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FRICTION AND STRESS EVALUATION OF COPPER WIRE DRAWING UNDER DIFFERENT LUBRICATION CONDITIONS[1]

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Abstract

ASTM C10100 W annealed copper wires with an initial diameter of 4.3 mm were drawn to a final diameter of 1.3 mm using a mineral oil lubricant of 0.06 Pa.s viscosity under hydrostatic pressures of approximately 35 MPa. Ten wire drawing dies (of 3.6 mm, 3.2 mm, 2.9 mm, 2.6 mm, 2.3 mm, 2.1 mm, 1.9 mm, 1.7 mm, 1.5 mm and 1.3 mm in diameter) were used to produce a total cross-sectional reduction of approximately 225%. Wire drawing forces under oil hydrostatic pressure with a graphite lubricant were compared to wire drawing forces without any lubricant. A measuring system was used to record the wire drawing forces over time and to study the frictional behaviour of the drawn wires. A wire drawing machine with a speed of 8 mm/s was used to verify the coefficient of friction fore wires drawn at low strain rates. Lubrication regimes were analysed for oil under hydrostatic pressure. The quasi-hydrodynamic regime ranged from 2.3 mm to 3.6 mm for the wire drawing die. An analytical model for calculating the wire drawing force/stress was developed to obtain the distribution of friction coefficients at each reduction of wire diameter. By controlling friction forces, it is possible to save energy and materials, as well as to determine the die replacement frequency. Wire drawing processes are used extensively in industry and research and will benefit from knowledge of the best working conditions.

Key words: Wire drawing; Copper wire; Lubrication; Friction.

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1 INTRODUCTION

Lubrication between wires and wire drawing dies allows separate surfaces to be kept in contact. Lubrication reduces friction, helps to maintain efficient manufacturing conditions, improves the surface finish of products, lessens wear on dies, decreases the force required for processing, saves energy and minimizes pollution.
The influence of wire drawing speed on wire drawing tension is governed by the resistance to deformation of the wire metal and the friction between the wire and the die.(1) The drawing tension decreases with increasing temperature caused by friction, when the wire drawing speed increases to produce an area reduction of approximately 22%.(1) However, with greater reductions in area, the wire drawing stress increases, even though the wire traction speed increases.(1) In this study, we used an area reduction of approximately 20% in our wire drawing bench laboratory. This deformation is commonly used in industry to prevent die wear (galling) to obtain precisely drawn materials and avoid wire seizure that can cause wire rupture and interrupt the manufacturing process.(1)
There are two types of wire drawing processes: bench and continuous. The speed used for bench wire drawing is approximately 150 to 1,500 mm/s.(1) For continuous drawing, two speeds are used. Ferrous metals are drawn at 10,000 mm/s and nonferrous metals are drawn at 30,000 mm/s.(1) However, increased drawing speeds can lead to difficulties with heat dissipation and inefficient lubrication that increases die wear.(1) In this work, we use a copper wire drawing velocity and draw length of approximately 8 mm/s and 2 m, respectively. This drawing velocity was much lower than those described above. However, a simple bench wire drawing process proved useful for analysing the behaviour of wires drawn at low shear rates and estimating the lubrication regime from friction and force data at low speeds.
Three lubrication regimes are defined with respect to the contact surfaces involved in metal forming processes:(2,3) 1. boundary (lubricant films with molecular-scale thicknesses where there are many points of contact between the wire and the die); 2. mixed (lubricants that are continuously dragged to maintain a lubricant coating between valleys at the interface of the wire and the die); and 3. hydrodynamic (there is no contact between the wire and the die surface). Consequently two interfaces occur: 1. die/lubricant; and 2. wire/lubricant.
The Stribeck diagram was used to display these regimes and to analyse lubrication and wear performance(2,3) (Figures 1 (a) and (b)). This diagram is expressed by the friction coefficient (μ) and a dimensionless parameter ($\rho\omega/p$), where ρ is the dynamic viscosity of the lubricant, ω is the rate of rotation, and p is the nominal bearing pressure. The main factor that differentiates one regime from the another is the film thickness of the lubricant relative to the characteristic of the interface.(2,3)
Each lubricant regime results from physical and chemical conditions within the system including lubricating properties, material properties of the tool and work piece, roughness of the contact bodies, speed, temperature and geometry of the bodies.(3,4) Small changes in these properties may change the regime. During processing, various regimes may exist at different regions of the interface. Therefore, the coefficient of friction is not constant.(2-5) In this work, the coefficient of friction was calculated for each wire drawing die.
Figure 1c shows the four zones of the wiredrawing die. Zone I contains a trumpet-shaped curvature that gives rise to (c), and an angle (β) that is greater than the angle (α) of the tapered bore zone (Zone II). This facilitates entrance of the lubricant. D_o is the initial wire diameter. Zone II is the work region where plastic deformation occurs

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to taper the wire. In this zone, the thickness of the lubricant decreases to define a new lubrication regime. Zone III is the wire gauge region used to obtain the final wire diameter required (D_f). In this zone, elastic deformation occurs, forming a film lubricant of constant thickness. Zone IV is the exit region, containing a high enough (45º) exit angle to avoid damage to the wire surface.

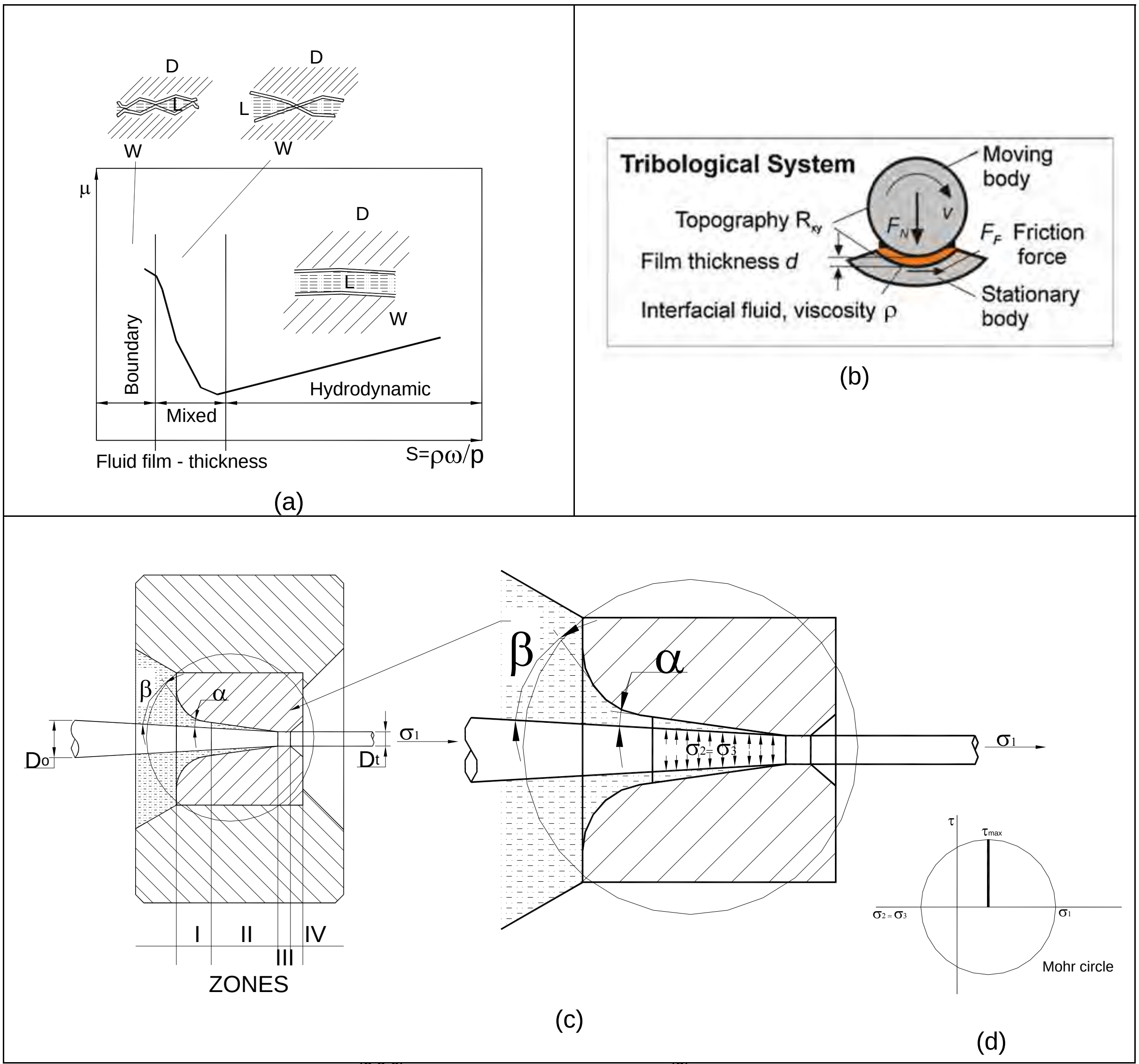

Figure 1. Stribeck diagram (a),[2,3,6] tribological system (b),[2] zones of the wire drawing die (c), and stresses acting (d).

The choice of lubricant used to deform the work piece is experimental and should be based on the type of material to be drawn, the amount of mechanical energy, the machine type and the speed of drawing.[4] Many types of lubricant are used in cold metal forming processes, and disposal of their residues is important for the health of the environment.[3] An emulsion lubricant (a suspension of oil particles, surfactant, and various polar substances in water) can be applied for copper drawing to control the friction between the wire and the die.[4]
Recently, two patents were filed for pressurised lubricants that reduce friction during wire drawing.[7,8] In these studies two die systems were used to provide hydrodynamic lubrication. Mineral oil and calcium stearate were used in these studies as lubricants. Calcium stearate changes from a semisolid state to a liquid

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under high pressures (80 to 500 MPa). The wire is drawn to a speed of 2 m/s, reduced to 10% for the first die and then reduced to 15% for the second die.

In this work, an area reduction of approximately 20%, a drawing speed of approximately 8 mm/s and an oil hydrostatic pressure of 35 MPa were used with or without graphite lubricants to compare the wire drawing performance. Hydrostatic pressures less than 35 MPa employing the same lubricants were studied previously.[9]

Various methods are used to produce the force required for metal forming processes to obtain optimal tool geometries.[3] The geometry and the material (tungsten carbide) of the wire drawing die used in our simulated testing were chosen based on industry specifications to guarantee the best performance.

Analytical methods were used to solve the external force/stress (σ_1) required to pull the wire through a drawing die with consideration to the angle of the conical die (α), a constant coefficient of friction (*μ*) between the wire and the die in conical bore Zone II, the principle of plasticity theory $(\bar{\sigma})$ and the redundant deformation (*Φ*) (internal distortion of the metal not contributing to the dimensional change). Equations 1 and 2 are based on the element method[1] and the equating forces at the wire and conical die surface, respectively.[10]

$$\sigma_t = \phi \cdot \bar{\sigma} \cdot \frac{1+B}{B} \cdot \left[1 - \left(\frac{D_f}{D_o} \right)^{2B} \right], B = \mu \cdot ctg\alpha \quad \text{, and} \qquad (1)$$

$$\sigma_t = \phi\bar{\sigma}(1+\mu \cot g\alpha)\ln\left(\frac{D_o}{D_f}\right)^2 . \qquad (2)$$

The redundant work $(\phi > 1)$ increases with die angle. These equations were used to estimate the coefficient of friction for wire drawing, considering the redundant work (*Φ*) to be 1.2.[9,11]

Experimental studies suggest that the redundant work factor for drawing round wire can be estimated by:[1]

$$\phi \approx 0.8 + \frac{\Delta}{4.4} \text{, and} \qquad (3)$$

$$\Delta = 4\frac{\alpha}{r}\left[1+(1-r)^{\frac{1}{2}}\right]^2 . \qquad (4)$$

Where *r* is the reduction of cross sectional area per pass, $r = 1 - A_o/A_f$, and α is the approach semiangle, in radians.

The objectives of this work were as follows: 1. determine the experimental drawing force and calculate the coefficient of friction under internal hydrostatic pressures of 35 MPa with and without graphite lubricant; 2. analyse the lubrication regime transition for ten wire drawing dies with a total reduction of approximately 225%; 3. estimate the redundant work factor (*Φ*); and 4. obtain an analytical equation that represent the wire drawing process.

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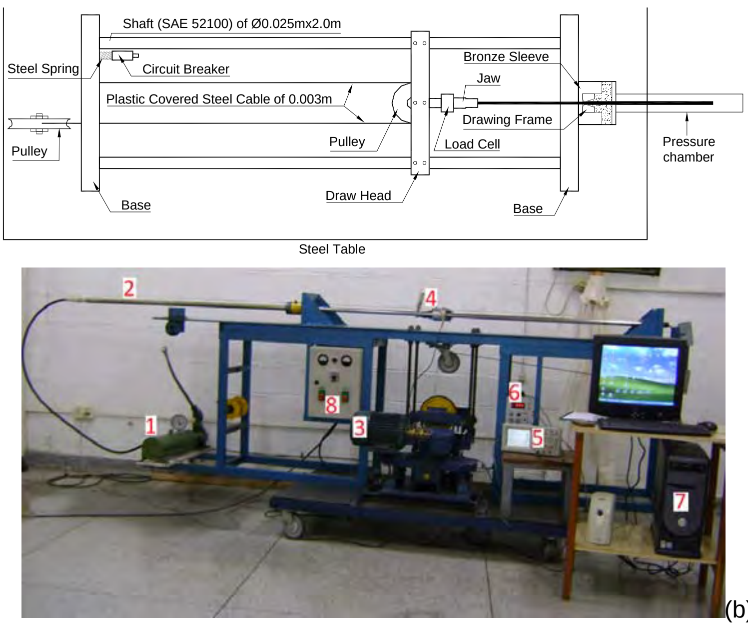
2 EXPERIMENTAL SET UP AND PROCEDURE

2.1 Machine Wire Drawing

Figure 2 shows the wire drawing bench machine used in this work. The machine has an AC motor (3/4 HP) that drives a gear box (16 rpm) that in turn drives a pulley that coils a steel cable. This steel cable pulls the wire through a system of pulleys, drawing the wire at approximately 8 mm/s. Lima Filho[12] previously described the assembly of this machine.
A 68 MPa oil pump with a 50 MPa marc Zürich manometer and a pressure chamber were used for wire drawing under hydrostatic pressure (Figure 2). The die containing the ASTM C10100 W annealed copper wire with a tapered end was placed inside the pressure chamber. The hydrostatic pressure inside the chamber was held constant by manually positioning the lever of the oil pump. This was necessary because the system leaked a small, almost imperceptible, amount of oil during wire drawing via Zone III. Figure 3 shows the parts of the pressure chamber that were designed to be fixed to the wire drawing machine. The oil was supplied via 35 MPa of hydrostatic pressure to examine its effect on friction under operating conditions.
The viscosity of the oil inside the pump (approximately 60 cSt) was obtained using a Soletest Oil Kit viscometer. This viscosity was similar to SAE 5w/30 oil at 313.15 K.[6] In practice, an increase in the temperature of the oil did not occur because the wire drawing speed was very low (8 mm/s). Therefore, the oil viscosity was constant.
Data acquisition was performed using a digital signal conditioner (TMDE Transdutec), an oscilloscope (Tektronix TDS 210) operating at 50 Hz, and a rigid load cell of 4.9 kN- 482 mV at the pull gripper to evaluate the value of the drawn force and calculate the coefficient of friction at the wire/die interface. A DELL computer containing a Pentium 4 processor operating at 2.0 GHz with 512 Mbites RAM was used to continuously monitor and record the pulling force on the die. Wires were first drawn without lubrication, before the lubricants (mineral oil under hydrostatic pressure (35 MPa) and graphite) were tested.



(a)
(b)

Figure 2. Schematic of the wire drawing machine (a) and its components (b): 1. oil pump; 2. pressure chamber; 3. motor and reducer; 4. load cell; 5. digital oscilloscope; 6. TMDE; 7. computer; and 8. command panel.

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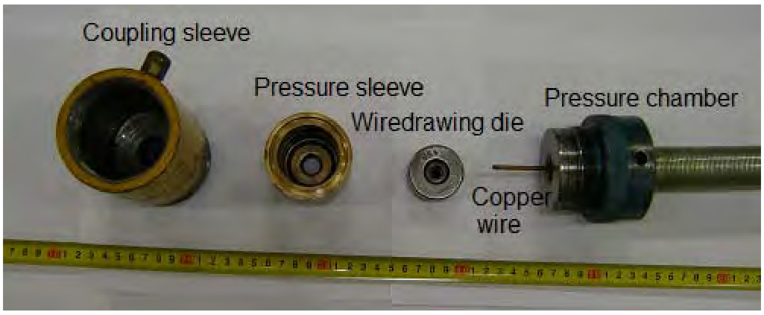
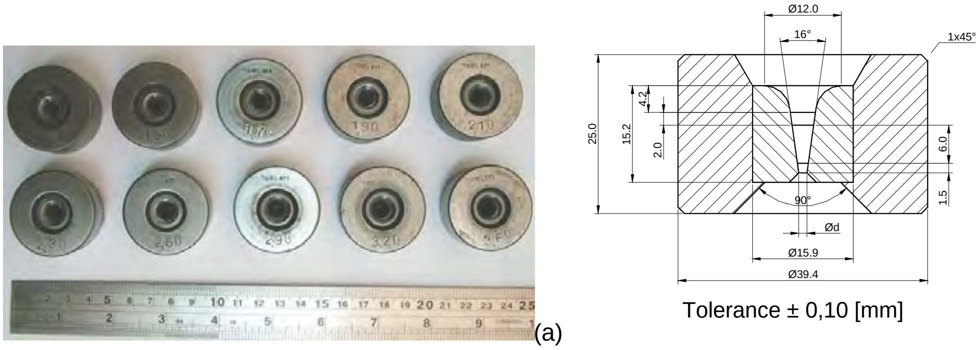


Figure 3. Details of the pressure chamber end to be plugged in the drawing machine for wire drawing under hydrostatic pressure.

2.2 Materials and Wire Drawing Dies

We used ASTM C 10100 W annealed copper wires drawn from 1.3 mm to 4.3 mm. Ten tungsten carbide dies were used with diameters ranging from 1.3 mm to 3.6 mm (Figure 4a). These dies gradually reduced the wire diameter in each pass by approximately 20%. The contact pressure distribution can be considered as uniform. The deformation degree is usually used in the drawing process to prevent wear on the die and to obtain precisely drawn materials. Figure 4b shows the geometry of the dies used in this study. The contact pressure distribution of the wire drawing test was uniform. All dies and wires were cleaned using gauze soaked in acetone to prevent contamination.



Item	Ød
1	1,3
2	1,5
3	1,7
4	1,9
5	2,1
6	2,3
7	2,6
8	2,9
9	3,2
10	3,6

Tolerance ± 0,10 [mm]

(a) (b)

Figure 4. Ten wire drawing dies (a) and their cross-sectional dimensions (b). The external casing is made of SAE 1040. The die is made of tungsten carbide.

The end of the wire was tapered using a file so that it could pass through the hole in the die and be gripped and pulled by the wire bench drawing machine. The copper drawn wires were tested at “São Marco Indústria e Comércio Ltda” (http://www.saomarco.com.br/site/empresa.asp) to obtain the ultimate tensile stress (UTS). The UTS values were important to calculate the force/stress needed for wire drawing for each operation and thus the coefficient of friction.

3 RESULTS AND DISCUSSION

3.1 Tensile Test

The tensile properties are shown in Figure 5. The wire strength after drawing followed a wave form with peaks and valleys. The greatest differences between wire drawing passes occurred at the beginning of the wire drawing process. The UTS resulted in minor differences at the ends of wire drawing passes (Figure 5). The small difference in wire strength at the last pass can be attributed to severe cold working

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conditions and a constant stress distribution throughout the wire cross-section. The diameter of the copper wire drawn at the end of wire drawing had tensile properties that were similar to hard-drawn copper wires (ASTM B1)(13) (Figure 5). The average UTS values $(\bar{\sigma})$ between each wiredrawing pass were used to calculate frictional coefficients.

ASTM C10100 W drawn copper wires			
Wire diameter (mm)	UTS (MPa)	Strength difference	UTS $\bar{\sigma}$ * (MPa)
4.3	250	-	-
3.6	360	30%	305 ±104
3.2	280	22%	320 ±75
2.9	330	15%	305±47
2.6	415	20%	372.5±80
2.3	395	5%	405±19
2.1	445	11%	420±47
1.9	415	7%	430±28
1.7	435	5%	425±19
1.5	425	2%	430±9
1.3	450	5%	437.5±24

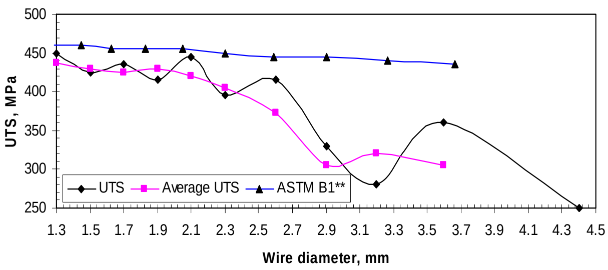

Figure 5. Results of wire tensile testing. * *denotes 80% confidence interval.*(13)

3.2 Wiredrawing Force/Stress Behaviour Under Different Lubrication Regimes

The two different lubrication conditions (Hydrostatic lubrication 35 MPa (HL-35 MPa) with Graphite powder lubrication (GL) and Without lubrication (WL)) were not different for different drawing forces and stresses for drawing dies smaller than 2.1 mm at a constant drawing speed of 8 mm/s (Figures 6 and 7). This suggested that a lubrication film does not form for wires drawn from 1.3 to 2.1 mm at 8 mm/s. Under these conditions, the frictional behaviour remained within the boundary lubrication regime because there were no significant differences in the force/stress when compared with wire drawing without lubrication (Figures 6 and 7).

For drawing dies between 2.3 mm and 3.6 mm, only oil lubrication under a pressure of 35 MPa produced significant lubrication effects (i.e., a decrease in the drawing forces/stresses) (Figures 6 and 7). For these dies, the lubrication regime changed to the mixed lubrication regime, before an oil film began to form for the 2.3 mm wire die. This occurred even at low wire drawing speeds. In fact, wire drawing peaked at 2.3 mm wire diameter and then remained constant (Figure 6). This is a typical characteristic for progression towards the hydrodynamic lubrication regime.(6) A hydrodynamic lubrication regime occurred for the wire 3.6 mm drawing die. For this die, a thick oil film may have formed under a pressure of 35 MPa at the wire/die interface. Thus, quasi hydrodynamic lubrication was possible for the low wire drawing speeds used in this work. The reduction in cross-sectional area and required wire drawing forces are indicated for each lubrication regime in Figure 6.

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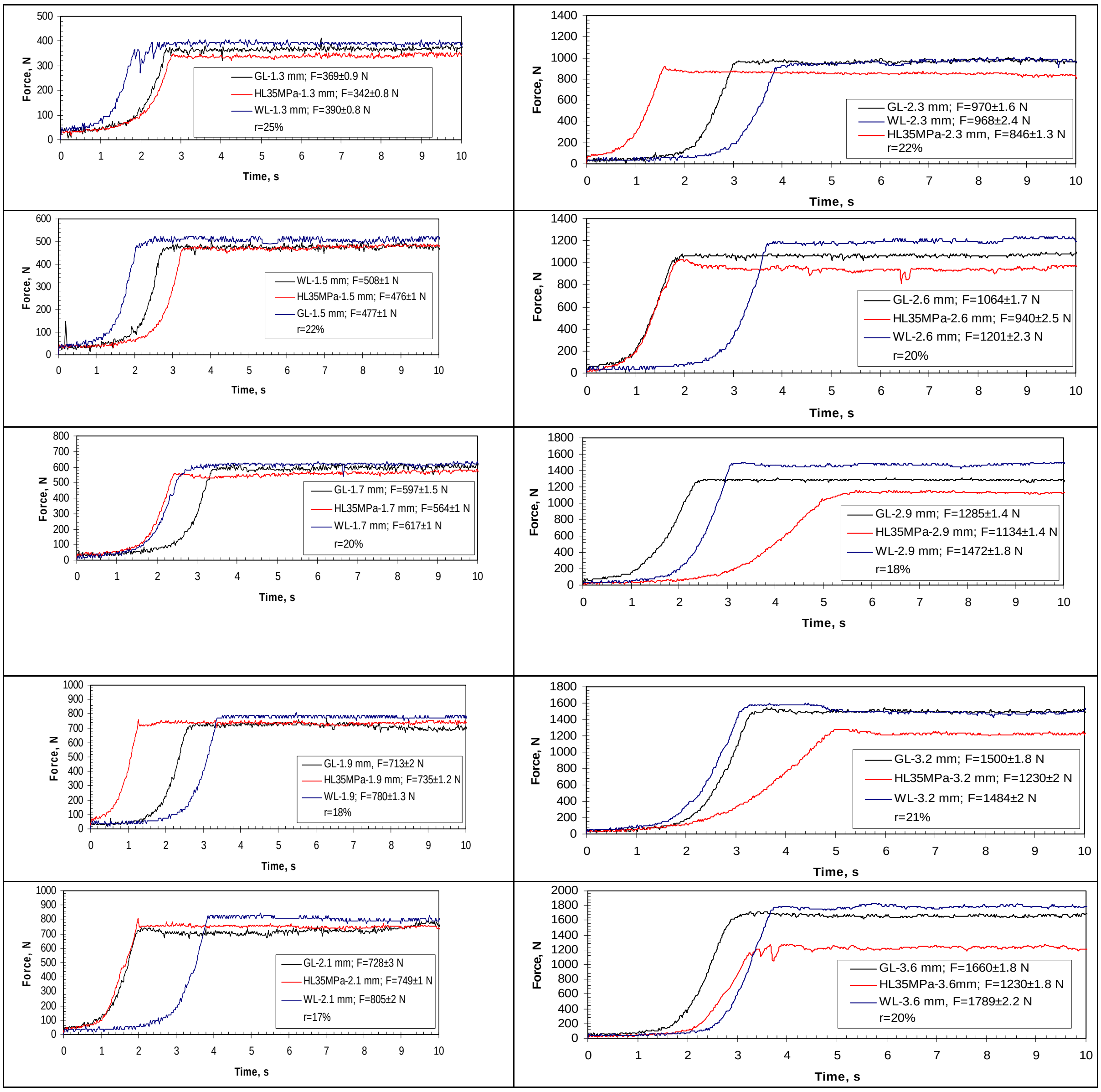

Figure 6. Continuous changes in wire drawing forces. *95% confidence intervals*.

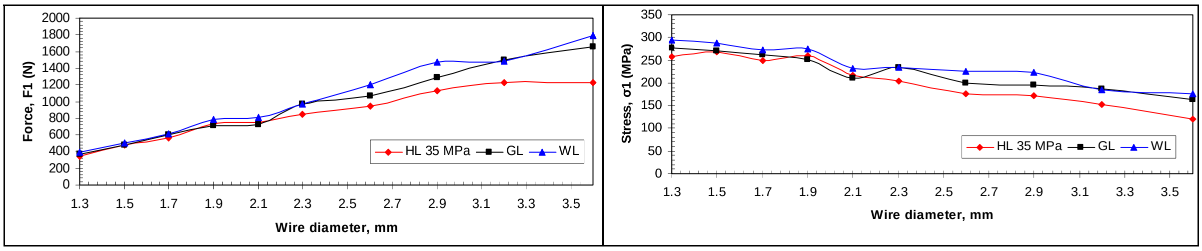

Figure 7. Profiles of the wire drawing forces and stresses under different conditions.

3.3 Frictional Behaviour for the Wire Drawing Dies

The wire drawing forces were constant at the drawing speeds shown above. In this work, the Stribeck parameter was modified by substituting the value of the rotation (ω) with the drawing speed (v) (8 mm/s) relative to the contact length at Zone II. The value of p $(\sigma_2 = \sigma_3)$ resulted from reactions on the die wall from the wire drawing stress (σ_1). The values for p were calculated in each wire drawing operation using

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von Mises' criterion. The yield stress $(\bar{\sigma})$ was the UTS average as shown in Figure 5. The applied hydrostatic pressure (35 MPa) was added into the value of p for each wire drawing die.
In practice, $\rho v/p$ cannot be related to the coefficient of friction for the entire wire drawing process because the geometry of the contact pressure changes among the ten wire drawing dies. In addition, the drawing speed was held constant at approximately 8 mm/s. We used the modified Stribeck parameter ($\rho v/p$) to relate the ten wire drawing dies and investigate changes in lubrication behaviour (Figure 8). Considering the data outlined above, the following lubrication regimes can occur: 1. boundary (dies from 1.3 mm to 2.1 mm); and 2. mixed/hydrodynamic (dies from 2.3 mm to 3.6 mm) (Figure 8).

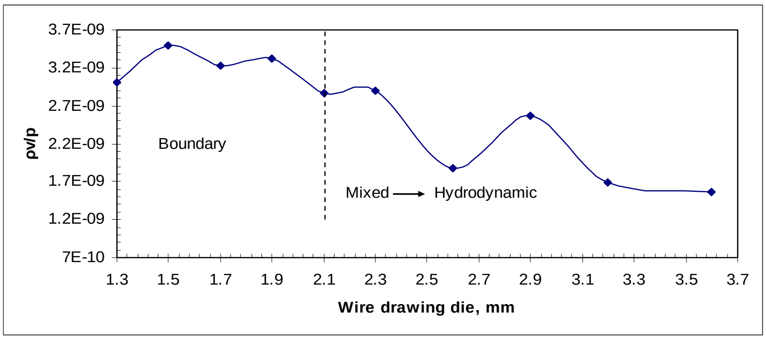

Figure 8. Bearing parameters ($\rho v/p$) related to the wire diameters.

3.4 Coefficient of Friction

The coefficient of friction between the wire and the drawn die was estimated using Equation 2 by substituting the redundant work (*Φ*) with $(1+r)$, where r is the area reduction:

$$\sigma_t = 2 \cdot \bar{\sigma} \cdot (1+r) \cdot (1+\mu \cot g\alpha) \ln\left(\frac{D_o}{D_f}\right). \qquad (5)$$

This is possible because the drawing area reduction in this work was approximately 20% and the die angle (*α*) was 8º. In this situation, the redundant work (*Φ*) should be approximately 1.5.[1] Equation (5) was used to investigate the coefficient of friction (*μ*) with and without lubrication, as follows:

$$\mu = \left[\frac{\sigma_f}{2(1+r)\bar{\sigma} \ln \frac{D_o}{D_f}} - 1\right] \frac{1}{\cot \alpha}. \qquad (6)$$

Figure 9 shows the distribution of the coefficients of friction with respect to the drawn wire diameter for the lubrication conditions applied in this work. The coefficient of friction followed a sine wave for all conditions tested. This was in accordance with the results from our previous studies.[9,11] This profile can be explained by the liberation of arrested dislocations that decrease the adherence at the wire/die interface even without lubrication. The coefficient of friction reached a maximum when many dislocations were arrested. Otherwise, even for low constant wire drawing speeds, wire diameters less than 1.9 mm decreased their contact area in Zone II, and thus

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should have locally increased their relative drawing speed. This might decrease the coefficient of friction even for severe cold-work. The wire drawing dies wear more rapidly for greater μ due to the higher amount of energy dissipation. Wire drawing dies of 1.3 mm, 2.6 mm and 3.6 mm will thus have more durability than the other wire drawing dies used in this work.

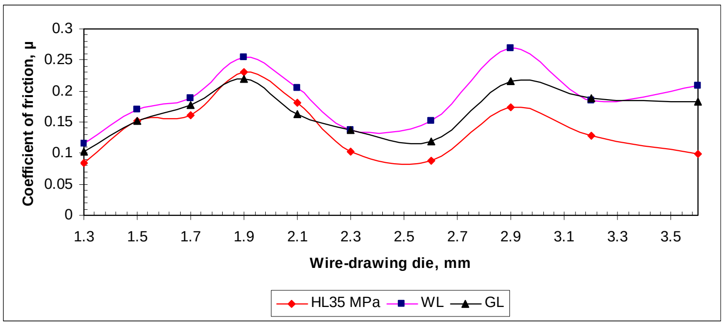

Figure 9. Variation of the friction coefficient for wire drawing under different lubrication conditions.

The coefficients of friction achieved in this work were in agreement with data reported by Wistreich[10] for copper wires from different die materials drawn at higher speeds (Table 1). This suggests that the our laboratory experiments performed at low speeds (8 mm/s) and high pressures (35 MPa) did not reduce the μ values, most likely because the sliding speed was not enough to reduce the friction. For the same reasons, the graphite powder lubricant did not improve the lubrication. Increasing the drawing speed by approximately four times had the same effect on the coefficient of friction for oil under a hydrostatic pressure of 35 MPa at 8 mm/s drawing speed (Table 1).

Table 1. Comparison of μ values obtained using our drawing speed of 8 mm/s at 35 MPa with those cited by Wistreich for copper wire[10]

Die	μ*	Lubricant**	Die material** die angle 3-8º	Speed (mm/s)**	μ**
3.6	0.08	Castor oil	Diamond	25.4	0.10
3.2	0.10		Carbide		0.10
2.9	0.20		Steel		0.15
2.6	0.10	Sodium stearate	Steel	30.5	0.02-0.03
2.3	0.10	-	-	-	-
2.1	0.20	-	-	-	-
1.9	0.22	-	-	-	-
1.7	0.17	-	-	-	-
1.5	0.15	-	-	-	-
1.3	0.09	-	-	-	-

The parameter $\rho v/p$ is very small for a wire drawing die of 3.6 mm in diameter, as is the coefficient of friction (Figures 8 and 9). The parameter $\rho v/p$ increases for wires drawn using 3.2 mm and 2.9 mm dies (Figure 8). This suggests that the lubrication regime was quasi hydrodynamic because there was only a small amount of oil leaking at Zone III. Thus, better lubrication and less wear should occur (Figure 10).

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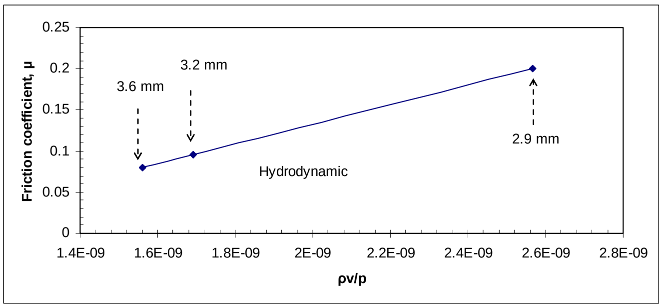

Figure 10. Bearing parameters ($\rho v/p$) and coefficients of friction for wire drawing dies of 3.6 mm, 3.2 mm and 2.9 mm.

4 CONCLUSIONS

The coefficients of friction for copper wires drawn from ten dies were estimated under two lubrication conditions (hydrostatic pressure – 35 MPa and graphite powder lubrication) and compared with copper wires drawn without lubrication using a bench wire drawing machine at 8 mm/s. These experiments are summarised as follows:

- the distribution of the UTS average profile $(\overline{\sigma})$ after each die pass was important for estimation of the coefficient of friction for copper wire; an increase in cold-work was observed and approximated to hard-drawn copper wires (ASTM B1) for the copper wires from 1.9 mm to 1.3 mm;
- transition between the lubricating regimes was easily identified. Boundary lubrication was dominant from 1.3 mm to 2.1 mm copper wires. This mode was easily identified because there was no differences in the wire drawing force/stress with or without lubrication. Mixed lubrication began from 2.3 mm under hydrostatic pressures of 35 MPa where the drawn copper wire force/stress decreased compared with graphite lubrication and no lubrication;
- graphite powder lubricant did not work properly for copper wire drawing at a speed of 8 mm/s;
- the modified Stribeck parameter was useful for evaluating the frictional behaviour of copper wires when considering difference between the stress/force of wire drawing;
- substituting of the redundant work Φ with the reduction area $(1 + r)$ was useful for estimation of the coefficient of friction. This could be used to predict the replacement of the wire drawing dies. Wire drawing dies of 1.3 mm, 2.6 mm and 3.6 mm in diameter had lower coefficients of friction. Therefore, the dies' wear was minimal in comparison with that of the other dies. Consequently, they will have more durability than other dies;
- the bearing parameter $\rho v/p$ related to the coefficient of friction for the wire drawing dies of 3.6 mm, 2.9 mm and 2.6 mm revealed the quasi hydrodynamic regime;
- the lubricants used in this work can be reused. These lubricants prevented seizure at the wire/die interface.

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