UDC 621.778:621.892

Determination of parameters and efficiency of process lubricant screw supercharger application when drawing

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Abstract
The viscosity characteristics and pressure of the soap lubricant before wire-drawing process are determined with the use of dimensional analysis and within the framework of the developed method for calculating the parameters of the drive screw supercharger, which provides hydronic friction mode in case of "dry" wire-drawing process. The test calculations showed that in case of use of such tool, energy saving is several times higher than its consumption by the driving mechanism. Moreover, the substantial increase of drawing dies wear resistance and reduction of breakages can be expected which makes reasonable the use of supercharger in the practice of dry wire-drawing.
Key words: DRAWING, PROCESS LUBRICANT, SCREW SUPERCHARGER, PARAMETER CALCULATION, EFFICIENCY

The developed method of parameters analysis of the screw supercharger for providing hydronic friction mode under the dry wire-drawing process with the dry soap lubricant is presented by the authors of the paper. It was also found out that viscosity and pressure in the process lubricant before its going into the drawing die are the key values determining the tool characteristics. The problem of efficiency evaluation of the application of such tool was also set.

The purpose of the paper is determination of viscosity and pressure in the "dry" soap process lubricant before wire-drawing process which are important for creating the hydronic friction mode in the deformation zone, updating the method to the level of relevant calculation procedure as well as evaluation of efficiency of application of such tool for wire-drawing process.

The dependences, which describe the complex process of the dry soap lubricant moving during the steel wire-drawing process, are presented in the paper [1]. It has been noticed that one-dimensional flow of viscous plastic liquid is subjected to Shvedov-Bingham law:

$$\tau_l = A + B\frac{\partial V}{\partial y} \qquad (1)$$

where $\partial V / \partial y$ − shearing stress and velocity gradient in the lubricant film respectively; A and B − boundary (minimal) stress of initial flow and plastic viscosity of process lubricant respectively, which depend on temperature and pressure. Moreover, at the wire-drawing speed V_0 for the process lubricant flow with the speed Vs at the output of screw supercharger (Fig. 1), it may be accepted:

$$\frac{\partial V}{\partial y} \approx \frac{2\cdot(V_0 - Vs)}{D_s - d_s}$$

but from the geometrical ratios, it follows that:

$$V_s = \pi\cdot\omega_s\cdot\frac{D_s - ds}{2}\cdot tg\varphi_{av}$$

where ω_s − angular rate of the screw supercharger shaft, s^{-1}; D_s, d_s − diameter of the screw according to the external element and diameter of its shaft respectively, *m* (Fig. 2); φ_{av} − average angle with the screw axis of the surface of its screw blade on the external element and on the shaft respectively, *grad* (6).

In this case,

$$\tau_l \approx A + B\frac{2\cdot V_0 - \pi\cdot(D_s - d_s)\cdot\omega_s\cdot tg\varphi_{av}}{D_s - d_s}. \qquad (2)$$

According to the investigation data [2] for the dry soap process lubricant with temperature *T* (*K)* and pressure p_0 (*N/m²*), the value *A* (*N/m²*) is determined by the empirical formula:

$$A = 0.067\cdot10^6 + 4,44\cdot10^{-4}\cdot p_0 + \frac{65.54\cdot10^6}{T-273} \qquad (3)$$

However, plastic viscosity of *B* (*Pa*s*) can be demonstrated by the computational scheme:

$$B = \frac{1+1,273\cdot10^{-9}\cdot p_0}{T-273}\cdot G \qquad (4)$$

where

$$T = \frac{1240+2.25\cdot10^{-4}\cdot\frac{V_0}{R_a}}{1+86.7\cdot(\frac{d_0}{R_a})^{-0,503}} \qquad (5)$$

$$G = 9.78\cdot10^{-5}\cdot G(\frac{V_0}{R_a})\cdot G(\frac{d_0}{R_a}) \qquad (6)$$

$$G(\frac{d_0}{R_a}) = -1,5\cdot\frac{d_0}{R_a} + 12000 \qquad (7)$$

$$\left.\begin{aligned}
&- G(\frac{V_0}{R_a}) = 35.6\cdot 10^3 - 9.88\cdot(\frac{V_0}{R_a})^{0,641} \quad \text{at } 0.02\cdot 10^6 \le \frac{V_0}{R_a} \le 0.2\cdot 10^6 \\
&- G(\frac{V_0}{R_a}) = 11.66\cdot 10^3 - 3{,}32\cdot 10^{-3}(\frac{V_0}{R_a}) \text{ at } 0.2\cdot 10^6 \le \frac{V_0}{R_a} \le 3.0\cdot 10^6; \\
&- G(\frac{V_0}{R_a}) = 1700 \quad \text{at } \frac{V_0}{R_a} > 3{,}0\cdot 10^6,
\end{aligned}\right\} \tag{8}$$

where, d_0, R_a − diameter and height of the work piece (wire) microrelief.

During the "wet" wire drawing with the use of the liquid process lubricant, the viscosity of the last one can be determined according to the data of technical literature [2].

In order to simplify the practical evaluation of p_0, the proximal change of the "accurate model" of the lubricant film forming under the "dry" wire-drawing process [1] is allowable by the empirical formula, the general form of which can be obtained as a result of dimensional analysis [3].

For this purpose, the value p_0 with its dimensions ($Pa=N/m^2=kg*m^{-1}*s^{-2}$) was accepted as response function.

And as arguments the following values were accepted with their dimensions:

index of plastic ("effective") viscosity of lubricant B ($Pa*s=kg*m^{-1}*s^{-1}$);

V_0 ($m/s= m*s^{-1}$);

index of friction mode $k=\frac{\xi}{R_a}$ (non-dimensional);

index of annular space at the output of supercharger h (m);

diameter of the work piece passing through supercharger d_0 (m);

temperature of the lubricant T (K);

coefficient of heat capacity (for "compensation" of the absolute temperature grade) c_g ($J/kg/K= m^2*s^{-2}*K^{-1}$).

The corresponding parameters equation is of the form:

$$p_0 = W\cdot\left[B^a\cdot V_0^b\cdot k^e\cdot h^x\cdot d_0^g\cdot T^z\cdot c \right. \tag{9}$$

The formula with the dimensions:

$$(kg\cdot m^{-1}\cdot s^{-2}) = (kg\cdot m^{-1}\cdot s^{-1})^a\cdot(m\cdot s^{-1})^b\cdot(1)^e\cdot(m)^x\cdot(m)^g\cdot(K)^z\cdot(m^2\cdot s^{-2}\cdot K^{-1})^r \tag{10}$$

Formula of their "balance":

- at the dimension «kg»: 1 = a;

at the dimension «m»: $-1=-a+b+x+g+2r$;

at the dimension «s»: $-2=-a-b-2r$;

at the dimension «K» $0=z-r$.

After simple transformations, the solving of this equations has determined that $a=1$; $b=1-2\cdot z$; $x=-1-g$; therefore, that the equation (9) obtained the following form:

$$p_0 = N\cdot\left[B^1\cdot V_0^{1-2q}\cdot k^e\cdot h^{-1-g}\cdot d_0^g\cdot T^z\cdot c_g^r\right]$$

From this equation, after connection of the parameters with equivalent power coefficients into non-dimensional combinations (criteria), it was found that:

$$(\frac{p_0\cdot h}{B\cdot V_0}) = W\cdot(\frac{T\cdot c_p}{V_0^2})^z\cdot(k)^e\cdot(\frac{h}{d_0})^g \tag{11}$$

The formula (6) is linearized by logarithming

$$\ln(\frac{p_0\cdot h}{B\cdot V_0}) = \ln W + z\cdot\ln(\frac{T\cdot c_g}{V_0^2}) + e\cdot\ln(k) + g\cdot\ln(\frac{h}{d_0}) \tag{12}$$

Thus, with application of the method of linear regression analysis to the field of design data obtained for the dry soap lubricant with the index

$$c_g = 2300\frac{\text{J}}{\text{kg}\cdot\text{K}}$$

by computer model [1] within the limits of values changes

$5\cdot 10^6 \le p_0 \le 200\cdot 10^6 (Pa)$; $6\le B\le 300 (Pa*s)$;

$0.2\le V_0\le 5 (m/s)$; $1\cdot 10^{-6}\le \xi \le 20\cdot 10^{-6}$ (m);

$1\cdot 10^{-6}\le R_a\le 20\cdot 10^{-6}(m)$; $1\le k\le 10$;

$0.02\cdot 10^{-3}\le h\le 10\cdot 10^{-3}(m)$;

$3.0\cdot 10^{-3}\le d_0\le 6.5\cdot 10^{-3}$(m);

$320\le T\le 580$ (K), or $47\le t\le 307$(°C),

it has been determined that In W = 4.59; z =0.074 ; e=2.80 ; g=1.09 (with the multiple correlation coefficients 0.93 and under probability 0.95).

As a result, the formula (9) has obtained the form:

$$(\frac{p_0\cdot h}{B\cdot V_0}) = 98{,}5\cdot(\frac{T\cdot c_p}{V_0^2})^{0,074}\cdot(k)^{2,80}\cdot(\frac{h}{d_0})^{1,09} \tag{13}$$

where:

$$p_0 = 98.5 \cdot \frac{B \cdot V_0}{h} \cdot \left(\frac{T \cdot c_p}{V_0^2}\right)^{0,074} \cdot (k)^{2,80} \cdot \left(\frac{h}{d_0}\right)^{1,09} \quad (14)$$

If the expression $k = \frac{\xi}{R_a} \to 3$ is accepted for the hydronic friction mode, the formula (14) could be slightly simplified:

$$p_0 = 711 \cdot \frac{B \cdot V_0}{h} \cdot \left(\frac{T \cdot c_g}{V_0^2}\right)^{0,074} \cdot \left(\frac{h}{d_0}\right)^{1,09}. \quad (15)$$

The comparison of formulas (14) and (15) allows calculating the interdepend parameters p_0, B and thereby the viscous shear τ_l according to the formula (3), the index of friction in lubricant film f_{lb} according to the formula (8), the moment on the screw shaft M_s (4) and, as the result, taking into account all necessary parameters, power N according to the formula (2).

Thus, on the basis of necessary power value N (kW) of the driving mechanism from the ordinary line of electromotor [5], it is possible to capture the certain type of the motor and determine its nominal speed n_n (r/min).

Taking this data into consideration, the total ratio i_Σ from the motor to the screw shaft is

$$i_\Sigma = \frac{n_n}{n_s} = \prod_{u=1}^{u} i_u , \quad (16)$$

where i_u is the gear ratio of u-element of speed transmission from the motor to the screw shaft; n_s is the screw shaft speed which conforms to the angular rate of the screw supercharger ω_s according to (3).

Accordingly, it is necessary to check whether the rated-load torque M_{load} ($N*m$) of the motor is sufficient comparing it to torque rating M_{rat}, which is determined by formula (4) from:

$$M_{rat} = \frac{M_s}{i_\Sigma} \le M_{load} , \quad (17)$$

where $M_{load} = \frac{9554 \cdot N_n}{n_n}$.

For implementation of calculated gear system ratio i_Σ taking into account conic gearing "embedded" into the supercharger (Fig.1), it is reasonably to use gear system and driving mechanism. The letter will allow "soft" keeping the necessary rotation frequency n_s of the screw during the pressure fluctuation. According to it, at the gear system ratio $i_s = 0.5...3$ of the conic gear, the selection and calculation of the gear system with gear ratio i_{gear} and the driving mechanism with gear ratio $i_{bel} < 5...7$ were conducted:

$$i_\Sigma = \frac{i_{gear} \cdot i_{bel}}{i_s}. \quad (18)$$

The calculations show that in such driving mechanism scheme, it is preferable to use the dual-stage worm gear system which can provide a great value of i_{gear} (up to several thousand).

With the purpose of test calculation of screw supercharger of dry soap process lubricant in actual practice of its use under the wire-drawing process, the dimensions of value are the following: $V_0 = 5\, m/s$; $d_0 = 7.0 \cdot 10^{-3}\, m$; $R_a = 4 \cdot 10^{-6}\, m$; the length of screw is $L = 120 \cdot 10^{-3} m$; efficiency of conic gear is η_s=1.0 ; efficiency of the supercharger is η_1=0.75; efficiency of the motor is η_{mot} = 0.55 ; efficiency of the gear system is η_{gear} = 0.30; efficiency of the driving mechanism is η_{dr} = 0.95;

$$c_g = 2300 \frac{J}{kg \cdot K};$$

the density of the initial soap lubricant is

$$\rho_s = 1000 \frac{kg}{m^3};$$

the density of lubricant after temperature and power impact is

$$\rho_{TP} = 1300 \frac{kg}{m^3};$$

the density of wrought metal is

$$\rho_{met} = 1300 \frac{kg}{m^3};$$

coefficient of safety of material of the screw shaft is $k_s = 2$; the screw spade material (Steel 10) with flow limit

$$\sigma_{T.spad} = 210 \cdot 10^6 \frac{N}{m^2};$$

the load factor is $k_{spad} = 3$. The following results were obtained according to the calculations, which are presented by the arrows, with the dimensions in square brackets and the use of represented formulas in the round brackets.

$d_{s..in} = 10 \cdot 10^{-3} [m]$ (1) ; $\to$ $d_s = 26 \cdot 10^{-3} [m]$; $\to$ $D_s = 40 \cdot 10^{-3} [m]$ when $a = 2,3$; $\to$ $H_s = 30 \cdot 10^{-3} [m]$ (9); $t = 4$ $t = 4$ (10); $\to V_0 / R_a = 1.25 \cdot 10^6 s^{-1}$; $\to$ $\frac{d_0}{R_a} = 1.75 \cdot 10^3$; $\to$ $T = 503 [K]$ (5); $\to$ $G (V_0 / R_a) = 7510$

(8); $\rightarrow$; $G(d_0/R_a) = 9375$ (7); $\rightarrow$ $G = 6886$ (6); $\rightarrow$ $B = 29.94 + 38.1 \cdot 10^{-9} \cdot p_0 [Pa \cdot s]$ (4); $\rightarrow h = 7 \cdot 10^{-3} [m]$; $p_0 = 1.122 \cdot 10^6 \cdot B\, [N/m^2]$ (15); $\rightarrow p_0 = 33.72 \cdot 10^6 [N/m^2]$ $\rightarrow$ and B = 31.2 [*Pa*s*] as a result of simultaneous consideration of (4) and (15); $\rightarrow A = 0.367 [N/m^2]$ (3); $\rightarrow P_s = 49000$ [*N*] (13); $\rightarrow \varphi_D = 13^0.4$ (6); $\rightarrow \varphi_d = 20^0.2$ (6) from; $\rightarrow \varphi_{aw} = 16^0.8 \succ 10^0$ (6); $\rightarrow M_s = 248$ [*N*m*] (4); $\rightarrow w = 3.45 \cdot 10^{-6} [m^3]$ – for (12); $\rightarrow \tau_{kr} = 71.9 \cdot 10^6 [N/m^2]$ for (12); $\rightarrow \sigma_{sg} = 100 \cdot 10^6 [N/m^2]$ for (12); $\rightarrow \sigma_{eq} = 175 \cdot 10^6 [N/m^2]$ for (12); $\rightarrow \sigma_T = 350 \cdot 10^6 [N/m^2]$, on the basis of which the screw shaft material is Steel 40X with $\sigma_T \geq 400 \cdot 10^6 [N/m^2]$ $\rightarrow M_{man} = -30.4 [N \cdot m]$ (14); $\rightarrow \delta_s \geq 1.61 \cdot 10^{-3} [m]$ (15), on its base it is accepted that $\delta_s = 2 \cdot 10^{-3} [m]$; $\rightarrow S_{corp} = 3.52 \cdot 10^{-3} [m^2]$ for (16); $\rightarrow l_D = 41.1 \cdot 10^{-3} [m]$ for (16); $\rightarrow l_d = 27.7 \cdot 10^{-3} [m]$ for (16); $S_{vit} = 0{,}5 \cdot 10^{-3} [mm^2]$ for (16); $\rightarrow S_{corp} > S_{vit}$ the condition (16) is performed; $\rightarrow$ it is accepted in advance f_{sm}=0.2 for (7) $\rightarrow k_{ots.1} = 0.222$ - the first base to the stepwise approximation according to (7) $\rightarrow \omega_s = 44 \cdot 10^{-3} [s^{-1}]$ - the first base to the stepwise approximation according to (20); $\rightarrow \tau_g = 0.39 \cdot 10^6$ [*N/m²*] – the first base to the stepwise approximation according to (2); $\rightarrow f_{sm}$=0.012 (8) $\rightarrow$ the check is $f_s \cdot H_s << d_s$ - the condition of absence of self-braking of lubricant substance is satisfied; $\rightarrow k_{br.2} = 0.17$ - the second base to the stepwise approximation according to (7); $\rightarrow \omega_s = 41{,}5 \cdot 10^{-3} [s^{-1}]$ - the first base to the stepwise approximation according to (20); $\rightarrow n_s = 0.013$ [*sp/s*]=0.4[*sp/ min*] (3); $\rightarrow q_{TP} = 2$ [*kg/tn*] (19), that is conformed with the practice of wire-drawing process; $\rightarrow N = 0.105$ [*kW*] (2), on the basis of which the asynchronous three-phrase motor of AIR 56A4 type with the nominal rating power N_n = 0.22[*kW*] is selected, nominal speed is $n_n = 1360$ [*sp/min*], efficiency of the η_{mot} = 66%, with weight 3.8 *kg*; $\rightarrow i_\Sigma = 3375$; $\rightarrow M_{calc} = 0.073 [N*m]$; $\rightarrow M_n = 0{,}573 [N*m]$; $\rightarrow M_n >> M_{calc}$; $\rightarrow$ for the driving mechanism of the screw supercharger; screw type double-stage regulator 5CH80/40 with $i_{eag} = 1250$, $M = 355 [N*m] >> M_s$ and with weight 38 *kg*; $i_{bel} = 2.7$ is selected for the transmitting rotation from the motor to the screw shaft (18).

Naturally, the necessary calculations should be conducted for all transmitting elements according to the known approaches.

Thus, let us compare the required power of the screw supercharger driving mechanism with the possible power saving during wire-drawing process and its application.

The power of the wire-drawing process is determined by the formula:

$$N_{draw} = \frac{\pi \cdot d_0^2}{4} \cdot V_0 \cdot \sigma_{draw} \quad (19)$$

where according to the formula (6):

$$\sigma_{draw} \approx \sigma_T \cdot \left[\ln\mu + 0{,}77 \cdot \alpha + \frac{f_{draw} \cdot \ln\mu}{\alpha + \alpha^2 + f_{draw} \cdot \ln\mu} + \frac{2{,}6 \cdot f_{draw} \cdot \alpha}{\alpha + f_{draw} \cdot \ln\mu + 2 \cdot f_{draw} \cdot \alpha} \right] \quad (20)$$

σ_{draw}, σ_T - wire-drawing stress and flow limit of the wrought material; μ - metal elongation ratio during wire-drawing process; α - half of the angle of conic working drawing die (Fig.1); f_{draw} - the friction ratio during wire drawing.

Usually, a = 0.1...0.12*rad*; μ = 1.25...1.40 at rough average steel wire drawing.

Taking into account the dependence of f_{draw} on the friction mode index

$$k = \frac{\xi}{R_a}$$

from the paper [7] , it may be accepted $f_{draw.0}$=0.2 for the usual terms (with «o» index), but $f_{draw.1}$=0.16 for the test score of the efficiency of screw supercharger application during the wire drawing with the hydronic friction mode (with «1» index).

Corresponding electric power reduction of the driving mechanism of wire-drawing machine under the comparable conditions:

$$\Delta N = N_0 - N_1 . \quad (21)$$

For the values $a = 0.12$; μ =1.35; $\upsilon_T = 25 \cdot 10^{-6}$ *N*/m², which are in the formulas (19) and (20), $\Delta N \approx 0.7$ *kW* or about 14 %.

The presented data suggest that the energy saving during the advanced wire-drawing process is several times better than the calculated power necessary for the screw supercharger driving mechanism. It indicates the applicability of such tool in practice of wire drawing.

Conclusion

The calculation method of the screw supercharger parameters for providing the hydronic friction mode during wire drawing with dry soap process lubricant was developed. The calculations have proved that power saving during such wire-drawing process is several times higher than its consumption by the driving mechanism. Moreover, the substantial increase of drawing dies wear resistance and reduction of breakages are expected that makes profitable the use of the screw supercharger.

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