A WIRE DRAWING MACHINE DESIGNED FOR RESEARCH AND EXPERIMENTAL TEACHING OF MECHANICAL AND METALLURGICAL ENGINEERING COURSES

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Abstract. *The aim of this work is to present a wire drawing machine bench designed and built for research and experimental teaching of mechanical and metallurgical engineering courses. This machine is a redesign of the one already presented at CONEM 2000 (Mechanical National Conference in North and North-East Brazil). It is currently set up to enable students to measure the wire drawing force for two pulling wire velocities (7.8x10^{-3}m/s and 3.2x10^{-2}m/s), using different lubricants, and so to allow comparison with theoretical models. During tests, copper wire was progressively drawn in stages from an initial 3.2mm diameter down to 1.3mm. For each pulling wire, eight tungsten carbide die were used and chosen to produce succesive area reductions of approximately 20%., resulting in a total true deformation of approximately 180.2%.. The effect of lubrication and lack of it on wire pulling force was measured, using olive oil and graphite spray for comparison. Graphite spray facilitated the least wire pulling force, whereas olive oil proved to be inadequate as a lubricant. Load cell measurements (500kgf (~ 4.9 kN) capacity) confirmed that the force needed to draw larger diameter wire is greater than for smaller diameters. However, students can also observe that as the wire diameter decreases there is a corresponding increase in pulling wire stress. The method of uniform deformation energy was used to compare with load cell measurements.*

Keywords. *Laboratory; Engineering teaching, Wire drawing, Copper wire, Prototype.*

1. Introduction

Many Web sites and much software designed for engineering courses have been developed in several universities all over the world. However, little attention has been paid to the creation and evolution of experimental benching equipment within such centres, surprisingly so since the cost of purchasing experimental equipment and test machines from outside companies is very high. This is particularly so for state universities in under-developed countries. Further it is the consensus, that to obtain maximum understanding of the subject, students need to be able to combine theoretical study with practical experiment. This kind of training should provide the student the optimum foundation for a future professional life.

This equipment was primarily designed to enable the measurement and study of the pulling force on wire being pulled through wire drawing die. This equipment as set up accommodates two wire drawing deformation velocities: 7.8x10^{-3} m/s and 3.2x10^{-2}m/s. These are selected by changing the gearing on a mechanism of two gears, driven by a motor of three phases. Furthermore, students can change the lubrication of the drawing operation, and measure its affect on the wire pulling force.

The wire drawing force can be measured by a load cell (of approximately 500 kgf (4.9kN) maximum capacity) and then compared with theoretical models. Metallurgical and mechanical aspects can be changed by alteration of the parameters in the machine set up, e.g. lubrication, degree and velocity of reduction. Thus, mechanical or metallurgical engineering students can experiment and learn the practice of good quality wire drawing.

2. General features of the wire drawing process

Products made by wire drawing such as tubes, wires, cables, are used in various industries. For example: electric power station, telecommunications, electric appliance, heat treatment, automobile, aircraft, aerospace, etc. (Schaeffer and Britto, 1999).

In modern technology, the drawing process is used to manufacture composite (pultrusion process), memory alloys for medical and robotic application, and for superconductor wires.

The wire drawing operation is characterised by a decrease in cross section of the wires, bars or tubes as they undergo drawing through a die by means of a traction force at room temperature (cold work). Due to the stress state, i.e. uniaxial tensile stress and biaxial compression stress, the pull stress is less than the yield stress of the material being drawn (Dieter, 1988). This stress state produces a reduction in the cross sectional area of the material and therefore its diameter, and a correspoding increase in its length.

A frictional force acts at the metal/drawing die interface during the pulling of the wire. This force causes die wears, and consequent wire defects (e.g. staggered diameter, cup and cone fracture, die scratches, etc.).

Lubricant acts to reduce the frictional force at the metal/die interface and reduce the amount of damage. Therefore, selection of a suitable lubricant is an important engineering and economical factor.

In general, the choice of lubricant is determined by the die and wire material, the pressure at the die/wire interface, and the velocity and temperature of processing. Temperature is dependent on the viscosity of the lubricant (hydrodynamic effects). The extent of these effects is dependent on the capacity of the lubricating fluid to maintain a film between the two surfaces in relative motion. In addition, lubricants must not react chemically with the surfaces involved, as this would cause contamination (Martinez and Button, 1999).

Thus, the wire drawing machine as set up allows for the measurement of the wire drawing force and a comparison of the quality of the finished surface of the wire for different lubricants.

3. Steps made in the development of the wire drawing machine

Modifications had to be made to the prototype wire drawing machine shown at CONEM 2000 (Lima Filho et all, 2000) in order to improve the performance of operation. As a result, drawing forces can now be measured and compared with theoretical models. The project was sponsored by FUNDUNESP (Foundation for development of the UNESP-São Paulo State University). The funding was approxiamately U$1250.00 and was used to buy the following. Two shafts (SAE 52100) of diameter 25.0mm and length 2000.0mm, two linear roller bearings (LBE 25UU), one low carbon steel sheet (1/4”) to make the table, six rectangular low carbon profiles (40.0x60.0x3.0mm) 6000.0mm in length to make the frames, four wheels to facilitate transportation, 6000.0mm of plastic covered steel cable, a control panel, circuit breaker, ten drawing frames, copper wire cables, nuts, bolts and washers. The remaining components were made by recycling discarded materials. These were obtained from CESP (Electric Company of São Paulo State) and other places. The machine was built in the workshops of São Paulo State University (UNESP) Campus of Ilha Solteira, Department of Mechanical Engineering. Machining and welding were used during construction.

Figure 1 shows both the prototype equipment and the present modified machine. Assembly of the machine is outlined in the following steps (see Figures 1, 2, 3 and 4).

1. Connection and alignment of the three phase motor (3/4hp; 898.5rpm) to the gear reducer (15.5rpm);
2. Placement of the two frames. These support a third frame which is the base for the steel table (6.4x3101.0x442.0mm);
3. Installation of the lifting table. This is fitted with with four alignment columns made up of four tap bolts (M19x2.5 and 610.0mm length). This table holds the cable drum and two gears, all of which are supported by a shaft (SAE 1040) of diameter of 25.0mm and 260.0mm in length. The gears operate through a gear reducer linked by a driving chain. Two ball bearings (6205-2Z) are attached to the end of the shaft.
4. Bolting of the two bases onto the steel table. This table houses two parallel shafts (SAE52100) of 25.0mm diameter and 2000.0mm in length. The wire pulling system was made in three parts. 1. Two linear roller bearings (LBE 25UU) cased in an aluminium sleeve, which run along each arm of the parallel shaft. 2. A strip of commercially pure aluminium that joins the two rollers. 3. The draw head, which is bolted to this strip. The draw head is a low carbon steel strip, 4,0mm thick, “u” shape in cross section. Here the jaw (3/4”mandrel) and load cell with 4.9kN capacity and 0.5% (24.5N) precision are assembled. The jaw is bolted to the load cell, which is itself bolted to the low carbon steel strip draw head. This draw head is pulled by a plastic covered steel cable, 3.0mm in diameter, via a pulley at the draw head.
5. Installation of the plastic covered steel cable, 3.0mm in diameter. One end of this cable is fixed to the base frame and then runs parallel with the shafts (SAE-52100) passing around the draw head pulley and back, via three further pulleys, down to the cable drum.
6. Placement of the tungsten carbide die inside of the die holder. This is where the diameter of the wire is reduced. After each reduction the tungsten carbide die is substituted.
7. Installation of a control board and a digital strain indicator.

1. Prototype wire drawing machine.

2. Present wire drawing machine showing extensive modification.

Figure 1. The prototype and present wire drawing machine showed.

Figure 2 shows a schematic plan view of the present machine, indicating the main components. The wire drum capacity allows for approximately 2000.0m of test wire, enough to obtain approximately 60-70 readings from the digital deformation and displacement indicator (model TMDE). The average of these is calculated to give a reading confidence interval of 95%. The drawing force is calculated from the characteristic of the load cell, i.e. 4000μm/m is equivalent to 500kgf (~ 4.9kN). At the end of testing the circuit breaker sends a signal to the control panel to stop the draw head. The spring placed at the end of the circuit breaker acts as a shock absorber allowing for a slight recoil inherent in the inertia of the pulling system (motor, gear reducer and cable drum). This protection is needed to prevent damage to the circuit breaker.

The drawn wire is released from the jaw, the wire cut and the rotation of the motor reversed. Manually the draw head is pulled back and the operation starts again. Naturally, to obtain further reduction of the wire, the die must be changed. The die holder is inverted to recover the lubricant into the container and to substitute the wire drawing die. This is cased in a bronze sleeve to extract heat due to the drawing (Figure 2).

The preparation for the next drawing begins by filing the end of the wire. The wire can then be threaded through the hole of the die, clamped at the mandrel and a lubricant selected. This can be tested and chosen to facilitate minimum wire drawing force. Figure 3 shows ten wire drawing die, each designed to obtain a 20% reduction in crosss sectional area.

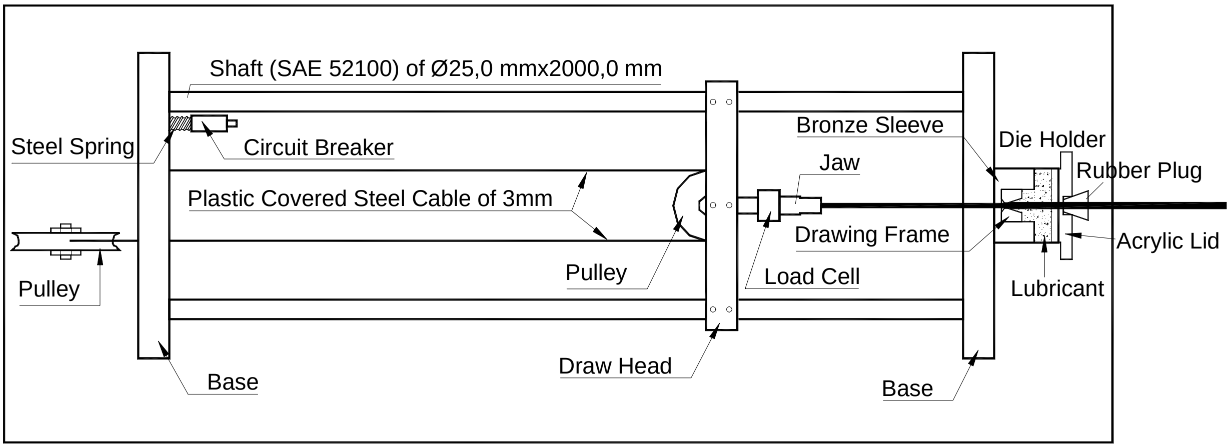


Figure 2. Schematic diagram showing plan view of the present wire drawing machine.

The next section describes the operation details of the wire drawing machine.

4. Preparation of the wire for drawing

Figure 4a shows the preparation of the wire tip prior to drawing. The diameter of the tip is first reduced by filing, and then a rubber plug seal is threaded over the wire and plugged into the acrylic lid. This is fitted with a rubber "o" ring seal. This assembly is mated up to the die holder (Figure 2). The wire is pulled through sufficiently to attach to the mandrel and with enough tension to ensure that the die holder will retain the lubricant oil. The lubricant can now be poured into the top of the die holder. The machine is then ready for working. Figure 4b shows the wire being drawn.

5. Theoretical models for calculating the wire drawing force and stress

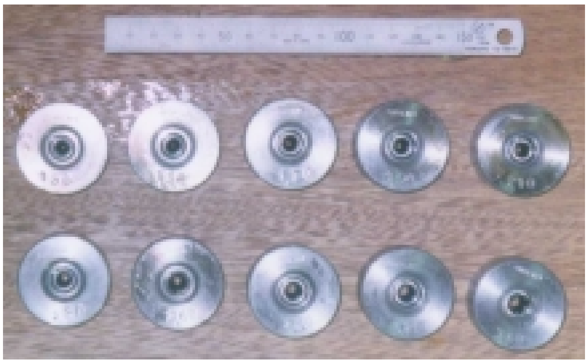
There are five methods available to calculate the wire drawing stress, which can be listed in increasing order of complexity (Dieter, 1988). These are: 1 uniform-deformation energy – calculates average forming stress from the work of plastic deformation, 2 slab - assumes homogeneous deformation, 3 slip-line field theory – permits point-by-point calculation of stress for plane strain conditions only, 4 upper and lower-bound solutions – based on the theory of limit analysis, uses reasonable stress and velocity fields to calculate the bounds within which the actual forming load must lie, 5 finite element – a technique called the matrix method allows large increments of deformation for rigid plastic materials, with considerable reduction in computational time (Lima-Filho et all, 1999). The two first methods are shown in Figure 5 for comparison, as they are the most used to solve problem of metal forming in engineering courses.

The uniform deformation energy method was chosen here, due its simplicity and practical nature. The predictions from this were then compared with the experimental data obtained from the load cell.

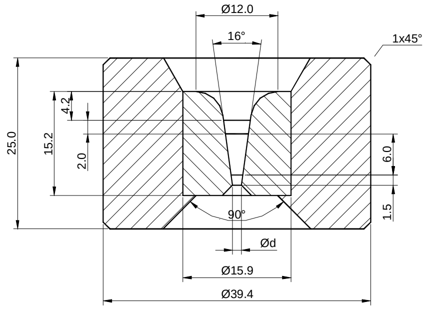
6. Results and discussion

6.1. Lubrication effects

Students can compare theoretical and experimental data. Table 1 shows the data obtained from the wire drawing, measured and calculated utilizing the uniform-deformation energy method (*vide* Figure 5) for copper, with initial diameter of 3.2mm and velocity of deformation of 7.8×10^{-3}m/s. This velocity was measured by timing the movement of a needle, positioned at the draw head, as it moves along a steel rule of 1000mm length (Figure 4b).



(a)



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]

(b)

Figure 3. Tungsten-carbide dies for wire drawing (a); and a cross section of the die showing the tungsten-carbide die cased with the SAE 1040 steel (b).

(a) The wire is filed to reduce its diameter.

(b) Wire being drawn.

Figure 4. Illustration showing the preparation of the wire for drawing.

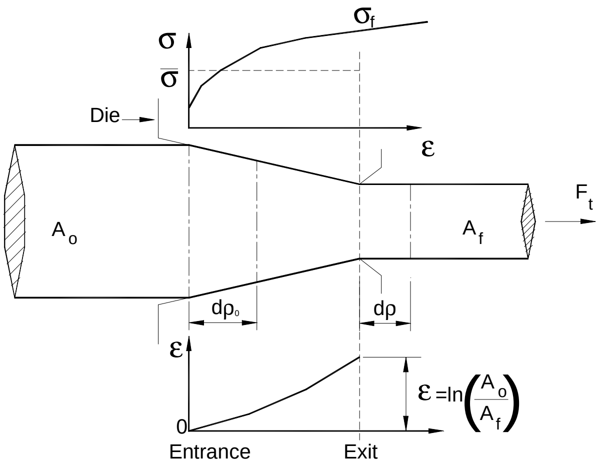
Both lubricants (olive oil and graphite spray) were used to compare drawing with and without lubrication. Naturally, the forces and stresses without lubrication are higher than with lubrication. However, the theoretical predictions (Method 1) are still less than the experimental values obtained from the load cell readings (Figure 6).

In practice, experimental data for olive oil as a lubricant showed no improvement on a non lubricated system (Table 1 and Figure 6). Clearly olive oil is not a suitable lubricant for this application. Graphite spray, however, did prove to be useful.

For all types of lubricant drawing forces are greater for larger diameter wire, but there is a point of convergence for small wire diameters where these forces are not so sensitive to the lubrication effect but more to the area of contact. As this reduces, the pulling force to draw the wire through the die reduces significantly (Figure 6).

6.2. Metallurgical effects

Conversely, drawing stress is greater for smaller wire diameters (Figure 7). The difference between the stress values for graphite spray and those calculated by Method 1 for copper wire for example, increases from a drawing frame of 2.3mm in diameter (see Table 1 and Figure 7) but tends to converge again at the smaller drawing frame diameter (1.3mm). These differences can be attributed to severe work hardening during the drawing process. As the copper structure (face centered cubic – fcc) is not severely hard drawn during the first three deformations, then the atomic planes slip relatively easy, occurring in few slip systems (atomic compact plane and direction). The difference in orientation of the slip elements such as direction and plane can change by rotation of the grain during deformation. As a result, new operative systems can be established and plastic deformation takes place by slipping. With further drawing, the work hardening increases quickly, giving rise to interaction between dislocations.



Uniform-Deformation Energy Method - Method 1

1. Internal energy (U_i)

$$U_i = A_0 \cdot d\rho_0 \int \bar{\sigma} \cdot d\varepsilon \,,$$

where $A_o, d\rho_o$, $d\varepsilon$ and $\bar{\sigma}$ are respectively initial area, displacement of the area A_o, increment of deformation, and the average yield stress $\left(\bar{\sigma} = \dfrac{k\varepsilon^n}{n+1}\right)$.

2. External energy (U_e)

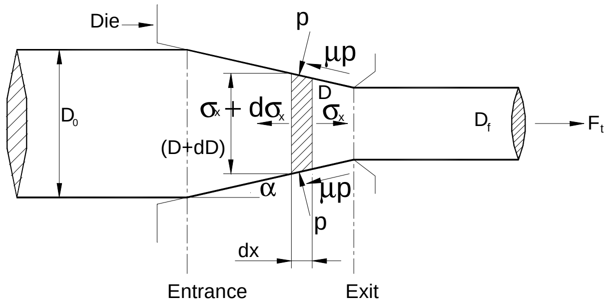
$$U_e = \sigma_t \cdot A_f \cdot d\rho \,,$$

$\sigma_t = \dfrac{F_t}{A_f}$, A_f and $d\rho$ are respectively the tensile stress on the wire, final area, and the length of wire drawn.

3. Making $U_i = U_e$, the stress (σ_t) or the force (F_t) of drawing is

$$\sigma_t = \frac{F_t}{A_f} = C \cdot \bar{\sigma} \ln\left(\frac{D_0}{D_f}\right)^2 ,$$

The magnitude of the average yield-stress term $\bar{\sigma}$ can be different using the von Mises' yield criterion, resulting in $\bar{\sigma} = \dfrac{2}{\sqrt{3}}\sigma_o$, where σ_o is the yield stress or yield strength, [Dieter, 1988].
$C \approx 1.6$ is a constant value due to the work to overcome the friction at the metal/tool interface and the redundant work [Al-Qureshi, 1991].



Slab Method - Method 2

1. Forces originated by longitudinal stresses with x increasing positively to the left:

$$\left(\sigma_x + d\sigma_x\right)\frac{\pi}{4}\left(D + dD\right)^2 - \sigma_x \frac{\pi}{4} D^2 \,.$$

2. Force originated by pressure applied by drawing frame at interface wire/drawing frame

$$p\left(\pi D \frac{dx}{\cos\alpha}\right)\operatorname{sen}\alpha \,.$$

3. Force originated by friction stresses at interface wire/drawing frame

$$\mu\, p\left(\pi D \frac{dx}{\cos\alpha}\right)\cos\alpha$$

4. Equilibrium condition of forces in the x direction

$$\frac{\sigma_x D\, dD}{2} + \frac{D^2 d\sigma_x}{4} + p\, D dx\, tg\alpha + \mu p\, D\, dx = 0 \,.$$

5. Equilibrium condition of forces in the x direction making geometric relation and neglecting the infinitesimal products

$$Dd\,\sigma_x + 2\left[\sigma_x + p\left(1 + \mu\, ctg\alpha\right)\right]dD = 0 \,.$$

6. Finding a relationship between σ_x and p considering the equilibrium of forces in y direction and applying the Tresca' yield criterion

$$\sigma_t = \bar{\sigma}\frac{1+B}{B}\left[1 - \left(\frac{D_f}{D_0}\right)^{2B}\right], B = \mu\, ctg\alpha$$

μ is the friction coefficient and α is the angle of the drawing frame.

7. Force of drawing (F_t)

$$F_t = \phi A_f \bar{\sigma}\frac{1+B}{B}\left[1 - \left(\frac{D_f}{D_0}\right)^{2B}\right],$$

ϕ is the redundant work ≈ 1.2.

Figure 5. Schematic drawing of the geometry and the stresses involved in the drawing processing by the Uniform-Deformation Energy (Method 1) and Slab (Method 2) methods.

Furthermore, the stacking fault energy (SFE) for copper (~80erg/cm^2) (Dieter, 1988) produces a wide separation between partial dislocations and therefore tends to inhibit cross slip, limit movement by dislocation to just one slip plane and show a deformation substructure of banded, linear arrays of dislocation. Consequently, copper wire work hardens very fast and twins easily during the annealing (Dieter, 1988). However, for high deformation, irregular sub-grains can be formed by screw dislocations undergoing cross slip and causing a decrease in their deformation energy.

Table 1.Comparison of experimental and theoretical values of drawing force and stress, using load cell data and Method 1 calculations (see Figure 5).

Variation in diameter, mm		Experimental data, 1. Without lubrication; 2. Olive oil; 3. Graphite spray.						Theoretical data, Method 1, see Figure 5.	
Start (D_o)	End (D_f)	(F_t) Force (N)*			(σ_t) Stress (MPa)*			Force** (N)	(σ_t)** (MPa)
		1	2	3	1	2	3		
3.2	2.9	1309.2±4.9	1273.9±6.9	1119.0±5.9	198.2±0.7	192.9±1.0	169.4±0.9	1056.8	160.0
2.9	2.6	1222.0±4.9	1164.1±7.8	1030.7±7.3	230.2±0.9	219.3±1.5	194.1±1.4	953.4	179.6
2.6	2.3	1045.4±6.9	1018.9±2.0	912.3±9.8	251.6±1.7	245.2±0.5	219.6±2.4	837.6	201.6
2.3	2.1	847.3±2.0	815.9±10.8	723.8±9.8	244.6±0.6	235.6±3.1	209.0±2.8	524.0	151.3
2.1	1.9	800.3±2.0	770.8±10.8	679.9±16.6	282.3±0.7	271.9±3.8	239.8±5.9	477.2	168.3
1.9	1.7	687.4±2.0	678.6±4.9	591.4±10.5	302.8±0.9	299.0±2.2	260.6±4.6	424.5	187.0
1.7	1.5	541.3±2.9	539.3±1.0	485.4±5.1	306.3±1.6	305.2±0.6	274.7±2.9	371.8	210.4
1.5	1.3	417.7±1.0	409.0±2.9	363.8±4.1	314.7±0.8	308.1±2.2	274.1±3.1	322.8	243.2

**95% confidence interval; ** The σ_o values were based on nominal tensile strength for hard-drawn copper wire according to wire diameter. ASM Handbook, vol.2 pp. 253.* $\bar{\sigma} = 2/\sqrt{3}\,\sigma_o$.

The theoretical values of drawing stresses (σ_t) using method 1 and shown in Table 1 are consistently and appreciably lower than the uniaxial flow stress values taken from the ASM Handbook (vol.2 pp. 253. Wire diameter 3.2mm – 440MPa; 2.9mm and 2.6mm – 445MPa; 2.3mm – 450MPa; 2.1mm and 1.6mm – 455MPa; 1.5 and 1.3mm – 460MPa).

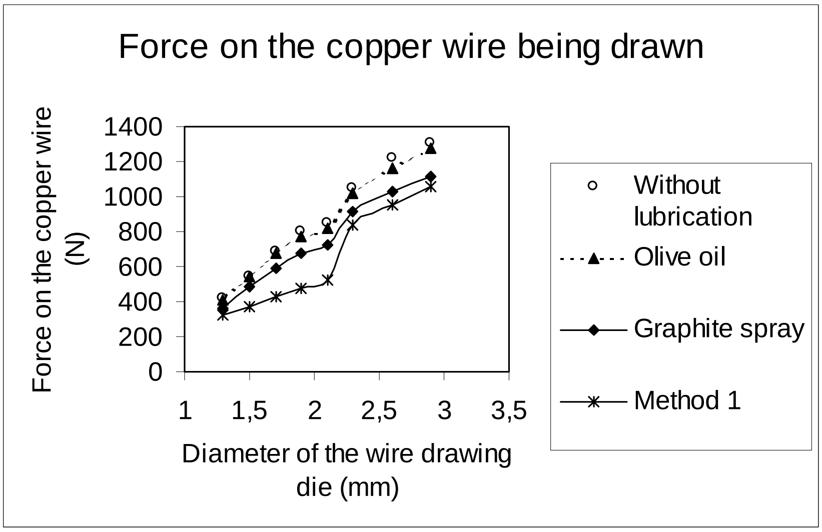


Figure 6. Variation achieved of the wire drawing forces for copper wire.

6.3 Features of the drawn copper wire

Figure 8 shows the reductions made in copper wire drawn from an initial diameter of 3.2mm down to 1.3mm, performing a true deformation $(\varepsilon = \ln A_o/A_f)$ of approximately 180.2%. To obtain this degree of deformation, it was necessary to pull the copper wire in stages using eight succesive drawing frames.

The maximum power $(P = FV)$, where F is the load (N) and V (m/s) the pulling speed, was $P = 1309.2x7.8x10^{-3}\,Nm/s = 10.2W$, occurring in the first reduction without lubrication (see Table 1).

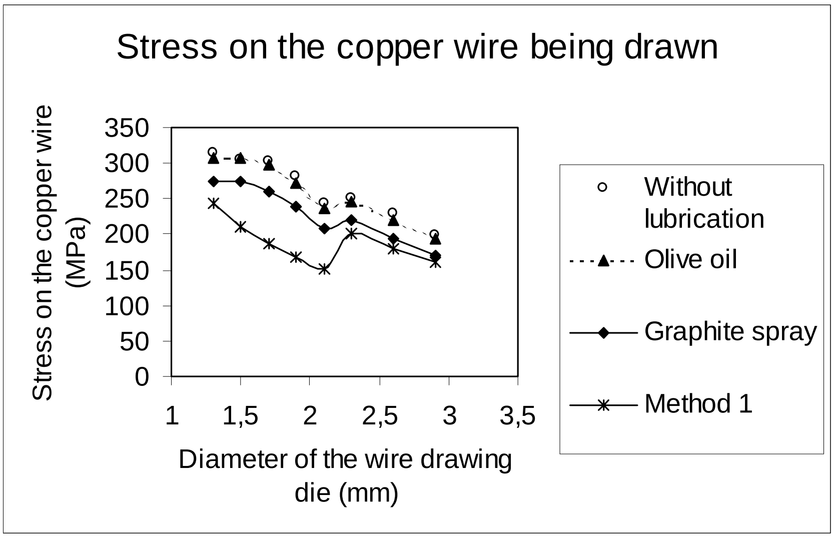


Figure 7. Variation achieved of wire drawing stresses for copper wire.

7. Conclusion

The original objective of this project has been achieved: the wire drawing machine currently allows the study of lubrication, metallurgical effects, and the observation of features of drawn wire, and consequently enhances the efficacy of teaching of mechanical and metallurgical courses. With this experience, a future development can be envisaged. Instead of using a system of pulley and steel cable to pull the wire, a new wire drawing machine is proposed that would use a spindle/screw driven by a self-reducing motor, allowing automatic control of the velocity of the draw head, together with an automated data acquisition system to simplify the whole operation.

Figure 8. Variation of the diameter of the copper wire obtained from the wire drawing process. The wire starts with diameter of 3.2mm and ends with a final drawing frame diameter of 1.3mm.

8. Acknowledgement

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