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[Following is a translation of an article by M. N. Potoskuyev in the Russian-language periodical Izvestiya Vysshikh Uchebnykh Zavedeniy, Chernaya Metallurgiya (News of the Higher Educational Institutions, Ferrous Metallurgy), Moscow, No 5, May 1960, Pages 61-67.]

In studying the phenomena of forward flow, which by its very nature is very interesting, a large amount of work of an experimental and theoretical character was carried out. This problem acquires special significance in forging complex and periodic profiles [1 - 4], continuous and automated forging processes [5], in several special conditions of the process [6 - 8], and under the conditions of large forgings.

As a result of the many-sided scientific study of forward flow, a whole series of equations was established which are used widely in the theory and practice of forging. The reasons and the most important factors determining the conditions and its degree of development were clarified; and definite experience in controlling this phenomenon was accumulated.

However, existing methods of experimental research on forward flow are based on measuring the path or speed of the front end of the strip where the corresponding sizes for all particles of the cross-section are identical. Meanwhile, it is known that the distribution of the speed of metal along the height of the outgoing cross-section of the zone of deformation is not uniform [9 - 11]. This cannot but exert a marked influence on the size and character of the connection of forward flow with the basic parameters of the forging process.

In the present study, an analysis is presented of the connection of forward flow S_{hk} with drawing μ and the gripping index $m = \frac{\alpha}{f}$, established on the basis of experimental research and the condition reflected at the boundary of the contact surface of the zone of deformation from the side of the front end of the strip. Such an analysis permits the establishment of a number of new relationships which determine the forging conditions with maximum, rising or falling forward flow and so on.

The following symbols were additionally adopted in the study:

v - peripheral speed of the rollers;

v_{Hk}, v_{hk} - speed of the contact particles of the metal corresponding to the ingoing and outgoing surfaces;

H, h - the initial and final thickness of the strip;

D - diameter of the rollers;

α - gripping angle;

γ - critical angle;

φ - variable angle.

The connection of forward flow with drawing and the gripping index. The study of the kinematics of the zone of deformation permitted the connection of the horizontal speed of the contact particles of the metal v_{xk} to be established in the following form [11]:

$$v_{xk} = v_{hk} \sqrt{1 - \left(1 - \frac{v_{Hk}^2}{v_{hk}^2}\right) \frac{\varphi}{\alpha}}. \qquad (1)$$

Forward flow at the boundary of the contact surface of the zone of deformation is $S_{hk} = \frac{v_{hk}}{v} - 1$, for the critical cross-section $v_{xk} = v \cos\gamma$ and $\varphi = \gamma$.

Assuming in the first approximation $\cos\gamma = 1$ and $\frac{v_{hk}}{v_{Hk}} = \mu$,

after the corresponding transformation of formula (1), we obtain:

$$1 = \frac{1 + S_{hk}}{\mu} \sqrt{1 + (\mu^2 - 1)\left(1 - \frac{\gamma}{\alpha}\right)}, \qquad (2)$$

whence

$$1 + S_{hk} \; \frac{\mu}{\sqrt{1 + (\mu^2 - 1) \quad 1 - \frac{\gamma}{\alpha}}}. \qquad (3)$$

Using the known condition of the equilibrium of forging forces [12], we find:

$$1 - \frac{\gamma}{\alpha} = \frac{2+m}{4} \qquad (4)$$

and expression (3) can have the following final form:

$$1 + S_{hk} = \frac{2\mu}{\sqrt{4 + (\mu^2 - 1)(m+2)}} \qquad (5)$$

By its content, equation (5) is universal since it reflects the connection of the forward flow with the conditions of m and the result of μ of the forging process. All other pertinent [prevkhodyashchiy] factors, such as the thickness and width of the strip, the diameter of the rollers and compression, the relationship $\frac{H}{D} = \Delta$ and the speed of forging, the state of the band and rollers, the temperature of the metal and other factors, exert their influence on the forward flow above all through m and μ and only in special, artifically created cases (with the constancy of m or α) is it possible to separate the connection of forward flow with the different, [prevkhodyashchiy] factors.

The coupling of forward flow with drawing and the gripping index is presented in Figure 1, in which the family of curves S_{hk}, emanating from a single common point on the abscissa when $m = 2$, satisfies the independent (in relation to α and f) changes of m from 0 to 2. The intensity of the influence of m on S_{hk} is found to be dependent on μ: the greater the value of drawing, the more intense is this influence.

Moreover, equation (5) is characterized by the influence of drawing. As Figure 2 shows, the intensive increase of the forward flow is satisfied by comparatively moderate drawings ($\mu < 4$). Even during drawings beyond 4, the forward flow begins to approach asymptotically the corresponding limiting size determined by the value $\mu = \infty$.

Limiting values of forward flow. The analysis of the equation of forward flow obtained permits the establishment of new regularities of its development in connection with a change in drawing and index m. In particular, as Figure 1 shows, forward flow only develops in known limits.

Actually, representing equation (5) in the form

$$1 + S_{hk} = \frac{2}{\sqrt{m + 2 + \frac{\mu - 2}{\mu^2}}}$$

we find that with an increase in drawing from 1 to   , forward flow increases correspondingly from 0 to several limiting values determined by the expression:

$$(1 + S_{hk})\ \text{limit} = \frac{2}{\sqrt{m + 2}} \qquad (6)$$

In this regard, a definite limiting value of the forward flow clearly corresponds to each value of m. Theoretically such values vary from 41% when $m = 0$ when $m = 2$. These and any other limits depend only on index m or, in other words, on the relationship between the gripping angle and the coefficient of contact friction. If such a relationship turns out to be equal or greater than unity ($m \geq 1$) in all cases of simple forging, forward flow will always be less than 15.6% this makes the fact that forward flow in production and laboratory studies rarely exceeds 12% understandable.

Moreover, owing to the existence of limiting values of forward flow, the corresponding curves in the functions of relative compression or gripping angle will not always have a completely falling arc; it will break at that value of m which corresponds to the condition $\mu = \varphi$. In the first approximation, when $H - h = 0.5 D\alpha^2$, such a value of m is determined by the expression:

$$m_{limit} = \frac{1}{f} \sqrt{2\Delta} \ . \qquad (7)$$

A completely declining arc of S_{hk} is possible only in those cases when the condition $m = 2$ is approached earlier than the condition $\mu = \varphi$.

Maximum value of forward flow. It is known [13] that the function of the critical angle of forward flow in the function of the gripping angle should correspondingly pass through the maximum. Knowledge of the conditions which determine such a maximum are scientifically and practically important.

We find the condition under which the function of the forward flow will have a maximum by means of comparing the first derivative of S_{hk} along α with zero. For this purpose, let us take

$$\mu = \frac{H}{h} \text{ and } H - h = 0.5D\alpha^2,$$

as a result of the transformation and substitution, we obtain:

$$\mu = \frac{2\Delta}{2\Delta - \alpha^2} \qquad (8)$$

whence

$$\frac{\partial \mu}{\partial \alpha} = \frac{\mu^2\alpha}{\Delta} \quad \text{and} \quad \frac{\partial \mu^2}{\partial \alpha} = 2\,\frac{\mu^3\alpha}{\Delta}. \qquad (9,10)$$

Introducing the notation

$$z = \sqrt{4 + (\mu^2 - 1)(m + 2)}; \qquad (11)$$

after a simple transformation taking account of (8 - 10), we obtain:

$$\frac{\partial z}{\partial \alpha} = \frac{\mu\alpha}{z\,\Delta}\left[m\,\frac{\mu + 1}{4} + (m + 2)\mu^2\right] \qquad (12)$$

In accordance with the condition for the maximum of the forward flow, we have

$$\frac{\partial}{\partial \alpha}(1 + S_{hk}) = \frac{2z\,\frac{\partial \mu}{\partial \alpha} - 2\mu\frac{\partial z}{\partial \alpha}}{z^2} = 0,$$

whence

$$z\,\frac{\partial \mu}{\partial \alpha} = \mu\,\frac{\partial z}{\partial \alpha}.$$

Taking account of (9 - 12), we obtain:

$$(4 + (m + 2)(\mu^2 - 1) = m\,\frac{\mu + 1}{4} + (m + 2)\mu^2,$$

whence the condition for the maximum of the forward flow takes the following final form:

$$\mu = \frac{8 - 5m}{m}. \qquad (13)$$

Thus, the size and position of the maximum of the forward flow in relation to the area of natural and positive gripping depends only on index m and drawing; and in this regard, each maximum of S_{hk} corresponds fully to the determined value of the one or the other. As it follows from Figure 3, the maximum of S_{hk} is numerically equal to 13.4% and only satisfies $\mu = 3$ at the boundary of natural and positive gripping ($m = 1$). In the very areas of natural ($m < 1$) and positive ($m > 1$) gripping, the maximums of forward flow are correspondingly more or less than 13.4%, satisfying the conditions $\mu > 3$ and $\mu < 3$. The values of the extreme maximums of S_{hk}, equal numerically to zero and 41%, correspond to the conditions $m = 0$; $\mu = \infty$; $m = 4/3$; $\mu < 1$. In this regard, the upper maximum coincides with its limiting value. As a result, the graph of maximum values of forward flow which begins at one common point with the graph of limiting values henceforth (with the increase of α) declines more and more from it, dividing the nomogram into two unequal parts one of which is characterized by a rising forward flow and the other by a falling forward flow.

The closed condition of the function of the forward flow. As Figure 3 shows, as m increases, the falling arc of the forward flow grows longer and longer and for several values of m which satisfy the maximum of S_{hk}, it falls to zero ($m = 2$), thus "closing" the function. We shall find that condition which determines the closed state of the function S_{hk}. For these drawing values, index m and the gripping angle, corresponding to the maximum and limiting values of S_{hk}, we shall use corresponding notation: μ_{max}, m_{max}, α_{max} and μ_{limit}, m_{limit}, α_{limit}.

In agreement with (7, 8) and the notation m, we have:

$$m_{max} = \frac{\alpha_{max}}{f}; \qquad m_{limit} = \frac{\sqrt{2\Delta}}{f} \quad \text{and} \quad \alpha_{max} = \sqrt{2\Delta\left(1 - \frac{1}{\mu_{max}}\right)}$$

whence, as a result of the simultaneous solution taking (13) into account, we find

$$m_{limit} = m_{max}\sqrt{\frac{8 - 5\,m_{max}}{8 - 6\,m_{max}}} \qquad (14)$$

It is clear that the first closed curve of forward flow will correspond to the condition $m_{limit} = 2$. Substituting this in (14), we obtain

$$m^2_{max} = 4 \frac{8 - 6 m_{max}}{8 - 5 m_{max}} \qquad (15)$$

whence by means of a graphical solution, we find $m_{max} \approx 1.215$. In this regard, the drawing satisfying the maximum of the corresponding curve S_{hk} is equal to 1.584 and the forward flow itself is $S_{nk} = 6.5\%$.

The analysis presented shows convincingly that in practical conditions, the graph of the forward flow passing through the maximum will always break at some value of index m, if at the same time it passes through a value exceeding 6.5%. Besides this, maximums of the closed curves of forward flow always satisfy the conditions of positive gripping ($\alpha < f$).

Conditions of forging with rising or falling forward flow. By means of the simultaneous solution of (8) and (13), taking account of the notation adopted, it is not difficult to obtain:

$$\Delta = \frac{\alpha^2_{max}}{2} \cdot \frac{8 - 5 m_{max}}{8 - 6 m_{max}} \qquad (16)$$

This expression determines the size of the relationship of the thickness of the strip to the diameter of the roller Δ for forward flow in the function of the gripping angle for a given value of the coefficient of contact friction. In particular, Figure 3 presents values of Δ for $f = 0.3$ and the table (in the graph) presents the values of Δ for these same curves of S_{hk} but for other values of f. As is clear, each curve of S_{hk} satisfies a whole series of Δ depending on the size of the coefficient of contact friction.

By comparing (16) with Figure 3, it is not difficult to establish the condition satisfying forging with a rising and falling forward flow. Actually, if in a given pass it turns out that

$$\Delta > \frac{\alpha^2}{2} \cdot \frac{8 - 5 m}{8 - 6 m} \qquad (17)$$

the process of forging still satisfies the rising arm of the forward flow since the right element of the inequality has not yet reached this value which satisfies the maximum of the forward flow, i.e., the value of the right element of expression (16). However, when the right element of condition (17) turns out to be greater than the left element, the process of forging corresponds to the falling arm of the forward flow.

Therefore, the condition of forging with a rising and falling forward flow in the general case can be expressed

$$\frac{H}{D} \gtrless \frac{\alpha^2}{2} \cdot \frac{8 - 5m}{8 - 6m}, \qquad (18)$$

where the sign for greater than ($>$) satisfies forging with a rising forward flow and the sign for less than ($<$) satisfies a falling forward flow.

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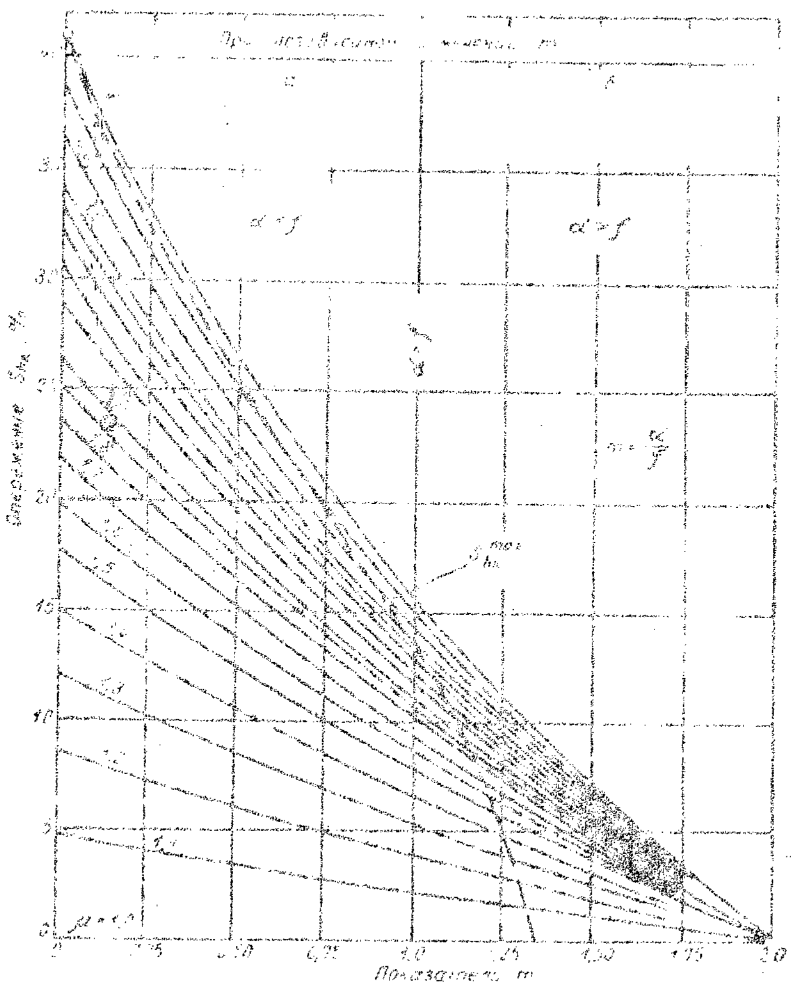
FIGURE APPENDIX

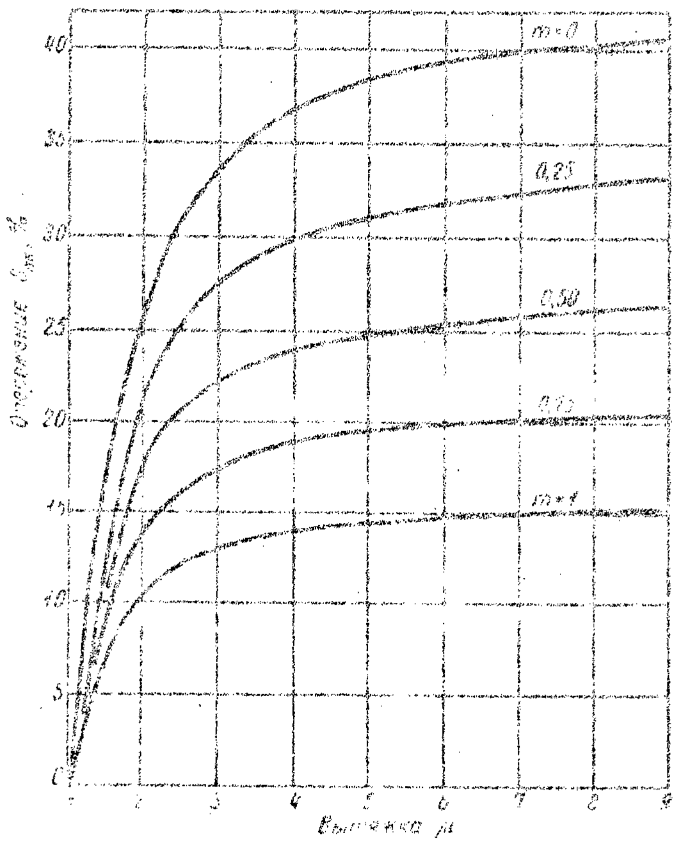


During independent change of m

Forward
Flow S_{bk}, %

Index m

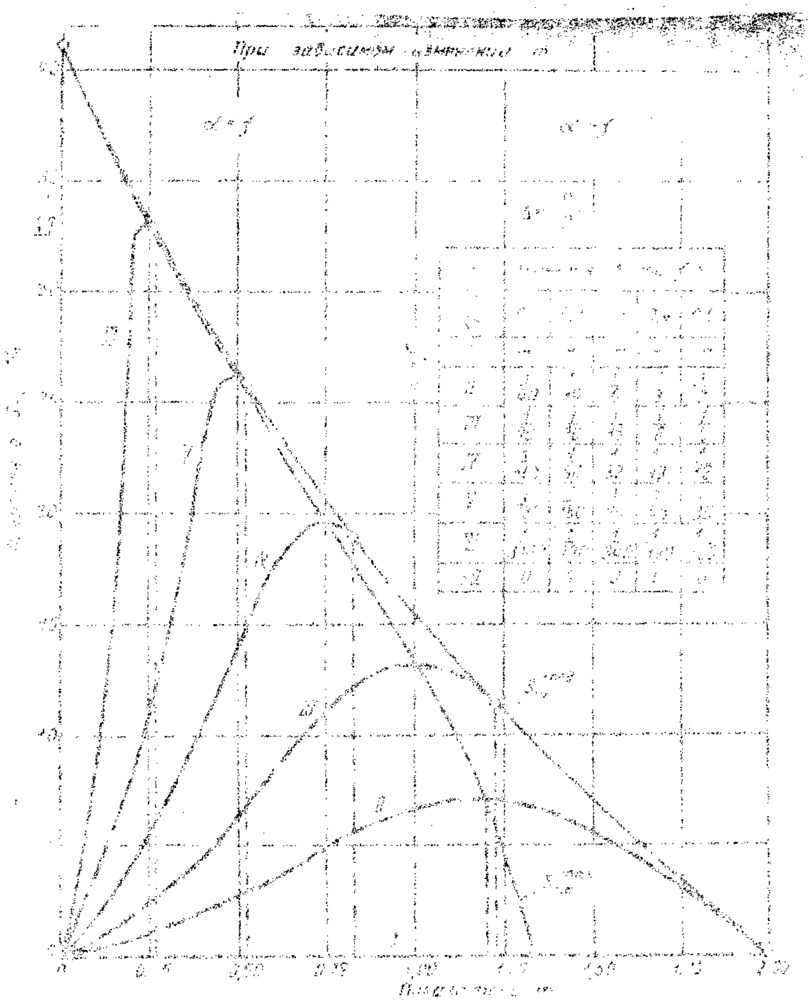
Figure 1. Illustration of the relationship of forward flow with drawing α and index $m = \frac{\alpha}{f}$; α - natural gripping; b - positive gripping.



Forward
Flow S_{nk}, %

Drawing μ

Figure 2. The dependence of forward flow on drawing.



During dependent change of m

Forward flow S_{nk}, %

Curve	Value of Δ for f = 0.1	0.2	0.3	0.4
I				
II				
S_{nk}^{limit}				
S_{nk}^{max}				

Index m

Figure 3. Illustration of the shape of curves of forward flow for various values $\Delta = \frac{E}{D}$.

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