STUDY ON INDUSTRIAL APPLICATION OF WIRE DRAWING WITH ROTATING DIE*

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(Received June 26, 1975)

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Introduction

The application of drawn products for conductors and other purposes is rapidly growing all over the world. This accounts for the broad-scale research work done by hundreds of researchers.

The development work resulted in several new solutions in the field of wire drawing. Among them, only new structural solutions, different from the traditional technology, will here be considered.

No extensive use of ultrasonic wire drawing can be expected because the ultrasonic effect can only be applied at very low drawing speeds [1].

High-pressure lubricant applied in hydrodynamic lubrication may significantly reduce the friction coefficient in drawing as compared to the ordinary technology, at an important increase of reducibility. No important drawing force saving is, however, possible but under several thousand atm. pressure [2], rather difficult to realize.

The technology of hydrostatic extrusion with pull-out is similar to the hydrodynamic lubrication in wire drawing, as shown schematically in *Fig. 1.*

Hydrostatic extrusion with pull-out permits reductions requiring 30—50 dies in traditional drawing. Notwithstanding, no wide-range application of the technology can be expected before some years, because of the need of means for the accurate control of the several-thousand-atmospheres-field pressure and of the high cost of the equipment [3].

In the course of wire drawing with rolling dies, deformation takes place between the free roller pair or pairs. The friction force decreases with the turning of rollers, enabling the reductions to be risen in one step. Very intensive research is going on in this field and the industrial application of wire drawing with rolling dies seems to gain ground [4, 5].

The principle and technology of wire drawing with rotating die have been known for more than 40 years [6, 7]. In recent times several publications

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* Abridged text of the Doctor Techn. thesis by the author

** Research Institute for Non-Ferrous Metals reported on the industrial application of wire drawing with rotating die [8, 9]. Further investigation of the problem is timely, the more so, as in the past 40 years only few publications appeared in this connection, whereas at present a wide-range industrial application may be expected [8, 14].

The small number of publications leave several details of wire drawing with rotating die even theoretically uncleared.

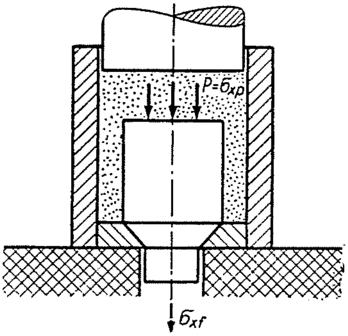

Fig. 1. Scheme of hydrostatic extrusion with pull-out of wire

In order to estimate the field of industrial applications, and to determine the meaningful fields of application, it is necessary to analyze and to establish the theory of the drawing process.

Previous works [6 to 15] permitted to make statements:

— by application a rotating die the drawing stress may be decreased permitting a higher one-step reduction [6 to 14];

— the decrease of the drawing force value depends on the applied lubricant and the drawing conditions [6 to 14];

— rotation of the die causes a more uniform wear in drawing and the initial ovalness of the die to decrease with drawing [12];

— following one reduction, the mechanical properties of steel wires drawn with rotating die do not or little differ from those drawn with fixed die [10, 11];

— the centric position of the drawing die is very important, since else, the helical scratches, drawing traces on the surface of the wire were more perspicuous than after traditional drawing [10, 11];

— the rotation of the drawing die improves the surface smoothness of the wire and this the more, the higher the speed of rotation [10, 11];

— depending on the peripheral-to-drawing-speed ratio inherent in the rotation, three ranges can be distinguished. In the first range, the drawing speed exceeds the peripheral speed, with no sensible decrease of drawing force. In the second range, the increase of the rotation-to-drawing-speed ratio lowers the drawing stress. After having reached a minimum, drawing stress will increase again with the increase of speed ratio (third range). The three ranges have been plotted *(Fig. 2)* on the basis of measurements [10]. The range limits are not indicated in the diagram, because these depend on the drawing speed and on other parameters of the drawing process;

— according to measurement results [11], in some cases the total power demand of drawing with rotating die may be lower than that of drawing with fixed die.

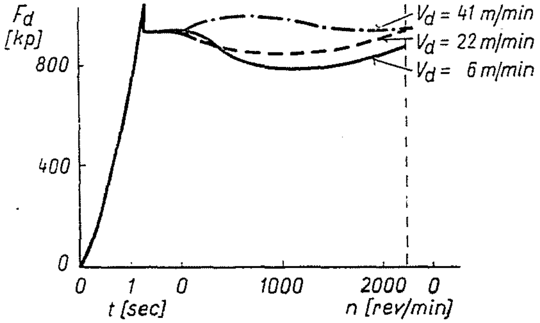

Fig. 2. Drawing forces in starting the drawing drum vs. die rpm

Available publications offer no unambiguous solution to the problem of applying rotation dies in industrial drawing machines because no questions of drawing non-ferrous metals have been dealt with so far, neither has the effect of rotating dies on the electrical conductivity or on the alteration of the material following the stepwise drawing. To facilitate industrial application, the following objectives have been set:

— to determine the theoretical possibility of savings in the overall power demand in drawing by rotating die, and its practical feasibility;

— to determine the effect of rotating die on the mechanical properties and electrical conductivity of aluminium and copper wires;

— to determine the above effect in series drawing;

— to determine the effect of modifying the cone angle of die on the decrease in drawing stress due to rotating die;

— to test whether the advantage of die rotation persists in the period of starting the wire-drawing machine (drawing drum);

— to interpret theoretically the obtained test results;

— to determine the fields of industrial application of rotated dies in the wire-industry, based on special literature and test results.

Theoretical considerations

The friction force in wire drawing with rotating die is assumed [6 to 14] not to change by size but by direction.

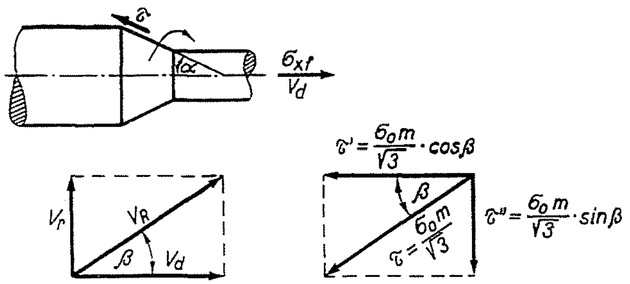

Fig. 3. Stresses and speeds of wire drawing with rotating die

Necessarily this will be opposite to the relative displacement of the die as indicated in Fig. 3.

Applying the upper-bound theorem, the relative drawing stress value in fixed-die drawing [16] is:

$$\frac{\sigma_{xj}}{\sigma_0} = f(\alpha)\,\varepsilon + $$
$$+ \frac{1}{\sqrt{3}}\left(\frac{2\alpha}{\sin^2\alpha} = 2\mathrm{ctg}\alpha + m\mathrm{ctg}\alpha\varepsilon + 2m\frac{R_f}{L}\right) +$$
$$+ \frac{\sigma_{nb}}{\sigma_0} \tag{1}$$

where R_f is the wire radius after reduction, σ_0 the flow stress of the material’ α is the semicone angle of the die and m the constant friction factor, L is the calibrating part of the die, σ_{xb} the back-pull stress, provided the pullback of wires has been taken into consideration. For practically applied angles ($2\alpha \leq 40°$), function $f(\alpha) \approx 1$ is a fair approximation.

According to Fig. 3, calculating the stress component parallel to the drawing axis from Eq. (1) is easy to transform for die rotation. The “virtual” constant friction factor derived from the vector triangle:

$$m' = m\cos\beta \tag{2}$$

Yielding for the rotating die drawing stress:

$$\frac{\sigma_{xfr}}{\sigma_0} = \varepsilon +$$
$$+ \frac{1}{\sqrt{3}}\left(\frac{2\alpha}{\sin^2\alpha} - 2\,\mathrm{ctg}\,\alpha + \mathrm{m}\cos\beta\,\mathrm{ctg}\alpha\,\varepsilon + 2\mathrm{m}\cos\beta\frac{L}{R_f}\right) +$$
$$+ \frac{\sigma_{xb}}{\sigma_0}\,. \tag{3}$$

The angle β of the relative displacement included with the wire axis is easy to calculate from the peripheral speed of rotation and from the drawing speed:

$$\cos\beta = \frac{1}{\sqrt{1+\left(\frac{v_r}{v_d}\right)^2}}\,, \quad \text{if}\, v_d \neq 0\,.$$

By reducing Eqs (1), (3) and (4) it is easy to determine the stress decrease due to die rotation vs. speed ratio:

$$\frac{\Delta\sigma_{xf}}{\sigma_0} = \frac{1}{\sqrt{3}}\,m\left(1-\frac{1}{\sqrt{1+\left(\frac{v_r}{v_d}\right)^2}}\right)\left(\varepsilon \operatorname{ctg}\alpha + \frac{2L}{R_f}\right). \tag{5}$$

The overall power demand in die rotation

Omitting a detailed mathematical analysis, rotation adds to the theorethical power demand of the drawing process, because the product of the friction stress component by the relative displacement speed will be proportional to the work related to unit time, necessary for overcoming friction, the stress component is assumed not to change, while the resultant speed increases upon rotation.

On the contrary, tests are quoted in [11] asserting event of overall power demand decrease upon rotation.

This is, however, possible for poor efficiencies of drawing equipment and machine.

Be η_1 and η_2 the efficiencies of the wire-drawing and rotating machines, respectively, the inequality

$$\frac{\eta_1}{\eta_2} \leq \frac{1}{2+\operatorname{tg}\beta} \tag{6}$$

will lead to a decrease of the overall power demand.

Eq. (6) — verifiable mathematically — shows energy saving with this technology to occur but for wire-drawing machines with poor efficiency. In the case of wire-driven dies the work per unit time exceeds that for the fixed die technology, the entire gear being involved in driving the rotation, at a loss of efficiency. This means that dies of such kind raise the pull stress, a backward to be avoided as a rule.

Thus, die rotation normally does not decrease drawing work, in some cases of machine efficiency ratios, however, it may be assumed to do so.

Experimental materials and equipment

Properzi EAl 99,5% (nominal diameter 10 mm), shaved OFHC Cu (diameter about 8 mm) and limed C 10 (diameter 6 mm) wires were applied as experimental materials. Wires with final diameter of 2.5 mm were produced from all three with and without rotating the dies. Wires of 4.7 mm diameter were tested on a draw-bench by a single reduction. An Italian-made device type MILL-FR-53, completed by a carefully calibrated load cell for accuracy, rotated the die at 50 rpm.

In experiments on the drawing drum rotated at its lowest speed (37.8 m per min) the peripheral to drawing speed ratio was 0.001 to 0.005 depending on the wire diameter. Readjusting the draw bench transmission to a drawing speed of 0.69 m/min resulted in a ratio of 0.89 ± 0.1. These two speed ratios are within two of the three ranges of practical significance. Eq. (5) shows no decrease of stress to be expected in the first case and its possibility in the second case.

In the second case the speed ratio was chosen to prevent the wire from twisting. This undesirable phenomenon occurs in the third range, entrains the increase of the drawing stress and invalidated the respective equations. Both surface scratch pitches and metallographic tests showed exemptness from wire twisting in this test series.

Each test value was averaged from at least three parallel measurements and evaluated by means of statistical methods for low populations.

Test results and interpretation

Force diagrams in the starting period of the drawing drum with fixed die and with a die that started to revolve earlier were recorded in the course of drawing aluminium wires of ∅4.7 mm to ∅4.1 mm. In both cases, five parallel measurements were taken.

As against expectations, the already rotating die was found not to reduce but even to raise a bit the maximum drawing force.

The five measurements average 150 kp with fixed die and 198 kp with rotated die. Because of the great standard deviations (55.5 and 14.5 kp, resp.) this difference is not significant (probability only 70%).

Further measurements seemed to be meaningless, the increase of force being anyhow unfavourable, however, not against applying a rotated die: at most die at rest and switch on the rotation after. The standard deviations is significantly lower with a rotating than with a fixed die. Test data in [10, 11] permit this phenomenon to be interpreted. In the initial period of starting, the ratio of peripheral-to-drawing speed is in a range where no decrease of the force can be observed. The decrease of the standard deviation upon rotation can be attributed to the lubricant film forming before the drawing is started.

Investigation of the drawn material properties showed mechanical properties (tensile strength, proof stress, area reduction) and resistivities not to change. This is illustrated by tensile strength, proof stress and area reduction diagrams of copper wire vs. strain in *Fig. 4.*

Drawing force changes on the effect of die rotation have been investigated at the two quoted speed ratios (0.001 to 0.005 and 0.89 ± 0.1). The theoretical change in the specific drawing stress is expressed by Eq. (5), expanded in series as:

$$\frac{\Delta\sigma_{xf}}{\sigma_0} = \frac{1}{2\sqrt{3}}\, m \left(\frac{v_r}{v_d}\right)^2 \left(\varepsilon \operatorname{ctg} \alpha + \frac{2L}{R_f}\right) . \tag{7}$$

Applying the constant friction factor value obtained in own measurements, the relative change of drawing force calculated from the change of specific stress proved to be very small (3×10^{-4}), undeterminable in drawing drum tests.

Bench tests made at a higher speed ratio permit, however, to determine the difference of forces calculated by Eq. (7).

This offered a possibility to test the effect of drawing conditions (strain, cone angle of dies) on the drawing-stress differences (Figs 5 to 7).

The actual strains are plotted on abscissae, whereas drawing-stress-by-flow-stress quotients on ordinata in Figs 5 and 6.

Fig. 7 shows the variation of stress by flow stress quotient vs. semicone angle of die.

In the three figures, the plots can be approximated by linear functions — according to Eqs 1, 3 and 7. The best fitting straights were determined by the method of least squares, and the obtained equations indicated in the figures. The correlation coefficient of the straight lines is in all cases greater than 0.8, meaning that for the given number of plots the approximation with straight line is permissible at a high probability (greater than 95%). In Figs 6 and 7, dashed lines indicate the theoretical relationship obtained from

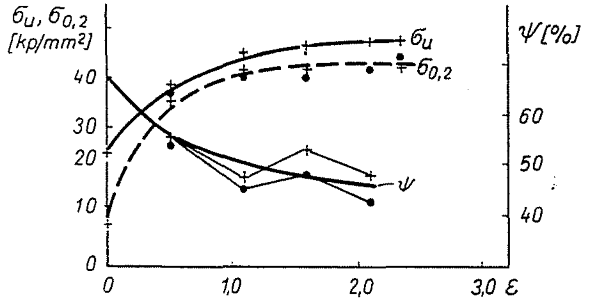

Fig. 4. Tensile strength, proof stress and area reduction vs. strain of copper wire

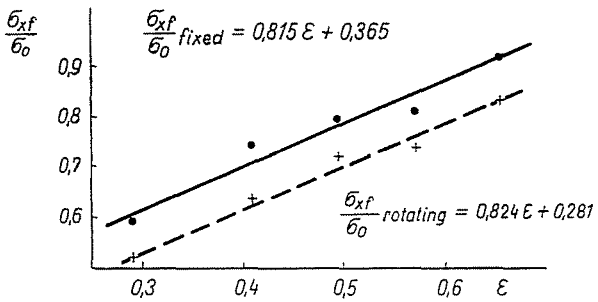

Fig. 5. Effect of strain of copper wire on the relative drawing stress with (+) and without (0) rotating die for wire C 10

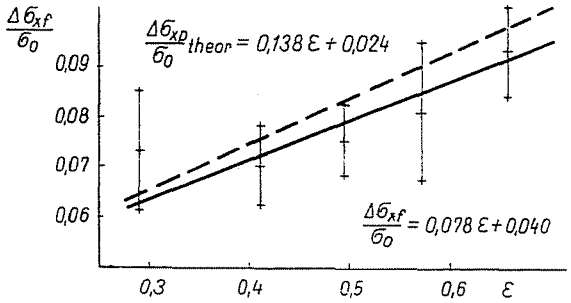

Fig. 6. Change of relative drawing stress due to rotating die vs. C 10 wire strain. —— experimental; - - - theoretical

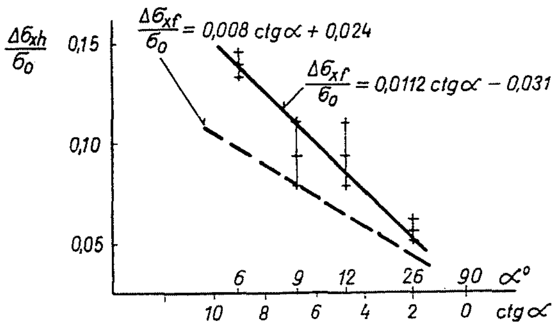

Fig. 7. Change of relative drawing stress due to rotating die vs. semicone angle for wire C 10. —— experimental; - - - theoretical

Eq. 7. Calculations were made with an m value of 0.093 assessed from measurements.

The qualitative and quantitative coincidence of the measured and calculated values shows the equations to be fairly realistic under the given circumstances, permitting further conclusions drawn on this basis (e.g., on energetic relations, optimum parameters) to be accepted as realistic.

Conclusion

The rotation of the die does not affect the mechanical properties of the drawn wires (tensile strength, proof stress and area reduction), neither their electrical conductivity. This statement is also true for the series drawing with rotated die.

In case of modern lubricants the decrease of the drawing force is unimportant, of the order of 10 per cent. The surface quality is improved by the relative high peripheral speed, but not to an extent to support the application of rotated dies.

From the aspect of energetics, the application of rotated dies can only be favourable in the case of wire-drawing machines with poor efficiency, but just at limited rotation speeds. The unfavourable energetics ratio contradicts wire drawing with wire-driven die.

The application of the rotated die does not eliminate difficulties arising in starting the drawing machine, nor the maximum-to-average-drawing-force ratio.

The application of slowly rotated dies is only advantageous by entraining concentric wear and decreasing the initial ovalness of the die. This fact defines the only field of application as for high-strength wires more or less deviating from the circle inherent in the conventional technology to be drawn to regular circular cross section, such as in the first stage of drawing rolled steel wires.

References, measurement results and theoretical considerations help to define the rather restricted field of application for rotated dies.

Summary

No information adequate for determining the industrial applicability of drawing with rotated die has been published so far. To this aim theoretical analyses and experimental investigations were required.

The series drawing with rotating die was studied for its effect on the mechanical properties and electrical conductivity of the material and on the development of drawing stress.

The industrial application of wire-drawing machines with rotating die has a single advantage: that of even, concentric wear of the die, suggesting its use in fields, where the even wear of die is of crucial importance.

References

1. LEHFELDT, E.: Draht **19** (1968) 10. 757.
2. BUTLER, L. H.: Wire Industry **32** (1965) 1055.
3. ALEXANDER, J. M.: Special lecture. Techn. Univ. Bp. 25. 03. 1970.
4. GOKYU, I.: Wire Industry **35** (1968) 1053.
5. GOKYU, I.: Wire Industry **35** (1968) 415.
6. SACHS, G.: Mitt. Deutsche Materialprüfanstalt (1931) 1.
7. GREENWOOD, H.—THOMPSON, F. C.: Nature **128** (1931) 3221.
8. FUHR, K.: Draht **8** (1967) 156.

9. Fuhr, K.: Gebrauchsmuster Nr. 1. 747 810. DBR.
10. Lietzmann, K. D.—Eichner, K. R.: Neue Hütte **14** (1969) 458.
11. Lietzmann, K. D.—Eichner, K. R.: Kohászati Lapok **104** (1971) 19.
12. Hofstein, C. O.—Lindstrand, E.: Jerkonten Annalen **142** (1958) 158.
13. Rothman, D.—Sansome, D. H.: Mach. Tool. Des. **10** (1970) 179.
14. Marciniak, H.: Wiad. Hutn. **26** (1970) 151.
15. Marciniak, H.: Wire Review **30** (1963) 144.
16. Avitzur, B.: Metal Forming Processes and Analysis. McGraw-Hill Book Company, New York (1968).

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