Nov. 24, 1953 H. M. GERSMAN 2,660,302

EXTRUSION

Filed June 5, 1946 2 Sheets-Sheet 1

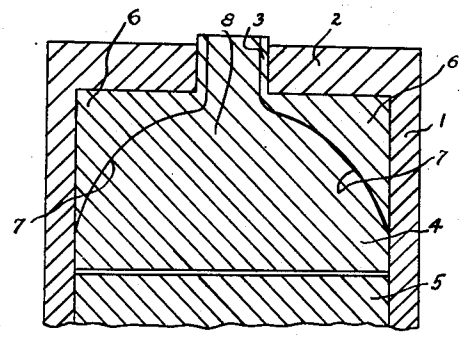



Fig. 1

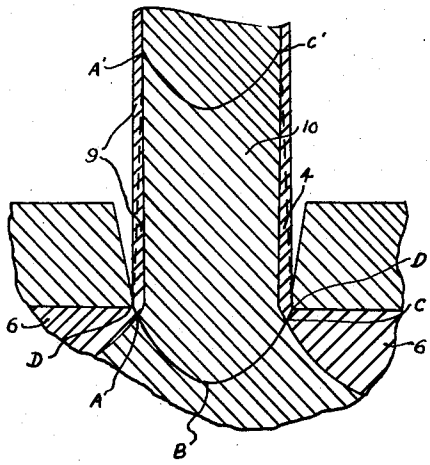



Fig. 2

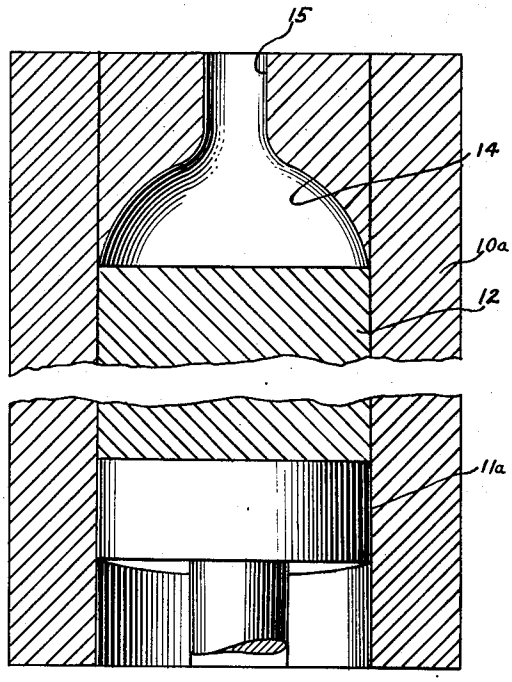



Fig. 3

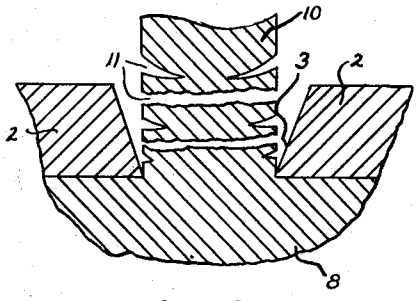



Fig. 2a

INVENTOR.
HARVEY M. GERSMAN.
BY Fay, Golrick & Fay
Attorneys.

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EXTRUSION

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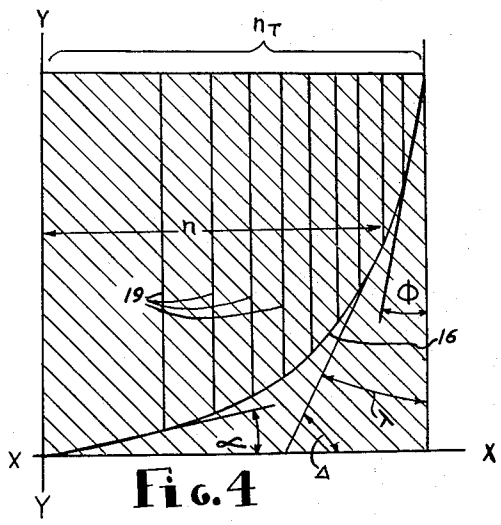



Fig. 4

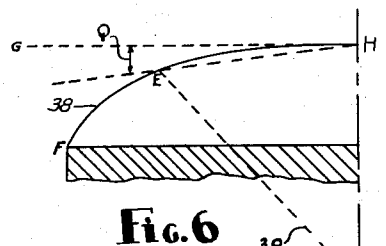



Fig. 6

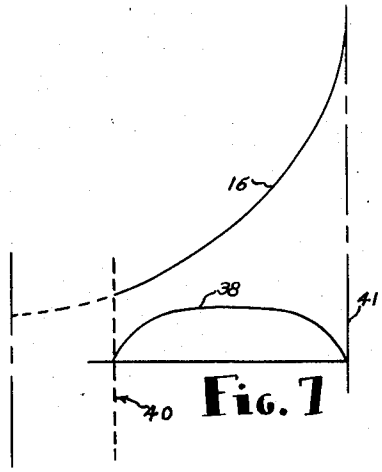



Fig. 7

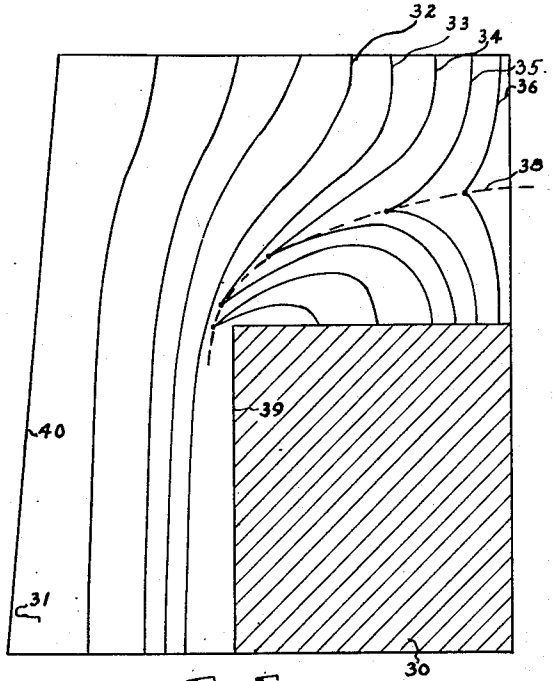



Fig. 5

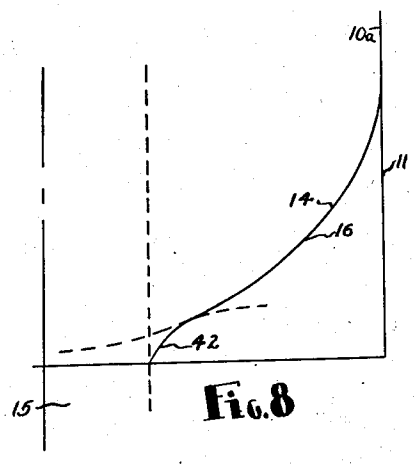



Fig. 8

INVENTOR.
HARVEY M GERSMAN
BY
Fay, Golrick & Fay.
Attorneys.

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2,660,302

# UNITED STATES PATENT OFFICE

2,660,302

## EXTRUSION

Harvey M. Gersman, New York, N. Y., assignor of one-tenth to George Jordan, Montclair, and one-tenth to Adolph G. Wigren, Glen Ridge, N. J.

Application June 5, 1946, Serial No. 674,584

12 Claims. (Cl. 207—17)

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The present invention, relates to extrusion of metals or other materials in a plastic state, such as metals rendered plastic by heating, and is more particularly directed to what may be termed direct extrusion, that is, the direct movement of the metal of a billet through an orifice in one end of a container by means of a moving ram acting against the other end of the billet to compress it and cause it to flow through an orifice of the container.

The present invention is primarily directed to the extrusion of such metals as those of the iron group, copper and copper-containing alloys or light alloy group, such as aluminum and magnesium, since I have found that the same general principles may be applied to the extrusion of all of these materials without the disadvantages and the objections which have heretofore been found, particularly in the extrusion of the higher melting point metals. The present methods caused extremely rapid die wear and poor products as well as generally high production costs.

To the accomplishment of the foregoing and related ends, said invention, then, consists of the methods and apparatus hereinafter fully described and particularly pointed out in the claims; certain of the annexed drawings as specified below and the accompanying description setting forth in detail one approved method and apparatus of carrying out the invention, such disclosed method and apparatus however, constituting but one of the various ways in which the principle of the invention may be used.

In said annexed drawings:

Fig. 1 is a diagrammatic, fragmentary, vertical mid-sectional elevational view of an extrusion cylinder, ram and die which illustrates certain phenomena that are inherent in conventional extrusion operations;

Fig. 2 is an enlarged fragmentary view corresponding to Fig. 1, further illustrating certain disadvantages of the prior art;

Fig. 2A shows a result sometimes occurring from the conditions illustrated in Fig. 2;

Fig. 3 is a partial mid-sectional elevational view of extrusion apparatus embodying the present invention;

Fig. 4 is a diagrammatic axial sectional elevation of one-half of a billet illustrating one method of determining the feed curve or the natural path of flow of the metal of the billet from the side wall of the container toward the orifice under the action of the ram, the curve being extended from the center line of the billet;

Fig. 5 is an axial sectional elevation of one-

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half a billet and punch impressed therein showing what is hereinafter termed a "punch test" for determining the angle of internal flow and that portion of the die which extends from the die feed curve of Fig. 4 to the edge of the orifice;

Fig. 6 is a curve formed by connecting the points determined in the curve of Fig. 5 found by punch test referred to and analyzed to follow the minimum angle of internal flow of the metal and also the curve required in the orifice portion of the die which is joined to the used portion of the feed curve;

Fig. 7 is the complete punch test curve of Fig. 6 for the full width of the punch, of which only one-half is shown in Fig. 5, reduced to the distance between the edge of the orifice and the edge of the side wall of the billet for which the complete die curve is to be found, and also shows thereabove the feed curve of Fig. 4, which when properly joined to the lower curve produces the entire die contour; and

Fig. 8 shows these two curves of Fig. 7 moved into a position of tangency, the full line of Fig. 8 showing the entire die contour from the side wall of the container to the edge of the orifice.

In the extrusion of metals of the types referred to, difficulty has always been experienced from certain factors which include very severe abrasion on the edge of the orifice die and very considerable power and temperature requirements. A third and, in some cases, still more important factor has been the creation of piping in the extruded product. Extrusion pipe consists of an outer layer on the extruded product formed of metal caused to flow or extrude under improper conditions and at a different speed than the core or central metal. This pipe increases in diameter as the extrusion progresses. Where such piping occurs, the product must be machined down to the minimum diameter of clean core metal if the product is to be employed where any considerable degree of strength is required or where it is to be further machined as the outer layer, that is, the piping, causes chattering of machine tools and prevents even and uniform machining. The metal at the juncture of pipe and core metal contains scale in some cases and the bond is only a mechanical one.

All of these difficulties and other extrusion difficulties arise from improper flow of the material of the billet to and through an orifice under the influence of the ram. While various forms of orifices have been suggested to improve the flow, none have produced uniform or straight-line flow through the orifice without any tur-

bulence around the edges of the orifice. Nor have they eliminated the factors which have caused the action within the billet which is detrimental to the smooth progressive flow of all the metal to and through the orifice so that all the metal may issue with uniform single directional flow parallel to the axis of the part being extruded.

So little beneficial effet has been secured from many of the various dies heretofore suggested for extrusion that the greater part of extrusion of all of the metals named hereinbefore has heretofore been carried out through an orifice which is merely a circular hole (or a hole shaped in cross-section to produce the part required) in a flat end plate of the container, there being no specially- contoured die as such of any kind.

It will, of course, be understood that when a billet of plastic metal or metal heated to plasticity is acted upon by a ram and is thereby being forced toward the end of the container and through an orifice formed in an end plate thereof, the metal of the billet will naturally move along some angular line from the side walls of the container toward the orifice. The metal will naturally not turn a right angle and will therefore not proceed directly along the side walls to the end of the container, then turn inwardly, moving across the end wall of the container and then again turn at a right angle and move out through the orifice. This is so obvious that it hardly needs to be stated. It is equally obvious that the metal along the side wall will move along some inclined or curved path starting at some distance on the side wall from the end wall and toward the orifice through which the metal may be extruded. The result of such action of the metal is, of course, to shear the main portion of the billet away from that portion resting in the corners of the container, thus leaving this more slowly moving and compacted metal in the corner portions of the die. This is obviously, however, an extremely wasteful procedure and cannot help but produce irregular flow of metal to and through the orifice. Nevertheless it has not heretofore been determined what path of flow the metal actually takes as a result of this shearing action. Therefore, it has not been possible to devise a die to conform to the natural flow of the material and to cause it to flow smoothly and uniformly to and through the orifice. The shearing action within the billet also requires a considerable pressure and considerable additional heat so that the billet is sufficiently plastic to permit this action to occur.

In a conventional die such as that referred to above, when the ram, of course, moves forward a given distance it will displace an equal volume of metal. This volume of displaced metal which is extruded through the orifice comes mainly from the central and obviously more rapidly flowing central portion of the billet. The relatively inert metal in the corners of the container which is acting as if it were a die due to the mentioned shearing action is moving much more slowly toward the orifice and is being crowded radially inwardly and over the edge of the orifice. Progressive movement of the ram increases the movement inward of this trapped corner metal and as the ram continues to move toward the orifice the opening in the orifice available for the faster moving central billet metal is progressively reduced, the balance of the orifice opening being filled by the flow from the trapped inert corner metal. This produces the increased piping or outer layer on the extruded product and this metal is neither straight



fibered metal with the fibers parallel to the axis of the extruded part nor is the bond between this extruded corner metal, and the central portion of the billet metal a true bond.

A further harmful effect resulting from the aforesaid type of movement is a checking or tearing of the surface of the extruded part, which tearing at times extends almost to the center line of the part itself. This is caused by the difference in the emerging speed between the core metal and the inert corner metal carried along on the outside. The condition of the extruded metal from a temperature standpoint, brittleness, etc., together with the overall rate of speed, will cause the extruded material to crack, which cracking in some instances appears simply as surface checking, whereas in other instances it will cause tears extending well into or through the extruded part.

This necessary elongation of the thin film of inert metal carried along into the orifice initially at a slower speed than the moving metal by reason of the differential in their speeds, appears to be self-evident when once pointed out, but has apparently never been recognized as the cause of severe loss in products of extrusion and is found in extrusion of any of the metals named where the conditions are those described above. The extent of this surface checking and tearing action is greatly dependent upon the overall emergent speed of the extruded part. The faster the speed the more the ripping or tearing action upon the stretched material on the outside of the part. The tensile strength of the metal decreases with increase in temperature and at the higher extrusion temperatures the tensile strength is so low that tearing due to the action described is more common. To avoid this heretofore, extrusion of many products had to be carried out at temperatures and speeds which are commercially undesirable.

The result of operating at such higher temperatures and pressures is, particularly in the case of metals of the ferrous group, that the pressures exerted against the die are higher than the available strength in die steels at that temperature and as regards pressures requires extremely heavy and expensive presses, which naturally reduces the otherwise very great savings of extrusion over other methods of metal reduction. It is also well known that to heat billets to the higher extrusion temperatures thus necessary, increases the costs disproportionately. In spite of all of the above objections in the existing methods and apparatus for extrusion, it is still, of course, widely practiced with the softer and lower melting point metals. This is true because of the very much lesser abrasive effect of such metals on the die, the lower temperatures required and the reduced structural strength required in many of the products, such for example, in architectural shapes, angles, moldings and the like.

From a great many of experiments from which I have determined, and which have been demonstrated, the objections and the defects in existing methods and apparatus for extrusion, I have found that extrusion can best be practiced only under conditions where the metal is allowed and confined so that it follows its own natural paths of flow through the orifice. The die employed must conform to these natural flow paths in order to prevent turbulence in the metal, excessive pressures at different points against the die face, and internal shearing of the metal with the resultant disadvantages. I have also found it possible to determine for any given metal the

precise flow paths which in turn determine the die curve and orifice, and although these vary for different metals, the variance is not as large as might be expected and can be accurately determined for any given metal by a simple and inexpensive preliminary test made upon the metal in question. When this is done, as will be explained hereinafter, I am able to produce a die which will confine the metal to the proper flow paths to and through the orifice and thereby greatly to reduce the pressure and temperature required, minimize or entirely avoid all of the objectionable flow features which have heretofore characterized extrusion and to produce continuously uniform, substantially parallel grained or fibered products.

It is evident that a proper die outlining and confining the flow of that portion of the billet which provides the core metal of the extruded part must be comprised of two sections, namely the proper contour of the shear line, since this shear line is formed as the result of the flow path taken by the properly flowing portion of the billet, and second, the orifice curvature as this properly flowing portion approaches and flows into the orifice. These two portions of the proper flow line or die line can be characterized as, first, the feed curve and, second, the orifice curve. Further experimentation with various sized orifices showed conclusively that the feed curve followed substantially the same contour, regardless of the orifice size, up to the point where the orifice curve began, and showed further that the orifice curve varied with the size of the orifice opening.

It became evident that the formation of the feed curve or the approach from the side wall to the orifice sector was the result of streamline or viscous flow within the billet itself. Such viscous flow is the result of varying speeds of flow within the billet itself. As a portion of the billet is displaced through the orifice as the result of a forward movement of the ram, other portions of the billet move to replace this material and continue onward to flow in turn through the orifice. Such flow to and through the orifice reaches its maximum speed at the center line and gradually decreases as the side wall is approached.

To lay out a die curve coinciding with this viscous flow for each material to be used, it is necessary to know the factors which govern the formation of this curve or the factors which govern the viscous flow within the billet itself. One of these governing factors is the angle of internal flow of each material in question.

By experiments I discovered that under standard conditions, the angle at which this viscous flow curve reached the center line of the billet was the same as the angle at which this curve began at the side wall of the container, and that this angle coincided with the angle of internal flow.

This discovery made it appear probable that I could use a simple and standard method for laying out this viscous flow curve for any given material and this was later found to be correct. This method is as follows: The billet is theoretically divided into portions of equal concentric volumes, usually 10 to 20. The beginning angle, or the angle at the side wall, as well as the last angle, approaching the center, being the same, and since the entire curve is contained within a 90° angle, it is then only necessary to determine the angular differential or increment to be added to the beginning angle to find the points at which the curve intersects the outline of each of the intervening volume portions until the last angle is reached. This differential can be determined by the standard formula for an arithmetic progression.

$$\text{gamma}=\text{phi}+(n-1)\ \text{beta} \tag{1}$$

where gamma is the slope, expressed in degrees or radians, of the flow curve at any point thereof, phi is the beginning angle, $n$ the number of equal volumes encountered in passing from the container sidewall to any point of the flow curve, and beta the angular increment added to alpha in passing from one volume to the next.

The final value of gamma is obviously $\pi/2-$ alpha, where alpha is the last angle at which the curve intersects the billet axis and as measured with reference to a line perpendicular to the axis of the billet. Thus

$$\text{beta}=\frac{\pi/2-\text{alpha}-\text{phi}}{N_T-1} \tag{2}$$

where $N_T$ is the total number of volumes into which the billet has been theoretically divided. And since, as above stated, alpha=phi, then

$$\text{beta}=\frac{\pi/2-2\ \text{alpha}}{N_T-1} \tag{3}$$

Since the billet is of constant height the above formulas apply to a transverse section thereof which is theoretically divided into concentric portions of equal area, in which case $N_T$ would be the total number of such areas and N the number of such areas disposed between the billet axis and an ordinate paralleling the axis from any point on the flow curve. Therefore, to properly construct the viscous flow curve or the feed line for any given material, it is necessary to know the angle of internal flow for that particular material.

From a number of tests I discovered that the action of the end face of the container, or in other words the die section against the billet was that of a punch. From this it followed that the orifice curve or the path which the metal would follow in flowing into and through the orifice was similar to the path which that metal would follow in flowing around the edge of a punch whose diameter was equal to the distance from the orifice edge of the side wall. Therefore, to properly outline the orifice curve, such a flow path around the edge of a properly dimensioned punch must be secured.

It was found that both needed factors, namely the angle of internal flow and the path around the edge of a punch, could be determined by means of one test. A billet of selected material at extruding temperature is confined within a die open at one end. A punch of lesser diameter than the billet is forced into the billet at that open end, the punch being heated to avoid creating a chill in the metal. The displaced metal flows from the center line of the punch in each direction towards the side of the punch and eventually around and past the end or edge of the punch. The metal adjacent to the face of the punch and outlined by this flow is static, regardless of the distance of punch penetration, and remains so unless deformed by other forces.

Analyses of the contour of this static zone adjacent to the face of the punch shows that for varying distances on either side of the center line, the displaced material flows on a true radius or arc of a circle. This true radius becomes a

parabola as it continues to flow to and around the edge of the punch. This parabolic portion provides the actual path which that particular type of material will follow in flowing around the edge of a punch of that diameter and therefore provides the elements required for establishing the orifice curve for that material for any given diameter and for any given orifice width. The angle contained by a line drawn parallel to the face of the punch through the apex of flow at the center line of the punch and a line drawn between that apex and the juncture point between the true radius and the parabolic section provides the angle of internal flow for that particular material. This is the angle phi in the formula already given.

Using this angle of internal flow in the manner previously described, I can thus establish the true and exact contour of streamline or viscous flow within the billet for any given diameter. This contour establishes the so-called feed line previously referred to and extends from the side wall to the center line of the billet. With the orifice dimensions established, the distance from the orifice edge to the side wall becomes known. Using this distance as the diameter of the punch a properly proportioned outline of the static zone can be drawn, including the true radius portion and the parobolic section up to the edge of the punch. Joining this punch test curve to the feed line at a point of tangency establishes the complete die line for the tested material for a given diameter and given orifice width.

Referring now to the drawings, in Fig. 1 I have shown a standard container 1 provided with an end wall 2, a die opening 3, a billet 4 in the process of being extruded therefrom and a ram 5. There is no die as such shown in this figure, the end wall 2, of the container with its opening 3 acting as the die, and as a result, that portion of the billet in the corners 6 of the container has to act more or less as a die in conjunction with the orifice, the billet being sheared away from these corner portions or zones along a surface of revolution having roughly the configuration in axial section illustrated as single lines 7, but which in practice are not only irregular but sometimes of considerable width.

In such an extrusion, proper flow cannot be secured as there is constant shear between the moving center portion 8 and the relatively unmoving corner portions 6 of the metal, with turbulence found in the flow along the boundaries 7 between the two portions; and also with the further result that metal from the corner portions 6 is gradually pushed and carried over to the edge of the orifice in increasing amounts as the extrusion progresses, producing, as is shown in Fig. 2, an exterior progressively thicker coating or pipe of metal 9 which comes from the corner portions 6 and which is not truly bonded to the actual core 10. This pipe is also not good metal and sometimes contains foreign material and has to be removed down to the minimum diameter of true metal in the extruded product 10 if the latter is to be used where strength is an important factor.

Still referring to Fig. 2, the core metal 10 approaches and is extruded through the orifice at a much higher rate of flow than the more or less inert corner material 6. As a result the outer layer or piping 9 of the extruded product is stretched compared to the core, often resulting



in surface tearing, which in some instances appears simply as surface checking, but which in other instances will extend well into or entirely through the extruded part, in the manner illustrated at 11 of Fig. 2A.

In Fig. 3 there is shown the same general type of extrusion apparatus as shown in Fig. 1, that is, it includes a container or cylinder 10*a*, a ram 11*a*, a billet 12 and a die 14 leading to an orifice 15. The construction of the die must be such that all of the metal in the billet will follow the natural path of flow of the metal without turbulence, and in such a way that the metal will issue from the orifice in streamline condition, that is, with straight parallel fibers of metal in the extruded product. The proper die to accomplish this purpose will now be described.

The contour of the die 14 is shown in its completed form in Fig. 8, but the portions which go into the complete contour of the die are arrived at by first laying out the die in several portions as illustrated in Fig. 7, which portions are then joined in the manner which is shown in Fig. 8 to produce the completed die.

In Fig. 4 for instance I have shown one-half the billet 12 of Fig. 3, the center line of the billet being represented by the line Y—Y and the lower end of the billet by the line X—X. This billet is then theoretically divided into ten or more portions of equal volume concentrically arranged around the center line Y—Y of the billet as indicated by the lines 19 representing concentric cylinders or tubes, and a series of points are determined by the method already described hereinbefore with reference to formula 1. Through these a curve 16 is drawn from the side wall or outer surface 17 of the billet to the axis or center line Y—Y thereof.

Thus with reference to the above formula

(1) $$\text{gamma}=\text{phi}+(n-1)\,\text{beta}$$

in Fig. 4, alpha is the angular slope with reference to the $x$ axis, of the tangent at any point on curve 16. Phi is the beginning angle at which the billet metal shears away from the extrusion die sidewalls, $n$ the number of portions 19 of equal volume, encountered in passing from the sidewall to any point on curve 16, and beta the angular increment added to alpha for each successive volume portion. Also in Fig. 4, alpha is the last angle as measured with reference to the $x$ axis, or $\pi/2$—gamma as measured with reference to the $y$ axis, while $N_T$ is the total number of equal volumes into which the billet is theoretically divided.

In order to derive curve 16, Fig. 4, as a continuous mathematical function of $x$ and $y$, it is for convenience rewritten with reference to the billet axis, $y$, as follows:

(4) $$\text{delta}=\text{alpha}+(n-1)\,\text{beta}$$

Assume now that the total number of equal volume portions $N_T$ into which the billet is theoretically divided is allowed to become extremely great, approaching infinity, in consequence of which the radial thickness of each volume portion 19, will become correspondingly small, equaling, at the limit, the differential thickness $dx$. As a result distance along the $x$ axis to any point in curve 16, will equal $n\,dx$, so that

(5) $$n=x/dx$$

Also each of the volumes 19 will become equal to

(6) $$2\pi x.dx.h=K$$

where $h$ is the billet height and K a constant,

since all volume are alike. Assuming the billet to have an outside radius $v$, its total volume is

(7) $$\pi v^2 h = 2\pi x dx . h . N_T$$

from which

(8) $$N_T = v^2/x.dx$$

from which and from Formula 3 above

(9) $$\text{beta} = (\pi/2 - 2\ \text{alpha}) . 2x dx/v^2$$

Substituting (5) and (9) in (4), neglecting second order components, integrating, solving for integration constant and substituting gives

(10) $$\text{delta} = \text{alpha} + (\pi/2 - 2\ \text{alpha})(X/v)^2$$

If $v$ is unity in the above formula or if X is taken as the ratio of the abscissae distance to any point on the curve to the total radius $v$ of the billet, (10) becomes

(11) $$\text{delta} = \text{alpha} + (\pi/2 - 2\ \text{alpha}) X^2$$

from which

(12) $$dy/dx = \tan(\text{alpha} + (\pi/2 - 2\ \text{alpha}) X^2)$$

and

(13) $$y = \int_0^{\pi/2} \tan\ (\text{alpha} + (\pi/2 - 2\ \text{alpha}) X^2)$$

If alpha and phi of Fig. 4 are not equal then

(14) $$dy/dx = \tan(\text{alpha} + (\pi/2 - \text{phi} - \text{alpha}) X^2)$$

(15) $$y = \int_0^{\pi/2} \tan\ (\text{alpha} + (\pi/2 - \text{phi} - \text{alpha}) X^2)$$

A feed curve constructed in the manner described will produce proper flow of the metal in the billet toward the orifice but does not control the flow of this metal directly adjacent to the orifice nor through it, and a second portion of the die of different contour must be provided and properly joined to control the flow of the metal in the area around and within the orifice.

It has already been explained how this portion of the curve is found and that I have discovered that the flow of metal to, around and through an orifice is the same as that of metal around a punch forced inwardly against and into a block of a given metal at an extruding temperature. In Fig. 5 I show half of such a section, in diagrammatic form, in which there is shown a punch 30 forced into a block or billet of metal 31. The billet in this figure is shown with scribed lines on the inner surface of half of the billet, the billet axially cut in two halves and the lines being initially scribed in spaced parallel relation running axially in the direction of movement of the punch into the billet and the billet halves welded together at the edges. As the punch presses into the metal it forces the metal inwardly and then outwardly, the metal having to flow laterally and then downwardly around the edge of the punch. The flow of metal can be determined exactly by study of the resulting distortion of the scribed lines 32, 33, 34, 35 and 36 due to the punch. It will be noticed that each of these lines, as the metal flows outwardly above and across the face of the punch, is formed into a small loop. A line 38 drawn through the apexes of all of the loops correctly represents the flow of the metal under the action of the punch. The curve 38 thus defined represents a natural path of flow of metal toward, within and through an orifice, the orifice in the case of the punch test shown in Fig. 5 being that portion between the edge 39 of the



punch and the side wall 40 of the billet or block into which the punch is forced. The curve 38, as I have already explained, consist of two joined but separate types of curves, the central portion being a portion of a circle and the outer or left-hand portion in Fig. 5 being a parabola. It will be understood of course that curve 38 is symmetrical about its centerline, the complete curve being as shown at 38 of Fig. 7.

The curve 38 of Fig. 5 is also shown in Fig. 6, wherein the portion EH is the circular portion of the curve with a radius 39, and the portion FE is the parabolic portion which is tangent and joined to the circular portion. The angle phi between the dotted lines GH and HE is the minimum angle of internal flow of the material, which determines the equal angles alpha and phi of Fig. 4.

To construct the entire die, first the feed curve 16 is laid out in the manner described above and as shown in Fig. 7, and the curve 38, Figs. 5 and 6, is then reduced in proportion to the distance between the edge of the orifice 40, Fig. 7, and the side wall 41 of the container, and is placed, as indicated in Fig. 7, beneath the feed curve 16 by moving curve 38 of this figure upwardly until it becomes tangent with the feed curve 16 in the manner shown in Fig. 8. This results in a composite die curve 14, as applied to a die, which extends from the side wall 19a to the orifice 15, thereof, in the manner shown at 14 of Fig. 3. The curve which is thus produced is one which will cause all of the metal in the billet to flow toward, to and through the orifice in such a manner as to produce a non-turbulent streamline flow with a minimum of internal friction and without the objectionable characteristics of the products of extrusion as heretofore practiced. Furthermore, with the present die I have eliminated the extrusion of any inert material along the path of flow of the metal adjacent to the die, have greatly reduced the friction all over the die but more particularly adjacent to the orifice where the greatest wear occurs, and have to an extent reduced the power required for the extrusion of any given material. It will be understood that in the extrusion of different metals, certain of the values here determined will be changed, such as the angle of internal friction, but by following the methods which I have described it is possible to determine the true and correct die curve for any given extrudable metal.

It should be understood in considering the drawings here shown, and particularly the various curves, that these curves are correctly described in the specification but may not be illustrated with precise accuracy in the drawings, and are not to be scaled or literally followed as shown in the different figures.

I claim:

1. In an extrusion die, a tubular member having inner sidewalls which converge at one end thereof toward an orifice along a concave feed surface, comprising, in axial section, a continuous curve constituted of an arithmetic progression of terms representing equal concentric volumes to be displaced during extrusion, said curve corresponding substantially to the formula

$$\text{gamma} = \text{phi} + (n-1)\ \text{beta}$$

wherein $n$ is the number of such equal volumes between the die sidewalls and any point on said curve, gamma is the angular slope of said curve at any point thereof, beta the angular increment by which said slope is changed in passing from

one said volume to the next, and phi the angle at which said curve diverges from said sidewalls.

2. In an extrusion die, a tubular member having inner sidewalls which converge at one end thereof toward an orifice along a concave feed surface, comprising, in axial section, a continuous curve constituted of an arithmetic progression of terms representing equal concentric volumes to be displaced during extrusion, said curve corresponding substantially to the formula

$$\text{gamma}=\text{phi}+(n-1)\,\text{beta}$$

wherein $n$ is the number of such equal volumes disposed between the die sidewalls and any point on said curve, gamma is the angular slope of said curve at any point thereof, beta the angular increment by which said slope is changed in passing from one said volume to the next, and phi the angle at which said curve diverges from said sidewalls, and wherein phi has a magnitude substantially equal to the minimum angle of internal flow of a metal to be extruded.

3. An extrusion die consisting of a tubular member the inner sidewalls of which converge at one end thereof along a concavely curved feed surface toward an orifice formed in said end of said die, said feed surface terminating adjacent said orifice in a convexly curved orifice portion tangential thereto and extending thence to said orifice, said feed surface comprising in axial section a continuous curve constituted of an arithmetic progression of terms representing equal concentric volumes to be displaced during extrusion, said curve corresponding substantially to the formula

$$\text{gamma}=\text{phi}+(n-1)\,\text{beta}$$

wherein $n$ is the number of such equal volumes disposed between the die sidewalls and any point in said curve, gamma is the angular slope of said curve at any point thereof, beta the constant angular increment by which said slope is changed in passing from one volume to the next, and phi the angle at which said curve diverges from said sidewalls of said die.

4. An extrusion die consisting of a tubular member the inner sidewalls of which converge at one end thereof along a concavely curved feed surface toward an orifice formed in said end of said die, said feed surface terminating adjacent said orifice in a convexly curved orifice portion tangential thereto and extending thence to said orifice, said feed surface comprising in axial section a continuous curve constituted of an arithmetic progression of terms representing equal concentric volumes to be displaced during extrusion, said curve corresponding substantially to the formula

$$\text{gamma}=\text{phi}+(n-1)\,\text{beta}$$

wherein $n$ is the number of such equal volumes disposed between the die sidewalls and any point in said curve, gamma is the angular slope of said curve at any point thereof, beta the constant angular increment by which said slope is changed in passing from one volume to the next, and phi the angle at which said curve diverges from said sidewalls of said die, said orifice portion having in axial section a substantially parabolic curvature extending tangentially to said orifice.

5. An extrusion die consisting of a tubular member the inner sidewalls of which converge at one end thereof along a concavely curved feed surface toward an orifice formed in said end of said die, said feed surface terminating adjacent said orifice in a convexly curved orifice portion



tangential thereto and extending thence to said orifice, said feed surface comprising in axial section a continuous curve constituted of an arithmetic progression of terms representing equal concentric volumes to be displaced during extrusion, said curve corresponding substantially to the formula

$$\text{gamma}=\text{phi}+(n-1)\,\text{beta}$$

wherein $n$ is the number of such equal volumes disposed between the die sidewalls and any point in said curve, gamma is the angular slope of said curve at any point thereof, beta the constant angular increment by which said slope is changed in passing from one volume to the next, and phi the angle at which said curve diverges from said sidewalls of said die, and wherein phi is substantially equal in magnitude to the minimum angle of internal flow of a metal to be extruded, and wherein said orifice portion conforms substantially to the flow path of said metal about the edge of a punch forced into said metal.

6. An extrusion die comprising, a tubular member the inner sidewalls of which converge at one end thereof along a concave feed surface to an orifice coaxial therewith, said feed surface in axial section conforming substantially to the formula

$$dy/dx=\tan\,(\text{alpha}+(\pi/2-\text{phi}-\text{alpha})\,X^2)$$

wherein the $y$ axis is the axis of said die, and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, phi is the angle at which said feed curve diverges from said sidewalls, alpha the angle between said feed curve continuation and said $x$ axis and X the ratio of any abscissa to said curve and the inner sidewall radius of said die at said axial section.

7. An extrusion die comprising, a tubular member having an inner sidewall portion of cylindrical configuration which converges at one end thereof along a concave feed surface of revolution in an orifice coaxial therewith, said feed surface in axial section conforming substantially to the formula

$$dy/dx=\tan\,(\text{alpha}+(\pi/2-\text{phi}-\text{alpha})\,X^2)$$

wherein the $y$ axis is the axis of said die, and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, phi is the angle at which said feed curve diverges from said sidewalls, alpha the angle between said feed curve continuation and said $x$ axis, and X the ratio of the abscissa to any point of said curve, and the inner sidewall radius of said cylindrical portion.

8. An extrusion die comprising, a tubular member the inner sidewalls of which converge at one end thereof along a concave feed surface to an orifice coaxial therewith, said feed surface in axial section conforming substantially to the formula

$$dy/dx=\tan\,(\text{alpha}+(\pi/2-\text{phi}-\text{alpha})\,X^2)$$

wherein the $y$ axis is the axis of said die, and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, phi is the angle at which said feed curve diverges from said sidewalls, alpha the angle between said feed curve continuation and said $x$ axis, and X the ratio of any abscissa to said curve, and the inner sidewall radius of said axial section, and wherein at least one of the angles alpha and phi is substantially equal in

magnitude to the minimum angle of internal flow of a metal to be extruded.

9. An extrusion die comprising, a tubular member the inner sidewalls of which converge at one end thereof along a concave feed surface to an orifice coaxial therewith, said feed surface in axial section conforming substantially to the formula

$$dy/dx=\tan(\text{alpha}+(\pi/2-\text{phi}-\text{alpha})X^2)$$

wherein the $y$ axis is the axis of said die, and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, phi is the angle at which said feed curve diverges from said sidewalls, alpha the angle between said feed curve continuation and said $x$ axis, X the ratio of the abscissa to any point of said curve, and the inner sidewall radius of said axial section, and wherein at least one of the angles alpha and phi is substantially equal in magnitude to the minimum angle of internal flow of a metal to be extruded, and wherein said feed surface extends to said orifice along a convexly curved surface portion tangential thereto, said convexly curved feed surface conforming to the flow path of said metal to be extruded, about the edge of a cylindrical punch forced axially into said metal.

10. An extrusion die comprising, a tubular member the inner sidewalls of which converge at one end thereof along a concave feed surface to an orifice coaxial therewith, said feed surface in axial section conforming substantially to the formula

$$dy/dx=\tan(\text{alpha}+(\pi/2-\text{phi}-\text{alpha})X^2)$$

wherein the $y$ axis is the axis of said die, and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, phi is the angle at which said feed curve diverges from said sidewalls, alpha the angle between said feed curve continuation and said $x$ axis, X the ratio of the abscissa to any point of said curve, and the inner sidewall radius of said axial section, and wherein at least one of the angles alpha and phi is substantially equal in magnitude to the minimum angle of internal flow of a metal to be extruded, and wherein said feed curve extends to said orifice along a convexly curved surface portion tangential thereto and of substantially parabolic configuration in axial section.

11. An extrusion die comprising, a tubular member the inner sidewalls of which converge at one end thereof along a concave feed surface to an orifice coaxial therewith, said feed curve in axial section conforming to substantially the formula

$$dy/dx=\tan(\text{alpha}+(\pi/2-2\text{ alpha})X^2)$$



wherein the $y$ axis is the axis of said die and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, alpha is the angle between said projected continuation and said $x$ axis and also the angle at which said feed surface diverges from said sidewalls, and X the ratio of an abscissa to any point of said curve, and the inner sidewall radius of said axial section, and wherein alpha is substantially equal in magnitude to the minimum angle of internal flow of a metal to be extruded, and wherein said feed curve extends to said orifice along a convexly curved surface portion tangential thereto and of substantially parabolic configuration in said axial section.

12. The method of forming a tubular die for the non-turbulent extrusion of a preselected metal to be extruded through an orifice formed in one end of said die, which comprises, forcing a cylindrical punch axially into a block of said metal, and determining from the resulting static zone formed in said metal beneath said punch, the minimum angle of internal flow of said metal and also the flow path of said metal about the embedded edge of said punch, imparting to the inner surface of said die a concave feed surface extending from the inner sidewalls thereof substantially to said orifice, said surface conforming in axial section substantially to the formula

$$dy/dx=\tan(\text{alpha}+(\pi/2-2\text{ alpha})X^2)$$

wherein the $y$ axis is the axis of said die and the $x$ axis intersects the same at a point where a projected continuation of said feed curve intersects said $y$ axis, alpha is the angle between said projected continuation and said $x$ axis and also the angle at which said feed surface diverges from said sidewalls, the magnitude of said angle alpha corresponding substantially to said minimum angle of internal flow of said metal, said feed curve extending to said orifice along a convexly curved surface portion tangential thereto and conforming substantially to the flow path of said metal about said punch.

HARVEY M. GERSMAN.


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