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Reduction of Friction During Wire Drawing by Electrode Control

Y.-Y. Su and M. Marek

In wire drawing, the wire is drawn through a series of dies sprayed with or immersed in an emulsion lubricant. The surface conditions of the wire play a vital part in the mechanism of lubrication, and the conditions can be affected by electrochemical parameters.

The electrochemical behavior of copper in selected emulsions was studied, and laboratory friction as well as pilot plant tests were performed. Reduction of friction was detected at various potentials depending on the lubricant composition. Surface quality of the wire was improved by the electrode control.

Keywords
drawing, electrode control, emulsion, friction

1. Introduction

The idea that friction may depend on the electric condition of wet surfaces in contact was suggested by Edison in 1877 (Ref 1). More recently, Rehbinder and Wenstrom developed a relation between friction and potential based on a change in surface energy with a change in the electrode potential (Ref 2). Bockris and Sen suggested that the frictional force is reduced when double-layer repulsion exists (Ref 3). Bowden found a relationship between frictional force and the interfacial potential for platinum in dilute sulfuric acid (Ref 4).

Several friction investigations involving electrode potential were reported in the past decades (Ref 5-8). The studies confirmed that friction can be reduced in one-phase electrolytes by proper potential control. The recent work described by Brandon et al. (Ref 9-10) demonstrated potential-dependent lubricant-film formation and static friction in aqueous solution of octanoic acid neutralized with sodium hydroxide.

In wire drawing, friction occurs between the wire and the dies. An emulsion lubricant (two-phase electrolyte) is sprayed on the wire, or the wires are immersed in it to reduce friction. Electrochemical reactions occurring on the wire exposed to the emulsion may affect the surface condition of the wire, which in turn determines the adsorption ability of fatty acid or other polar substances on the wire surface. The requirement of adsorption of fatty acid on the oxide layer of the wire surface for proper lubrication was postulated by Bowden and Tingle (Ref 4, 11).

The objective of this research was to determine if electrode control can be used to affect lubrication in wire drawing of copper and to investigate the mechanism. First the electrochemical behavior of copper in selected emulsion lubricants was evaluated. Based on these studies, laboratory friction tests were performed. To determine the friction-potential relationship under dynamic conditions, pilot plant tests were then conducted, and the quality of the wire surface was evaluated.

Experimental Methods

Oxygen-free high conductivity (OFHC) copper was used in the electrochemical tests. The as-received OFHC copper rod (1/2 in. diameter) was cold rolled to a thickness of 8 mm, and then fully annealed at 400 °C for 30 min. The annealed plate was then subjected to 50% reduction of area, and specimens 10 × 10 mm were cut. Each specimen was attached to a stud, cast in epoxy, metallographically wet polished on silicon carbide papers through 2400 grit, ultrasonically cleaned in water and methanol, and air dried.

Commercial emulsion lubricants used in copper wire drawing were collected from different sources. Several emulsion concentrations were employed for the electrochemical tests, and a 3% emulsion concentration was chosen for most of the further experimental studies. In most tests, the temperature of the emulsion lubricant was controlled at 40 °C. Different temperatures of emulsion lubricant were also used to investigate the influence of temperature on the electrochemical behavior.

The electrochemical tests were performed using a standard 3-electrode, temperature-controlled cell, and a microproces-

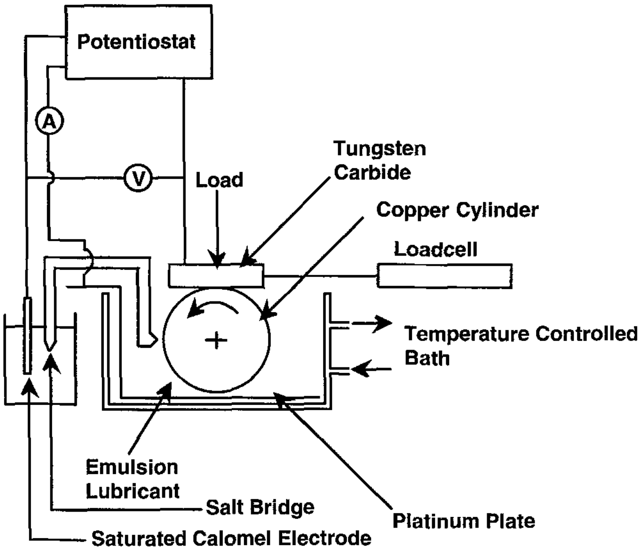

Fig. 1 Schematic illustration of the laboratory friction test setup.

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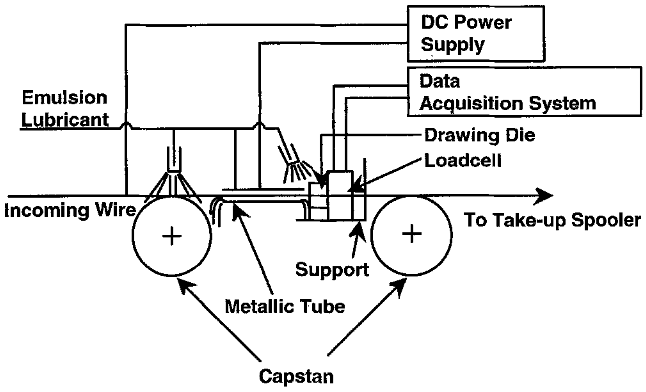


Fig. 2 Schematic illustration of electrode-control for friction reduction in wire drawing.

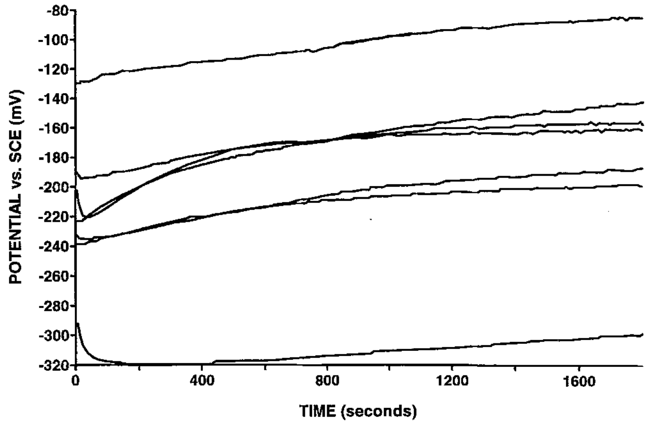


Fig. 3 Open-circuit potentials of copper in selected commercial emulsion lubricants at 3% concentration and 40 °C.

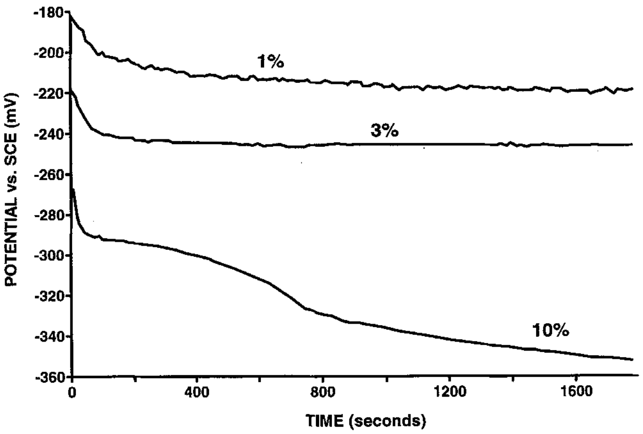


Fig. 4 Open-circuit potentials of copper in a commercial emulsion lubricant at 40 °C for different concentrations.

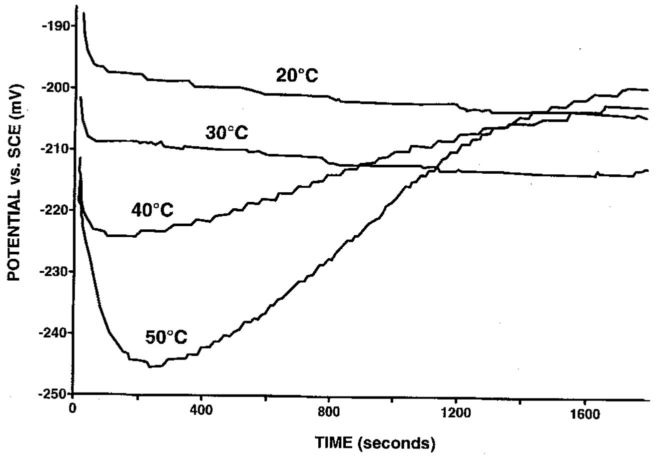


Fig. 5 Open-circuit potentials of copper in a commercial emulsion lubricant at 3% concentration for different temperatures.

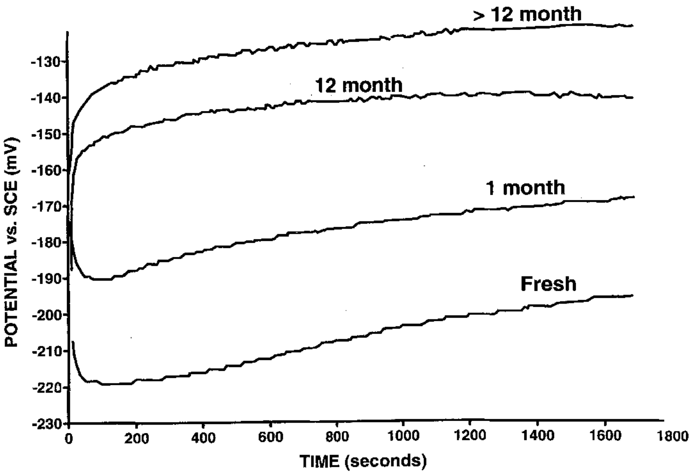
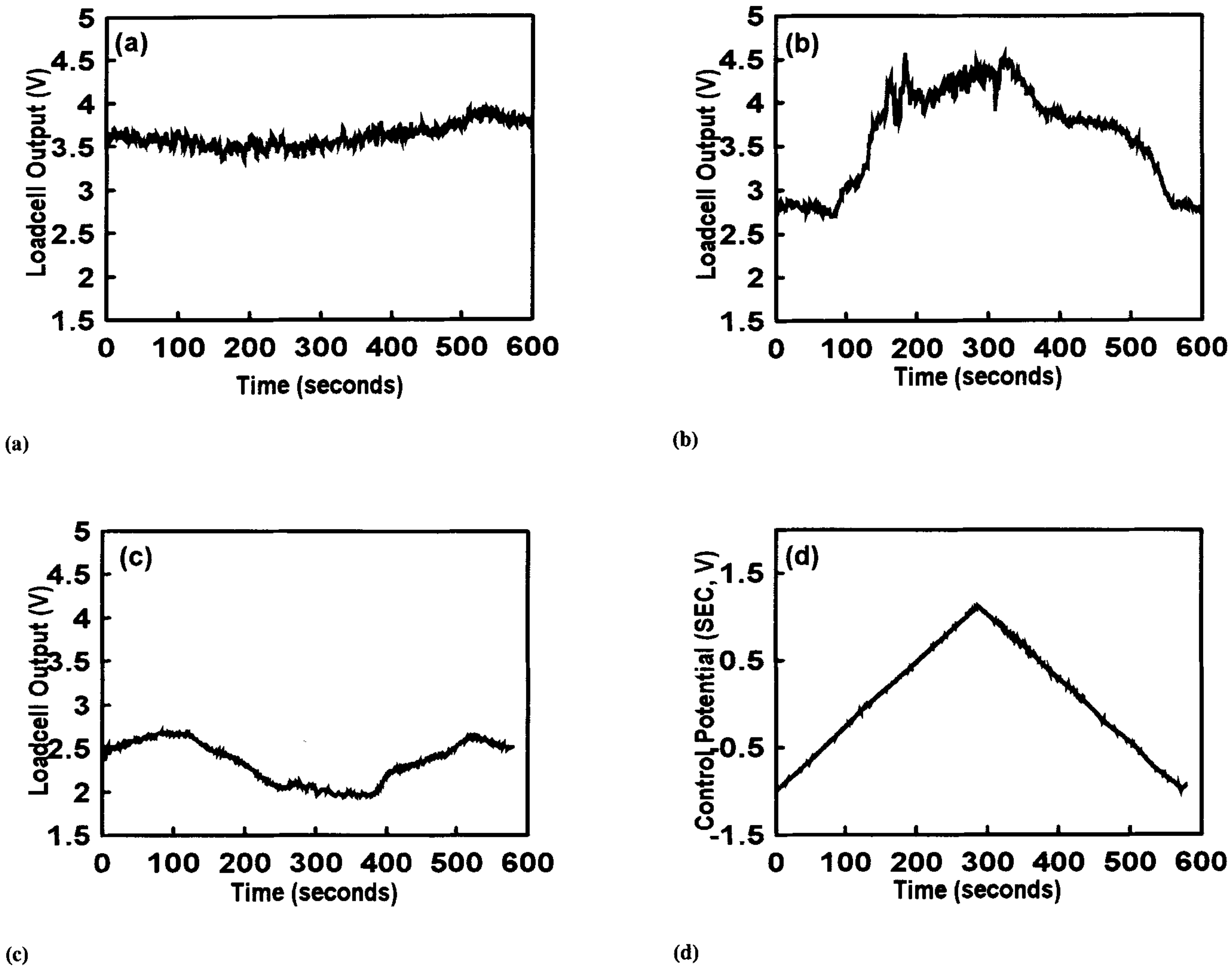


Fig. 6 Open-circuit potentials of copper in a commercial emulsion lubricant at 40 °C and 3% concentration for different lubricant aging times.

sor-controlled electronic potentiostat, Model 351 (EG&G Princeton Applied Research, Trenton, NJ). The open-circuit potential (corrosion potential) of copper was measured with respect to a reference electrode (saturated calomel electrode, SCE), and recorded as a function of time. The solution was aerated to simulate conditions in wire drawing, and measurements were performed at different concentrations, temperatures, and periods of thermal aging.

A laboratory test was set up using tungsten carbide pressed against a rotating copper cylinder in the presence of an emulsion lubricant to examine the effect of applied voltage on friction. The copper cylinder was rotated by an electric motor at 1750 rpm. A platinum sheet served as an auxiliary electrode in a temperature-controlled cell, and a saturated calomel electrode (SCE) was used as reference. The setup is shown schematically in Fig. 1. The potential of copper was varied using an electronic potentiostat, which applied appropriate direct current (dc) between the copper cylinder and the auxiliary elec-



(a) (b) (c) (d)

Fig. 7 Effect of electrode potential on friction for different types of emulsion lubricants. (a) Potential-independent emulsion. (b) Positive potential-dependent emulsion. (c) Negative potential-dependent emulsion. (d) Control potential sweep curve.

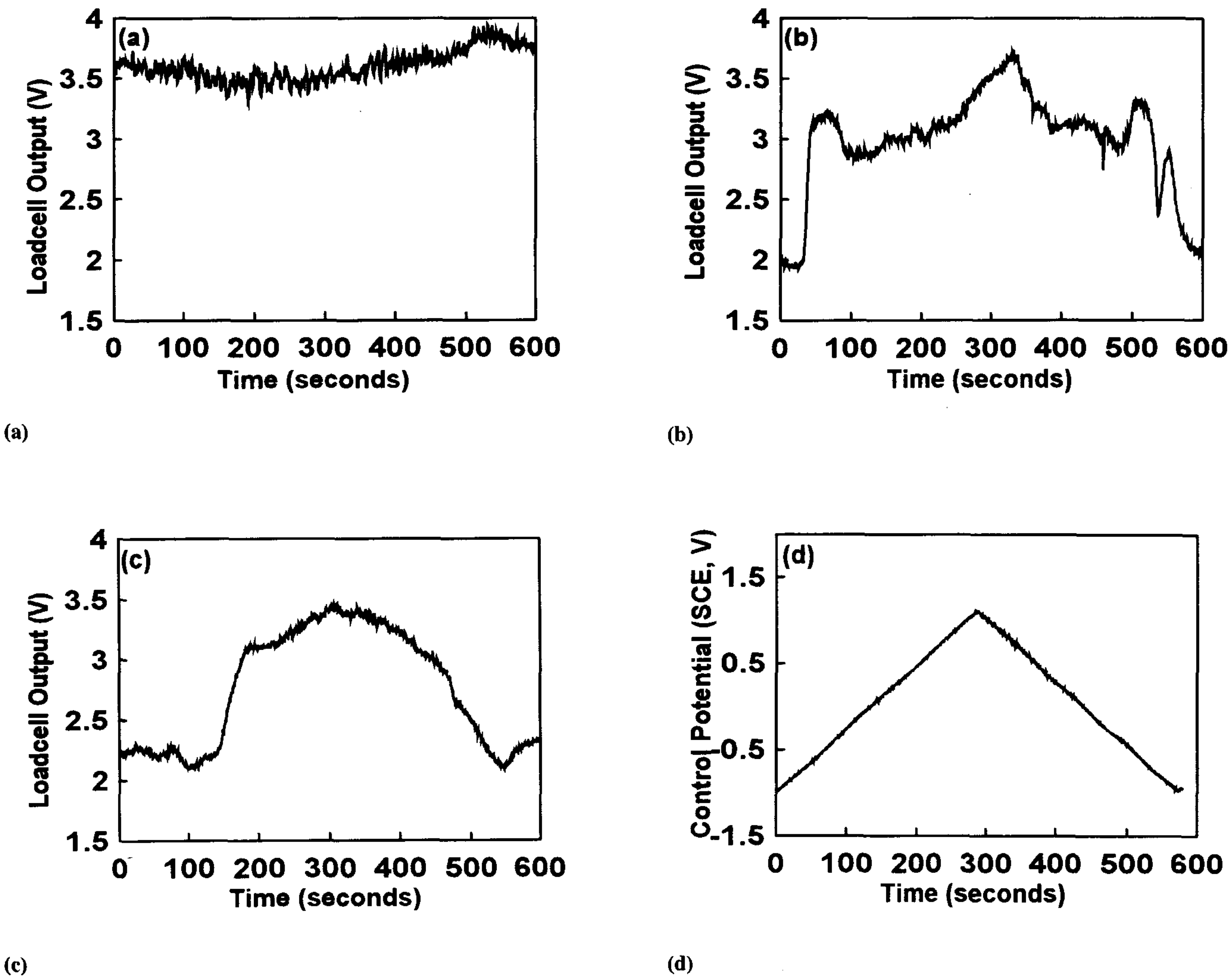
trode. The potential was swept from a value negative to the open-circuit potential to a positive value and then back to a negative potential at a scanning rate of 10 mV/s. The frictional force, with and without electrode control, was continuously measured using a load cell and recorded.

Further tests were conducted using an industrial wire drawing machine. A tubular auxiliary electrode was fitted around the wire in front of the drawing die, and the emulsion lubricant was flown through the tube, as shown schematically in Fig. 2. DC voltage was applied between the wire and the auxiliary electrode, and the pulling force on the die was continuously monitored and recorded using a load cell. A scanning electron microscope, Hitachi S-800 (Hitachi Instrument, Inc., Danbury, CT) operating at 15 kV was used to evaluate the wire surface quality of the drawn wire.

The copper wire surface, including the residual film after deformation in the lubricant, for open-circuit conditions as well as electrode control, was examined by electron spectroscopy for chemical analysis (ESCA). Binding energies of O_{1s} and Cu_{2p} were measured using an Al target X-ray source operating at 10 kV and 22 mA. Standard samples were prepared to distinguish the binding energies and to determine the possible chemical reactions. Argon ion sputtering operating at 4 keV and 4×10^{-7} torr was used to remove the top oxidized layer and perform depth profile examinations for the residual and reacted lubricant film on the copper surface.

Results

The open-circuit potentials of seven selected commercial emulsion lubricants, freshly prepared, measured at 40 °C and 3% concentration, are shown in Fig. 3. A wide range of open-circuit potential values was observed. Figure 4 shows the effect of emulsion concentration on the open-circuit potential at 40 °C for a selected fresh emulsion. The results indicated more active conditions for the 10% concentration of emulsion than for lower concentrations.



(a) (b) (c) (d)

Fig. 8 Modification of the potential-friction relationship by changing concentration of a polar substance. Concentration of polar substance is increasing from (b) to (c). Control potential sweep curve is shown in (d).

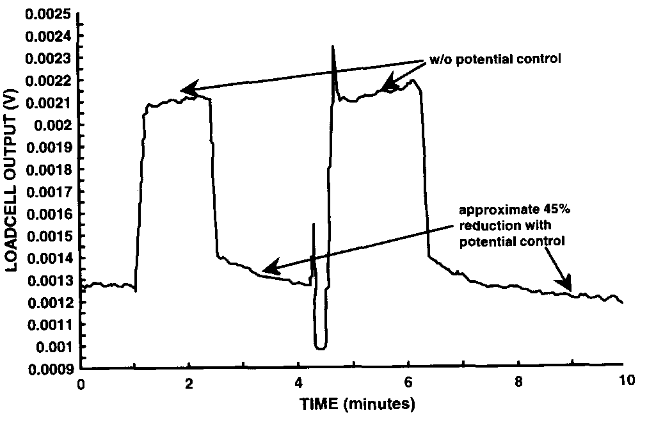
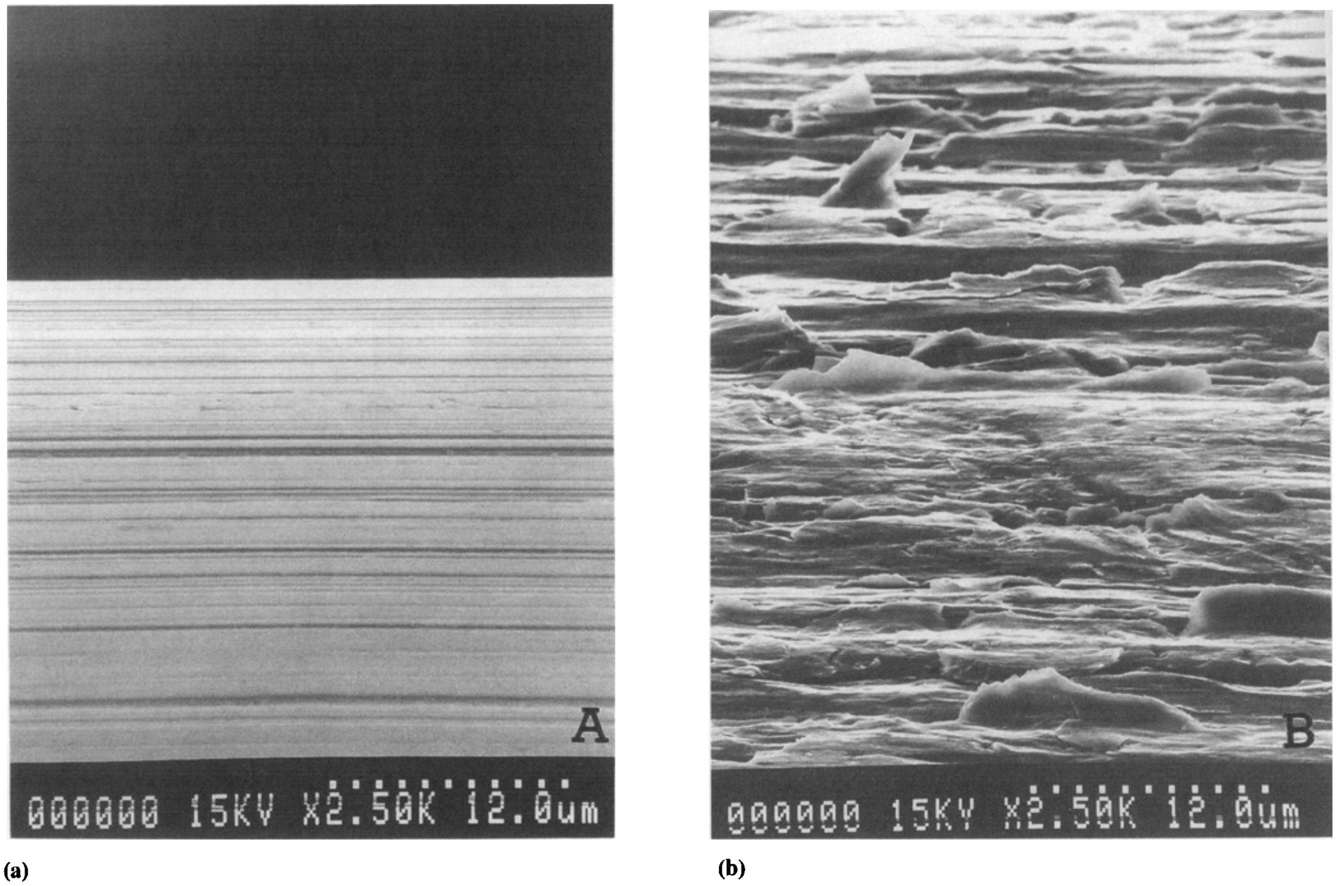


Fig. 9 Load cell output, proportional to the friction force, during an industrial wire drawing test, showing 45% reduction of friction by electrode control.

The influence of temperature on the open-circuit potential for a selected fresh 3% emulsion is shown in Fig. 5. Copper surfaces became more active initially as they reacted with the emulsion. For temperatures of 20 and 30 °C, the potential remained virtually constant for the rest of the test period. At 40 and 50 °C, after the initial activation, the open circuit potential increased and stabilized, indicating formation of a passive film.

The aging of emulsion lubricant by the synergistic effect of thermal and mechanical forces had a significant effect on the open-circuit potential. Figure 6 shows that the open-circuit potential increased with aging of the solution, indicating a more effective passivation of the copper surface. In a fresh solution and for short aging times, copper first activated before turning passive. However for longer periods of aging, passivity was generated immediately after the exposure, and the open-circuit potential quickly stabilized.

In the simulated friction test, the load was applied radially to the copper cylinder, and the coefficient of friction, μ, was calculated as follows (Ref 12):



(a) (b)

Fig. 10 SEM micrographs of surfaces of wires drawn (a) with electrode control and (b) without electrode control.

$$\mu = f/N \quad \text{(Eq 1)}$$

where N is the normal force and f is the shear force. Since the normal force was constant, the shear force, measured by the load cell, was linearly proportional to the coefficient of friction. A higher output signal from the load cell corresponded to higher friction.

Results of friction measurements and the effect of electrode control are shown in Fig. 7. For some emulsion lubricants, friction was significantly reduced at specific potentials. Lubricants exhibiting potential-independent friction could be modified by adding a specific polar substance for friction to make them potential-dependent, as shown in Fig. 8. The potential-dependent range widened as the concentration of the polar substance increased.

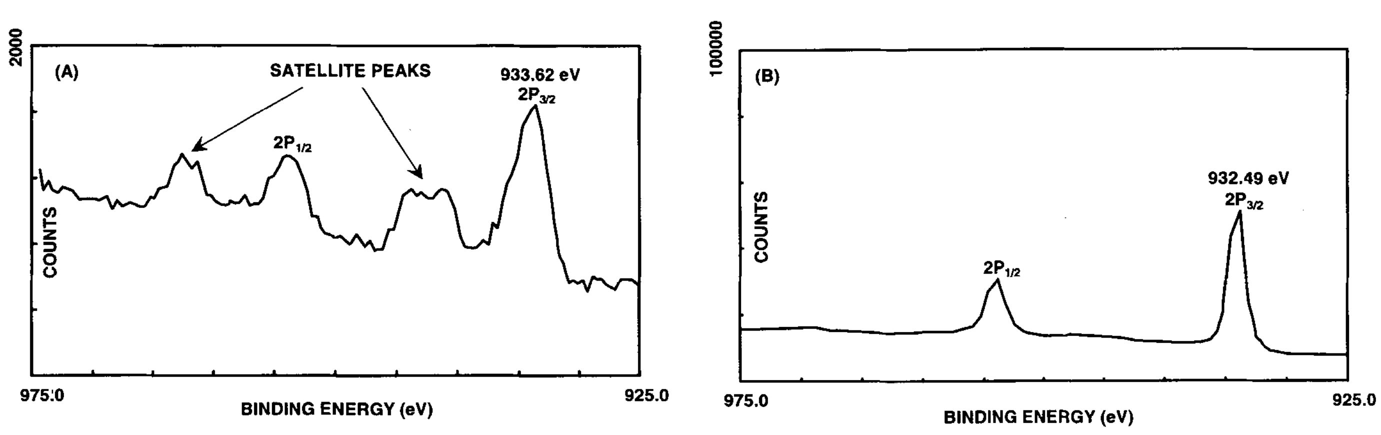
Based on the laboratory results, electrode-control was tested in an industrial drawing test stand. Results for fine wire drawing are shown in Fig. 9. Reduction of friction as high as 45% was observed in typical tests when a control voltage was applied between the copper wire and the auxiliary electrode.

Surface qualities of drawn wires, with and without electrode control, are compared in Fig. 10. Under electrode control, the wire surface was found to be exceptionally smooth with only minor parallel scratches. Fines, check marks, slivers, folds, and deep scratches were found on wire surfaces drawn under conventional open-circuit condition.

Results of the ESCA analysis are shown in Fig. 11 and 12. The Cu_{2p} peaks associated with satellite peaks on the top layer of copper surface, shown in Fig. 11, identified the top layer as CuO (Ref 12-14). After sputtering, the $Cu_{2p3/2}$ occurred at a binding energy at 933.44 eV in the absence of satellite peaks, indicating that the remaining layer was Cu_2O. This result was obtained for both electrode-control and open-circuit conditions. The Cu_2O layer was thicker, however, for electrode control, judged from the depth profile examination.

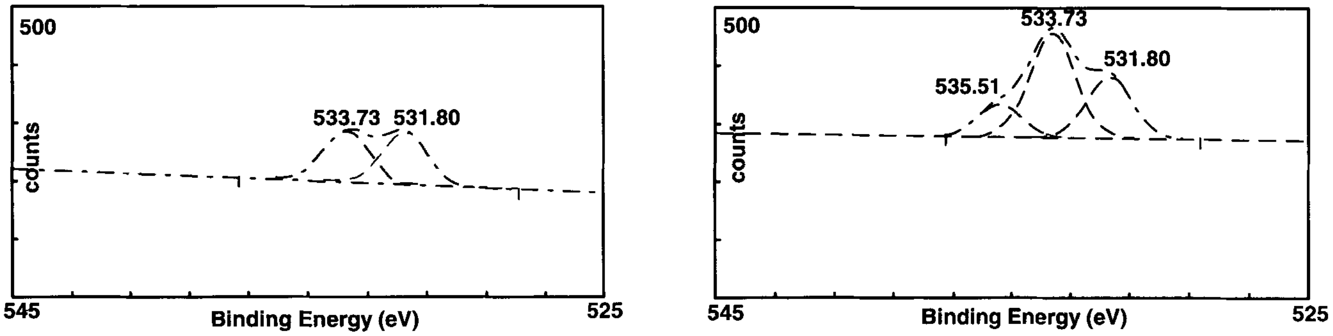
For copper surface obtained with electrode-control, the O_{1s} spectrum showed high energy peaks after a top layer was removed by sputtering (Fig. 12). Using C_{1s} binding energy at 284.50 eV for reference, the spectrum was deconvoluted into three distinctive peaks: 531.80, 533.73, and 535.51 eV. These energy peaks were observed even after a sputtering period of 720 s. The O_{1s} spectrum under open-circuit condition was resolved into 531.80 and 533.73 eV.

The 531.80 eV peak is related to the formation of copper oxide (Ref 13). The peak at about 533.73 eV appears as a result of a reaction of copper oxide with water (Ref 14); it also seems to be indicative of the formation of a carbohydrate compound re-



(a) (b)

Fig. 11 Results of ESCA analysis showing binding energies for copper in surface layers of a drawn wire. (a) Top layer of CuO. (b) Underlayer of Cu_2O.



(a) (b)

Fig. 12 Results of ESCA analysis showing binding energies in the O_{1s} spectrum for the residual lubricant film on a drawn copper wire. (a) Conventional wire drawing. (b) Wire drawing with electrode control.

lated to the presence of a surfactant since the energy varied slightly with the chemical nature of the surfactant. The 535.51 eV peak seldom appeared under open-circuit condition; it was detected on surfaces obtained under electrode control and appears to be due to a chemical interaction between copper oxide and a fatty acid.

Discussion

The force required to pull the wire through a drawing die formulated as follows (Ref 15):

$$P = \sigma_f(1 + \mu\cot\alpha)\varphi\xi \qquad \text{(Eq 2)}$$

where σ_f is the flow stress, α is the die half angle, ϕ is the index of inhomogeneity of deformation, ξ is the strain, and μ is the coefficient of friction.

For a given reduction and a particular die, the pull force is directly proportional to the coefficient of friction. For boundary lubrication, adsorption of fatty acid depends strongly on the presence of an oxide layer on the asperities of copper wire surface before and during the deformation process (Ref 4, 11). It has been demonstrated theoretically that the activation energy required for adsorption of polar substances and the coverage of organic polar substances on the metal surface are a function of the potential (Ref 16-18). The effectiveness of electrode control in reducing friction can be attributed to lowering of activation energy for adsorption and increasing the coverage of substances required for lubrication.

Results of the friction tests indicate that electrode control can improve lubrication and prevent direct contact between a tool and the worked metal. In wire drawing, poor lubrication results in high friction (Ref 4, 19-22) and damage to the wire surface. Reduction in friction by electrode control has a potential for energy saving (Ref 23) and reduction of wire drawing defects.

Conclusion

- Dynamic friction tests, including laboratory and pilot plant wire drawing tests, have demonstrated potential-dependent friction in commercial emulsion lubricants.
- Reduction of friction by electrode control depends on adsorption of fatty acid on oxidized copper surface as well as presence of polar substances.
- For application of electrode control in industrial wire drawing, the optimum electrode conditions must be determined based on the type of the lubricant and other conditions in the plant.
- Improvement of lubrication by electrode control in wire drawing can result in energy saving and improved surface quality of the product.
- In principle, electrode control of friction and lubrication can be applied to metals other than copper and processes other than wire drawing.

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