# Effects of Inclusion on Inclusion Front Tensile Stress During Copper Shaped-Wire Drawing by 2D FEA

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**Abstract**

The purpose of this research was to investigate the effect of inclusion on inclusion front tensile stress during copper shaped-wire drawing. The effect of inclusion length on copper shaped-wire drawing was investigated. The deformations and the mean normal stress ($\sigma_m$) of copper shaped-wires that contain an inclusion were calculated by two-dimensional finite elemental analysis. As the FEA results, while the inclusion passed through the die, the neck due to inclusion wire drawing occurred on some parts of copper wire surface in front of and near the leading edge of the inclusion. The effect of inclusion length ($L_i/D_o$) on tensile stress in front of inclusion during copper shaped-wire drawing was carried out. For $L_i/D_o > 1.0$ the inclusion length did not effect on inclusion front tensile stress. In case of $1 > L_i/D_o > 0.2$ and $L_i/D_o < 0.2$, inclusion length slightly and strongly influences on inclusion front tensile stress, respectively.
**Keywords:** wire fracture, 2D FEA, copper shaped-wire, inclusion, mean normal stress

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## Introduction

The greater tensile strength copper wire was first developed by Dolittle in the USA (Morton, 1999). This new method of copper wire production enabled high-conductivity rods to be cold drawn without heat treatment and this doubled its tensile strength. This method became known in the trade as "hard-drawn" copper. Recently, there are two methods of superfine wires manufacturing; one is to use a wire rod as the raw material and repeatedly subject the wire rod to wire drawing and heat treatment and the other is to obtain a metallic fibre directly from molten metal. Except for certain materials, most practically used metallic products are manufactured by the former method as it provides favourable wire quality, stability and processing cost.

Many researchers (Yoshida, 2000; Avitzur, 1968; Avitzur, 1971; Coffin and Roger, 1967; Yoshida, 1982) have investigated optimal wire drawing conditions with respect to various factors such as die angle, reduction, annealing conditions and selection of lubricants for the defects. Chen *et al.*, (1979) and Yoshida *et al.*, (1979) studied the causes of internal cracking and how such cracks grow, using finite elemental analysis (FEA) and proposed some processing conditions to prevent defects. The most important problem is wire fracture due to inclusions. In this research, the effect of inclusion on inclusion front tensile stress during copper shaped-wire drawing was investigated.

**Theoretical Wire Drawing Model Analysis**

The wire drawing processes are classified as indirect compression processes, in which the major forming stress results from the compressive stress as a result of the direct tensile exerted in drawing (Mielnik, 1991). The converging die surface in the form of a truncated cone is used. The analytical or mathematical solutions are obtained by freebody equilibrium method.

By summing the forces in the wire drawing direction of a freebody diagram at an element in the reduction zone, the longitudinal stress is obtained. Summing the forces in the radial direction, the radial or die-breaking stress is obtained. Then combining those results, integrating the resulting differential equation, and simplifying, the following equation for the average drawing stress is obtained.

$$\frac{\sigma_x}{\bar{\sigma}} = \frac{1+B}{B}\left[1-\left(\frac{D_f}{D_o}\right)^{2B}\right] \qquad (1)$$

Where $\bar{\sigma}$ is the mean flow stress, B is equal to $\mu$ cot $\alpha$, and $D_o$ and $D_f$ are the original and final diameters. In the derivation of Eq. (1) for drawing for a constant shear factor, neither the back push stress $\sigma_{xb}$ nor the redundant work is included. These terms may be added, respectively, to give the following equation for the front pull stress $\sigma_{xf}$ for drawing.

$$\frac{\sigma_{xf}}{\bar{\sigma}} = \frac{1+B}{B}\left[1-\left(\frac{D_f}{D_o}\right)^{2B}\right] + \frac{\sigma_{xb}}{\bar{\sigma}}\left(\frac{D_f}{D_o}\right)^{2B} + \left(\frac{2}{\sqrt{3}}\right)\left(\frac{\alpha}{\sin^2\alpha} - \cot\alpha\right) \qquad (2)$$

By use of the upper-bound theory, which gives the upper bound on energy consumption, Avitzur derived the following equations for the drawing stress of round wire for a constant frictional shear factor with no backward tension in drawing:

$$\frac{\sigma_x}{\bar{\sigma}} = 2f(\alpha)\ln\frac{R_o}{R_f} + \left(\frac{2}{\sqrt{3}}\right)\left[\frac{\alpha}{\sin^2\alpha} - \cot\alpha + m(\cos\alpha)\ln\frac{R_o}{R_f} + m\frac{L}{R_L}\right] \qquad (3)$$

Where $\sigma_x$ = front pull stress; $\bar{\sigma}$ = flow stress of the perfectly plastic metal; $\alpha$ = the die half-angle; $R_o$ and $R_f$ = the initial and final radii of the cylindrical workpiece, respectively; $R_L$ = $R_f$ for drawing; $L$ = length of the cylindrical surface in contact; $m$ = constant frictional shear factor; $f(\alpha)$ = complex function involving $\sin^2\alpha$ and $\cos\alpha$, which varied from 1 to 1.666 as $\alpha^o$ varied from 0 to $90^o$ (Mielnik, 1991).

The above mentioned equations are only used for homogeneous wire drawing investigation. But non- homogeneous wire drawing such as wire drawing which contain an inclusion is more complicated problem to investigate by those simply equation. In this case, the behaviors of wire drawing with an inclusion are easily investigated by two-dimensional FEA.

## Optimal Die Half-Angle Experiment

The author (Norasethasopon and Tangsri, 2001) investigated the effects of die half-angle on drawing stress during wire drawing by experiment to find out the optimal die half-angle of copper wire. The copper wire were used as specimens have their properties as E = 120 GPa, $\sigma_Y$ = 150 MPa, and $\nu$ = 0.3. They have a diameter of 5.5 mm. The reduction/pass of copper wire drawing was 17.4 % so that drawn wires have a diameter of 5 mm. As the experimental result, the optimal die half-angle for a copper wire drawing was approximately 8 degrees.

## FEA Results and Discussion

A two-dimensional finite element method was used for analyze the effect of an inclusion on copper shaped-wire drawing. Figure 1 shows the analytical model was used. The black part was an inclusion in a copper shaped-wire. The inclusion was located at the center axis of copper shaped-wire.

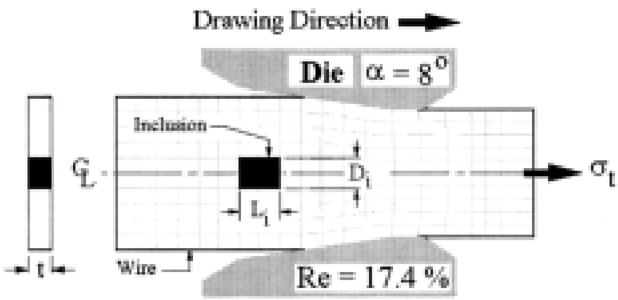


**Figure 1.** The FE model was used

The authors assumed that the inclusion was a sintered hard alloy and has the material properties and drawing conditions used in this analysis were shown in Table 1. The inclusion length was set to be $L_i/D_o$, the ratio of inclusion length to dimension of wire cross section, and varied as 0.0, 0.26, 0.52, and 0.78. The die half-angle ($\alpha$), reduction of area (Re) and coefficient of friction ($\mu$) (Mielnik, 1991) were set at 8 degrees, 17.4 %, and

0.05, respectively. The author assumed that the inclusion and the copper matrix were joined at the boundary, and that the materials used were not work - hardened during the process. This analysis, a wire was considered as a copper shaped-wire that contains a hard inclusion subjected to steady deformation.

**Table 1**. Material properties and drawing conditions used for FEA

| | | | Copper (wire) | Sintered Hard Alloy (inclusion) |
|---|---|---|---|---|
| Young's modulus | E | (GPa) | 120 | 1000 |
| Yield stress | $\sigma y$ | (MPa) | 150 | 1000 |
| Poisson's ratio | $\nu$ | | 0.3 | 0.22 |
| Die half-angle | $\alpha$ | (deg) | 8 | |
| Single pass reduction | Re | (%) | 17.4 | |
| Coefficient of friction | $\mu$ | | 0.05 | |

The distribution of mean normal stress ($\sigma_m$) and deformation behaviour of copper shaped-wires with a different length inclusion for inclusion size ($D_i/D_o$) equal to 0.4 while wire drawing were obtained as shown in Figure 2. The wire was deformed specifically around the inclusion as shown in Figure 2.

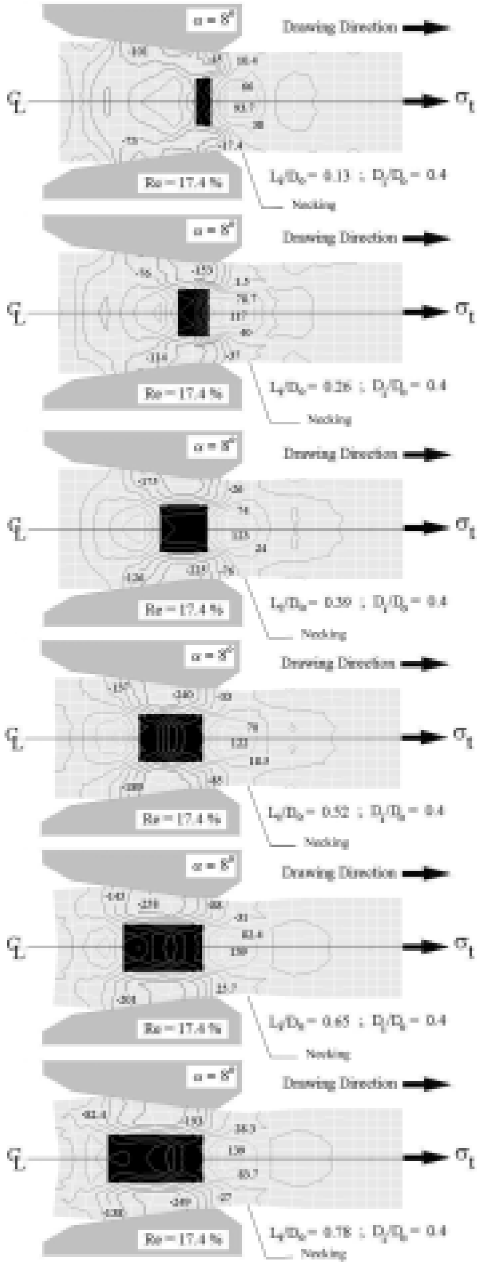


**Figure 2.** The distributions of mean normal stress ($\sigma_m$) and deformation of copper shaped-wires with a different length inclusion during wire drawing where $D_i/D_0 = 0.4$

The inclusion was negligibly deformed because of its hardness, resulting in large copper deformation. As the inclusion passed through the die, the neck due to inclusion wire drawing occurred on some parts of copper wire surface in front of and nearby inclusion and increased in accordance with $L_i/D_o$ increased.

When the high tensile stress in front of inclusion during wire drawing occurred, the internal crack or chevron crack easily occurred. The inclusion front tensile stress ratio ($\sigma_{t,i} / \sigma_t$), the ratio of tensile stress in front of an inclusion ($\sigma_{t,i}$) to drawing stress ($\sigma_t$), in a copper wire with an inclusion as an inclusion passes through the die was shown in Figure 3.

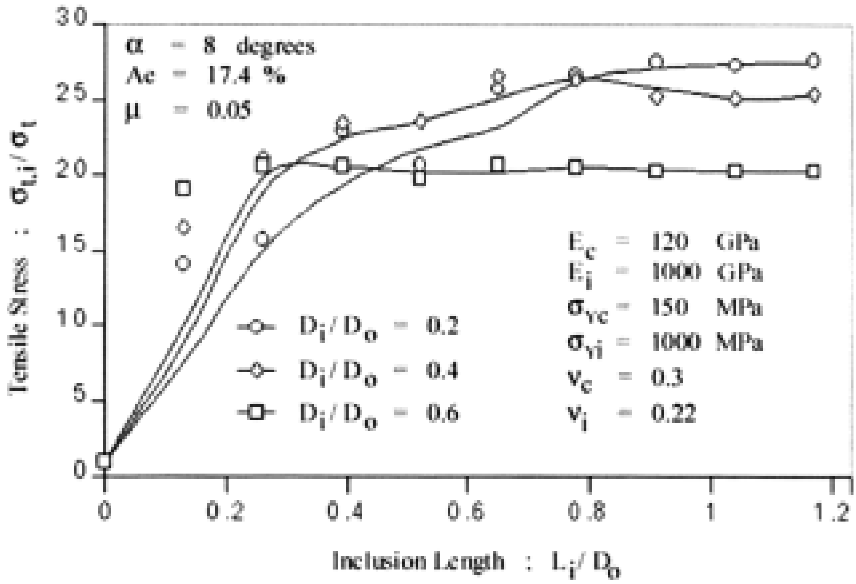


**Figure 3.** Variations of tensile stress with the inclusion length

The $L_i/D_o$ strongly influence on tensile stress for $L_i/D_o$ approximately less than 0.2. The tensile stress rapidly increases as $L_i/D_o$ and $D_i/D_o$ increase. For $L_i/D_o$ was between 0.2 to 1.0, $L_i/D_o$ influence on tensile stress and influence transition of $D_i/D_o$ from directly to inversely influence on tensile stress was occurred. The tensile stress was not effected by inclusion length when $L_i/D_o$ approximately greater than 1.0.

## Conclusions

1. Necking occurred on the copper shaped-wire surface in front of inclusion near inclusion boundary and its magnitude increase as inclusion size and length increase as shown in Figure 2.
2. The inclusion length strongly influences on tensile stress for a wire that contained a short inclusion which $L_i/D_o < 0.2$.
3. For intermediate inclusion which $1 > L_i/D_o > 0.2$, inclusion length slightly influenced on inclusion front tensile stress.
4. In case of long inclusion which $L_i/D_o > 1.0$ the inclusion length did not effect inclusion front tensile stress.

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