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Finite Element Analysis on Drawing of Copper Wire containing an Inclusion and A Cavity

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ABSTRACT

In this paper, the influence of an eccentric inclusion and cavity on copper shaped-wire drawing were investigated. An experimental investigation for optimal die half-angle was conducted. Based on experimental data of optimal die half-angle, the deformations, the mean normal stress and the plastic strain of both copper shaped-wires containing an eccentric inclusion and cavity were calculated by finite element analysis. The same parameters for both copper shaped-wires containing a centric inclusion and cavity were also calculated using the same method. Necking, bending and misalignment were observed during drawing of a wire containing an eccentric inclusion. However, only necking was observed during drawing of a wire containing a centric inclusion. It was found that the inclusion rotated during drawing and extremely compressive stress occurred on the die contact surface during drawing of wire containing eccentric inclusion. For the same inclusion size, the drawing stress was strongly influenced by inclusion size and slightly influenced by eccentric length. The drawing stress of wire containing centric inclusion was greater than that of wire containing eccentric inclusion. It was found that the drawing stress decrement was due to a cavity and the deformation behaviour of a wire containing a cavity was opposite to that of a wire containing an inclusion.

Keywords: finite element analysis, wire breakage, copper shaped-wire, inclusion, necking, drawing stress, mean normal stress

ABSTRAK

Dalam kertas ini, pengaruh rangkuman dan rongga sipi dalam tarikan dawai terbentuk kuprum disiasat. Untuk tujuan ini, suatu siasatan uji kaji bagi separuh sudut acuan yang optimum dijalankan. Berasaskan data uji kaji separuh sudut acuan yang optimum, ubah bentuk, tegasan normal min dan terikan plastik bagi kedua-dua dawai terbentuk kuprum yang mengandungi rangkuman dan rongga sipi dihitung dengan analisis unsur terhingga. Parameter-parameter yang sama bagi kedua-dua dawai terbentuk kuprum yang mengandungi rangkuman dan rongga pusat juga dihitung. Perleheran, pelenturan dan salah jajaran dicerap ketika penarikan dawai yang mengandungi rangkuman sipi. Meskipun demikian, hanya peleheran dicerap ketika penarikan dawai yang mengandungi rangkuman pusat. Kajian ini juga mendapati bahawa rangkuman berputar ketika penarikan dan tegasan yang amat memampat berlaku di permukaan sentuhan acuan ketika penarikan dawai yang mengandungi rangkuman sipi. Bagi saiz rangkuman yang sama, tegasan penarikan dipengaruhi dengan kuat oleh saiz rangkuman dan dipengaruhi dengan lemah oleh panjang sipi. Tegasan penarikan bagi *dawai yang mengandungi rangkuman pusat adalah lebih besar daripada tegasan bagi dawai yang mengandungi rangkuman sipi. Kajian ini mendapati bahawa penurunan tegasan penarikan disebabkan kehadiran rongga dan kelakuan nyahbentuk dawai yang mengandungi rongga adalah berlawanan arah dengan kelakuan nyahbentuk dawai yang mengandungi rangkuman.*

Kata kunci: *analisis unsur terhingga, pemecahan dawai, dawai terbentuk kuprum, rangkuman, perleheran, tegasan tarikan, tegasan normal min*

INTRODUCTION

The greater tensile strength of copper wire production was first developed by Dolittle (Morton 1999). This enabled high-conductivity rods to be cold drawn without heat treatment and this doubled its tensile strength. This became known in the trade as 'hard-drawn' copper.

Recently, there are two methods of manufacturing superfine wires; one is by using a wire rod as the raw material which is repeatedly subjected to wire drawing and heat treatment, while the other is through a metallic fibre directly obtained 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. One of the reasons for the high manufacturing costs of superfine wires is the breakage of wires during processing. The causes of wire breakage have been actively studied for a long time. However, there are few published reports.

Many researchers 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. Avitzur (1968, 1971) proposed the conditions under which internal fracture occurred using an energy method. Yoshida (1982, 1987) studied the occurrence of damage and voids during the drawing using a slip-line field method. Chen (1979) and Yoshida (2000) studied the causes of internal cracking and how such cracks grow, using finite-element analysis (FEA) and proposed some processing conditions to prevent defects. The most important problem is wire breakage due to inclusions. Raskin (1997) reported the causes of wire breakage during copper wire drawing based on his survey of 673 wire breaks, that 52%, 13%, 13%, 5%, 5%, and 12% are attributable to inclusion, central bursting or cupping, tension break, weld break, silver break and others, respectively, as shown in Fig. 1. Hence the most important problem of wire breakage during copper wire drawing is wire breakage due to inclusions as shown in Fig. 2.

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 stresses as a result of the direct tensile stress exerted in drawing (Edward 1991). The converging die surface in the form of a truncated cone is used. The analytical or mathematical solutions are obtained by free body equilibrium method. By summing the forces in the wire drawing direction of a free body equilibrium diagram of an element of the wire in the process of being

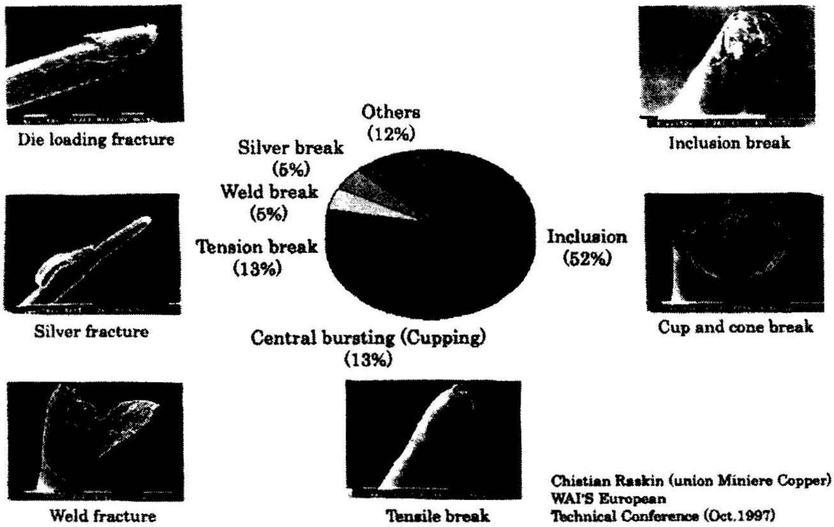

FIGURE 1. Causes of wire breakage during copper wire drawing (673 Samples)

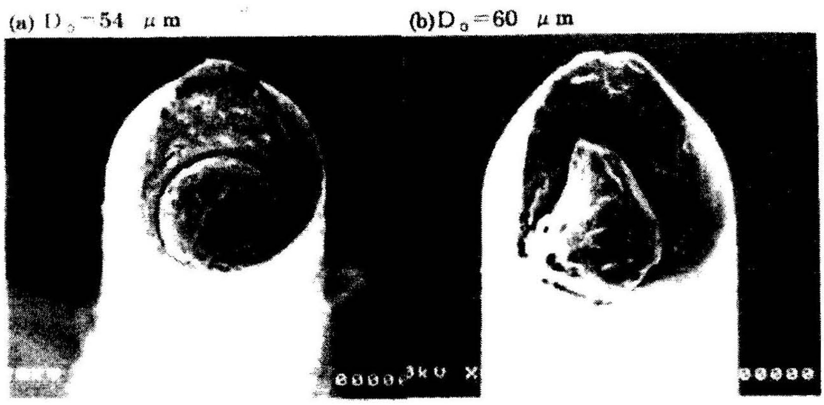

FIGURE 2. Wire breakage due to inclusion

reduced, then combining the yield criterion with equation for the axial force, integrating the resulting differential equation, and simplifying, the equation for the average drawing stress is obtained. In the derivation of this equation for drawing at a constant shear factor, neither a back pull stress nor the redundant works were included. These terms may be added, respectively, to give the equation for the front pull stress for drawing.

The above equations are only used for homogeneous wire drawing investigation. But non-homogeneous wire drawing such as drawing of wire containing an inclusion is a more complicated problem to investigate by these simple equations. In this case, the behaviour of wire drawing with an inclusion are easily investigated by two-dimensional FEA.

OPTIMAL DIE HALF-ANGLE EXPERIMENT

Norasethasopon (2001) investigated the effects of die half-angle on drawing stress during wire drawing by experiment in order to determine the optimal die half-angle of copper wire. The properties of the copper wire used as specimens were $E = 120000$ MPa, $\sigma_Y = 150$ MPa and $\nu = 0.3$. The reduction/ pass of copper wire drawing was 17.4 %.

In this experiment, various die half-angles such as 4, 6, 8, 10, and 12° were used. The drawing stresses of copper wire during drawing at room temperature versus the die half-angle were obtained. For a die half-angle of 4°, the drawing stress was large. For the die half-angle of 6, 8, 10, and 12°, the drawing stress decreased as the die half-angle increased until at approximately 8°, it increased as the die half-angle increased. The minimum drawing stress and the largest elongation were at a die half-angle of 8°. Therefore the optimal die half-angle for copper wire drawing was approximately 8°.

FEA RESULTS AND DISCUSSION

In this investigation, the model solution was obtained by using MSC.MARC finite element program. The element type, wire and inclusion material, die material, friction model and analysis type were set as quadrilateral, isotropic (elastic-plastic), rigid, Coulomb and plane strain (large deformation), respectively.

COPPER SHAPED-WIRE CONTAINING AN INCLUSION

The effect of centric and eccentric inclusion on copper shaped-wire drawing was analysed by FEA. Fig. 3 shows the analytical model that was used. The black part was an inclusion in a copper shaped-wire. The inclusion was eccentrically located from the copper shaped-wire centre-line and the eccentric length was set as L_e/D_o, the ratio of the inclusion eccentric length to wire cross section dimension. It was assumed that the inclusion was a sintered hard alloy (WC). Table 1 shows the material properties and the drawing conditions that were used in this analysis. The inclusion length was set to be constant at L_i/D_o of 0.26, and the inclusion size D_i/D_o, the ratio of inclusion cross section dimension to wire cross section dimension, was varied from 0.0, 0.2, 0.4, 0.6 to 0.8. The die half-angle (α), reduction of area (Re) and coefficient of friction (μ) were set at 8°, 17.4 %, and 0.05, respectively. It was assumed that the inclusion and the copper matrix were joined at the boundary, and that the materials were not work-hardened during the process.

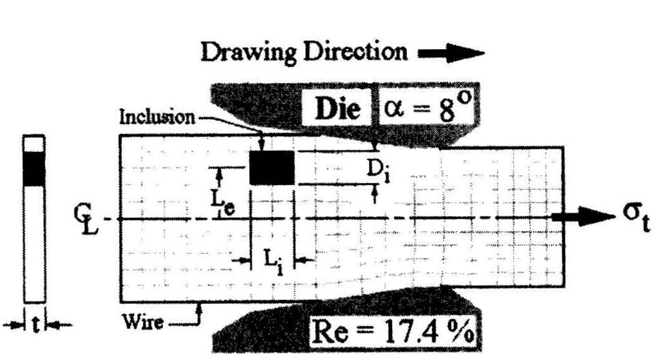

FIGURE 3. Model of copper shaped-wire containing an inclusion

TABLE 1. Material properties and drawing conditions were used for FEA

			Copper (wire)	WC (inclusion)
Young's modulus	E	(MPa)	120000	1000000
Yield stress	σ_Y	(MPa)	150	1000
Poisson's ratio	ν		0.3	0.22
Die half-angle	α	(deg)	8	
Single reduction	Re	(%)	17.4	
Coefficient of friction	μ		0.05	

In this analysis, the wire was considered as a copper shaped-wire containing an eccentric hard inclusion that was subjected to steady deformation. A copper shaped-wire containing a centric hard inclusion subjected to steady deformation was also considered.

ECCENTRIC LENGTH EFFECT

The deformation behaviour of drawn wires containing an eccentric inclusion with $D_i/D_o = 0.2$ and L_e/D_o = 0.0, 0.1, 0.2, 0.3, and 0.4 were obtained as shown in Fig. 4. Mean normal stress distributions, plastic strain distributions and deformations of the mesh were shown in Fig. 4(a), (b), and (c), respectively.

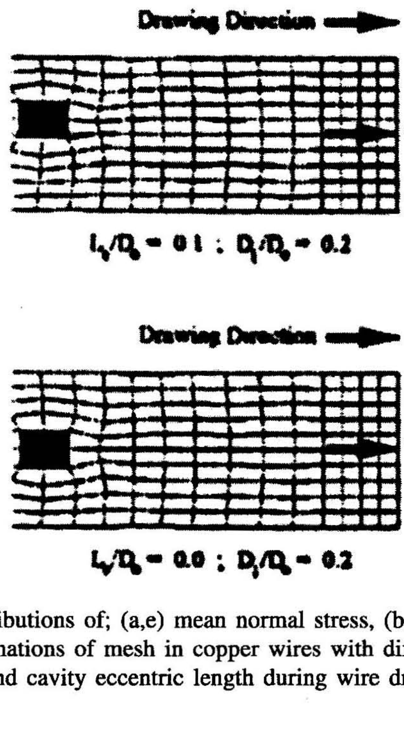

FIGURE 4. Distributions of; (a,e) mean normal stress, (b,d) plastic strain, and (c,f) deformations of mesh in copper wires with different inclusion and cavity eccentric length during wire drawing

Meshes of the drawn wires containing an eccentric inclusion were deformed specifically around the inclusion as shown in Fig. 4(a), (b) and (c), and the inclusion was negligibly deformed because of its hardness, resulting in large copper deformation. As the inclusion passed through the die, necking, bending and misalignment due to the eccentric inclusion occurred at some parts of the wire. Necking occurred on the copper shaped-wire surface in front of the inclusion near the inclusion boundary and increased as L_e/D_o increased. Bending and misalignments also increased as L_e/D_o increased and occurred at the die inlet zone as shown in all the figures. In addition, inclusion rotation was observed. Angular displacement increased as L_e/D_o increased and at its maximum, L_e/D_o angular displacement was equal to the die half angle. The inclusion was rotated in a clockwise directuion when it was located over the wire centre-line and in a counterclockwise direction if it was located under the wire centre-line.

The normal stress distributions of drawn copper shaped-wire containing an eccentric inclusion were shown in Fig. 4(a). During the drawing of wires containing an eccentric inclusion, a tensile stress in front of the inclusion decreased as L_e/D_o increased. The extremely compressive stress occurred on the die contact surface that was nearest to the inclusion and increased as L_e/D_o increased until L_e/D_o was equal to 0.3 and then decreased. This caused the die contact surface to wear easily.

The plastic strain distributions of drawn copper shaped-wire with an eccentric inclusion were shown in Fig. 4(b). The plastic strains of the matrix around the inclusion boundary were very low and lower than the matrix plastic strain that was far away from the boundary of the inclusion. The matrix plastic strain increased as the distance from the inclusion increased. This caused the wire to bend and misalign. Hence the wire bending and misalignment increased when L_e/D_o increased.

INCLUSION SIZE EFFECT

For D_i/D_o = 0.2, 0.4, 0.6, and 0.8, the deformation behaviour of drawn wires containing an eccentric inclusion with L_e/D_o = 0.0 and 0.1 were also obtained in Fig. 5 and Fig. 6, respectively. The mesh deformations were shown in Fig. 5(a), (b) and (c) and Fig. 6(a), (b) and (c). The mean normal stress distributions were shown in Fig. 5(a) and Fig. 6(a), and the plastic strain distributions were shown in Fig. 5(b) and Fig. 6(b).

Meshes of both drawn wires containing eccentric and centric inclusions were also deformed specifically around the inclusion as shown in Fig. 5 (a), (b) and (c) and Fig. 6 (a), (b) and (c). For D_i/D_o = 0.2 to 0.6, the inclusion was negligibly deformed. It was the same wire as used in Fig. 4. As the inclusion passes through the die, necking, bending and misalignment due to eccentric inclusion occurred at some parts of the wire for L_e/D_o = 0.1, 0.2, 0.3, and 0.4. However, for L_e/D_o = 0.0, only necking due to centric inclusion occurred. The necking occurred on the copper shaped-wire surface in front of the inclusion near the inclusion boundary and increased as D_i/D_o increased. Bending and misalignments also increased as D_i/D_o increased and occurred at die inlet zone. Inclusion rotation was observed for L_e/D_o = 0.1 only. Angular displacement increased as D_i/D_o increased and at the maximum D_i/D_o, angular displacement was equal to the die half-angle. During drawing of

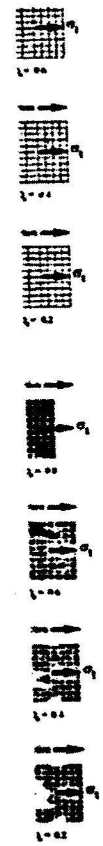

FIGURE 5. Distributions of; (a,e) mean normal stress, (b,d) plastic strain, and (c,f) deformations of mesh in copper wires with different eccentric inclusion and cavity size during wire drawing

wires containing eccentric inclusion, it was also found that a tensile stress in front of the inclusion increased as D_i/D_o increased. The extremely compressive stresses still occurred on the die contact surface that was nearest to the inclusion and increased as D_i/D_o increased. The plastic strains of the matrix around the inclusion boundary were low and increased rapidly as D_i/D_o increased.

DRAWING STRESS COMPARISON

When a high drawing stress during wire drawing occurred, wire breakage occurred easily. Fig. 7 shows the ratio of the drawing stresses (σ_i/σ), where σ_i is the drawing stress of wire containing an inclusion) and σ is the drawing stress of wire without any inclusion, as it passes through the die. The drawing conditions were D_i/D_o = 0.2, 0.4, 0.6 and 0.8 and L_e/D_o = 0.0, 0.1, 0.2, 0.3, and 0.4.

The ratio L_e/D_o had a slight influence on the drawing stress, but D_i/D_o had a strong influence on drawing stress. For constant D_i/D_o, the maximum drawing stress was found in wires containing an inclusion that was located

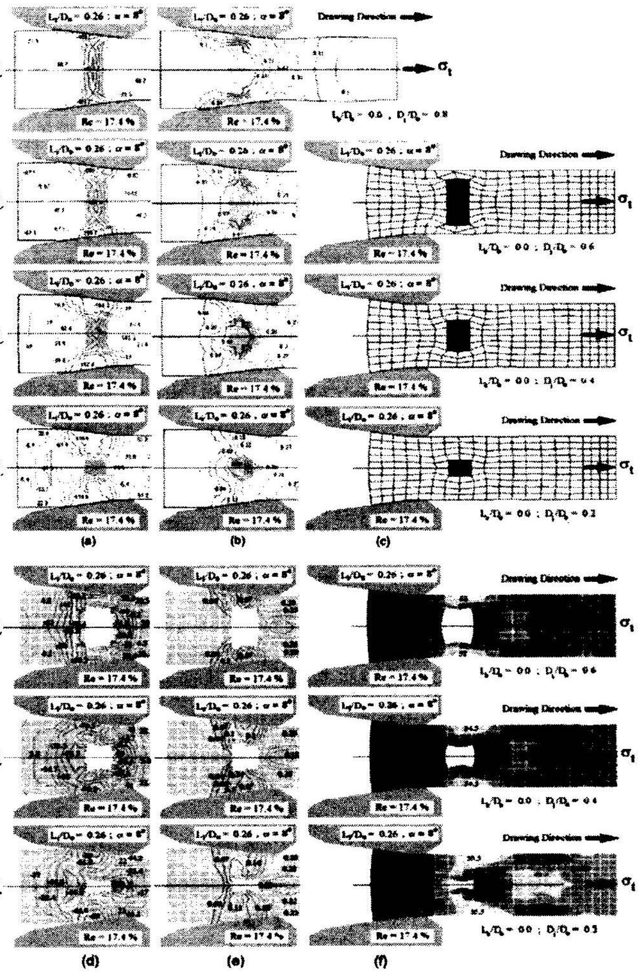

FIGURE 6. Distributions of; (a,e) mean normal stress, (b,d) plastic strain, and (c,f) deformations of mesh in copper wires with different with different centric inclusion and cavity size during wire drawing

on the wire centre-line and decreased as L_e/D_o slightly increased. Because of the influence of inclusion rotation that occurred during eccentric inclusion wire drawing, for the same D_i/D_o, it was found that the drawing stress of the wire containing an eccentric inclusion was lower than that for the wire containing a centric inclusion. In case of $L_e/D_o = 0.0$ and $D_i/D_o = 0.6$, the drawing stress was approximately 2.2 times of that for the wire without any inclusion where $D_i/D_o = 0.0$. In case of $L_e/D_o = 0.1$ and $D_i/D_o = 0.6$, the drawing stress was approximately 2.0 times of that for the wire without any inclusion. However in both cases, $L_e/D_o = 0.0$, 0.1 and $D_i/D_o = 0.8$, the drawing stress rapidly increased until the wire finally broke. This occurred as a result of a rapid increase in the drawing stress.

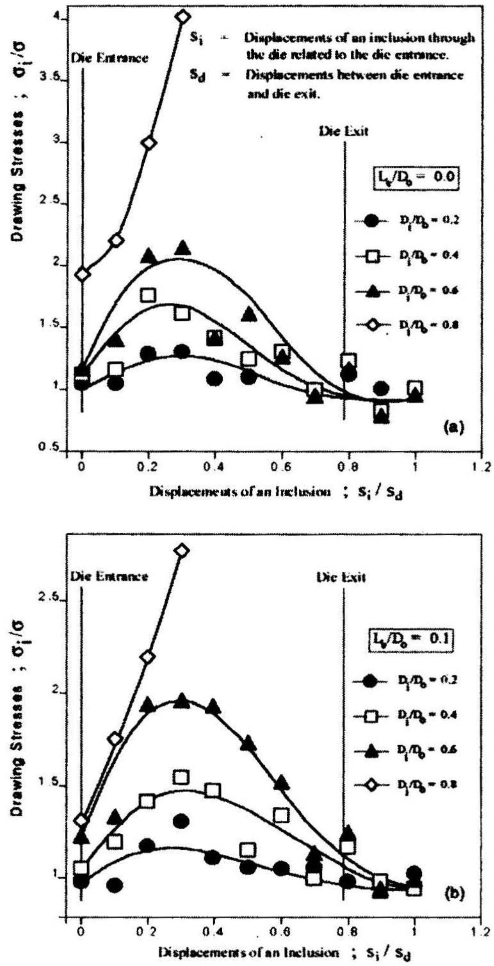

FIGURE 7. Drawing stresses versus inclusion displacements through the die

COPPER SHAPED-WIRE CONTAINING A CAVITY

By substituting the inclusion, shown as the black area in Fig. 3, with a cavity and by using FEA, the effect of centric and eccentric cavity on copper shaped-wire drawing can easily be analysed. The white part shown in Fig. 4, 5 and 6 was a cavity in a copper shaped-wire. It was assumed that the pressure in the cavity was the same as atmospheric pressure and the pressure change in the cavity can be neglected. In this analysis, all parameters, all data excluding inclusion and cavity materials properties, experimental data and other assumption of wire drawing with cavity were set as in the case of inclusion in wire drawing. The deformation behaviour of drawn wires containing an eccentric constant sized cavity, a constant eccentric length for various cavity sizes and a centric cavity of various sizes were obtained as shown in Fig. 4(d-f), Fig. 5(d-f) and Fig. 6 (d-f), respectively. Mean normal stress distributions of the mesh were shown in Fig. 4(d), Fig. 5(d) and Fig. 6(d). Plastic strain distributions of the mesh were shown in Fig. 4(e), Fig. 5(e) and Fig. 6(e). Deformations of the mesh with mean normal stress distributions were shown in Fig. 4(f), Fig. 5(f) and Fig. 6(f). The material properties of the inclusion and the cavity were opposite to each othe., For example, the inclusion was harder than the copper shaped-wire but the cavity was softer than the copper shaped-wire. Hence opposite deformation behaviours were observed. In this case, it can be clearly see that the necking due to centric and eccentric cavity wire drawing occurred only slightly and can be neglected. The deformations of matrix around the cavity boundary were very large. The cavity was not rotated but its shape was transformed.

ECCENTRIC LENGTH EFFECT

As the cavity passed through the die, it was observed that wire bending and misalignment due to the eccentric cavity wire drawing occurred in the opposite direction compared to that for the case of inclusion wire drawing. Bending and misalignments increased as L_e/D_o increased and occurred at die inlet zone. The mean normal stress distributions of drawn copper shaped-wire containing an eccentric cavity were shown in Fig. 4 (d). During the drawing of wires containing an eccentric cavity, a maximum tensile stress on the side surface of the cavity increased as L_e/D_o increased until L_e/D_o equaled to 0.2, but it decreased as L_e/D_o increased when L_e/D_o is higher than 0.2. A maximum tensile stress in wire cross section containing the cavity when the cavity was observed at the die exit and it decreased as L_e/D_o increased. Extreme compression occurred on the die contact surface on the opposite side that was far away from the cavity location as shown in Fig. 4(d), and increased as L_e/D_o increased. The plastic strain distributions of drawn copper shaped-wire with an eccentric cavity were shown in Fig. 4(e). The plastic strains of matrix around the cavity boundary were very large and larger than the matrix plastic strain that was located far away from the boundary of the cavity. This matrix plastic strain increased while L_e/D_o increased. This caused large deformation of the cavity boundary and transformation also occurred. At the die inlet zone, bending and misalignment increased when L_e/D_o increased.

CAVITY SIZE EFFECT

For D_i/D_o = 0.2, 0.4, 0.6, and 0.8, the deformation behaviour of drawn wires containing an eccentric cavity with L_e/D_o = 0.0 and 0.1 were obtained as shown in Fig. 5 and Fig. 6, respectively. The deformations of mesh were shown in Fig. 5(d), (e) and (f) and Fig. 6(d), (e) and (f). The mean normal stress distributions were shown in Fig. 5(d) and Fig. 6 (d), and plastic strain distributions were shown in Fig. 5(e) and Fig. 6(e). Meshes of both drawn wires containing eccentric and centric cavities were largely deformed around the cavity boundary as shown in Fig. 5(d), (e) and (f) and Fig. 6(d), (e) and (f). It is the same as the wire shown in Fig. 4. As the cavity passed through the die, bending and misalignment due to eccentric cavity wire drawing occurred in opposite direction to that due to eccentric inclusion wire drawing. Bending and misalignments also increased as D_i/D_o increased and occurred at the die inlet zone. During the drawing of wires containing an eccentric cavity, a maximum tensile stress around the cylindrical surface of the cavity and in wire cross section containing the cavity ahen the cavity was at the die exit increased as D_i/D_o increased. In case of centric wire drawing, the maximum tensile stress increased as D_i/D_o increased until D_i/D_o equaled

0.4, but it decreased as D_i/D_o increased when D_i/D_o was higher than 0.4. The extremely compressive stress occurred on the die contact surface, on the opposite side that was far away from the cavity location as shown in Fig. 4(d), and increased as L_e/D_o increased. The plastic strains of matrix around the cavity boundary were very large and slightly increased as D_i/D_o increased.

DRAWING STRESS COMPARISON

Fig. 8 shows the ratio of the drawing stress (σ_c/σ), where σ_c is the drawing stress of wire contains cavity and σ is the drawing stress of wire without cavity, as a cavity passed through the die. The drawing conditions were D_i/D_o = 0.2, 0.4, 0.6 and 0.8 and L_e/D_o = 0.0, 0.1, 0.2, 0.3, and 0.4. L_e/D_o caused slight influence on drawing stress decrement. However, D_i/D_o has a strong influence on drawing stress decrement. The drawing stress decreased as L_e/D_o decreased and D_i/D_o increased. For constant D_i/D_o, the lowest drawing stress was found in the wire containing a cavity that was located on wire centr-line. Because of the influence of cavity deformation during eccentric cavity wire drawing, the drawing stresses of wire containing an eccentric cavity were higher than for wires containing a centric cavity for the same D_i/D_o'.

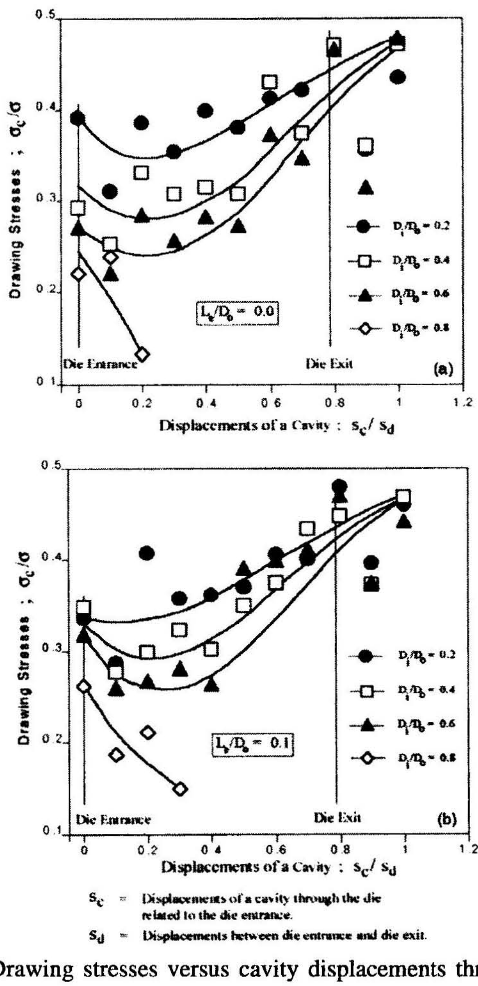

FIGURE 8. Drawing stresses versus cavity displacements through the die

CONCLUSIONS

Necking, bending and misalignment were observed during drawing of a wire containing an eccentric inclusion. However, only necking was observed during drawing of a wire containing a centric inclusion. It was found that the inclusion rotated during drawing and extremely compressive stress occurred on the die contact surface during drawing of wire containing eccentric inclusion. For the same inclusion size, the drawing stress was strongly influenced by inclusion size and slightly influenced by eccentric length. The drawing stress of wire containing centric inclusionwas greater than that of wire containing eccentric inclusion. It was found that the drawing stress decrement was due to a cavity and the deformation behaviour of a wire containing a cavity was opposite to that of a wire containing an inclusion.

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NOTATION

E	Young's modulus
D_i/D_o	Ratio of inclusion cross section dimension to wire cross section dimension
L_e/D_o	Ratio of inclusion eccentric length to wire cross section dimension
Re	Reduction of area per pass
α	Die half-angle
μ	Coefficient of friction
v	Die half-angle
σ_Y	Yield stress

REFERENCES

Avitzur, B. 1968. Analysis of central bursting defects in extrusion and wire drawing. *Trans. ASME (B)* 90 (1): 79-91.

Avitzur, B. 1979. *Metal Forming: Processes and Analysis*, (Edisi dicetak semula). Huntington: Krieger Publishing Co.

Avitzur, B. 1971. Study of flow through conocal converging dies. In A. L. Hoffmanner, (ed.), *Metal Forming*. New York: Plenum Press.

Chen, C. C., Oh, S. I. and Kobayashi, S. 1979. Ductile fracture in axisymmetric extrusion and drawing. *Trans. ASME(B)* 101: 23-44.

Mielnik, E. M. 1991. *Metalworking Science and Engineering*. New York: McGraw-Hill, Inc.

Morton, J. 1999. Thomas Bolton & Sons and the rise of the electrical industry. *Eng. Sci. Edu. J.* 8 (1): 5-12.

Norasethasopon, S., and Tangsri, T. 2001. Experimental study of the effect of a half-die angle on drawing stress during wire drawing. *Ladkrabang Eng. J.* 18: 134-139.

Raskin, C. 1997. The causes of wire breakage during copper wire drawing. *Proc. WAI Int. Tech. Conf.* Italy, pp. 80-86.

Tanaka, H. and Yoshida, K. 1979. Relation between oxygen contents and the cupping of tough pitch copper wire. *J. Japan Inst. Metals* 43: 618-625.

Yoshida, K. 2000. FEM analysis of wire breaks in drawing of superfine wire with an inclusion. *Wire J. Int.* 33: 102-107.

Yoshida, K. and Tanaka H. 1987. Cup-shaped defect in copper wires drawn from rods of continuous casting and rolling. *Advanced Technology of Plasticity*, pp. 857-862.

Yoshida, K. 1982. Study on cuppy defects in wire drawing. PhD dissertation, Tokai University, Japan.

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