DETERMINATION OF THE DEPENDENCE OF THE TOTAL DRAWING FORCE ON THE DIE APROACH ANGLE, PARTIAL STRAIN AND FRICTION DURING DRAWING OF STEEL WIRE

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Abstract

One of the most important parameters used for qualitative evaluation of lubricants in cold drawing of steel wires is the coefficient of friction. Its magnitude cannot be determined directly, but it can be determined from the measured total drawing force (TDF) or total drawing torque (TDT). In addition to the coefficient of friction, the TDF is mainly influenced by the size of the partial strain during pass and also by the geometry of the die, which is mainly described by the die approach angle. In order to determine the coefficient of friction for the individual analysed lubricating oils, a series of experiments was carried out, consisting of drawing a phosphated low-carbon steel wire with a diameter of 5.5 mm in one pass on a Koch KGT direct drawing machine. In total, two single pass reduction values were used for the evaluation of four oils (when drawn to a diameter of 5.1 resp. 4.9 mm, it was 14 resp. 20.6 %) and 6 different die approach angles (8 to 18°). The TDF was determined from the measured TDT and the coefficient of friction was determined inversely from the Siebel TDF equation. For a strain of 20.6 %, the correlation between the measured and calculated values as a function of die approach angle was high, but at a strain of 14 % the data showed a low correlation. Therefore, the data were corrected using the contact pressure value, which is also a function of die geometry. Thanks to this modification, a new equation was established for calculating the frictional component of the TDF under conditions of mixed friction.

Keywords: Steel wire, drawing, coefficient of friction, total drawing force, lubricating oils, geometry of die

1. INTRODUCTION

At present, in wire drawing technology, emphasis is placed on reducing energy requirements and on the service life of tools - drawing dies. Both are closely related to the magnitude of the frictional forces between the die and the steel wire. The selection of a suitable type of lubricant is thus a very important task in the technological practice of wire drawing mills. One of the most important parameters used for qualitative evaluation of lubricants in cold drawing of steel wires is the coefficient of friction. Its magnitude cannot be determined directly, but it can be determined from the measured TDF or TDT. The TDF according to Siebel [1,2] F_{Total} in Newton is based on the sum of the forces required to deform the wire F_d, to overcome external friction F_f and the force to overcome internal losses F_l:

$$F_{Total} = F_d + F_f + F_l \tag{1}$$

$$F_d = S_1 \cdot R_{ms} \cdot ln\frac{S_0}{S_1} \tag{2}$$

$$F_f = S_1 \cdot R_{ms} \cdot ln\frac{S_0}{S_1}\frac{\mu}{\alpha} \tag{3}$$

$$F_l = S_1 \cdot R_{ms} \cdot ln\frac{2}{3}\alpha \tag{4}$$

$$F_{Total} = S_1 \cdot R_{m,ag} \cdot ln\frac{S_0}{S_1} \cdot (1 + \frac{\mu}{\alpha} + \frac{2\alpha}{3ln\frac{S_0}{S_1}}) \tag{5}$$

Where:

S_0, S_1 - input and output cross-section of the wire (mm^2)

$R_{m,avg}$ - average ultimate tensile stress (MPa)

μ - coefficient of friction (-)

α - semi-die approach angle (RAD) see **Figure 1**.

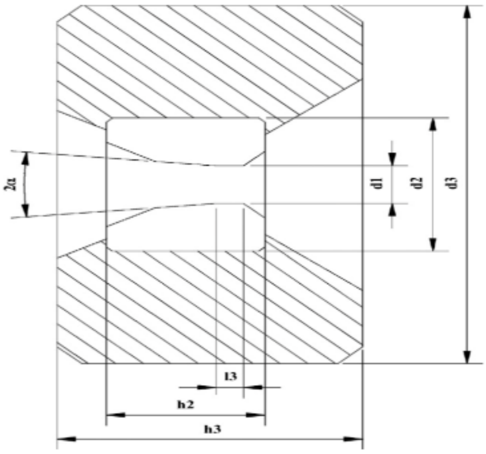

Figure 1 Drawing die geometry

The drawing force F_d required for homogeneous deformation is not influenced by the size of the die approach angle, as follows from equation (2). On the contrary, the force F_l to overcome the friction in the die (3) increases with the decreasing angle, as this increases the contact area between the wire and the working surface of the die, so it represents an external loss. The force required to overcome the shear (inhomogeneous) deformation F_l (4), which arises as a result of the change in metal flow in the surface regions of the wire, decreases with decreasing angle, as the metal flow becomes smoother and represents the loss due to excess work and therefore the internal loss.

During drawing, external friction occurs between the working parts of the die and the surface of the drawn wire, which depends on the quality of the surface, the type of lubricant and the drawing conditions (drawing speed, reduction and contact pressure). Friction during the wire drawing is undesirable and needs to be minimized. This means a reduction of the coefficient of sliding friction. With a certain simplification, in sliding friction, four types of lubrication arise according to Stribeck [3]: dry, boundary, mixed and hydrodynamic. In technological practice when using a sufficient amount of lubricant mixed or hydrodynamic lubrication occurred. Mixed friction corresponds to the region to the left of the minimum of the Stribeck curve. We can therefore observe here a negative effect of contact pressure on the coefficient of friction (speed difference of the contact surfaces and the viscosity of the lubricant are assumed constant for the same lubricant and technology). In the case of hydrodynamic lubrication, the coefficient of friction decreases with increasing contact pressure.

2. DESCRIPTION OF EXPERIMENT

The drawing was carried out on a KOCH KGT 25-E laboratory wire drawing machine at VŠB-TUO. Phosphated low-carbon hot rolled steel wire with a diameter of 5.5 mm, yield point of 283 MPa and a tensile strength (UTS) of 375 MPa was used for testing. A total of 48 different samples of wire were drawn using four different types of oils, two single pass reduction (when drawn to a diameter of 5.1 or 4.9 mm, it was 14 or 20.6 %) and 6 different die approach angles 2α (8 to 18°). The ratio of the instant torque to the maximum engine torque was recorded, during drawing. It was used to determine the TDT of the wire drawing block, which was recalculated to the TDF.

3. RESULTS

3.1 Mean yield strength model

Based on the yield point and UTS values determined by the tensile test of rolled wire, the constants K and n of the Holomon equation for the description of yield strength (YS) were determined:

$$YS = K \cdot e^n \quad , \qquad (6)$$

where: e - logarithmic strain.

The constants K and n were determined numerically, using the MS Excel. The initial estimation of K and n constants was performed using the YS model for S235JR steel from the Simufact Forming program database

(K = 589.58 MPa and n = 0.1281). First YS is calculated acc. Eq. (6) for the estimated constants *K* and *n*. YS is then recalculated to the engineering curve of the tensile diagram, thanks to the knowledge of the instant cross-section of the wire calculated on the basis of the law of conservation of volume from the instant longitudinal strain. The engineering curve shows a peak corresponding to UTS, which is caused only by the fact that the decrease of the instant measured force during the tensile test due to the reduction of cross section area of the wire during homogeneous deformation is greater than the increase in force due to the strain hardening of the steel. Therefore, it is not true that the peak of the engineering curve of the tension diagram represents the beginning of inhomogeneous deformation and the necking. Thanks to this fact, such values of the constants *K* and *n* can be found for which YS at a deformation of 0.2 % will be equal to the yield point $R_{p0.2}$ together the maximum stress value on the engineering curve will be approximately equal to UTS. YS model of hot rolled wire was established in the following form:

$$YS = 520 \cdot e^{0.1} \tag{7}$$

The value of Mean YS is then determined according to this equation:

$$MYS = \frac{1}{e}\int_0^e K \cdot e^n \cdot de = \frac{520}{e} \cdot \frac{e^{1,1}}{1,1} \ (MPa) \tag{8}$$

3.2 Calculation of the total drawing force

Instant TDF during drawing for various reductions and die approach angles can be calculated as follows:

$$M_D = \frac{\tau_{measured} - \tau_{no\ load}}{100} \cdot M_{D\max} \tag{9}$$

where:

$\tau_{measured}$ - the ratio of the instant torque to the maximum engine torque (%),

$\tau_{no\ load}$ - the ratio of current torque without load to maximum engine torque (measured 2%),

$M_{D\max}$ - maximum engine torque (240 Nm).

TDF in Newton was determined as follows:

$$F_{Total,measured} = \frac{M_D}{r} \tag{10}$$

where: *r* - radius of drawing block (m).

3.3 Determination of the coefficient of friction by inverse calculation from the TDF

For each sample, we calculate the measured friction force $F_{f,\ measured}$ using a modified equation (1):

$$F_{f,measured} = F_{Total,measured} - F_{D,calculated} - F_{l,calculated}$$

where: $F_{D,calculated}$ resp. $F_{l,calculated}$ are calculated according to eq. (2) resp. (4).

Now we plot the dependence of $F_{f,measured}$ on the inverse value of semi-die approach angle in radians and determine the slope of the regression line under the condition that *y(0) = 0* (see **Figure 2**). Using the slope, we can calculate the coefficient of friction according to the equation:

$$\mu = \frac{slope}{F_{D,calculated}} \tag{11}$$

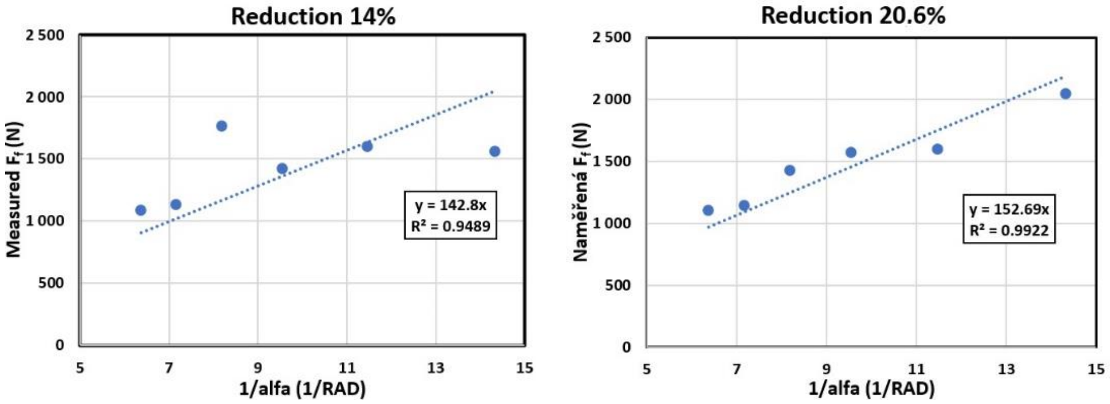

Figure 2 Dependence of the measured friction force on the inverse value of semi-die approach angle (oil A)

4. DISCUSSION OF RESULTS

4.1 Comparison of oils and determination of optimal die approach angle values

An overview of the determined values of the coefficients of friction for all combinations of single pass reduction and the oil used is provided in **Table 1**. The lowest coefficient of friction was obtained when using oil D (Top Oil Services, Inc. Czech Republic).

Table 1 Calculated friction coefficients for individual oils and both reductions

Oil	A	B	C	D
Reduction 14%	0.109	0.103	0.105	0.090
Reduction 20.6%	0.076	0.080	0.081	0.070

If we know the coefficient of friction, we can determine the optimal die approach angle, at which F_{Total} = min. When comparing the optimal angles (see **Table 2**), we see that oil D is significantly different from the remaining oils. The use of a die with an optimal angle will lead to a reduction of energy consumption and reduction of the wear of the dies. E.g.: If using oil D at a reduction of 20.6 % and using a die with an optimal angle, F_{Total} will be lower by 3.3 % compared to oil C under the same conditions.

Table 2 Calculated optimal die approach angle and minimal F_{Total}

Optimal angle - $F_{Total,\ min}$	Oil							
	A		B		C		D	
Reduction 14%	18°	3 120 N	18°	3 068 N	18°	3 086 N	16°	2 956 N
Reduction 20.6%	19°	3 892 N	19°	3 943 N	19°	3 951 N	18°	3 820 N

4.2 Comparison of calculated and measured values F_f

The graphs in **Figure 3** shows the dependence of the calculated F_{Total} and its individual components on the die approach angle 2α for both reductions and oil A. For comparison, the measured values of F_f are also shown here. It is clear from the comparison that for a larger reduction (20.6 %) we have a good match between the calculated and measured values of F_f. For the smaller reduction (14 %), the match is not good because F_f appears to decrease more slowly with increasing angle than it does for the 20.6 % strain. The same is the case with other oils, which is evidenced by the calculated values of the coefficient of determination (see **Table 3**).

Table 3 Calculated coefficients of determination for individual oils and both reductions

Oil	A	B	C	D
Reduction 14%	-0.7558	-0.5256	-7.8720	0.4582
Reduction 20.6%	0.8197	0.8970	0.9102	0.9761

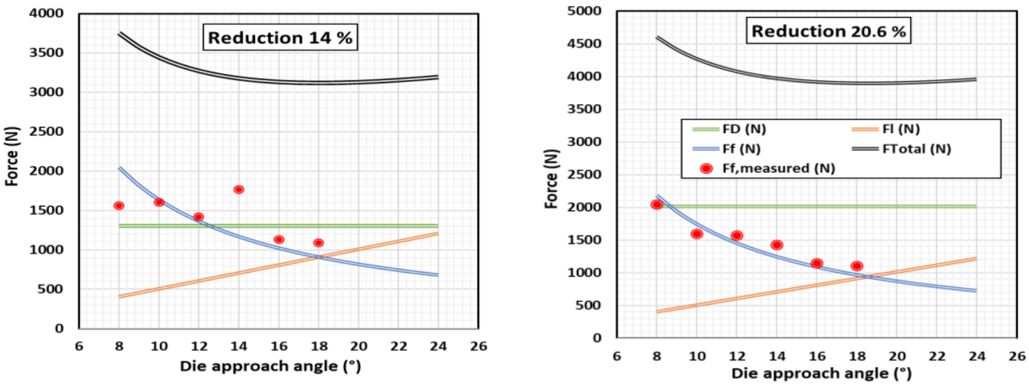

Figure 3 Comparison of measured and calculated values (oil A)

4.3 Determination of the coefficient of friction as a function of contact pressure

Due to the low values of the coefficients of determination for smaller reductions, we decided to assess the effect of the contact pressure during wire drawing on the coefficient of friction. We determine the contact pressure according to this equation:

$$p = \frac{F_{Total} \cdot S_{contact}}{\sin(\alpha + \mathrm{arctg}\mu)} \ (MPa) \qquad (12)$$

where: $S_{contact}$ - the size of the contact area between the wire and the die (mm²).

Acc. Eq. (12) calculated *p* values are shown in the graph in **Figure 4**. At first glance, we can see that the reduction does not have a big effect on the contact pressure, even though it significantly affects F_{Total}. The size of the contact area, which is also a function of the reduction, has a bigger influence. Depending on the current position on the Stribeck curve, the friction coefficient increases (hydrodynamic friction) or decreases (mixed friction) with increasing inverse value of the contact pressure. Both types of dependence μ = f(1/*p*) were created by conversion from the constant coefficient of friction and constant contact pressure. If we use the obtained dependences μ = f(1/*p*) to calculate F_{Total} and F_f, we can compare the calculated values with the measured values (see **Figure 5**). It is clear from the comparison that we get much better results if we assume mixed lubrication.

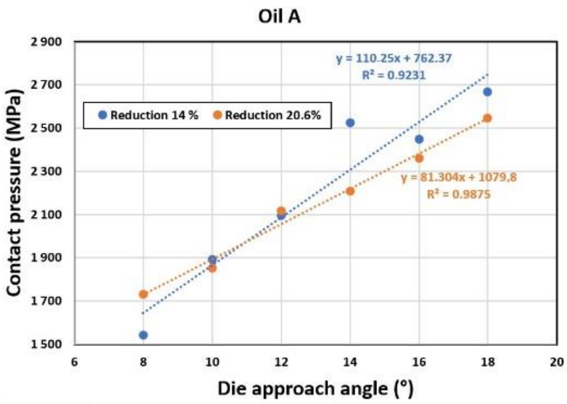

Figure 4 Dependence of the contact pressure on the die approach angle and reduction

Since the contact pressure is a function of the TDF, we cannot directly use the dependence of the friction coefficient on the contact pressure. Instead, we use the dependence of friction coefficient on the die approach angle. We will thus calculate the F_f according to the modified equation (5):

$$F_t = S_1 \cdot R_{ms} \cdot ln\frac{S_0}{S_1} \cdot \frac{a \cdot \alpha + b}{\alpha} \qquad (13)$$

The values of coefficients *a* and *b* from Eq. (13) for all oils and both reductions are given in **Table 4**. We average the individual coefficients and use them to calculate F_f. We assume that the coefficient *a* is dependent on the reduction, but because the experiment took place only for two values of the reduction, it is not possible to determine the dependence *a* = f(*reduction*). The values of the coefficients of determination for individual oils and both reductions are given in **Table 5**. It can be said that by using the coefficient of friction as a function of the contact pressure (through its dependence on the die approach angle) we obtained a more accurate model for smaller reductions, but for larger reductions the accuracy slightly decreased (compare with **table 3**).

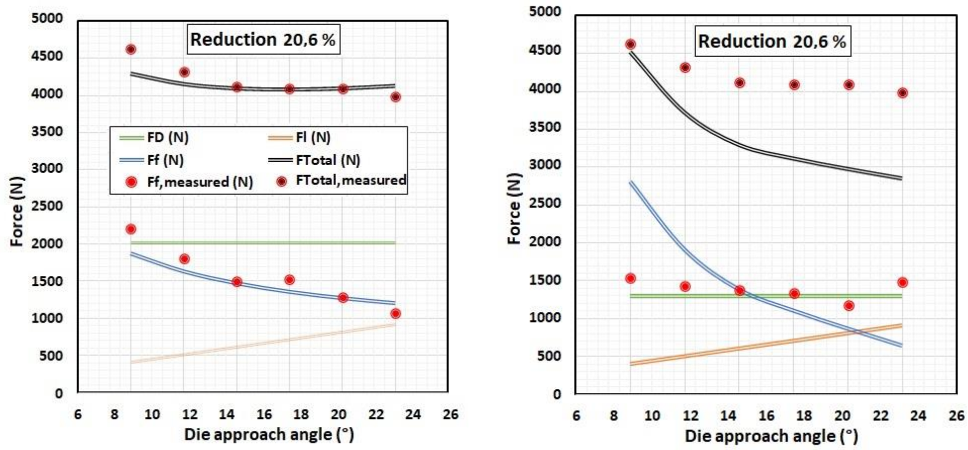

Figure 6 Comparison of measured and calculated F_{Total} values and their components F_D, F_f a F_l, **left m**ixed lubrication **right** hydrodynamic lubrication (oil C)

Table 4 The values of coefficients *a* and *b* from Eq. (13) for individual oils and both reductions

a	A	B	C	D	Average	*b*	A	B	C	D	Average
14 %	0.606	0.62	0.752	0.597	**0.6430**	14	0.050	0.044	0.032	0.032	**0.042**
20.60 %	0.352	0.333	0.323	0.325	**0.3332**	20.6	0.042	0.048	0.049	0.039	

Table 5 Calculated coefficients of determination for individual oils and both reductions acc. eq. (13)

Oil	A	B	C	D
Reduction 14%	0.250	0.810	-0.387	-0.139
Reduction 20.6%	0.882	0.789	0.770	0.724

5. CONCLUSION

This paper presented a methodology for determining the coefficient of friction during drawing a steel wire in conditions close to industrial application. It was shown how the knowledge of the coefficient of friction can be used to evaluate the quality of the lubricant. As part of the discussion of the results, a correction of the equation for calculating the TDF was proposed so that the effect of the contact pressure on the friction coefficient was taken into account.

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