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Finite-Element Simulation on Wire Breakage Induced by Eccentric Inclusion in Shaped Wire Drawing

by

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Abstract

The causes of wire breakage have long been studied. The most significant problem of wire breakage during fine wire drawing is breakage due to inclusions. In this paper, the effects of eccentric length (L_e) and inclusion size (D_i) of a noncenter-axis-located inclusion on shaped wire drawing were investigated. For this purpose, an experimental investigation for the optimal die half-angle was conducted for copper wire. Based on experimental data of the optimal die half-angle, the deformations, the mean normal stresses, the drawing stresses and the plastic strains of copper wire which contain an eccentric or centric inclusion were calculated by finite element analysis. It was found that during wire drawing, necking, wire bending and misalignment occur for eccentric inclusion wire drawing but only necking occurs for centric inclusion wire drawing. Inclusion rotation was found for eccentric wire drawing. Highly compressive stresses act on the die contact surface nearest to the eccentric inclusion so that the die contact surface easily wears out. For the same inclusion size, the drawing stresses are strongly influenced by inclusion size and slightly influenced by eccentric length, and drawing stresses of centric inclusion wire are greater than eccentric inclusion wire. The larger the inclusion size and the smaller the eccentric length, the higher the drawing stress, which leads to a higher possibility of wire breakage.

Keywords: Drawing, Wire break, FEA, Inclusion, Fine wire, Shaped Wire

1. Introduction

By the nineteenth century, the telegraph represented the first large-scale commercial application of electric current. Interest had been greatly stimulated by the growth of the railway. Some early land telegraphs used copper wire, but this was soon replaced by steel wire for greater tensile strength (most wires were strung between telegraph poles) and for cheapness. Copper telegraph wire, being expensive, was often the target for thieves. Steel had sufficient conductivity for the simple Morse signals, provided that relays were used. A huge market was thus initially lost to the copper industry, except for railway tunnels where copper was used to combat dampness and acidic corrosion. As the century progressed, there were new developments[1]. The dynamo, the high-speed telegraph and the telephone, electric lighting and electric transport created a whole new industry. The new high-speed telegraph and the telephone needed better conductivity, so copper wire was winning back from the steel wire makers the huge worldwide market for overhead telegraph wire. High conductivity was of great commercial importance to the telegraph operators because it allowed a greater message-carrying capacity. However, greater tensile strength was needed and this was provided by a new method, first developed by Dolittle in the USA. 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 [1), 2)].

Presently, there are two methods of extra-fine wire 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 fiber directly from molten metal[3]. Except for

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certain materials, most practical metal products are manufactured by the former method, as it provides favorable 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[4]. The causes of wire breakage and the internal defects have been actively studied for a long time [5~10]. Raskin 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, center bursting or cupping, tension break, weld break, silver break and others, respectively[11]. Hence the most important problem of wire breakage during fine wire drawing is breakage due to inclusions.

2. Basic Theory of Wire Drawing

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 tension exerted in drawing. The converging die surface in the form of a truncated cone is used. The analytical or mathematical solutions are obtained by the freebody equilibrium method.

This is performed by summing the forces in the wire drawing direction of a freebody equilibrium diagram of an element of the wire in the process of being reduced. Then by combining the yield criterion with the equation for the axial force, integrating the differential equation, and simplifying, the following equation for the average drawing stress is obtained [12,13]:

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

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 a back pull stress σ_{xb} nor the redundant work were included. These terms may be added, respectively, to give the following equation for the front pull stress σ_{xf} for drawing.

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

The above equations are only used for non-inclusion or homogeneous wire drawing investigation. But wire drawing containing an inclusion is a more complicated problem to investigate by this simple equation. In this case, inclusion wire drawing behavior is easily investigated by FEA.

3. Experiments

The authors experimentally determined the effects of die half-angles on the drawing stress during round to round wire drawing by using the universal tensile testing apparatus as shown in Fig. 1, to find out the optimal die half-angle of copper wire. The properties of copper wire are used as specimens are : E = 120000 MPa, σ_Y = 150 MPa, and ν= 0.3. The reduction/pass of copper wire drawing are 20% and 35%.

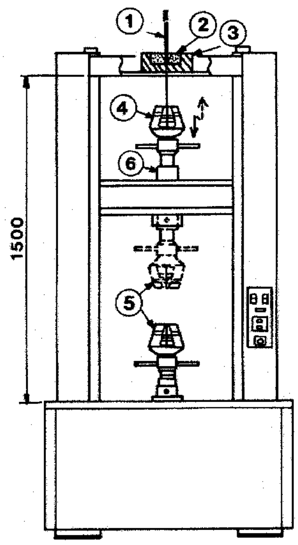


Fig.1 Apparatus for drawing and tensile-test.
① : test piece ② : die ③ : die holder
④ : grip for drawing ⑤ : grip for tensile-test
⑥ : load cell

In this experiment, the die half-angles: 2,3,4,5,6,7,8,10,12,14 and 16 degrees are used. The drawing stresses of copper wire during drawing at room temperature versus the die half-angle are obtained (Fig.2). It becomes curved bottom. At about 8 degrees, the drawing stress becomes a minimum value.

The effects of die half-angle on the drawing stress during wire drawing by FEA were investigated (see Fig.2). We can see that the experimental results agree well with the FEA results. The minimum drawing stress is at a die half-angle of 8 degrees. Thus the optimum die half-angle for copper wire drawing is approximately 8 degrees.

4. FEA Results and Discussion

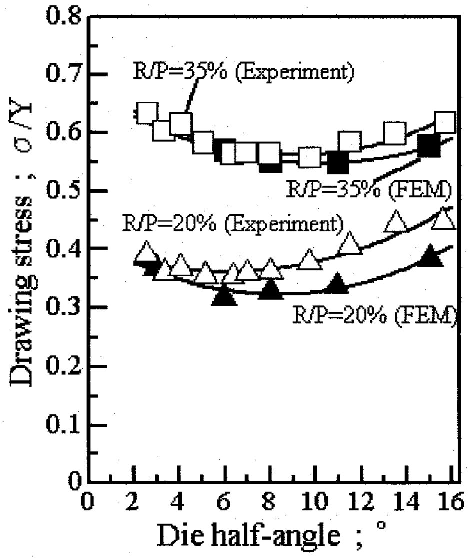


Fig. 2 Drawing stress vs. die half-angle, determined by experiments and FEA.

A finite element method was used to analyze the effect of a eccentric inclusion on copper wire drawing. The analytical model used in this analysis is shown in Fig. 3.

The inclusion is eccentric, located off the copper wire center-axis, and the eccentric distance was set at L_e/D_o , the ratio of the inclusion's eccentric distance to the wire diameter. The authors assumed that the inclusion was a sintered hard alloy (WC) and whose material properties and drawing conditions used in this analysis are shown in Table 1. The inclusion length was set to be constant at L_i/D_o = 0.26, and the inclusion size D_i/D_o, the ratio of inclusion diameter to wire diameter, was varied as 0.0, 0.2, 0.4, 0.6 and 0.8. The die half-angle (α), reduction of area (Re) and coefficient of friction (μ) 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 therefore considers a copper wire with

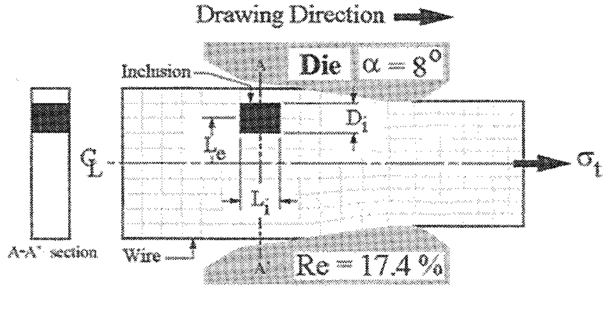


Fig. 3 Model of a fine shaped wire containing an inclusion used in this analysis.

Table 1 Material properties and drawing conditions used for FEA.

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

with eccentric hard inclusion subjected to steady deformation. A copper wire with a centric hard inclusion subjected to steady deformation is also considered.

4.1 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. The deformation of the mesh, normal stress distributions and plastic strain distributions were shown in Fig. 4 (a) and (d), Fig. 4 (b), and Fig. 4 (c), respectively.

In Fig. 4 (a) and (d), it can be seen that the meshes of the drawn wires containing an eccentric inclusion were deformed specifically around the inclusion, and the inclusion was negligibly deformed because of its hardness, resulting in large copper deformation. As the inclusion passes through the die, necking, wire bending and mis-alignment due to eccentric inclusion wire drawing occur at some parts of the wire. Necking occur on the copper wire surface near the front of an inclusion and increases as L_e/D_o increases. Wire bending and mis-alignments also increase as L_e/D_o increases and occur at the die inlet zone as shown in all figures. In addition, inclusion rotation was found. As the inclusion passes through the die it inclines in the direction of the die surface. Angular displacement increases as L_e/D_o increases and at maximum L_e/D_o, the angular displacement is equal to the die half-angle. The inclusion was rotated clockwise when located over the wire center axis and counterclockwise when located under the wire center axis.

Fig. 4 (b) shows the mean normal stress distribution of drawn copper wire with an eccentric inclusion. It was found that tensile stress in front of the inclusion decreases as L_e/D_o increases. An extremely compressive stress occurs on the die contact surface nearest to the inclusion and increases as L_e/D_o increases until L_e/D_o equals 0.3 and then decreases. This causes the die contact surface to wear easily.

Fig. 4 (c) shows the plastic strain distributions of drawn copper wire with an eccentric inclusion. The

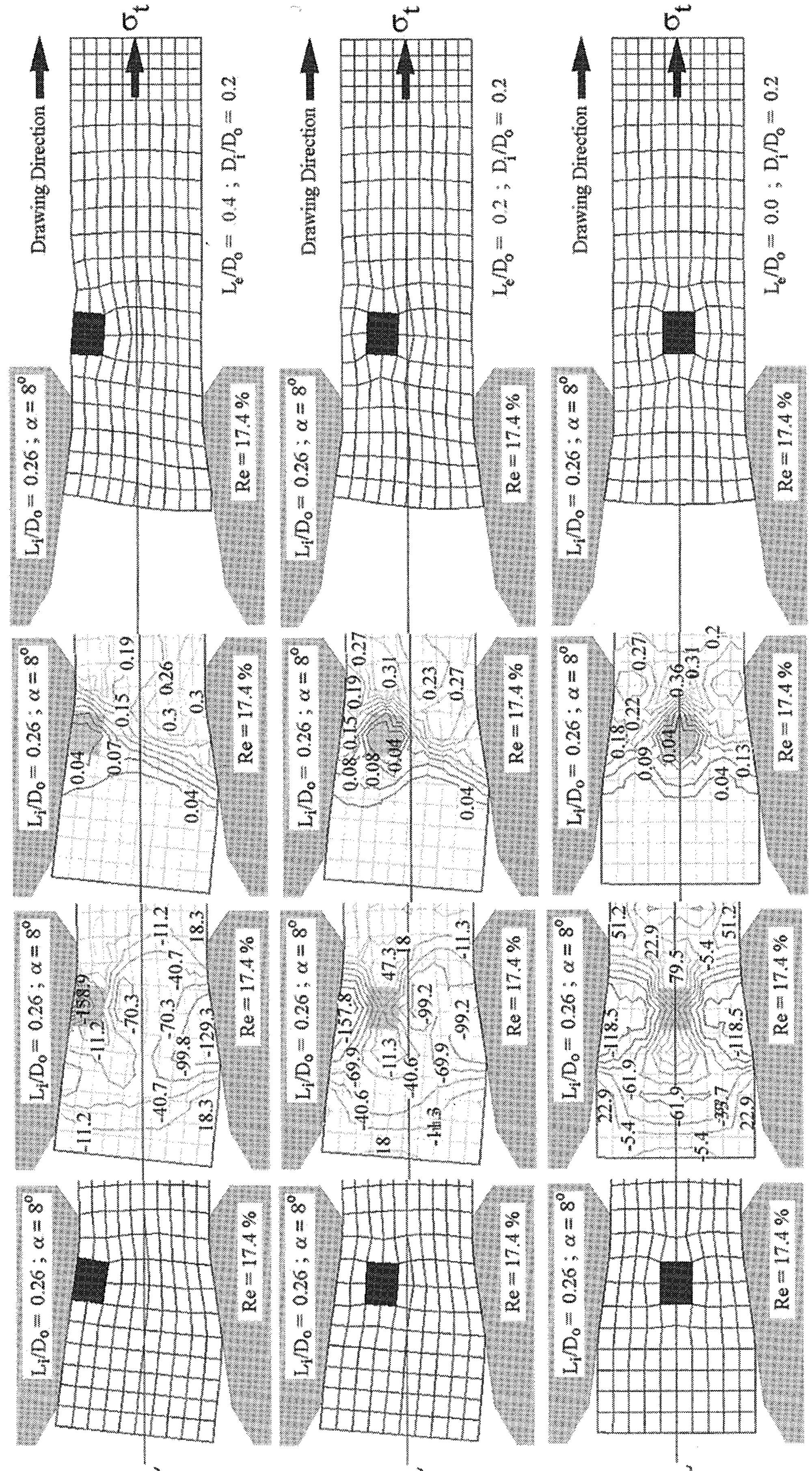


Fig. 4 Deformation of the mesh ((a) and (d)), distributions of mean normal stress (b) , and distributions of the plastic strain (c) in drawing with different ratios of inclusion eccentric length to wire diameter during wire drawing.

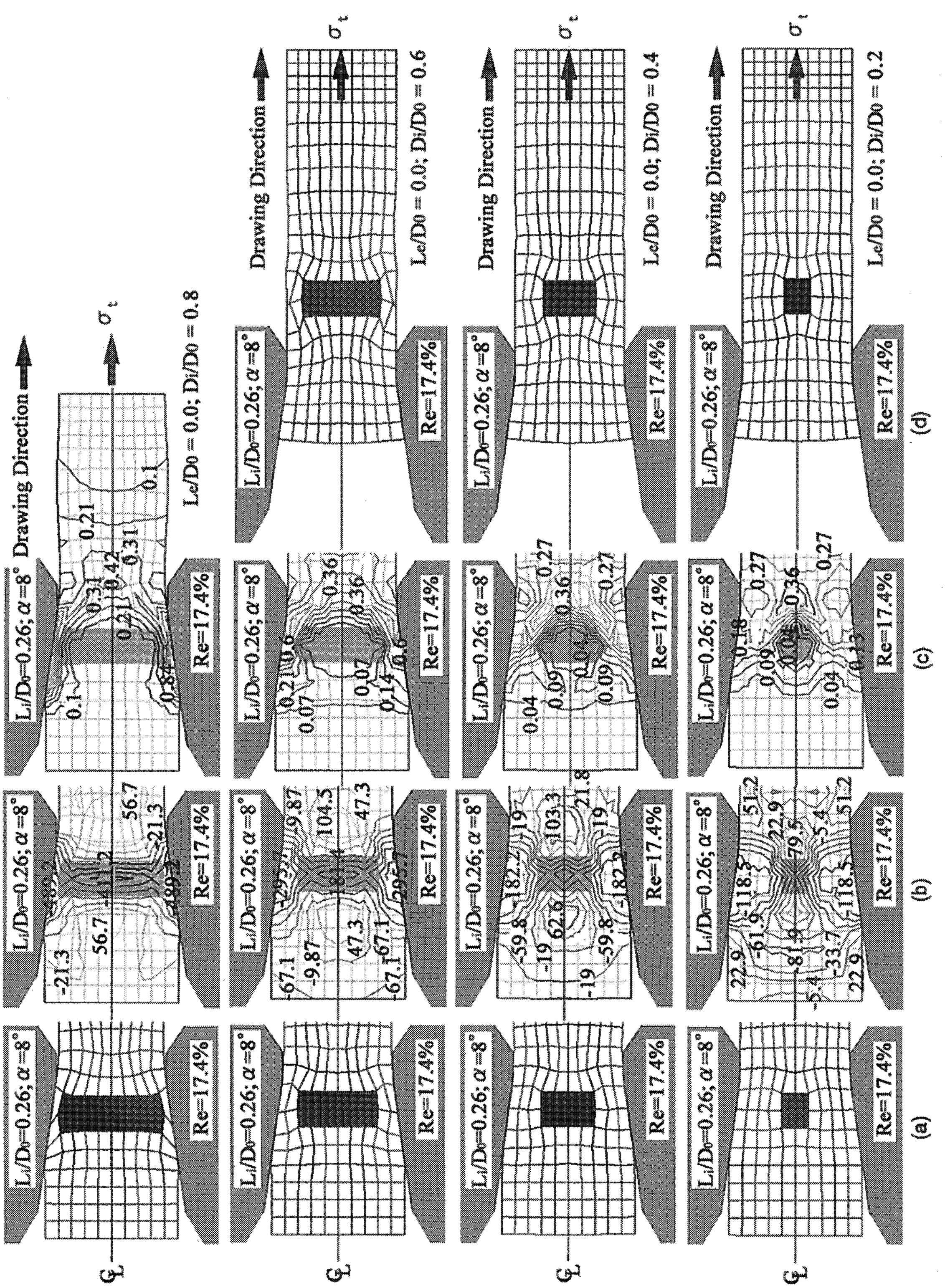


Fig.5 Deformation of the mesh ((a) and (d)), distributions of the mean normal stress (b), and distributions of the plastic strain (c) in drawing wire with an inclusion in the center and different ratios of inclusion diameter to wire diameter during wire drawing.

plastic strains of the matrix around the inclusion boundary are very low and lower than the matrix plastic strain that is far away from the boundary of the inclusion. The matrix plastic strain increases as the distance from the inclusion increases. This causes wire bending and mis-alignment occurs. Hence it can be determined that wire bending and mis-alignment increase when L_e/D_o, the ratio of the inclusion eccentric length to wire diameter, increases.

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 deformations of the mesh were shown in Fig. 5 (a) and (d) and Fig. 6 (a) and (d). The normal stress distributions were shown in Fig. 5 (b) and Fig. 6 (b). The plastic strain distributions were shown in Fig. 5 (c) and Fig. 6 (c).

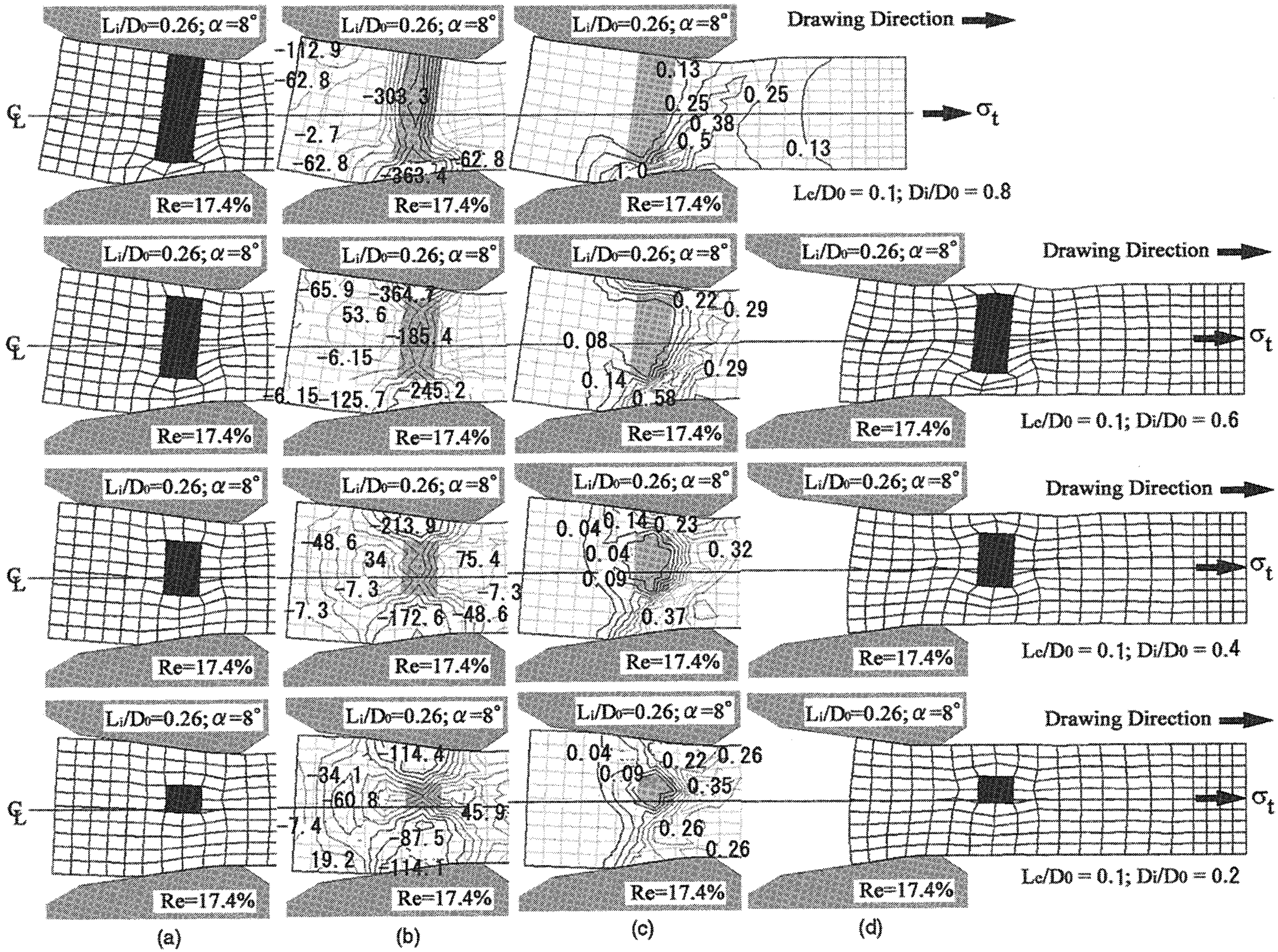


Fig.6 Deformation of the mesh ((a) and (d)), distributions of the mean normal stress (b), and distributions of the plastic strain (c) in drawing shaped wire with an inclusion which is not located in the center and different ratios of inclusion diameter to wire diameter during wire drawing.

4.2 Inclusion Size Effect

In Fig. 5 (a) and (d) and Fig. 6 (a) and (d), the meshes of the drawn wires containing both an eccentric and a centric inclusion were deformed specifically around the inclusion. For D_i/D_o= 0.2 to 0.6 exclude D_i/D_o= 0.8, the inclusion was negligibly deformed. It is the same as a wire shown in Fig. 4, as the inclusion passes through the die, necking, wire bending and mis-alignment due to eccentric inclusion wire drawing occurs at some parts of the wire for L_e/D_o = 0.1, 0.2, 0.3, and 0.4. Necking occurs on the copper wire surface near the front of an inclusion and increases as D_i/D_o increases. Wire bending and mis-alignments also increase as D_i/D_o increases and occur at the die inlet zone. Only for L_e/D_o = 0.1, was inclusion rotation found and angular displacement increases as D_i/D_o increases and at maximum D_i/D_o, the angular displacement is also equal to die half-angle.

Fig. 5 (b) and Fig. 6 (b) show the normal stress distributions of drawn copper wire with an eccentric and a centric inclusion. During the drawing of wires containing an eccentric inclusion, it was found that tensile stress in front of the inclusion increases as D_i/D_o increases. Extremely compressive stresses occur on the die contact surface nearest to the inclusion and increase as D_i/D_o increases.

Fig. 5 (c) and Fig. 6 (c) show the plastic strain distributions of drawn copper wire with an eccentric and a centric inclusion. The plastic strain of the matrix around the inclusion boundary is low and increase rapidly as D_i/D_o increase. Wire bending and mis-alignment only occur for L_e/D_o = 0.1.

4.3 Drawing Stress Comparison

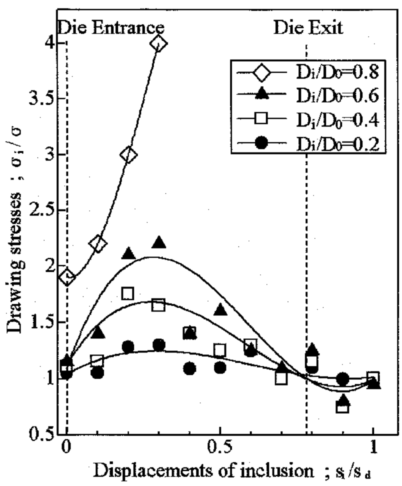
When high drawing stress during wire drawing occurs, wire breakage occurs easily. Fig. 7 shows drawing stress (σ_i/σ), the ratio of drawing stress of a wire with an inclusion to drawing stress of a wire without an inclusion, as an inclusion passes through the die. The drawing conditions were D_i/D_o = 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. It can be seen that the L_e/D_o slightly influences drawing stress. But D_i/D_o strongly influences drawing stress. As D_i/D_o is constant, the maximum drawing stress is found in the wire which contains an inclusion that is located on the wire centerline and decreases as L_e/D_o increases. Because of the influence of inclusion rotation that occurs during eccentric inclusion wire drawing, in the case of the same D_i/D_o, the drawing stress of the wire containing eccentric an inclusion is lower than the wire containing a centric inclusion. In the case of L_e/D_o = 0.0, when D_i/D_o = 0.6, the drawing stress was approximately 2.2 times the wire without an inclusion (D_i/D_o = 0.0). In the case of L_e/D_o = 0.1, in wires which contain inclusions with D_i/D_o = 0.6, the drawing stress was approximately 2.0 times the wire without an inclusion. But in both cases, L_e/D_o = 0.0 and 0.1, for D_i/D_o = 0.8, the drawing stress rapidly increase and that wire finally breaks. The wire breaks occur as a result of a rapid increase in the drawing stress.

5. Conclusions

The following effects of eccentric inclusions compared with centric inclusions on copper wire drawing were obtained by FEA:

1. Necking, wire bending and mis-alignment due to eccentric inclusion wire drawing occurs for L_e/D_o = 0.1, 0.2, 0.3, and 0.4.

(a) an inclusion in the center



(b) an inclusion which isn't located in the center

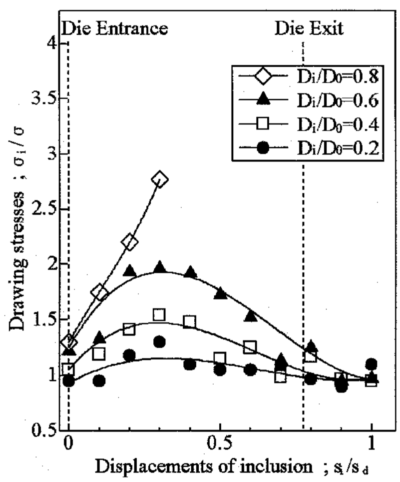


Fig. 7 Drawing stresses versus inclusion displacements through the die.

2. Necking occurs on the copper wire surface near the front of an inclusion and increase as D_i/D_o increases.

3. Wire bending and mis-alignments increase as D_i/D_o and L_e/D_o increase and occur at the die inlet zone.

4. For L_e/D_o = 0.1, 0.2, 0.3, and 0.4, inclusion rotation was found. The inclined inclusion movement occurs as it passes through the die. This causes the drawn wire to be bent. Angular displacement increases as D_i/D_o and L_e/D_o increase and at maximum D_i/D_o, angular displacement is also equal to the die half-angle.

5. The matrix plastic strain increases as the distance from the inclusion increases. For wire drawing with an eccentric inclusion, this causes wire bending and mis-alignment to occur. Thus wire bending and mis-alignment increase when L_e/D_o and D_i/D_o increase.

6. The tensile stress in front of an eccentric inclusion decreases as L_e/D_o and D_i/D_o increase but increases as L_e/D_o and D_i/D_o increase for a centric inclusion.

7. An extremely compressive stress occurs on the die contact surface nearest to the eccentric inclusion and increase as L_e/D_o increases until L_e/D_o is equal to 0.3 and then decreases and only increases as D_i/D_o increases in the case of centric inclusion. This cause the die contact surface to wear.

8. The drawing stresses are strongly influenced by D_i/D_o and slightly influenced by L_e/D_o.

9. For the same inclusion size, the drawing stress of a wire which contains an inclusion that is located on the wire centreline is greater than the wire which contains an inclusion which is not on the center axis.

10. The larger the inclusion size and the smaller the eccentric length, the higher drawing stress occurred and leads to a higher possibility of wire breakage.

The occurrence of wire breaks due to inclusions in the wire material and also the inclusions in the shaped wire induced by dust in the wire drawing environment during the shaped wire drawing process lead to obtained low productivity and high production cost. The location of inclusions in wire rod and also inclusions in shaped wire after passing through shaped wire processing which requires a large number of passes of wire drawing are generally located on or near the wire centre axis. But the location of inclusions, which induced by dust in the wire, drawing environment located on or near the wire surface break at once. In order to prevent wire breaks, based on the FEA results above, the wire drawing operating and processing must be in a clean room and the most important wire break prevention is strict purity control of the wire material used in the wire rod production.

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