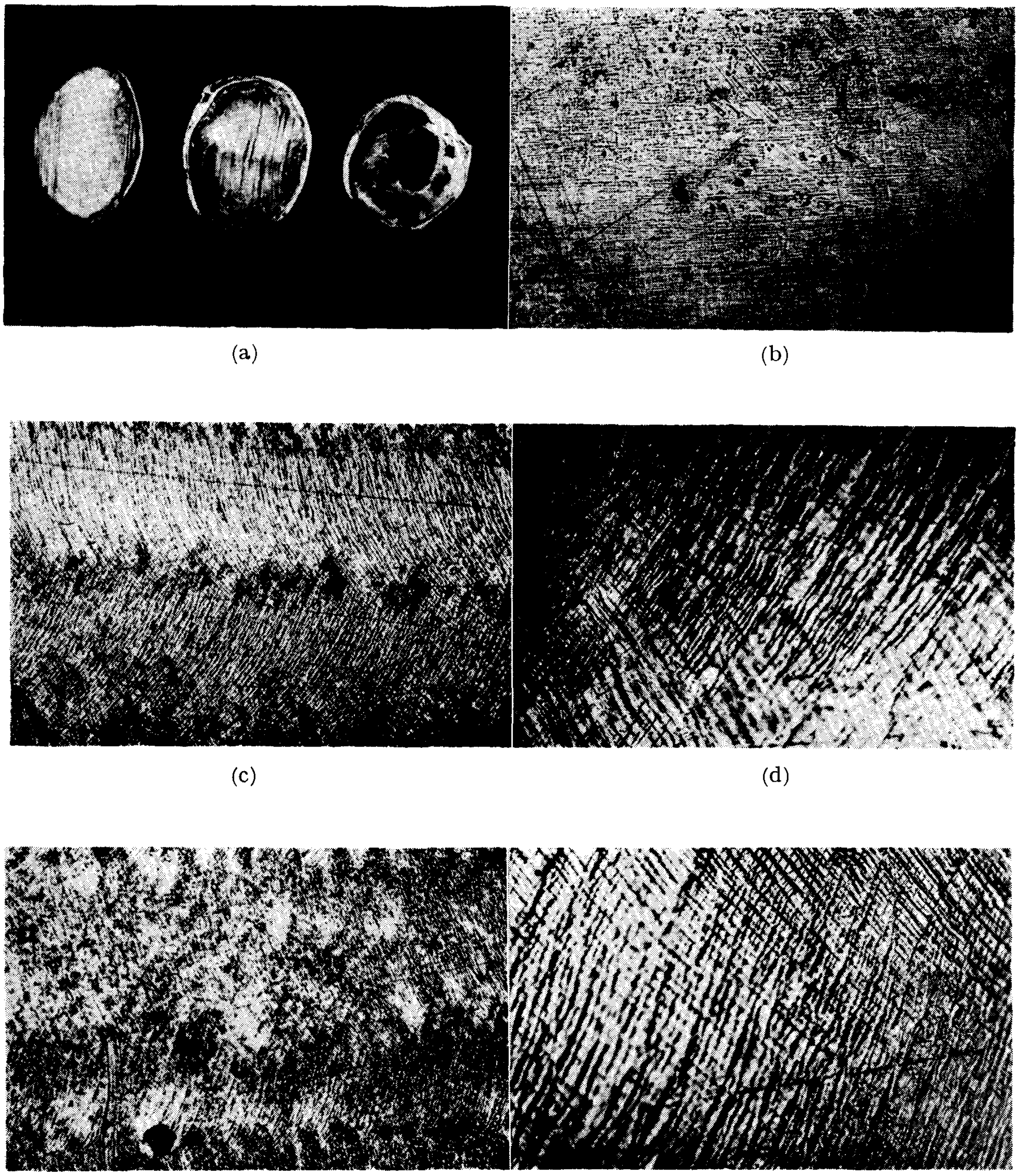
Fig. 1. Roughness of cold rolled aluminium surface (Lubricated with palm oil).

In order to investigate the surface irregularities formed on the surface of the specimen shown in Fig. 1, single crystals, polycrystals and as-worked polycrystals of aluminium were compressed by using variouls lubricants and their surfaces were observed with a microscope.

Phot. 3 (a) shows the surface figures produced when single crystals were compressed under various lubricating conditions. Phots. 3, (a)-1, (a)-2 and (a)-3 show the surface figures of the specimens compressed without lubricant, with 120♯ machine oil and with palm oil, respectively. Phot. (a)-1 shows a round deformation owing to a high friction force between the tools and the specimen in spite of single crystal, while Phots. (a)-2 and (a)-3 show an oval deformation in the direction of metal flow because of a weak contact force. In Phot. (b) is shown the optical micrograph of Phot. (a)-1, in which the scratches formed by the tools are seen clearly. In Phot. (c) is shown the optical micrograph of Phot. (a)-2, in which groups of narrow and long bands are found. In Phot. (d) is shown the micrograph observed by a further magnification. These long and narrow bands should be regarded as "deformation bands"[9] which were formed by subdividing a single crystal with the growth of the slip bands. In Phots. (e) and (f) are given the optical micrographs of Phot. (a)-3, and the same can be said of them as of Phots. (c) and (d).

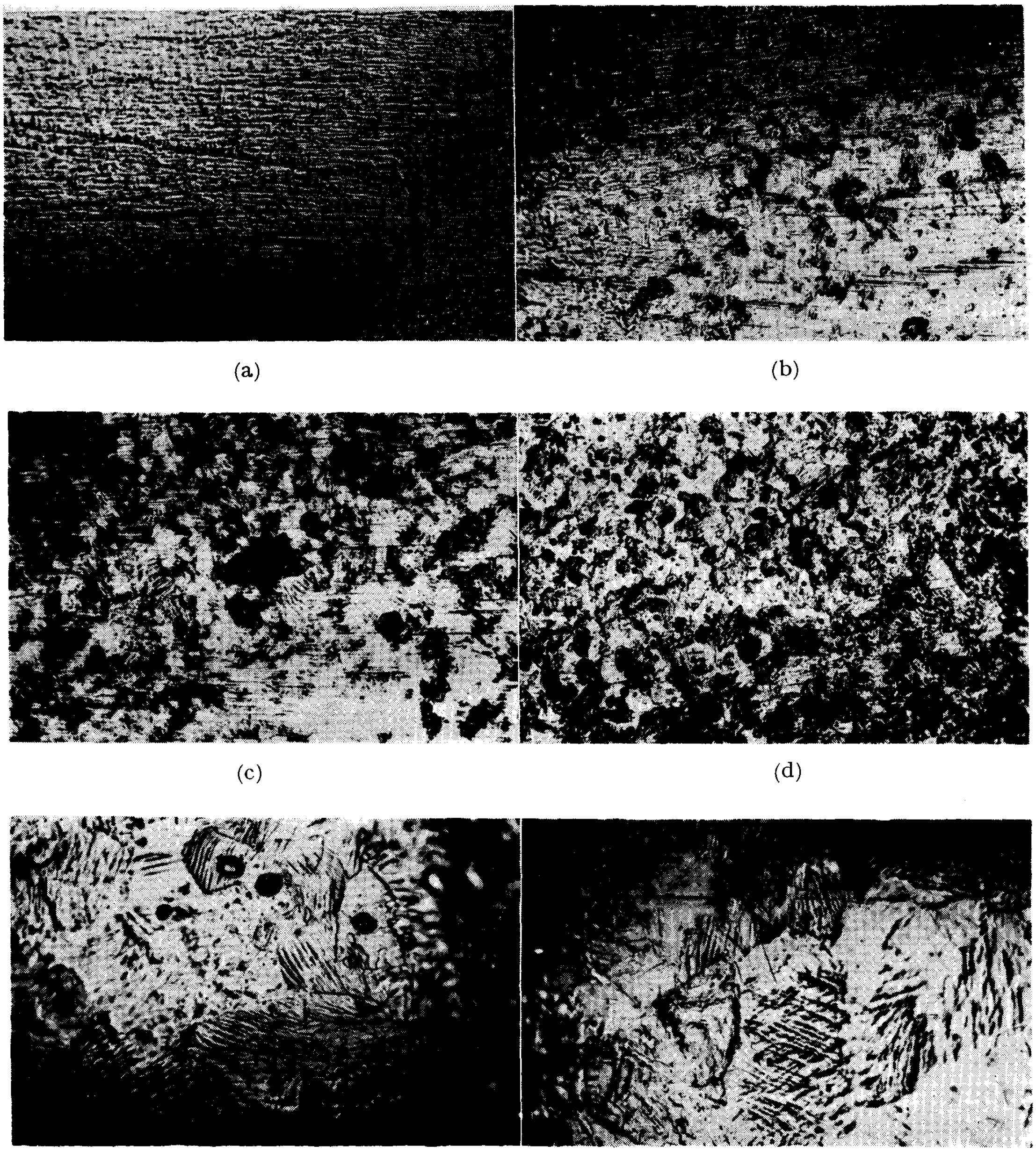
Phot. 4 shows the results of the similar tests obtained by compressing polycrystals of aluminium to various reductions with various lubricants. Such scratches as shown in Phot. 3 (b) are also seen in Phot. 4(a), in which lubricant was not used. Phots. 4 (b) and (c) show the micrographs in 25% and 60% reductions, respectively, when 120 ♯ machine oil was used. Such slip bands as observed in the single crystals are partly seen, their surface irregularities being $1 \sim 5$ microns in depth. Phots. 4 (d), (e) and (f) show the optical micrographs in 25% reduction, with palm oil which were seen when Phot. (d) was further magnified, and obtained in 60% reduction.

(8) N. Soda, The paper of Lecture with Metal Working and Lubrication (1959).
(9) C.S. Barett, *Structure of Metals* (1952).



Phot. 3. Effect of lubrication on surface figure during compression of Al-single crystal. (a) Above; without lubricant, Middle; lubricated with 120# machine oil. bellow; lubricated with palm oil. (b); without lubrication ($\times 84$) (c); lubricated with 120# machine oil ($\times 84$) (d); lubricated with 120# machine oil ($\times 326$) (e); lubricated with palm oil ($\times 84$) (f); lubricated with palm oil ($\times 326$).

When palm oil was used, the slip bands became clear in contrast to the case without lubrication or 120# machine oil, and the ratio of the area covered by the slip bands to that of the whole surface area was considerably large. Directions of slip bands were different with different grains and their hollows were $1 \sim 10$ microns in depth.



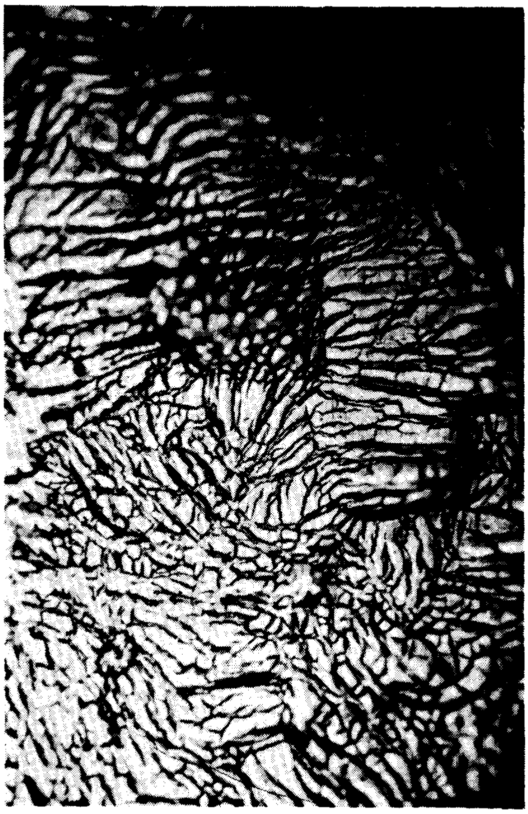
Phot. 4. Effect of lubrication on surface figure during compression of aluminium.
(a); without lubrication (×84), Reduction 25%. (b); lubricated with 120# machine oil (×84), Reduction 25%. (c); lubricated with 120# machine oil (×84), Reduction 60%. (d); lubricated with palm oil (×84) Reduction 25%. (e); lubricated with palm oil (×326), Reduction 25%. (f) lubricated with palm oil (×326), Reduction 60%.

Phot. 5 shows the optical micrographs of the worked polycrystal aluminium which was polished after being compressed by 25% reduction and then further compressed by using palm oil as lubricant. Although the surface shows such retiform figures as shown in Phots. 5 (a), (b) and (c), and their figures are much complicated, the slip bands are also observed similarly to those shown in Phot. 4.

Similar experiments were performed with various metals shown in Table 2. The

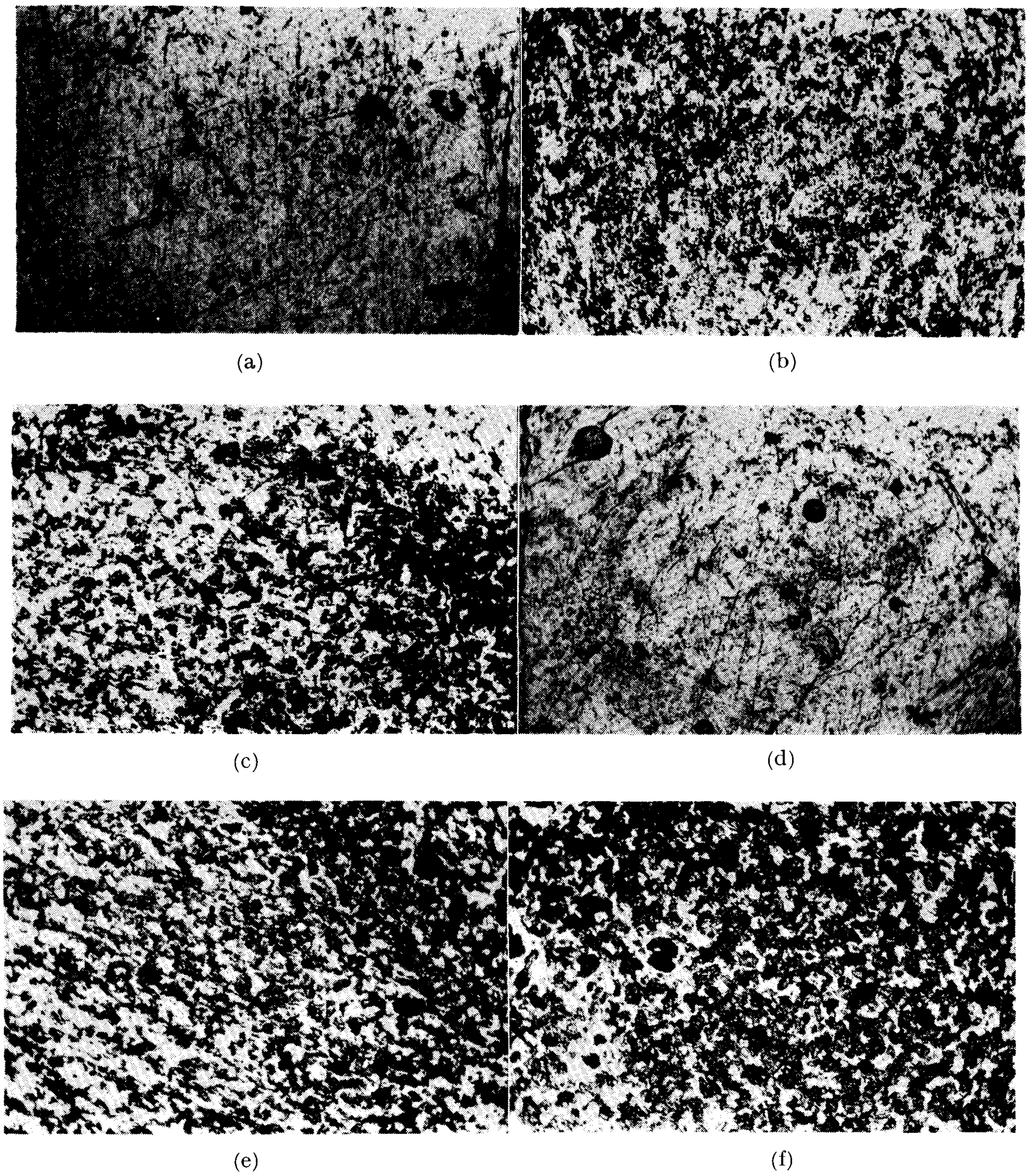
(a)

(b)



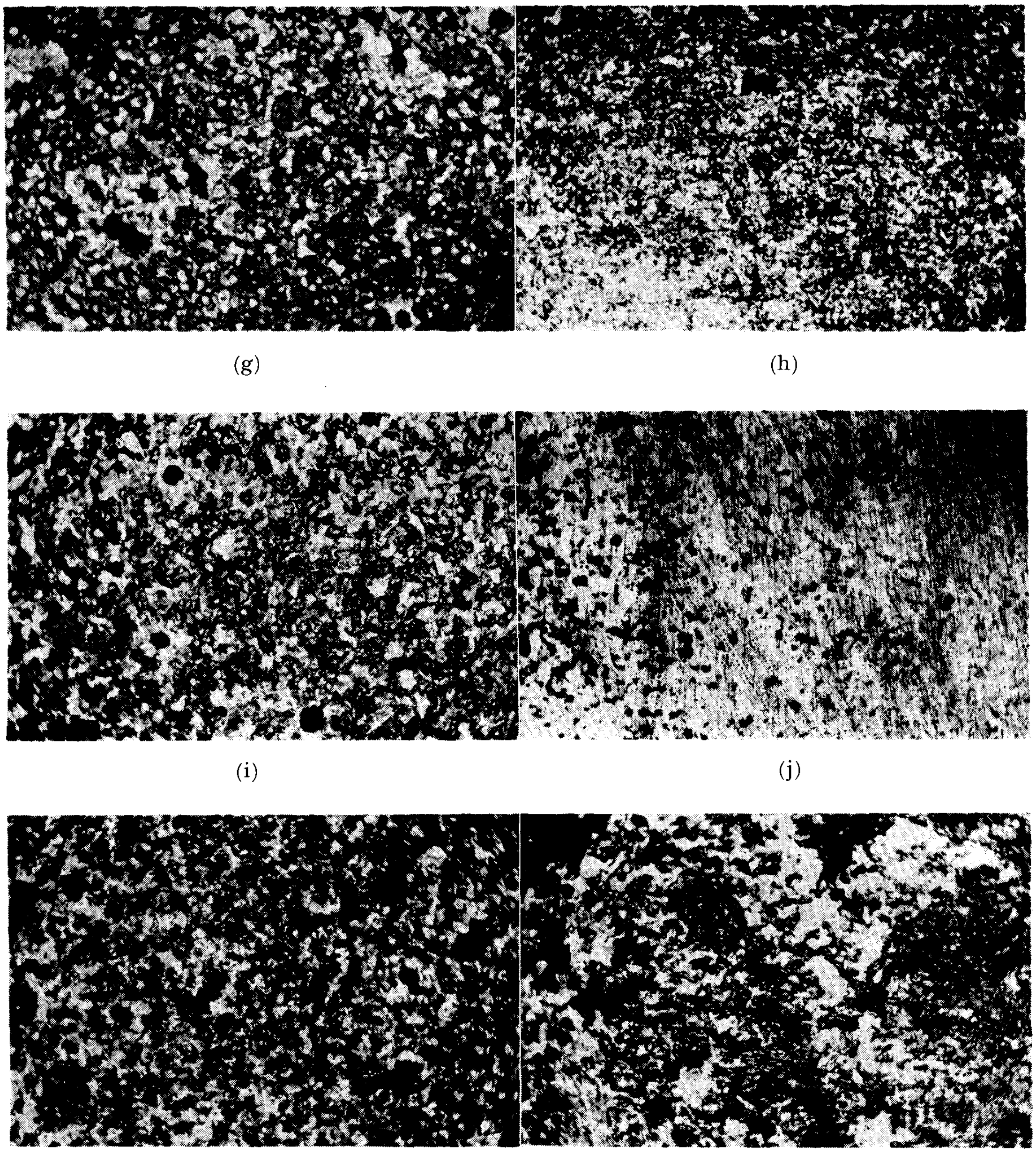
(c)

Phot. 5. Effect of lubrication on surface figure during compression of aluminium, as worked 25%.
(a) ; lubricated with palm oil, Total reduction 60% (×42), (b) ; (a) ×2, (c) ; (a) ×8



Phot. 6. Effect of lubrication on surface figure during compression of mild steel. (×84)
(a) Lubricated with palm oil, temp.: 100°C, Coefficient of friction; 0.14. (b) Lubricated with chlorinated paraffine, temp.: 100°C, Coefficient of friction; 0.22. (c) Lubricated with potassium stearate, temp.: 100°C, Coefficient of friction; 0.15. (d) Lubricated with palm oil, temp.: 200°C, Coefficient of friction; 0.19. (e) Lubricated with chlorinated paraffine, temp.: 200°C, Coefficient of friction; 0.12. (f) Lubricated with potassium stearate, temp.: 200°C, Coefficient of friction; 0.08.

deepest hollows observed were 13 microns in aluminium, 14 microns in copper, 9 microns in mild steel and 3 microns in stainless steel. The ratio of the area of the hollow to the contact area was 70~80% in aluminium or in copper, 50~60% in mild steel and about 10% in stainless steel. It was found with the same lubricant that the larger the area covered by the hollow, the lower the coefficient of friction.



(g) (h)

(i) (j)

(k) (l)

Phot. 7. Effect of lnbrication on surface figure during compression of mild steel (×84). (g): Lubricated with palm oil, temp.; 300°C, Coefficient of friction; 0.09. (h); Lubricated with chlorinated paraffine, temp.; 300°C, Coefficient of friction; 0.06. (i) Lubricated with potassium stearate, temp.; 300°C, Coefficient of friction; 0.08. (j): Lubricated wth palm oil, temp.; 400°, Coefficient of friction; 0.13. (k); Lubricated with chlorinated paraffine, temp.; 400°C, Coefficient of friction; 0.11. (1); Lubricated with potassium stearate, temp.; 400°C, Coefficient of firiction; 0.11.

Phots. 6 and 7 show the surface figures obtained when mild steel was compressed with various lubricants at temperatures 100°, 200°, 300° to 400°C, respectively. The black parts seen in each photograph correspond to the hollows mentioned above. Phots. 6 (a) and (d) show the optical micrographs obtained by compression with palm oil at 100°C and 200°C, respectively. These results indicate, in contrast to those at room temperature, that the hollows considerably decreased. This fact corresponds to the case where the coefficient of friction obtained by palm oil is fairly lower than that with others at room temperature, but rapidly increases at 100°C or 200°C.

Phots. 7 (a) and (j) also show that the coefficient of friction decreases at 300°C, but increases again at 400°C. With chlorinated paraffine, it decreased at 200°, 300° and 400°C rather than at 100°C, while with potassium stearate it was similarly low at 200°, 300° and 400°. It was found that a relation existed between the surface figure and the coefficient of friction.

Summary

The present results may be summarized as follows:

(1) The surface figures formed in rolling are so similar to those in compression that it suggests the similarity of both lubricating mechanisms.

(2) In the case of a large coefficient of friction, a large area of test-piece is in direct contact with tools and appears to be bright. With lowering of the coefficient of friction the surface becomes less bright.

(3) Dull surface is composed of microscopic surfoces of irregularities and their depths are in the range from a few to ten odd microns. It may be conceivable that these parts are in contact with tools through a fluid film filling these hollows.

(4) The ratios of the surface covered by fluid film to the total area of friction at 60% reduction using palm oil as lubricant are 70～80% in aluminium or copper, 50～60% in mild steel and approximately 10% in stainless steel. These results linearly correspond to the coefficient of friction, and these ratios are different according to the lubricating condition, but can be measured without difficulty.

(5) The microscopic irregularities on the surface during working seem to be deformation bands.

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