Study on Impact Extrusion Method for Non-Ferrous Metals

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ABSTRACT: The blanks of non-ferrous metals such as aluminum and its alloys, copper, yellow brass, zinc and lead, were formed into cylindrical shells by statical backward extrusion under a material testing machine and by dynamical backward extrusion under a mechanical crank press, mainly at room temperature. Thereby, the effects of various working conditions, that is, the dimension and shape of extruding tool and blank, the working temperature and speed, applied lubricant and the degree of surface finish of tool, on the extruding force or pressure were examined. From the results, an empirical formula for the estimation of the maximum extruding pressure was developed. Moreover, the effects of working conditions on the hardness, failures and surface state of extruded shell were observed.

1. PURPOSES OF THE STUDY

The cold extrusion or impact extrusion method in which blank metal is extruded or squeezed out from between extruding tools on mechanical press at room temperature has been adopted in commercial industry for many years as a fabricating process for lead and tin collapsible tubes. Recently, this method has come to be applied also in forming most of the high-melting metals including mild steels and low alloy steels. In our country, at present, the commercial application seems to be still limited only to lead, tin, aluminum and zinc. These practices, however, are revealing that the process is an excellent and economical fabricating method for many kinds of metal parts.

In spite of its long history, hardly any report on systematic research on the process has been published to date. This is the case particularly for non-ferrous metals. Only the works by Prof. I. Gokyu and his coworkers[1] were reported recently.

The purpose of the present study was, then, to clarify the effects of various working conditions on the extruding forces and the properties of extruded products on the backward extrusion of cylindrical shells of non-ferrous metals at room temperature and, accordingly, to determine the proper working conditions and the limits of application of this method.

2. BLANKS AND EQUIPMENT FOR EXPERIMENT

a) *Extruding Blanks*

In Table I are tabulated the chemical compositions, processing conditions, heat treatments and Vickers hardness numbers of metals which were used as the blank material for detailed tests. Other metals such as Muntz metal, aluminum-copper, -silicon, -magnesium, and -silicon-magnesium alloys, and lead were also tested in some cases. In general, they were cut out from cold or hot rolled plates, machined to

Table I. Chemical Compositions, Processing Conditions, Heat Treating Conditions and Vickers Hardness Numbers of Blank Metals Tested

Blank Material	Chemical Composition (%)	Processing Conditions	Heat Treatment	Vickers Hardness Numbers
Aluminum (soft)	Al 99.5	cold rolled to plate	400°C×1 hr., f.c.	19.5
Aluminum (hard)	commercial pure	hot extruded and cold upset	as worked	43
Copper (soft)	Cu >99.5	cold rolled to plate	700°C×1 hr., f.c.	38
Copper (hard)	commercial pure	hot extruded and cold upset	as worked	110
Zinc	Fe 0.002, Pb 0.03, Cu 0.01, Cd, Sn trace, Zn rest	hot rolled	100°C×1 hr., a.c.	34
Duralumin	Si 0.26, Cu 4.49, Fe 0.25, Zn 0.29, Mn 0.55, Mg 1.49, Al rest	hot extruded to bar	420°C×1 hr., f.c.	65
Yellow Brass	Cu 65.17, Fe 0.01, Pb, Sn, Al trace, Zn rest	cold rolled to plate	550°C×1 hr., f.c.	55

circular discs, and heat treated. The diameter of the blank was made slightly less than that of the die cavity, and the thickness was usually 5 mm. In some cases, other shapes and sizes were used.

b) *Extruding Tools*

Various types of tools were made and tried for the experimental study of backward extrusion of cylindrical shells. Finally, the one shown in Fig. 1 was found to be the most simple and suitable for the authors' purpose. In this die assembly, an extruding punch was guided in a conical brass sleeve, which initially rested on a conical surface provided above the die cavity. This enabled the correct centering of the punch, because the guide sleeve of the punch was located very close to the work piece during the initial stage of extrusion. As the extrusion proceeded, the sleeve was lifted by the upper edge of the extruded cup, until the punch was no longer guided. The extrusion was continued succeessfully, however, if the ram face and the bolster plate of the crank press or the testing machine was kept exactly parallel to each other and if the clearance between punch and die was not too small.* The die ring and punch were

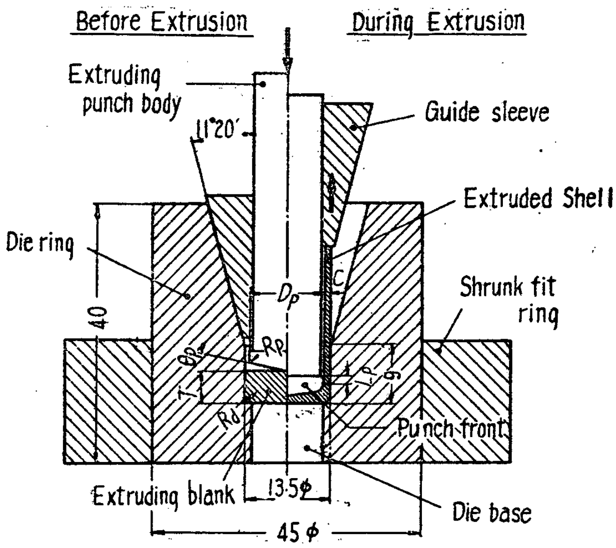


Fig. 1. Tool Assembly Used for Extruding Test with Die Cavity of Diameter 13.5 mm.

* For the extruding tests with a clearance of 0.2 mm, another type of tool assembly was used, which was of a sub-press type.

made from a special tool steel containing 2% tungsten, hardened and tempered to Shore hardness of 80~85, ground to size, and lapped with fine carborundum papers. The die ring was reinforced by a shrunk fit ring as shown in Fig. 1. The notations for the tool and blank dimensions are also shown in the figure.

c) *Loading Equipment*

For low speed extrusion, a Matsumura 30-ton universal testing machine was used, and for high speed extrusion, a mechanical crank press ("C" type frame, capacity: 18 ton, 160 strokes/min.) was used. The latter is shown in Fig. 2.

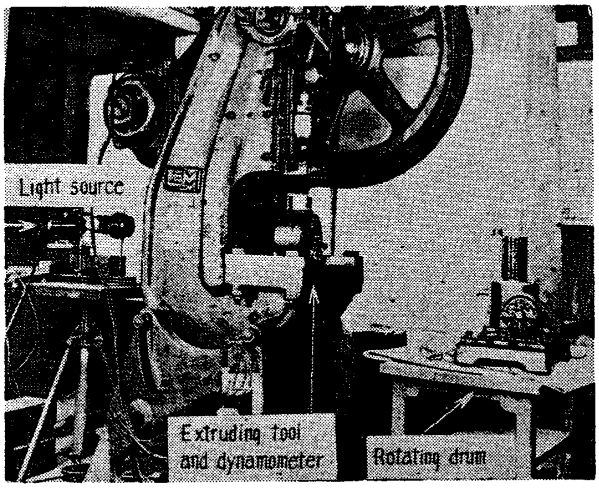


Fig. 2. Photograph Showing Crank Press, Extruding Tool and Ring Dynamometer Used for Experiment.

d) *Measuring Devices*

A mechanical autographic recorder installed on the testing machine was used in most cases to record the load-stroke curves for the statical extrusion at low speed. Detailed measurement on medium speed extrusion by the testing machine was carried

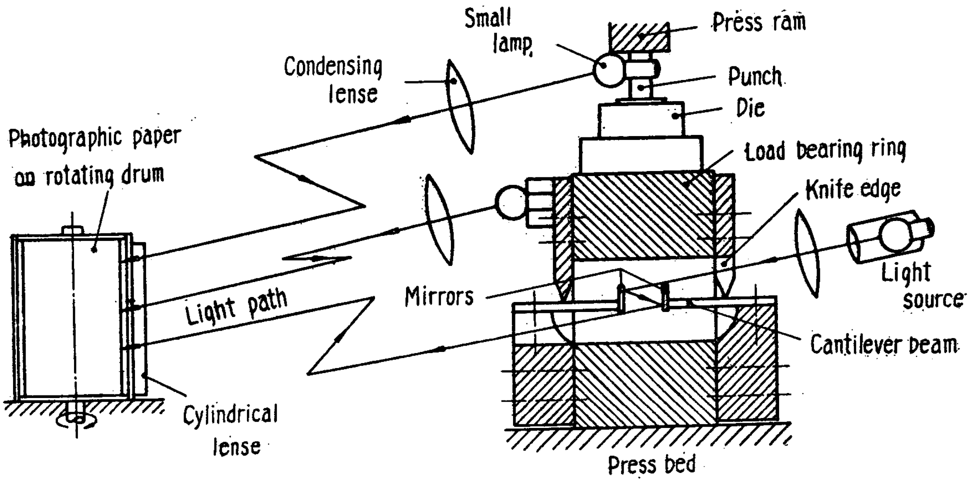


Fig. 3. Load and Displacement Recording Devices Used for Dynamical Extrusion.

out by filming continuously the load indicator of the machine and two dial gauges set between the upper and lower platen.

A specially designed dynamometer as shown in Fig. 3 was used for the impact or dynamical extrusion by the crank press. (See also Fig. 2.) Its load bearing body consisted of a medium carbon steel ring. The distortion of the ring under pressure was transmitted through knife edges to a pair of spring steel cantilever beams, and consequently, mirrors cemented to the ends of the beams were inclined. These small rotations were enlarged by means of an optical lever and was recorded on a rotating drum. One pair of mirrors enabled not only the doubling of the sensitivity of the dynamometer but the elimination of the effect of inclination and rotation of the dynamometer as a whole. The lowest natural frequency 2,200 cycle/sec. of the cantilever was satisfactory for the authors' study.

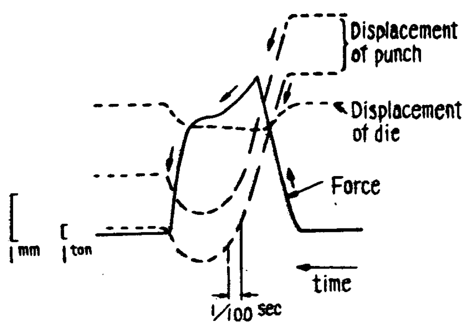


Fig. 4. An Example of Record of Punch Force and Displacement in Dynamical Extrusion of Copper. (D_p=11.3 mm, T=5 mm, C/D_p= 0.097, Water Emulsion with Palm Oil)

On the other hand, the fast movement of the extruding punch against the die ring was directly recorded on the rotating drum by light spots from three lamps attached to the punch and the base of die ring, respectively, through two condensing lenses.

An example of this dynamical record is illustrated in Fig. 4, which was obtained for a copper blank. The time marks were marked on the displacement curves by blinking of lamps resulting from the alternating of electric current.

3. EXPERIMENTAL RESULTS

[A] Extruding Force

a) Force-Stroke Diagram

In Fig. 5, typical statical extruding force-stroke diagrams for aluminum, copper and zinc are illustrated. An initial gentle rise in the curve corresponded to the filling up of the die cavity by metal pressed under the punch. A sudden rise then followed, and after the extrusion began, the force was kept almost constant or decreased steadily at varying rates toward the end of the stroke. In almost all cases, a minimum appeared on the curve, then a steep rise followed with thinning of shell bottom. This steep rise began when the bottom thickness was reduced down to about one-tenth of the punch diameter, owing to the increased effect of frictional resistance on the surfaces of the bottom.

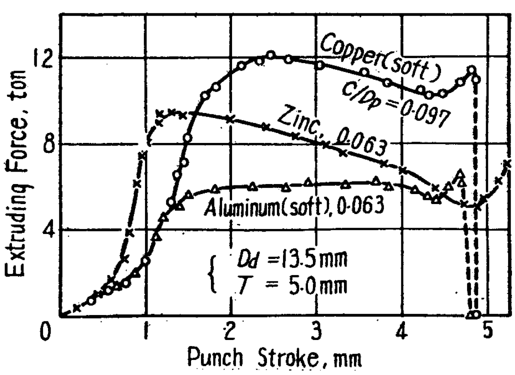


Fig. 5. Statical Extruding Force-Stroke Diagrams.

The variation in extruding force with proceeding punch stroke as described above, can be explained mechanically by the so-called "double compression process" of metal flow suggested by von M. Dipper[2]. The practical extruding force-stroke diagram, however, was affected greatly by many other factors.

In the authors' study, the initial maximum pressure p_{max} and the minimum pressure p_{min} per unit area of punch front face were taken as the characteristics of extruding forces. Moreover, the shapes of the force-stroke diagram were also taken into consideration if necessary.

b) *Factors Affecting the Extruding Force*

The working conditions that seem to affect the extruding forces are: (1) the blank material and its temper, (2) the extruding speed and temperature, (3) the diameter of the extruding punch and its shape, (4) the extruding clearance between punch and die or the side-wall thickness of shell to be extruded, (5) the shape of die cavity, (6) the dimensions and form of blank, and (7) the surface roughness of punch and die and the condition of lubrication.

Theoretically, the extruding force is considered to depend upon three fundamental factors, namely, the flow-stress of blank metal, the geometrical configuration and size of tool and the coefficient of friction between the tool and metal surfaces. Accordingly, the experimental results on the relations between the working conditions and the extruding forces have been arranged and discussed from this fundamental point of view.

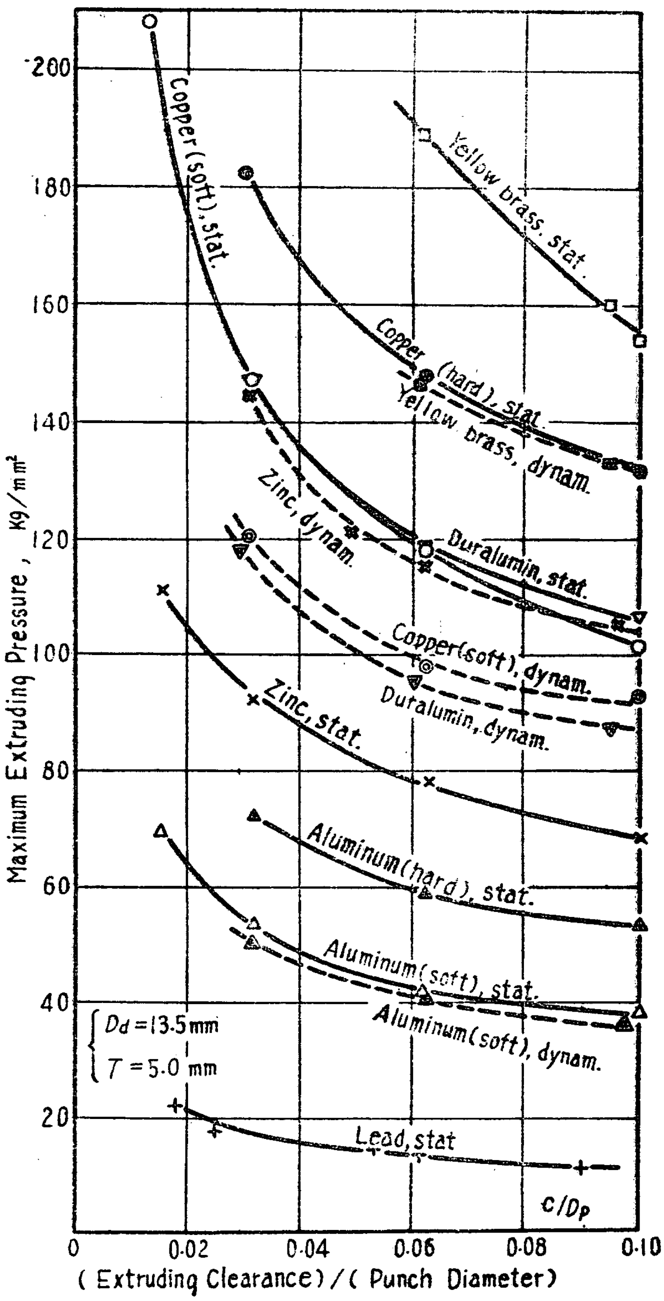


Fig. 6. Maximum Extruding Pressures for Various Metals and Tempers as Functions of Ratio of Extruding Clearance to Punch Diameter.

c) *Effect of Blank Material and its Temper*

The maximum extruding pressure (, see Fig. 6,) varied widely depending upon the blank materials and their tempers under the otherwise identical working conditions. For example, the maximum pressure was about 13 kg./mm^2. for lead and 190 kg./mm^2. for yellow brass, when the extrusions were carried out statically at room temperatures with an extruding punch of 12 mm. diameter having an extruding clearance of 0.75 mm. (, i.e., with extruding clearance ratio $C/D_p=0.063$).

These differences in extruding pressures for various metals and tempers were considered to have resulted primarily from the different flow-stresses or deformation resistances inherent in these metals. To ascertain this, compression tests of these metals were carried out on a material testing machine, and a series of curves for

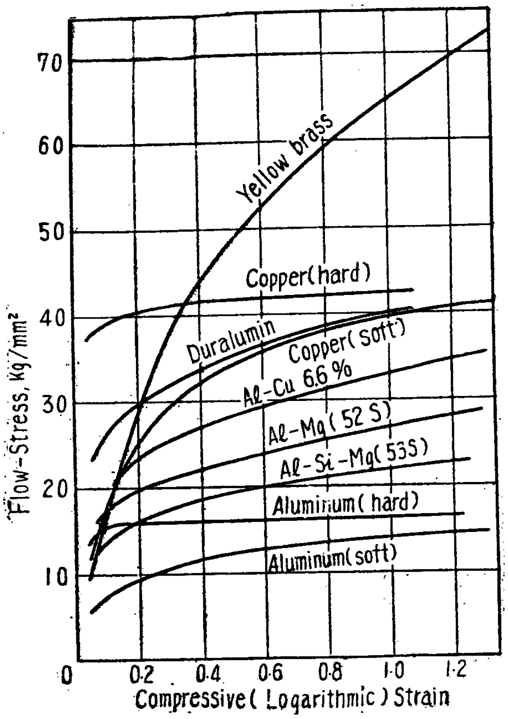


Fig. 7. Statical Flow-Stress Curves or Compressive Stress versus Strain Relations for Metals Tested.

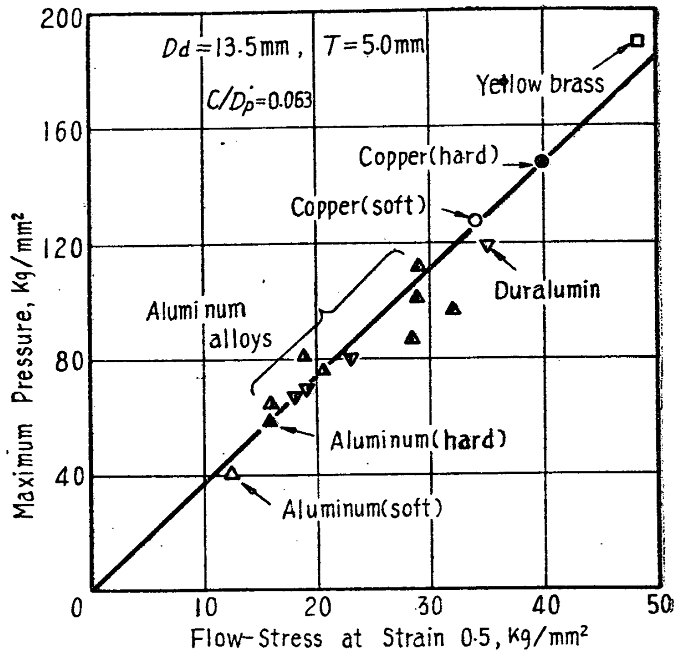


Fig. 8. Relation between Maximum Extruding Pressures and Flow-Stresses of Metals.

compressive flow-stress versus logarithmic strain was obtained as compiled in Fig. 7. Taking, tentatively, the flow-stresses at logarithmic strain of 0.5 as the mean flow-stresses Y_m of metals during extruding process, and plotting the maximum extruding pressures under a given set of working conditions against them, a nearly proportional relation was found for various kinds of high-melting metals and their tempers. (See Fig. 8.) This fact obviously showed that the effect of blank material and its temper on the extruding force appeared predominantly through its flow-stress. Another effect of blank material which concerns the coefficient of friction is discussed later.

It may be mentioned that the pronounced pressure drop exhibited in the extruding force-stroke diagram for pure zinc on the statical extrusion, (see Fig. 6,) is closely related to the work-softening phenomenon of the metal as revealed by its flow-stress curve shown later in Fig. 12.*

d) Effect of Working Temperature

In Fig. 9, the maximum extruding pressures for copper and zinc have been compiled for the case when the extrusions were carried out with the extruding tools and blanks

* It is said that the work-softening phenomenon of zinc is related to the twinning and recrystallization of its crystal structure.

heated up to various predetermined temperatures. According to the figure, it was found that the required forces decreased with increasing temperature and the trend was marked for zinc even at room temperature. This again seems to be a direct result of the temperature sensitiveness of flow stress of zinc as will be seen from the flow-stress versus temperature curve for zinc shown in Fig. 9, its ordinate being enlarged to 4 times.

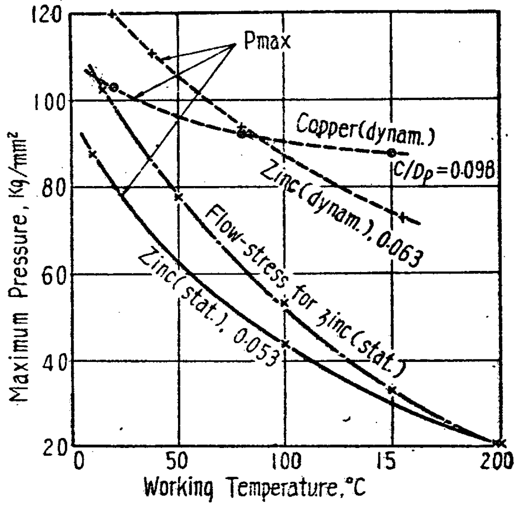


Fig. 9. Some Examples of Temperature Dependencies of Flow-Stress and Extruding Pressures.

e) Effect of Working Speed

The broken-line curves drawn in Fig. 6 represent the maximum pressures for copper, aluminum, zinc, duralumin and yellow brass on the dynamical extrusions by the crank press at room temperature. The maximum pressures for copper, duralumin and yellow brass in impact extrusion were lower than those in statical extrusion by from a few per cent to about twenty per cent, contrary to Dipper's results on aluminum[2]. On the other hand, the maximum pressures for zinc in dynamical extrusions were increased by several ten per cent. Plotting the maximum pressures for aluminum, copper and zinc as functions of logarithmic punch speed at the moment of maximum force, nearly linear relations were obtained as will be seen from Fig. 10. In Table II,

Table II. Ratios of Maximum Pressure on Dynamical Extrusion (by Crank Press) to Those on Statical Extrusion for Various Metals.

	$(p_{max})_{dyn}/(p_{max})_{stat}$		
Blank Metal \ C/D_p	0.031	0.063	0.100
Aluminum (soft)	0.94	0.95	0.95
Copper (soft)	0.82	0.83	0.91
Duralumin	0.80	0.79	0.82
Yellow Brass	—	0.77	0.83
Zinc	1.57	1.48	1.52

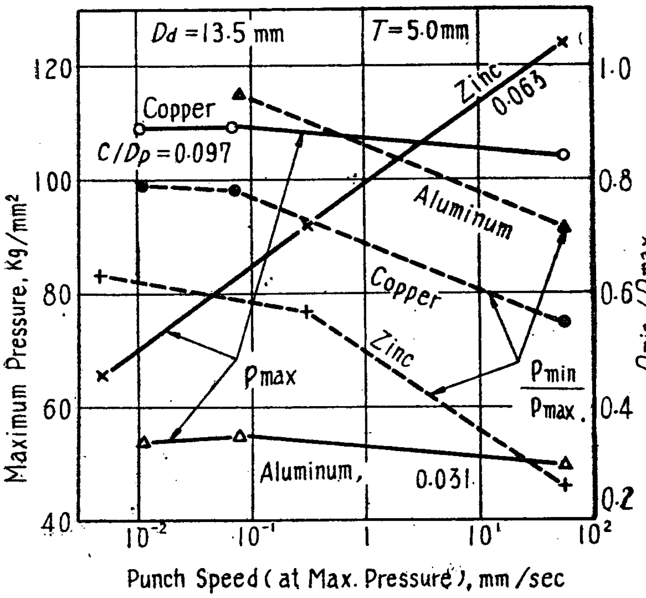


Fig. 10. Effect of Extruding Speed on Maximum Pressure and on Ratio of Minimum to Maximum Pressure.

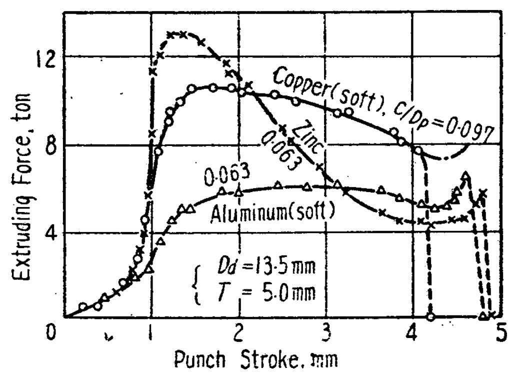


Fig. 11. Dynamical Extruding Force-Stroke Diagrams.

also the ratios of maximum pressures in dynamical extrusion to those in statical extrusion are listed.

The extruding force-stroke diagrams for copper, aluminum and zinc in dynamical extrusion are illustrated in Fig. 11. From the figure, the drop of the extruding force with advancing punch was found very large compared with that in statical extrusion (shown in Fig. 5) for each metal, and it was especially the case for zinc. This is clearly shown also by broken lines in Fig. 10, in which the ratios of minimum extruding pressure to maximum have been plotted against the punch speed.

For the purpose of examining the source of these different manners of speed effect, compression tests of the metals were carried out on a material testing machine as well as on the crank press, and the flow-stresses of metals thus obtained at high and low strain rates were compared to each other. The strain rate through any one compression process under the crank press naturally could not be kept constant. Therefore, the whole compression process of each specimen was divided into several steps, thus giving the specimen a comparatively small amount of reduction at each blow of the press. After this stepwise compression test the true compressive stress or flow-stress versus total logarithmic strain diagram for each step was drawn to begin with. From this series of diagrams, points were then taken up corresponding to a given strain rate and were connected by a single curve. The curve was regarded as the flow-stress to strain relation for the given metal at the given strain rate. In Fig. 12, the flow-stress curves for a high and a low strain rate obtained in this way are assembled. It was shown in the figure that, for copper and aluminum, the flow-stresses were increased by from a few to about ten percent when the strain rate was made 10^3 times, according approximately to the results by other investigators[3]. On the other hand, the flow-stress for zinc became as high as 2.5 times for 10^2 times multiplication of strain rate. Of course, the latter was caused by the fact that the working of zinc at room temperature belonged to the hot working range as is generally recognized.

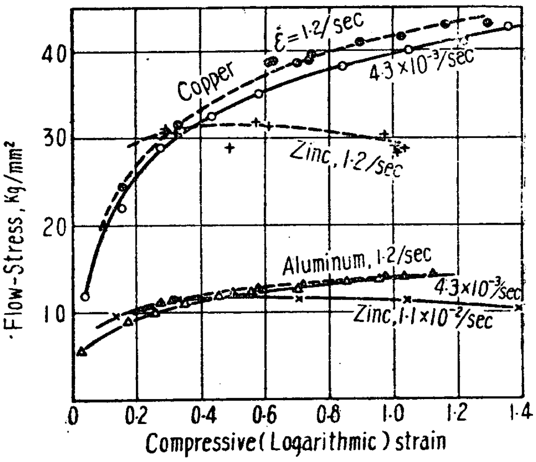


Fig. 12. Flow-Stresses at High and Low Strain-Rates.

Although the marked positive speed dependency of extruding pressures for zinc can be explained as a direct result of the effect of strain rate on its flow-stress, the same cannot be applied for aluminum and copper, whose extruding pressures had negative speed dependencies.

A possible reason for this is the temperature rise in metal under extrusion. During extrusion, the heat generated by the plastic work in metal and the frictional work on the sliding surfaces between metal and tool would raise the temperature of metal appreciably if the extruding speed is so high that sufficient time is not allowed for heat to be conducted into the surrounding tools. In Table III are listed the calculated

Table III. Estimated Temperature Rises in Metal during Dynamical Extrusions

Blank Metal	Die Diameter, D_d, mm.	Clearance Ratio, C/D_p	Blank Thickness, T, mm.	Estimated Temperature Rise, °C	
				At Maximum Pressure	At Minimum Pressure
Aluminum (soft)	13.5	0.063	5.0	45	230
Copper (soft)	13.5	0.097	5.0	40	220
Zinc	13.5	0.063	5.0	25	200

temperature rises of the bottom parts of the shells during extrusion from experimentally obtained dynamical extruding force-stroke diagrams, with the assumption that the total work done was transformed into heat and the extruding process was perfectly adiabatic (as the duration of the process under the crank press was of the order of one-tenth of a second). Though the temperature rises listed in the table are of rough approximation, these may suggest that the extruding pressure, especially the minimum pressure, was possibly affected by the lowering of flow-stress of metal caused by temperature rise in dynamical extrusion. Also the extraordinary low minimum extruding pressures in the dynamical extrusions of zinc, whose flow stress is very sensitive to temperature, (see Fig. 9,) may be interpreted in this way.*

The extruding speed seems to have a certain effect also on the coefficient of friction between the metal and tool surfaces. This will be referred to in later article.

f) *Effect of Tool Dimension*

No special experiment was carried out on the effect of absolute dimension of tool on extruding force. However, from some data for aluminum and lead, including that with the punch diameters of about 20 mm. and 30 mm., it was found that the maximum extruding pressures were approximately equal for the blanks and with the tools of geometrically similar forms.

According to the theoretical study by Dr. H. Suzuki[4] on the law of similarity for extruding process, the stress and strain distributions within metal are generally not similar, even if the extrusions are carried out with the tools, blanks, and lubricants of the same materials, respectively, and with the tools and blanks of geometrically similar shapes but of absolutely different dimensions. This conclusion is understood as follows: To keep the same strain rates for two different cases, the extruding punch speed must be proportionated to the absolute dimension of tool in each case. Apparently, this results in different temperature distributions for the two cases because of different conditions of heat conduction from metal to tool.

It may be expected, however, the law of similarity holds approximately for a certain range of tool dimension when high-melting metals, whose flow-stresses are usually less sensitive to strain rate, are extruded either very rapidly (i.e., adiabatically) or very slowly (i.e., isothermally). In the present paper, therefore, extruding pressure

* Another possible reason for these low minimum extruding pressures is the fact that the punch speed becomes quite slow near the lower dead center point of the crank press mechanism.

per unit area of punch face and non-dimensional quantities standing for the geometrical configurations of the tools were taken in treating the test data.

g) Effect of Extruding Clearance

The maximum extruding pressure was related to the clearance C between extruding punch and die or the side-wall thickness of extrusion in a manner shown in Fig. 6. The maximum pressure for a given metal with a given ratio of blank thickness to diameter showed increasingly sharp rise when the clearance ratio C/D_p was decreased. These tendencies were similar for all kinds and tempers of metal tested. This was obviously caused by the increased degree of constraint on the blank surface by the extruding tool, and by the increased amount of strain within metal with the narrowing of the extruding clearance.

These tendencies were in agreement with the results after Gokyu[1], but the absolute values were somewhat discrepant for the same metals. This is probably due to the differences in some working conditions.

h) Effect of Local Shape of Extruding Tool

(i) Edge radius of punch front. In Fig. 13 are shown the relations between the maximum extruding pressure and the edge radius of punch front R_p. The ordinate stands for the pressure relative to that for zero radius and the abscissa for the ratio of edge radius to front-end diameter of punch. The extruding pressures generally increased with increasing radius ratio. This may be caused by the so-called wedge-action of the punch. This trend, however, was hardly noticeable for zinc (at a high speed) but was marked for copper (at a low speed). The data for zinc and aluminum under statical extrusion after Gokyu were also plotted in the figure. The presence of these different tendencies may be attributed partially to the straining of metal which was induced before the maximum extruding force was reached, when a rounded punch was used. In other words, this prestraining would have caused strain-hardening for high-melting metals, while this would have resulted in strain-softening for low-melting metals such as pure zinc. Consequently, the effect of the edge radius upon the maximum extruding pressure may include both factors: the wedge action of the punch and the strain-hardening or softening of metal caused by pre-straining.

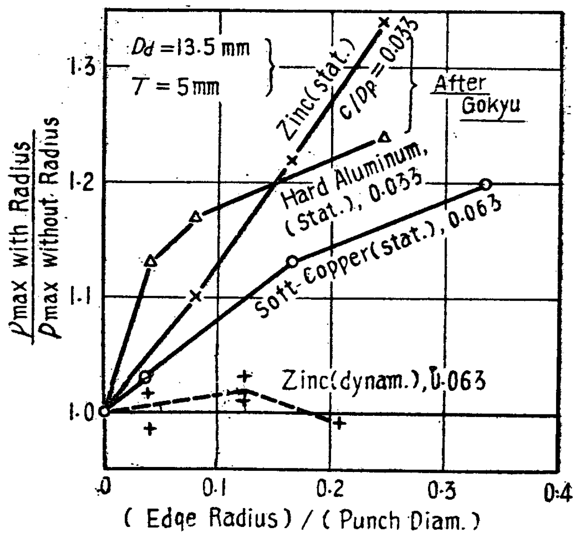


Fig. 13. Effect of Edge Radius of Punch Face on Extruding Pressure.

(ii) Side angle of punch front. The provision of conical shapes with the side angle θ_p of 4 degrees to the punch face did not affect the maximum extruding pressure for copper, while considerable rise in pressure occurred with the punch of 8 degrees.

(See Fig. 14.) Again, this may be understood as the wedge action of the punch. On the other hand, the initial shock at the moment of contact of the punch with the blank under dynamic extrusion was less for the punch with larger side angle.

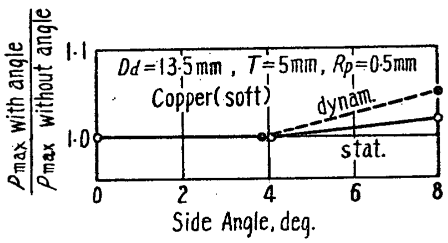


Fig. 14. Effect of Side Angle of Punch Face on Maximum Extruding Pressure.

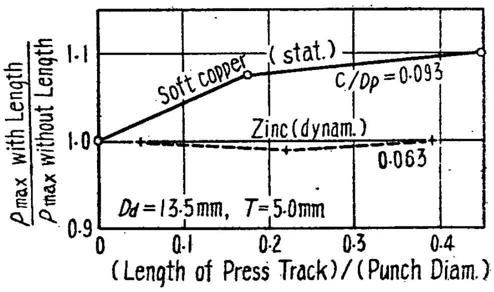


Fig. 15. Effect of Length of Press Track on Maximum Extruding Pressure.

(iii) Length of press track. The maximum extruding pressures with punches having various lengths of press track or land L_p are shown graphically in Fig. 15. The increase in pressure was expected with the length of press track because of increase in frictional resistance acting on the metal flowing through the orifice. This was the case for copper but not for zinc as will be seen from Fig. 15. In the latter case, the increase in extruding pressure during the ascending of the top of extruded metal through the cylindrical orifice was probably canceled by the considerable decrease in flow-stress of the metal as mentioned above.

(iv) Fillet radius of die bottom. When a certain radius R_d to the bottom corner of the die cavity was provided, the maximum extruding pressure for copper was found to be lowered to some extent. (See Fig. 16.) No more lowering of the pressure was found when the ratio of fillet radius to punch diameter exceeded about 0.2. As will be seen from the fact that a dead metal region was formed at the sharp bottom corner (, see Fig. 24), the flowing resistance of metal from beneath the punch front towards the orifice was probably higher for smaller radius. It may be added that the effect of fillet radius on the maximum pressure will disappear for thicker blanks.

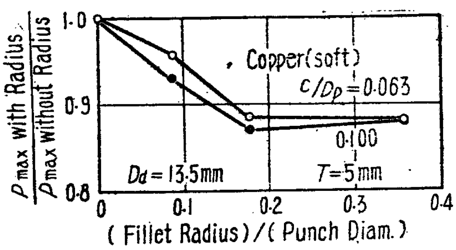


Fig. 16. Effect of Fillet Radius of Die Bottom on Maximum Statical Extruding Pressure.

i) *Effect of Thickness of Blank*

Thick blanks are required for tall shells and heavy bottomed shells. As is shown in Fig. 17, the maximum extruding pressure increased with the thickness of blank T. This increase, however, became steadily small for ratios of the thickness to the punch diameter above one half. The main reason for this is probably as follows:

During the extruding process of a comparatively thin blank, the metal lying between the punch face and the die bottom flows nearly uniformly towards the orifice as was pointed out by Dipper. In this case the resistance produced by the die bottom on the the bottom surface of this flowing metal is a frictional force. The frictional force is comparatively small if the tools are properly lubricated. On the other hand, if a thick blank is used and the distance between punch face and die bottom is sufficiently large, only a metal layer with certain thickness under the punch face flows at any stage of extrusion. This fact was pointed out theoretically by one of the authors[5)], and was confirmed experimentally by M. Kunogi[6)]. In this case, the flowing metal layer is naturally resisted by a shear resistance of the underlying stationary metal. As the shear resistance of metal is usually higher than the frictional resistance, it may be concluded that the thicker blanks generally requires higher extruding pressures than the thinner blanks.* The effect of blank thickness on the maxiuum extruding pressure may be expected to diminish if the thickness exceeds a certain limit above which the steady state of metal flow is realized during extrusion.

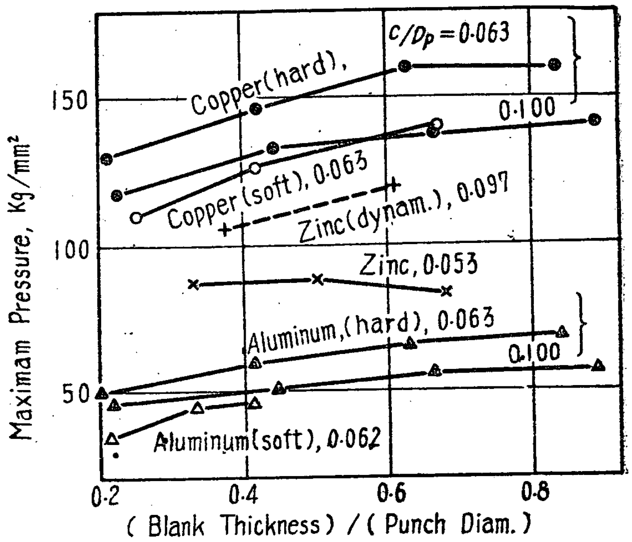


Fig. 17. Effect of Initial Blank Thickness on Maximum Statical Extruding Pressure.

The tendency for zinc under slow extrusion (, see Fig. 17), again differed from that for other metals. This may be explained as a consequence of strain-softening of the metal with the progress of extrusion.

j) *Effect of Blank Form*

The maximum extruding pressures for aluminum, copper and zinc blanks of two irregular shapes are tabulated in Table IV. The first type was of tall cylindrical form

Table IV. Ratios of Maximum Extruding Pressure for Irregular Blanks to That for Standard

Blank Metal	Punch Diameter, mm.	Clearance Ratio, C/D_p	Extruding Speed	Blank Form	Blank Size, mm.	Relative Pressure
Aluminum (soft)	12.7	0.031	Dynamic.	Cylindrical	10.0φ×8.0h	1.08
				Square	8.9×8.9×8.2h	1.10
Copper (soft)	11.3	0.097	Dynamic.	Cylindrical	10.0φ×8.0h	1.09
				Square	8.9×8.9×8.2h	1.07
Zinc	12.0	0.063	Dynamic.	Cylindrical	9.0φ×7.8h	0.69
				Square	8.8×8.8×8.0h	0.77
Zinc	12.0	0.063	Static.	Cylindrical	9.0φ×7.8h	0.80
				Square	8.8×8.8×8.0h	0.88

* If an extremely thin blank is extruded, the required extruding pressure may again be very high.

with undersize diameter, and the second had a square section inscribed in the die cavity. Their dimensions were such that the volume of each was equal to that of the standard blank.

The maximum pressures for the irregular blanks of copper and aluminum were higher than those for the standard blank while the situation was reversed for zinc. These different tendencies were considered again as the result of different responses of metals to straining. On working the blank of irregular type, the extrusion was preceded by an upsetting of about 50% reduction in height to fill the die cavity up with metal. This prestraining would have induced strain-hardening of the aluminum and copper blanks. The heat developed in the upsetting process would not be enough to eliminate the hardening effect. On the contrary, considerable lowering of flow-stress for zinc would have occurred owing to the combined effect of work-softening and softening by temperature rise in the upsetting process. In this respect, J. D. Shoemaker[7] has already referred to the undersize blank of aluminum alloys which he called "low pressure blank".

k) *Effect of Lubricant*

For the purpose of examining the effect of applied lubricant on the extruding force, aluminum, copper, zinc, duralumin and yellow brass blanks were extruded using a commercial special wax for extrusion, a colloidal graphite in water, lard oil, soya-bean oil, a water emulsion with palm oil, a water emulsion with spindle oil and spindle oil as the lubricant.

(i) In case of statical extrusion. The forms of extruding force-stroke diagrams when the metals were extruded by smoothly finished tools with a lubricant of relatively good quality, have been illustrated above in Fig. 5. Different forms, however, as shown

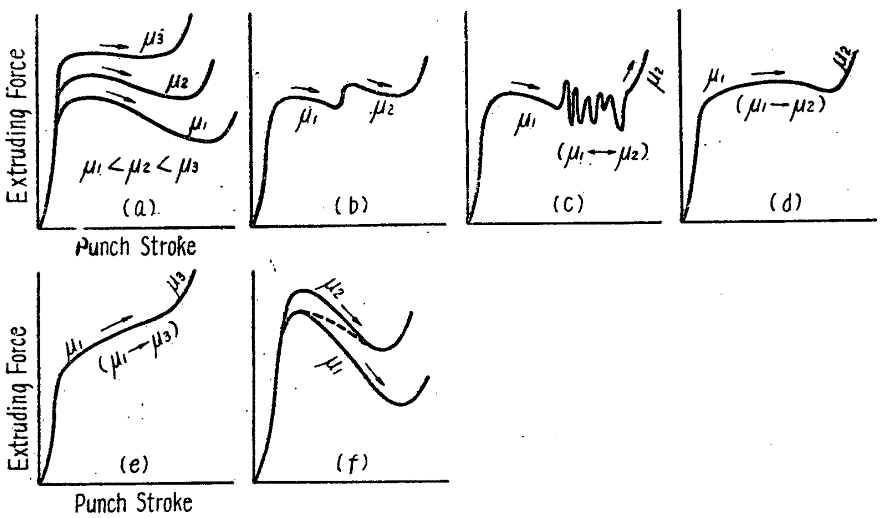


Fig. 18. Schematic Figures of Extruding Force-Stroke Diagram to Explain Effect of Coefficient of Friction.

schematically in Fig. 18*b*, *c*, *d* and *e* were seen when a lubricant of low quality such as spindle oil was used. Fig. *b* shows a type of force-stroke diagram having two maxima as well as two minima. In some cases, zig-zags were seen on the diagrams after the first maximum was exceeded. (See Fig. *c*.) In the case of type shown in Fig. *d*, the extruding force increased continuously even after the extrusion had begun, until it decreased slightly, thus exhibiting a minimum. In such a case, the maximum point was located near the end of the stroke, and the difference between the maximum and minimum forces or pressures was very small. Sometimes the minimum did not appear as is seen from Fig. *e*.

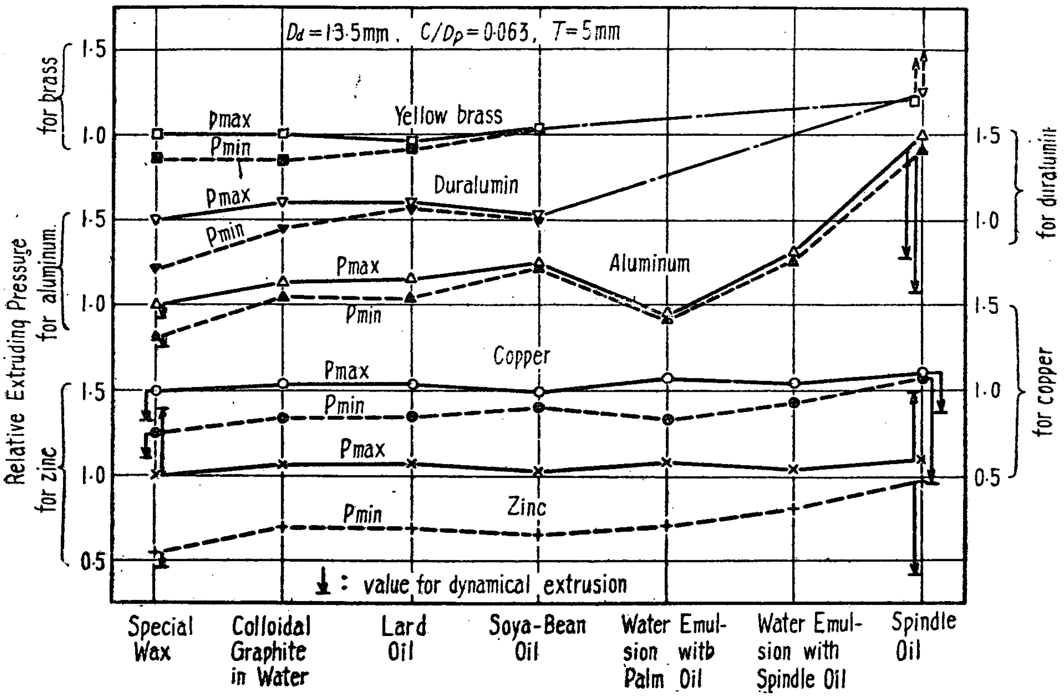


Fig. 19. Effects of Applied Lubricant on Statical Maximum and Minimum Extruding Pressures Using Tools Finished by Fine Carborundum Paper.

In Fig. 19 are plotted the values of the maximum and minimum extruding pressures with various kinds of lubricant, these values being expressed as ratios relative to the maximum pressure with the special wax for each metal. When the force-stroke diagram was of the type shown in Fig. 18*b* or *c*, the absolute maximum value and the last minimum value were taken.

The effects of applied lubricant on the maximum and minimum pressures were different depending upon the kind of blank metal. For copper and zinc, the maximum pressures were not affected appreciably by the lubricants except for the spindle oil. The minimum pressures for copper were almost constant except for the spindle oil. The minimum pressures for zinc were again nearly constant for all lubricants tested but for the spindle oil and its water emulsion. On the other hand, for aluminum, both the maximum and minimum pressures were largely affected by the kinds or types of lubricant used. The maximum and minimum pressures were almost equal to each other for the soya-bean oil, the water emulsion with palm oil, the water emulsion with spindle oil and the spindle oil. In the case of yellow brass, the maximum pressure with the special wax, the colloidal graphite in water, the lard oil and the soya-bean oil were nearly the same, while the minimum pressures were rather sensitive to the quality of lubricant. The tendency for duralumin was similar to that for aluminum. In particular, when the yellow brass and duralumin were extruded with the use of the spindle oil, no maximum, and consequently, no minimum extruding force was revealed until even up to a point where very severe stresses were induced in the extruding punches, and the extrusions had to be given up.

The above mentioned effects of applied lubricants on the form of extruding force-stroke diagram, on the maximum and minimum extruding pressures, as well as on the different tendencies of these effects depending upon the kinds of blank metals may be interpreted as follows:

The typical extruding force-stroke diagram for a work-hardenable metal with a lubricant of best quality, which gives a very low and consistent coefficient of friction, may be such as that shown schematically by the lowest curve in Fig. 18*a*. If extrusions are carried out with comparatively higher coefficients of friction the force-stroke curves will be such as those shown by the upper curves in Fig. *a*. This is expected from the model of metal flow suggested by Dipper[2]. Here, the difference between the maximum and the minimum pressures is very small, or no minimum appears. (C.f. discussion in Section A, i).) These facts are considered to be one reason why the minimum extruding pressures were more sensitively affected by the kind of lubricant rather than were the maximum pressures.

Another possible reason for this may be a lowering of lubricating function of the applied lubricant during the extruding process. At the initial stage of extrusion, a part of the applied lubricant may be trapped between the metal and tool, and a lubricant layer of certain thickness would then be left there[8]. It is to be expected, therefore, that the maximum extruding pressure for any one metal which develops generally in the initial stage of extrusion may be nearly equal regardless of the properties of the lubricant. On the other hand, as the extruding process progresses, the surface area of the blank naturally expands to as much as several times or several tens of times of the original, thus resulting in the thinning of the lubricant layer on the metal surface. Under such circumstances, the lubricating function of a lubricant would depend largely upon its film strength. Accordingly, the minimum extruding pressure, which develops usually near the end of the process, is considered to vary widely for different kinds or types of lubricant. The tendency of the lowering of lubricating function with progressing extrusion was also confirmed by the appearance of the extruded shells as will be seen later in Fig. 25. From Fig. 18*a*, then, it is to be expected that two maxima and minima as shown in Fig. *b* will appear on the extruding force-stroke diagram if an initial better lubricating condition changes suddenly into a worse condition at a certain stage of the extrusion. If the change occurs gradually from one condition to another, the corresponding force-stroke diagram may be such as that illustrated in Fig. 18*d* or *e*. Moreover, a certain unstable state between the two different lubricating conditions will probably develop zig-zags on the diagram. (See Fig. *c*.)

The above discussion shows that the comparison of the minimum pressures is more suitable than that of the maximum for testing the adaptability of lubricant for extrusion. In addition, it is supposed that a lubricant of better quality may be required for producing longer shells.

The differences in the effects of lubricant for different metals is thought to originate in the differences in the chemical properties as well as in the flow-stresses of the metals. The former is probably related to the rupture-strength of lubricant film on the metal surface, while the latter is probably related to the normal pressure acting on the film. It was seen from Fig. 19 that the extruding pressures for aluminum were very sensitive to the type or kind of lubricant, in spite of aluminum's relatively low flow-stress. It has been established already that the lower the pressure is, the more favorable will the condition be for boundary lubrication if the pressure is above several tens of kg./mm^2. as is the case for the cold extrusion of metal[9]. Accordingly, the appreciable difference between the extruding pressures for aluminum with various types of lubricant may be attributed to its unfavorable chemical properties for lubrication. It has been reported that aluminum and iron (which is the tool material) are poorly lubricated by a fatty acid, but that the metals such as zinc and copper are well lubricated[10]. This data is in accordance with the different manners in which the extruding pressures for aluminum, copper and zinc depended on the type or kind of lubricant. This holds also for yellow brass and duralumin, the chemical properties of which are rather similar to those of copper and aluminum, respectively. From the authors' test data, the possible effects of large differences in the flow-stresses of yellow brass and copper as well as of duralumin and aluminum were not clearly seen. These interpretations stated here were confirmed also by the surface states of extruded shells as will be seen later. The only result, then, that was common for all metals tested was that the special wax produced the lowest extruding pressures, while the spindle oil produced the highest among the lubricants tested.

ii) In case of dynamical extrusion. The lubricating action in the dynamic extrusion by the crank press seemed to differ to some extent from that in the statical extrusion. This is illustrated in Fig. 19, where the maximum and minimum impact extruding pressures with the wax as well as with the spindle oil are also shown by points of arrows. From the figure it will be seen that the pressure lowering effects of extruding speed (, c.f. Section *e*.),) for aluminum, copper and zinc were more pronounced with the spindle oil than with the wax. This was the case especially for the minimum pressures. One probable reason for this is that more heat is generated and, accordingly, the flow-stress of metal is decreased, if the coefficient of friction between metal and tool is higher.

Another possible reason may be an influence of sliding speed upon the lubricating function of the lubricant. For a viscous lubricant with high film strength such as the wax, the increase in sliding speed might have caused the increase in the coefficient of friction because of a viscosity effect. On the other hand, the reverse might be the case for a less viscous lubricant with low film strength such as the spindle oil, because such an oil would have been introduced between the sliding surfaces more readily as the sliding speed was increased[11]. Again, the interpretation was confirmed by the observation of the surfaces of extruded shells. (See Fig. 25.)

l) *Effect of Surface Finish of Extruding Tool.*

The effect of the surface finish of extruding punch and die on the extruding pressure was examined for aluminum, copper and zinc with the special wax and with the spindle oil. Thereupon, the surface finishes of three different grades were prepared. The first was ground, lapped with a fine carborundum paper and then buffed with powder of chromium oxide. The second was as lapped by the fine carborundum paper, and the last was abraded with a coarse carborundum paper. Moreover, these finishing operations were repeated after each extrusion to remove the adherent metal on the tool surface and thus to obtain consistent experimental data. The surfaces finished in these ways had the surface roughnesses along the direction of metal flow corresponding approximately to the designation of JIS 0.4S, 1S and 4S respectively.*

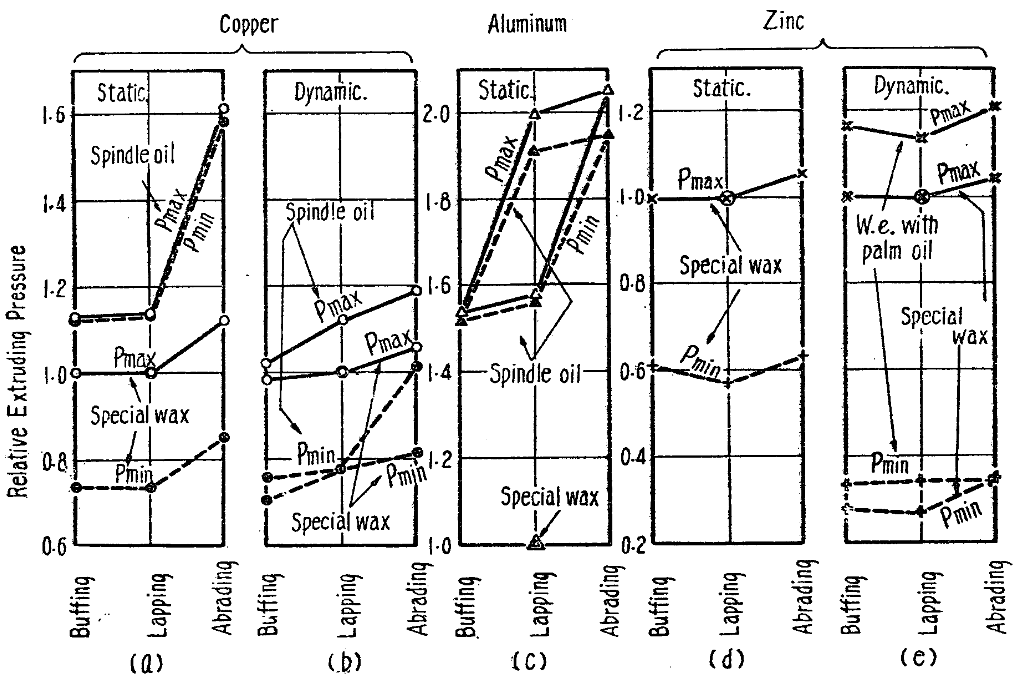


Fig. 20. Effects of Surface Roughness of Extruding Tool on Maximum and Minimum Extruding Pressures. (Extruding ratio $C/D_p=0.063$, die diameter 13.5 mm., blank thickness 5 mm.)

The test data were complied in Fig. 20, where the maximum and minimum extruding pressures were plotted as the ratios to the maximum pressure with the special wax for each metal and for each extruding speed. For most cases, the differences between the extruding pressures with the buffed tool and lapped tool were zero or very small, if any. However, the fact that two decidedly different series of pressure values were obtained for the statical extrusions of aluminum with the lapped tool using the spindle oil (, see Fig. 20 c), will indicate that two different states of friction

* The number in the designation of surface roughness according to the Japanese Industrial Standards (JIS) represents the maximum depth of valley in microns from the ideal reference surface.

may occur under this set of working conditions.

The extruding pressures for copper and aluminum with the tool of abraded surface increased appreciably, while for zinc, no effect of surface roughness of tool was found. The effect was more pronounced with the spindle oil than with the special wax, and was more pronounced in the statical extrusion than in the dynamical.

An analogous interpretation to that discussed above concerning the effect of lubricant will be applied here. For, the use of the extruding tool of rougher surface is thought to produce an effect on the lubricating condition equivalent to that produced by the use of lubricant of lower quality. The coincidence of extruding pressures for the tool surfaces finished by buffing and by lapping shows that the lubricating condition is hardly altered if the sliding surfaces are finished beyond a certain degree of smoothness as was reported already.[12,13,14]

A question arises, then, why the extruding pressure for zinc with the abraded tool was not increased, though the side-wall of shell extruded under this condition was heavily scratched. This may be explained as follows: The extruding force-stroke curve for a work-softenable metal such as zinc is such that shown in Fig. 5, in which a pronounced drop in the force follows an initial maximum. This is illustrated schematically in Fig. 18f for two different values of coefficient of friction. The maximum pressure with the abraded tool, therefore, is probably not higher than that with the lapped tool if the initial coefficient of friction is comparatively low and even if it increases with progressing extrusion as was stated in Section k). (See the broken-line curve in Fig. 18f.) This interpretation is analogous to that stated in Section h), (iii) concerning the effect of the length of press track of extruding punch on the maximum extruding pressure for zinc. In fact, the maximum for zinc appeared at or near the initial stage of extrusion under any working condition. On the other hand, the insensitiveness of the minimum extruding pressure for zinc to the surface roughness should be attributed to the variation of the flow-stress of the metal caused by the heat generated during working.

[B] Properties of Extruded Shell

a) *Hardness*

Table V shows the Vickers hardness numbers of the unworked blanks and extruded shells. The high-melting metals tested have generally reached their fully strain-hardened states in all shells extruded with the clearance to punch diameter ratios from 0.015 to 0.100. These hardness values were equal to those for the metals compressed to more than about 70 per cent reduction in height. Because of insufficient cold working, lower values were found at the upper portions of the side-wall of all shells as well as at the bottoms which were not heavily reduced.

No speed effect was seen on the hardness in all cases.

On the other hand, however, no appreciable change in hardness by extrusion was seen for zinc and hard tempered metals.

Table V. Vickers Hardness Numbers of Extruded Shells

Metal	Hardness of Blank	Punch Diameter, D_p, mm	Clearance Ratio, C/D_p	Extruding Speed	Thickness of Shell Bottom, mm	Hardness of Shell		
						Upper Portion of Wall	Lower Portion of Wall	Bottom
Aluminum (soft)	19.5	11.25 12.00 12.70 12.00	0.100 0.063 0.031 0.063	static. static. static. dynamic.	0·74 0.39 1.15 1.06	39 44 45 45	39 44 45 48	45 47 45 48
Aluminum (hard)	43	12.00	0.063	static.	0.42	51	50	50
Copper (soft)	38	11.25 12.00 12.70 12.00	0.100 0.063 0.031 0.063	static. static. static. dynamic.	0.50 0.37 1.02 0.32	113 120 125 117	124 124 124 116	127 127 129 121
Copper (hard)	110	12.00	0.063	static.	0.32	128	129	133
Duralumin	65	11.25 12.00	0.100 0.063	static. static.	1.04 0.50	110 124	125 131	135 140
Yellow Brass	55	11.25 12.00	0.100 0.063	static. static.	0.45 0.59	157 195	214 223	223 223
Zinc	34	12.00	0.063	static.	0.22	37	38	36

b) *Faults*

Generally, all metals tested were able to deform or flow without fracturing in extrusion in spite of the extremely severe strains induced. This was the case even for certain metals such as aluminum alloys containing silicon of more than 8% as well as those containing copper of more than 4%, which fractured by shear during compression tests. According to Gokyu and his coworkers,[1] pure magnesium and Dow metal were successfully impact extruded with reductions of area above 80% at room temperature, but failed with reductions of area below 70%. These results confirm the well-known law that the ductility of metal increases with increasing mean pressure or the mean value of three principal compressive stresses acting on it.

i) Tearing of shell wall. The tearing of shell as shown in Fig. 21 was caused by improper centering or guiding of punch, especially for thin walled shells. This fact may set a lower limit to the extruding clearance or wall thickness of shell regardless of extruding pressure.

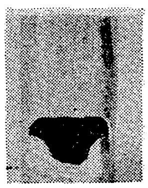


Fig. 21. Tearing of Thin Wall of Extruded Shell Caused by Floating of Punch.

ii) Cracking at the edge of wall. Radial cracks were found at the wall edges of copper shell (, see Fig. 22 a), when they were extruded from undersize blanks. This would be due to a circumferential tensile stress developed in the upper periphery of the blank in filling the die cavity, as will be seen from Fig. 22 b. If the metal has insufficient ductility, cracking may result from such stress.

iii) Circumferential cracking and thinning in the lower portion of wall. Crackings of this type usually accompanied by a local thinning of the portion were found sometimes when the shell bottoms were reduced very severely. (See Fig. 23 a.) This phenomenon may be explained as follows:

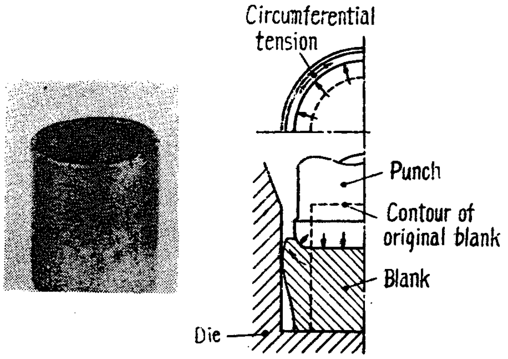


Fig. 22. Photograph and Descriptive Figure for Radial Cracking at Top Edge of Extruded Shell Wall.

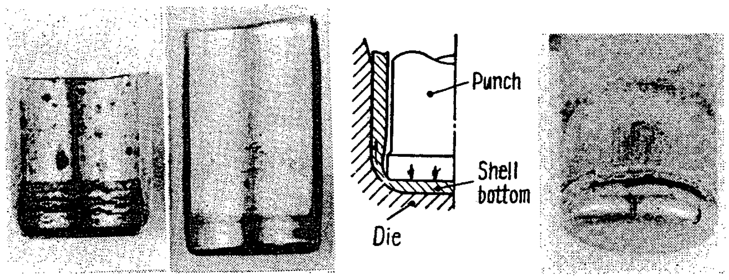


Fig. 23. Thinning at Lower Portion of Extruded Side-Wall Accompanied by Circumferential Cracking of Wall or Radial Cracking at Bottom Edge.

The width of orifice between punch and die will become narrower in the later stages of extrusion if a die with relatively large fillet radius is used. (See Fig. 23 b.) This obviously results in a gradual thinning of the base of extruded side-wall as will be illustrated in Fig. 23 a. The same type of thinning was also found in some cases with sharp fillet corner of die bottom and with relatively large edge radius of punch front. That is, during extrusion of a shell, after the thickness of the bottom is reduced below that of the side-wall, the metal lying between punch front and die bottom can be squeezed out around the punch edge without changing its thickness or by bending. The unsupported thin section of the wall thus formed may readily buckle or fail under a longitudinal compressive stress, as the metal of the portion has already been fully hardened and there acts no transverse pressure which increases the ductility of the metal.

In some cases when rather brittle metals, such as certain aluminum alloys, were extruded, radial cracking at the periphery of the shell base was also found (, see Fig. 23 c), together with circumferential cracking and thinning at the lower portion of side-wall.

For light bottomed extrusions, the thinning of the base of side-wall, and consequently the cracking, were prevented if a relatively sharp corner was provided at the fillet of the die bottom.

iv) Faults at bottom edge. The fault of this type was caused by the presence of dead-metal when a sharp fillet corner of die bottom was used. (See Fig. 24 a and b.) Owing to the severe shearing on the boundary between the dead-metal and flowing metal during extrusion, the annular dead-metal corner frequently dropped off after the shell was taken out from the die, and the result was a bevelled edge

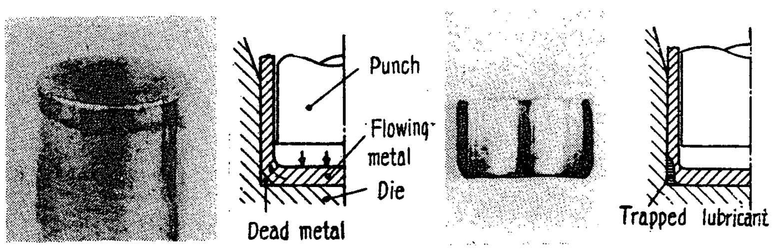


Fig. 24. Photographs and Discriptive Figures for Failures at Bottom Edge of Extruded Shell.

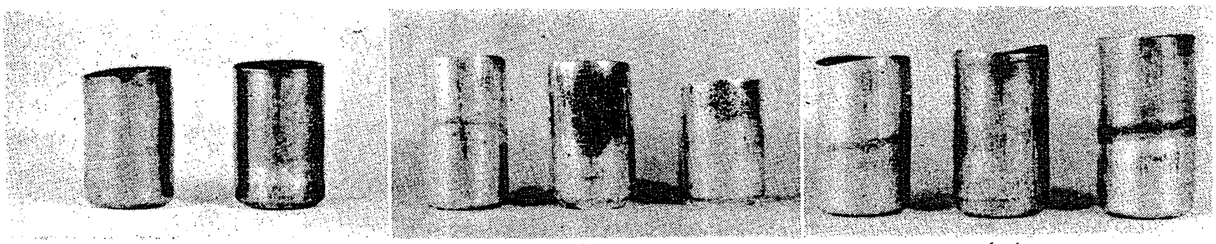
of the shell bottom.

Another source of the bevelled edge was the lift up of the bottom edge of relatively thick-walled shell when the shell bottom was heavily reduced. (See Fig. 24 c.) Also a type of fault at the bottom edge of extruded shell which resembled that shown in Fig. 23 a when the extrusion was carried by a blind die with abundant lubricant. This was caused by the presence of the lubricant of considerable amount which was trapped at the corner of the die bottom. (See Fig. 24 d.)

c) Surface State

The surface roughness of extruded shell varied greatly depending on the kind of blank metal, the applied lubricant, the degree of surface finish of tool, and the working speed. Very smooth surfaces were obtained over the whole side-walls of copper and zinc shells extruded with the buffed tool with the used of the wax. An example of the appearance of such smooth surfaces is shown in Fig. 25 a (left). A magnified

Special wax, stat. | Spindle oil, stat. | Special wax, stat. | Spindle oil, stat. | dynam. | Special wax, stat. | Spindle oil, stat. | dynam.



(a) Copper (b) Aluminum (c) Zinc

Fig. 25. Surface Appearances of Extruded Shells As Were Affected by Kind of Lubricant and by Extruding Speed.

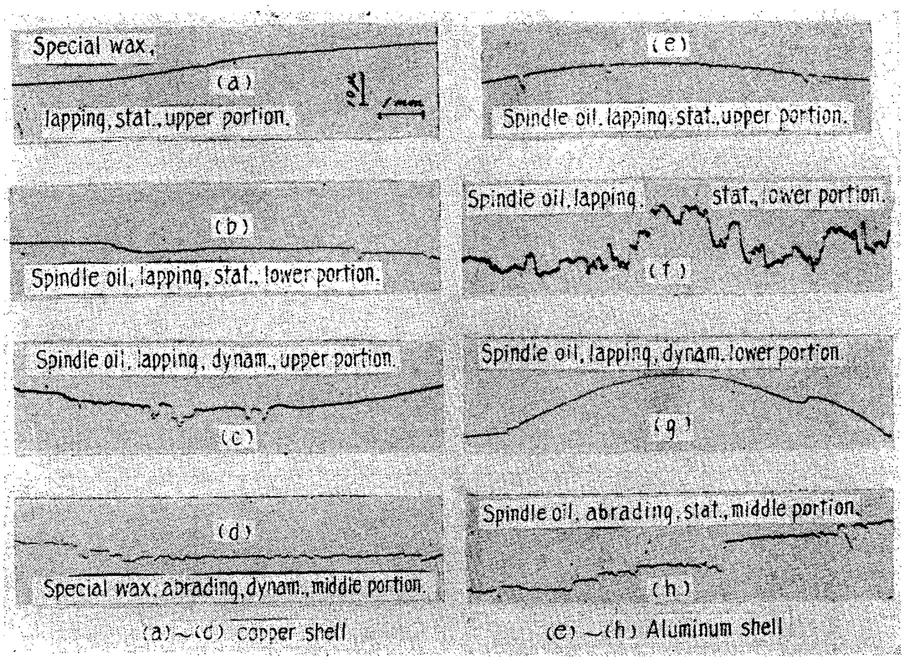


Fig. 26. Examples of Surface Roughness Prolfie Along Circumference of Extruded Side-Wall Showing Effects of Lubricant, Surface Finish of Tools, Blank Metal and Working Speed.

profile of such surface taken along the circumferential direction is illustrated in Fig. 26 a, the roughness of which is of the order of JIS 1S or below. Under less favorable lubricating conditions, that is, for instance, when copper or zinc was statically extruded with the spindle oil or when aluminum was statically extruded with the special wax, both with the smoothly finished tool, the upper surfaces of the side-wall were again very smooth or slightly scratched, while the lower surfaces of the wall were roughened to varying extents by longitudinal scratches. (See Fig. 25 a (right), b (left, center) and c (left, center) as well as Fig. 26 b, e and f.) The fact that the lower surfaces of extruded side-walls were rougher than the upper confirms the lowering tendency of lubricating function of lubricant with progressing extrusion as mentioned already. In all cases when the metals were extruded by the abraded tool, the whole surfaces of the extruded shells were covered by severe scratches. (See Fig. 26 d and h.)

Examples of the surfaces of dynamically extruded shells are shown in Fig. 25 b (right), c (right) and Fig. 26 g. It is clear from these figures, that the surface states of the lower portions of dynamically extruded side-walls were considerably improved

Table VI. Effect of Applied Lubricant on Surface State of Statically and Dynamically Extruded Side-Wall of Shells. ($C/D_p=0.063$)

Lubricant	Extruding Speed	Surface State of Extruded Side-Wall *									
		Aluminum		Copper		Zinc		Yellow Brass		Duralumin	
		Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Special Wax	Static.	S	M-SC	S	L-SC	S	L-SC	S	L-SC	L-SC	M-SC
	Dynamic.	S	L-SC	G	L-SC	S	L-SC	S	L-SC	S	L-SC
Colloidal Graphite in Water	Static.	L-SC	H-SC	S	M-SC	S	L-SC	L-SC	L-SC	L-SC	H-SC
	Dynamic.	—	—	S	L-SC	S	L-SC	—	—	—	—
Lard Oil	Static.	L-SC	H-SC	G	L-SC	S	M-SC	S	L-SC	L-SC	H-SC
	Dynamic.	G	L-SC	G	L-SC	G	L-SC	—	—	—	—
Lanolin	Dynamic.	G	M-SC	G	M-SC	G	L-SC	—	—	—	—
Rape Oil	Dynamic.	G	M-SC	G	M-SC	G	M-SC	—	—	—	—
Soya-Bean Oil	Static.	L-SC	M-SC	S	L-SC	L-SC	H-SC	S	L-SC	L-SC	M-SC
Palm Oil	Dynamic.	G	M-SC	S	L-SC	G	L-SC	—	—	—	—
Water Emulsion with Palm Oil	Static.	S	L-SC	L-SC	H-SC	S	M-SC	—	—	—	—
	Dynamic.	S	L-SC	S	L-SC	S	L-SC	—	—	—	—
Sulphurized Oil	Dynamic.	G	M-SC	G	M-SC	G	M-SC	—	—	—	—
Spindle Oil	Static.	L-SC	H-SC	G	M-SC	G	H-SC	H-SC	H-SC	M-SC	H-SC
	Dynamic.	G	L-SC	G	L-SC	G	L-SC	—	—	—	—
Water Emulsion with Spindle Oil	Dynamic.	S	H-SC	L-SC	L-SC	S	H-SC	—	—	—	—

S: smooth, G: granular, SC: longitudinal scratches, H: heavy, M: medium, L: light compared with those extruded statically under otherwise the same working conditions. These observations seem to verify the improvement in the lubricating condition as the sliding speed is raised as was suggested in [**A**], k), (ii).

Another feature of the surface which was observed often on the dynamically extruded shell-walls was a granular appearance at the upper portion. (See Fig. 25 b (right), c (right) and Fig. 26 c.) This granular surface was formed also in one or two cases of statical extrusion. The source of this is thought to be due to the result that granular surface developed on the side of blank by plastic deformation is not perfectly crushed and smoothed up if too thick a lubricant layer was trapped between the metal and tool. This interpretation is probably correct because the granular appearance occurred very often on the upper surfaces of dynamically extruded side-wall rather than on those statically extruded, and moreover, no granular surface was found even on a dynamically extruded shell if the excessive lubricant applied on the metal was wiped off before working. From this discussion, therefore, it may be concluded that the application of excessive lubricant is unfavorable, especially for dynamical extrusion, and, consequently, that a lubricant of high film strength is required.

Table VII. Effect of Surface Finish of Tool on Surface State of Extruded Side-Wall. (C/D_p=0.063)

Blank Metal	Extruding Speed	Applied Lubricant	Surface States of Extruded Side-Wall					
			Buffing Finish 0.4S		Lapping Finish 1S		Abrading Finish 4S	
			Upper	Lower	Upper	Lower	Upper	Lower
Copper	Static.	Special Wax	S	S	S	L-SC	L-SC	M-SC
		Spindle Oil	L-SC	L-SC	L-SC	L-SC	H-SC	H-SC
	Dynamic.	Special Wax	S	S	S	L-SC	M-SC	M-SC
		Spindle Oil	G	L-SC	S	L-SC	H-SC	H-SC
Aluminum	Static.	Special Wax	—	—	S	M-SC	—	—
		Spindle Oil	L-SC	M-SC	L-SC	H-SC	H-SC	H-SC
Zinc.	Static.	Special Wax	S	S	S	L-SC	M-SC	M-SC
	Dynamic.	Special Wax	S	S	S	L-SC	M-SC	M-SC
		Water Emulsion with Palm Oil	S	L-SC	S	L-SC	M-SC	H-SC

The various types and grades of surface states of extruded shell walls described above were listed in Tables VI and VII, with the use of the signs representing them for various kinds of metals, lubricant, and surface finishes of tool. There exist obvious correlations between the surface states listed in these tables and the extruding pressures complied in Figs. 19 and 20. From these tables, it will be seen that the surface finish of working tool of grade above JIS 1S is favorable for the cold extrusion of metal, and that lubricant must be selected depending on the kind of blank material. In addition, it is seen that lubricants of lower quality than those required for statical extrusion can be used for dynamical extrusion.

[C] Failures of Extruding Tool

Although no special test on the strength of working tool was carried out in the authors' study, it may be of some value to note the failure of tools encountered by them. Fig. 27 shows some examples.

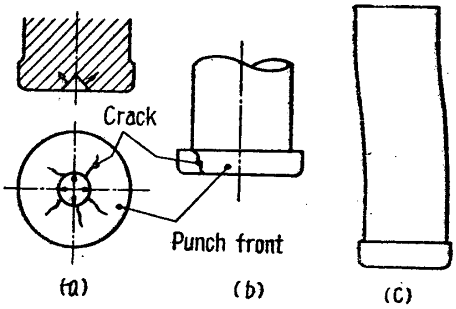


Fig. 27. Various Types of Punch Failure: (a) radial cracking around centre hole on punch front, (b) breakage of projected thin punch front, (c) buckling failure of punch body.

Radial cracking was frequently seen around the center hole provided on the punch front for machining. (See Fig. 27 a.) Clearly, this was caused by the internal pressure acting from the metal which filled the hole during extrusion. After the elimination of this hole, no more failures of this type were found.

Breakage of the prolonged and thin shoulder of the punch front often occurred as is illustrated in Fig. 27 b.

Plastic buckling of the punch body sometimes followed by fracturing was seen frequently under a compressive stress of more than about 200 kg./mm^2. (See Fig. 27 c.) It is to be noted that these buckling stresses or breaking stresses for the fully hardened punches used by the authors seemed to be lower than the conventional allowable stresses, probably because the upper ends of the punch bodies were not fixed to a holder and, moreover, a screw hole was provided at the upper end of each for the sake of handling.

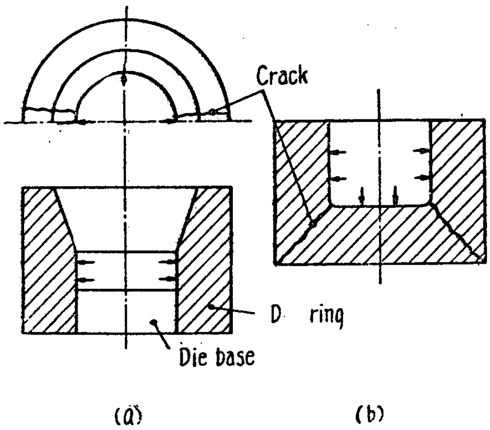


Fig. 28. Radial Cracking (a) and Cracking along Conical Surface (b) of Die.

The failures of the dies can be subdivided into two types. One was the radial cracking of the die ring and the other was the cracking along a conical surface extending from the bottom corner of the die cavity into the die base. (See Fig. 28 a and b.) The latter was prevented by separating the die into two part, namely, a die ring and a die base, as shown in Fig. 1. Also the radial cracking of the die ring was not seen after the ring was reinforced by a shrunk fit annulus.

4. ESTIMATION OF EXTRUDING PRESSURE

The estimation of extruding pressure based on any exact analysis of the process is impossible at present. A possible flow model of metal for the backward extrusion of a cylindrical shell was suggested by M. Dipper[2] in 1949. He calculated the variation of punch pressure during the process according to this model. His method of calculation, however, included some improper assumptions as were pointed out by one of the authors[5]. For example, Dipper's assumption requires that the maximum extruding pressure increases uniformly with increasing thickness of blank. According to the authors' experimental results, however, the increase in the maximum pressure was very small for the blank with the thickness of above about one-half of its diameter if it was properly lubricated.*

In the present paper, the authors have suggested an empirical formula based on the data for the estimation of the maximum pressure required in the backward extrusion of cylindrical shell. The formula attempted is of the type:

$$p_{\max}=K\cdot F_1\left(\frac{C}{D_p}\right)\cdot F_2\left(\frac{T}{D_p}\right)\cdot Y_m,$$

where, K is a constant, F_1 is a function of the ratio of extruding clearance to punch diameter, F_2 is a funtion of the ratio of blank thickness to punch diameter and Y_m stands for the mean flow-stress of metal during extrusion. Though the mean flow-stress of metal may vary with C/D_p and T/D_p, it was treated for simplicity as an independent variable and an inherent magnitude in a given metal.

For the determination of the constant and the form of the functions in the above formula, the experimental values, which were obtained under relatively favorable working conditions, of maximum statical extruding pressures for high-melting metals were utilized. From the relation between the maximum pressure and the clearance ratio given in Fig. 6, it was found that the function F_1 was nearly of the form $(C/D_p)^{-1/3}$ for every metal. As was already shown in Fig. 8, the maximum extruding pressures for various metals were in proportion to their flow-stress at the logarithmic strain of about 0.5. It was considered, here, that the mean flow-stress of a metal during extrusion was equal to the compressive flow-stress of the metal at logarithmic strain of 0.55. On the other hand, the form of the function F_2 was approximated by $(T/D_p)^{1/6}$. (See Fig. 17.)

The expression for the formula of maximum pressure obtained in this way is,

$$p_{\max}=1.60\cdot\left(\frac{C}{D_p}\right)^{-1/3}\cdot\left(\frac{T}{D_p}\right)^{1/6}\cdot Y_{0.55},$$

$$(C/D_p=0.015\sim0.100,\quad T/D_p=0.2\sim1.0).$$

The numerical values of $(C/D_p)^{-1/3}$ and of $(T/D_p)^{1/6}$ are shown graphically in Fig. 29 against (C/D_p) and (T/D_p) respectively.

In Table VIII, the values of maximum statical extruding pressures obtained by the experiments for high-melting metals are compared with those calculated from the above formula. In almost all cases, the deviations of the experimental values from the calculated values were within 10 per cent of the latter.

* A nomograph for the pressure required in the backward extrusion based on Dipper's analysis was offered by H. J. Pessel[15]. After examining the authors' test data with this nomograph, it is found that this overestimates the maximum extruding pressures to a considerable extent. The application of Siebel's formula for piercing[16] was also attempted by the authors and was proved effective to some extent.

Table VIII. Comparison of Values of Maximum Statical Extruding Pressures for High-Melting Metals Obtained by Experiment and by Empirical Formula

Blank Metal	Applied Lubricant	Mean Flow Stress, Y_m, kg/mm²	Punch Diameter, D_p, mm	Blank Thickness Ratio, T/D_p	Extruding Clearance Ratio, C/D_p	Maximum Extruding Pressure, kg/mm²: Experimental Value	Maximum Extruding Pressure, kg/mm²: Calculated from Empirical Formula
Aluminum (soft)	W.E. with Palm Oil	12.7	13.10	0.38	0.015	69	70
			12.70	0.39	0.031	53	55
			12.00	0.42	0.063	41	44
			11.25	0.44	0.100	38	38
			12.00	0.21	0.063	35	39
			20.60	0.24	0.035	48	48
			19.00	0.21	0.081	34	36
Aluminum (hard)	W.E. with Palm Oil	16.2	12.70	0.39	0.031	72	70
			12.00	0.42	0.063	59	56
			11.25	0.44	0.100	53	49
			12.00	0.20	0.063	50	50
			12.00	0.63	0.063	65	60
			12.00	0.84	0.063	68	63
			11.25	0.22	0.100	46	43
			11.25	0.67	0.100	56	52
			11.25	0.89	0.100	57	55
Copper (soft)	Special Wax	35.0	13.10	0.38	0.015	208	193
			12.70	0.39	0.031	147	151
			12.00	0.42	0.063	118	122
			11.25	0.44	0.100	101	105
			12.00	0.25	0.063	110	111
			12.00	0.67	0.063	140	132
Copper (hard)	W.E. with Paim Oil	41.9	12.70	0.38	0.031	182	180
			12.00	0.21	0.063	147	146
			11.25	0.44	0.100	132	126
			12.00	0.21	0.063	130	129
			12.00	0.63	0.063	160	156
			11.25	0.22	0.100	118	112
			11.25	0.67	0.100	136	136
			11.25	0.89	0.100	141	143
Duralumin	Special Wax	35.8	12.70	0.39	0.031	147	154
			12.00	0.42	0.063	119	125
			11.25	0.44	0.100	106	108
Yellow Brass	Special Wax	50.8	12.00	0.42	0.063	189	177
			11.25	0.44	0.100	154	152

Table IX Maximum Extruding Pressures for Low-Melting Metals and Their Ratios to $(C/D_p)^{-1/3}\cdot(T/D_p)^{1/6}$

Blank Metal	Applied Lubricant	Extruding Speed	Punch Diameter, D_p, mm	Blank Thickness Ratio, T/D_p	Extruding Clearance Ratio, C/D_p	Maximum Extruding Pressure (Exp.) kg/mm²	$\frac{P_{max}(\text{Exp.})}{(C/D_p)^{-1/3}\cdot(T/D_p)^{1/6}}$ kg/mm²
Lead	Grease	Static.	12.00	0.42	0.018	21	6.4
			12.00	0.42	0.053	14	6.1
			12.00	0.42	0.095	11	5.8
			30.39	0.20	0.011	22	6.5
			29.80	0.20	0.022	17	6.2
			28.96	0.20	0.037	14	6.2
Zinc	Special Wax	Static.	13.10	0.38	0.015	111	32
			12.70	0.39	0.031	92	34
			12.00	0.42	0.063	77	34
			11.25	0.45	0.100	67	36
	W.E. with Palm Oil	Dynamic.	12.70	0.39	0.031	145	54
			12.00	0.42	0.063	115	50
			11.30	0.44	0.097	105	55

The magnitude of non-dimensional constant K in the above formula may naturally be somewhat higher than 1.60 if a certain working condition, for example, the lubricating condition, is improper.

For high-speed or dynamical extrusion, the circumstances are more complicated than those for low-speed or statical extrusions as was discussed above in Chapter 3. [A], e). That is, the maximum dynamical extruding pressures for high-melting metals were somewhat lower than those for statical extrusions, while their flow-stresses were higher for faster strain rates. For practical purposes, however, the maximum extruding pressures for these metals in high-speed extrusions on mechanical presses may be safely regarded to be equal to those in statical extrusion.

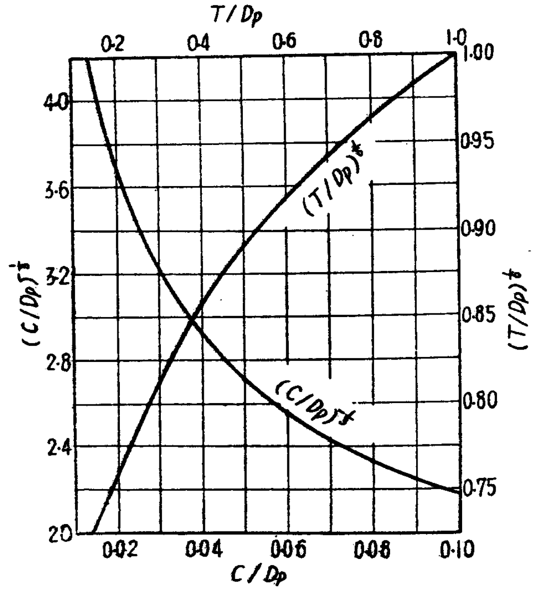


Fig. 29. Graphical Representation of $(C/D_p)^{-1/3}$ and $(T/D_p)^{1/6}$ Included in Empirical Formula for Maximum Statical Extruding Pressure.

The above mentioned method which derived the maximum extruding pressure from the flow-stress of metal, however, could not be applied for the low-melting metals such as zinc whose flow-stresses depended largely upon strain-rate. That is, the mean flow-stresses of such metals during the extruding process could not be taken from the compression test data, because the strain-rates of the metal in extrusion is quite obscure. In such cases, therefore, the maximum extruding pressures for any clearance ratio may be estimated only when a value corresponding to $p_{max}/(C/D_p)^{-1/3}\cdot(T/D_p)^{1/6}$ is obtained from an extruding test. (See Table IX.)

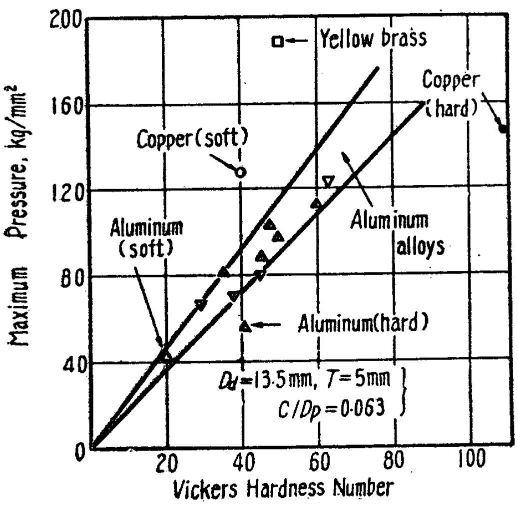


Fig. 30. Relation Between Maximum Extruding Pressures and Vickers Hardness Numbers of Metals.

In Fig. 30, the maximum extruding pressures for the metals of various kinds and different tempers under a given set of working conditions have been plotted against their Vickers hardness numbers. The figure shows that there exists no unique correlation between them as was pointed out by Dipper[2]. A linear relation, however, seems to hold for a group of metals such as the soft annealed aluminum and its alloys which have similar strain-hardenabilities.*

5. SUMMARY

1) When a metal was formed into a cylindrical shell by the backward extruding

* This appears to be confirmed by the fact that the Vickers hardness numbers of many metals are nearly proportional to the flow-stresses at the strain of 0.08 as was pointed out by Tabor[17].

method, the extruding force generally reached a maximum value in the initial stage, then, it decreased slowly or rapidly as the process progressed, and after a minimum was developed, a steep rise followed with narrowing of the thickness of metal between punch face and die bottom. For thick blanks, the extruding forces were kept nearly constant over a certain duration of the process. In some cases when the lubricating condition was not proper, more than one peak and valley appeared on the extruding force-stroke diagram, or the maximum developed near the end of extruding stroke.

2) The maximum extruding pressure per unit area of punch face was primarily affected by the kind and temper of blank metal, the ratio of extruding clearance to punch diameter and the ratio of blank thickness to punch diameter. An emprical formula was suggested for the approximate estimation of the maximum extruding pressure from the above factors.

3) The maximum extruding pressure increased also with the edge radius, side angle and press track length of punch front. These tendencies, however, were not remarkable for zinc. The provision of fillet radius at the corner of die bottom lowered the maximum pressures to some extent for relatively thin blanks.

4) The extruding pressure decreased with increasing working temperature because of the decrease in flow-stress of metal, and this was especially pronounced for zinc even at room temperature. When high-melting metals such as aluminum, copper, duralumin and yellow brass were extruded dynamically by a crank press at room temperature, the extruding pressures were somewhat lower than those required for statical extrusions. This effect was more marked for the minimum pressure, and was considered to be a result of the temperature rise in metal caused by the heat generation during the working. On the other hand, the maximum pressure for zinc increased largely with increasing speed of the extruding punch.

5) When the zinc blanks with narrow sections were extruded, the maximum pressures were lowered appreciably compared with those for the standard blank. The reverse was the case for aluminum and copper. These effects were thought to be caused by the strain-hardening of metal as well as by the temperature rise.

6) The effect of applied lubricant was generally more appreciable on the minimum extruding pressure than the maximum. This was considered to be attributed partly to the thinning of the lubricant layer between metal and tool as the extrusion progressed. The extruding pressure for copper, zinc and yellow brass were less sensitive to the kind of lubricant than those for aluminum and duralumin. In all cases, the extruding pressures were lowest with the special wax and they were highest with the spindle oil among the lubricants tested.

7) The extruding pressure with the tools of surface roughness of JIS 0.4 S and 1 S were nearly equal to each other, but those of JIS 4 S increased considerably. No effect of surface roughness of tool on the pressure, however, was found for zinc. From the data on the effects of lubricant as well as of surface roughness of tool, the lubricating condition seemed to be improved in the dynamical extrusion compared with the statical.

8) The extruded metals almost reached their fully work-hardened states if the wall-thickness of the shell was less than one-tenth of the punch diameter and if the bottom thickness was less than one-fifth of the thickness of original blank. No appreciable change in the hardness of zinc was found. Moreover, the effect of working speed on the hardness of extruded product was not definitely seen.

9) In the case of extrusions with the ratio of extruding clearance to punch diameter below 0.10, all metals other than Muntz metal were formed without failure. The breakages in the shell walls of thickness less than 0.2 mm were often seen because of the difficulty of centering the punch against the die cavity. Other local failures of extruded shells could be eliminated by controlling some working conditions.

10) Surfaces of extruded shells smoother than JIS 1S were obtained when both an extruding tool with smooth surface and a lubricant of good quality were used. The surface states for aluminum and duralumin were worse and more sensitive to the lubricating conditions than those for copper, zinc and yellow brass. Moreover, the effect of lubricating condition appeared more markedly on the lower portion of shell-wall than on the upper. Usually, more scratches were found on the statically extruded shells than on the dynamically extruded. The application of too much lubricant on the blank often caused granular surfaces on the upper walls of extruded shells, especially in the dynamical extrusion.

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References

1) I. Gokyu and H. Suzuki: *Jour. Japan Inst. Met.*; vol. 18 (1954), pp. 232~239, pp. 321~324, pp. 375~382, pp. 437~440; vol. 19 (1955), pp. 351~358, pp. 575~577; vol. 20 (1956), pp. 378~381.
2) von M. Dipper: *Archiv. f. Eisenhüttenwes*; vol. 20 (1949), pp. 275~286.
3) For Example, A. Nadai and M. J. Manjoin: *Jour. App. Mech.*; vol. 8 (1941), pp. A–77~91.
4) H. Suzuki: *Trans. Japan Soc. Mech. Engrs.*; no. 53, vol. 16 (1950), pp. 106~112.
5) H. Kudo: Not printed.
6) M. Kunogi: *Trans. Japan Soc. Mech. Engrs.*; vol. 22 (1956), part IV, pp. 429~437.
7) J. D. Shoemaker: *Amer. Machinist*; no. 14, vol. 97 (1953), pp. 129~140.
8) N. Soda: "Friction and Lubrication", Tokyo, 1953, pp. 116~122.
9) N. Soda: ibid.; pp. 210~212.
10) F. P. Bowden and D. Tabor: "The Friction and Lubrication of Solids", London, 1954, pp. 200~202.
11) N. Soda: loc. cit.; pp. 132~135.
12) F. P. Bowden and D. Tabor: ibid.; p. 78.
13) T. Hisamoto and K. Kakizaki: *The Hitachi-Hyōron*; vol. 35 (1953), pp. 847~857.
14) T. Ōi: Not printed.
15) H. J. Pessel: quoted in *Materials and Methods*; no. 2, vol. 42 (1955), p. 116.
16) E. Siebel: "Die Formgebung in Bildsamen Zustand" Düsseldorf, 1932, p. 54.
17) D. Tabor: *Sheet Met. Ind.*; vol. 31 (1954), pp. 749~757.