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# Effect of coating material and lubricant on forming force and surface defects in wire drawing process

S. M. BYON[1], S. J. LEE[2], D. W. LEE[1], Y. H. LEE[3], Y. LEE[2]

1. Department of Mechanical Engineering, Dong-A University, Busan, 604-714, Korea;
2. Department of Mechanical Engineering, Chung-Ang University, Seoul, 156-756, Korea;
3. Wire Rod Research Group, POSCO Technical Research Laboratories, Pohang, 790-785, Korea

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**Abstract:** A pilot wire drawing machine as well as wire end-pointing roller was developed. Using these machines, a wire drawing test for four different coating materials and two different lubricants was performed as the reduction ratio increased from 10% to 30%. Materials used for a substrate in this study are plain carbon steel (AISI1045) and ultra low carbon bainite steel. To compute the friction coefficient between the coating layer of wire and the surface of die for a specific lubricant, a series of finite element analyses were carried out. SEM observations were also conducted to investigate the surface defects of wire deformed. Results show that the behavior of drawing force varies with the lubricant-type at the initial stage of drawing. The powder-typed lubricant with a large particle causes the retardation of full lubrication on the entire contact surface and the local delamination of coating layer on the wire surface. As the flow stress of a substrate increases, the delamination becomes severe.
**Key words:** coating; lubricant; wire drawing; delamination

## 1 Introduction

Wire drawing is a process, which pulls the rod manufactured in the groove rolling process through a die with a hole by means of a tensile force applied to the exit side of the die. Products made by this process are called wire. Thin wire, i.e., wire with small diameter (50 μm−3 mm), is usually used for making wire rope and supporting the rubber structure inside tire of automobile. Thick wire, i.e., wire with big diameter (3−40 mm), is used for manufacturing bolt and fastener through a cold heading (forging) process.

In the cold heading process, the geometry change of products is very radical locally. As a result, the friction between material and die is very high and subsequently the surface quality of wire during the process deteriorates. To minimize the friction in the cold heading process, a non-metallic material was applied on the wire surface as a lubricant coating before it goes into the drawing process and cold heading process. Most widely used the material for the lubricant coating nowadays is the phosphate that is a chemical compound and contains phosphorus[1]. The terminology ‘lubricant coating’ is expressed as ‘coating’ or ‘coating layer’.

However, the coating made of the phosphate may be delaminated or becomes thin depending on the choice of wire grade, die geometry and liquid and/or powdered soap type lubricant used during wire drawing. Noting an additional lubricant is usually added to protect the coating during the wire drawing. Once the coating layer on the wire is delaminated or becomes thin, the wire cannot be forged owing to seizure between wire and die. Hence, a great effort was devoted to the study of the friction condition on the coating layer and lubricants during the wire drawing process.

HAUW et al[2−3] derived a constitutive relation of zinc-coated steel and its substrate, and then analyzed plastic deformation of the zinc-coated steel using stamping process. They also carried out Brinell indentation test and FE analysis to obtain the constitutive relation. LEE et al[4] enhanced the accuracy of the constitutive relation using nano-indentation and artificial neural network technique. Unlike the investigation for the coating layer and bulk behavior[2−4], PARISOT et al[5] employed crystal plasticity and examined the crystalline behavior of zinc coating.

Phosphate is a traditionally used material for coating, but recently, organic is being used[6]. The change of seizure resistance upon the usage of coating

**Corresponding author:** Y. LEE; Tel: +82-2-8245256; E-mail: ysl@cau.ac.kr

type has been mainly evaluated by performing a test for friction coefficient. MATUSZAK[7] and PESCH et al[8] used a sheet-drawing test to evaluate friction coefficient of a coating layer of an organic lacquer and TiN, respectively. The evaluation results of coating of sheet were given in Ref.[7] and the results of coating of tool (or die) were given in Ref.[8]. On the other hand, LAZZAROTTO et al[9] and DUBOIS et al[10] employed an upsetting-sliding test to estimate friction coefficient of phosphate material. This method, applicable to bulk forming as well, fixes a wire inside a special stand and can measure friction coefficient while a slider that a load cell is installed is moving along the length direction of wire.

Previous studies[2−10] mostly focus on the evaluation of friction coefficient and deformation behavior of a coating and a substrate. However, these studies have some problems to be corrected. Firstly, the evaluation of friction coefficient is performed by a separate testing machine, not by an actual process. Contact condition between an actual process and a testing machine is quite different due to deformation state of material, lubricant condition and temperature. Secondly, the previous studies estimated the friction coefficient in an average sense. But the friction coefficient might vary during drawing. Finally, the previous studies did not examine the state that coating layer at a substrate surface is delaminated during an actual process.

In this study, we investigated relation among delamination of coating, powdered soap type of lubricant and drawing process condition. For this purpose, we designed a pilot wire drawing machine. Four types of phosphate coatings were used and two types of powdered soap lubricants were used. Phosphate coated carbon or alloy steel wire was drawn in the pilot wire drawing machine and drawing force was measured when reduction ratio was changed (10%, 20% and 30%). We examined the variation of friction coefficient during drawing using the drawing force measured. We took an image of the wire surface drawn with SEM (Scanning electron microscope) and observed whether delamination occurred or not. To compute the friction coefficient between the coating layer of wire and the surface of die for a specific lubricant, we carried out a series of finite element analyses.

## 2 Experimental

### 2.1 Pilot wire drawing machine

Fig.1 shows a pilot wire drawing machine with die, lubricant box and jawing system, and a pointing machine to make the top-end of a wire specimen sharpen. Fig.2 shows the shapes of an initial specimen and a deformed specimen. In the figure, the top-end of deformed specimen denoted as the tapered part is processed by the pointing machine. The adequate tapered length is the interval from the exit of lubricant box to the exit of die, as shown in Fig.1(b). When the specimen passes the lubricant box, the powder-type lubricant is covered on the surface of the specimen. The top-end of specimen is bitten in the jaw and drawn to the other side, i.e., the position of a drawing motor. Drawing force is measured by a load cell equipped in a moving slider driven by the motor.

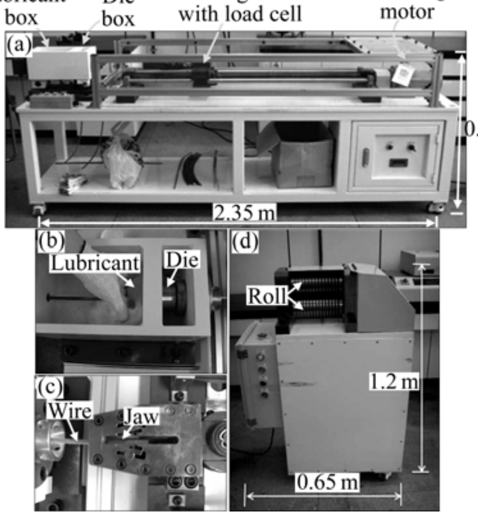



**Fig.1** Pilot wire drawing machine to measure drawing force and state of coating layer: (a) Structure of pilot wire drawing machine; (b) Anointment of powder-type lubricant; (c) Operation of drawing machine; (d) Pointing machine

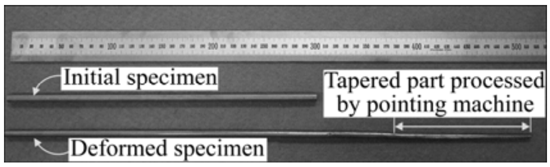



**Fig.2** Shapes of initial specimen and deformed specimen

### 2.2 Specimen

We fabricated four kinds of specimens, which consist of a substrate and a coating, as shown in Table 1. As the substrate, ULCB (Ultra low carbon bainite) and AISI1045 were used. ULCB is a non-heat treated steel which has very deformable characteristics in a drawing machine without any heat treatment of a raw wire processed from a wire rod mill. AISI1045 is a conventional medium carbon steel which is commonly used in drawing process after heat treatment. A phosphate is commonly used as a coating to prevent the substrate from seizing on the die surface of the wire drawing and cold heading process. Coating 3670 is normal phosphate used in the coating of AISI1045.

Others are variants of 3670 to fit to ULCB. Table 2 shows the specimen geometries and the material parameters of substrates. It is noted that the yield stress and the modulus of elasticity of ULCB are much higher than those of AISI1045 steel.

**Table 1** Specimen structure composed of coating material and drawing steel (substrate)

| Specimen type | Coating material | Drawing steel (substrate) |
|---|---|---|
| A | 3670 | AISI1045 |
| B | 3670X | ULCB |
| C | 3675 | ULCB |
| D | 181X | ULCB |

**Table 2** Specimen geometry and material parameters of substrates

| Specimen | Diameter/ mm | Length/ mm | Yield stress (0.5% offset)/MPa | Elasticity modulus/ GPa |
|---|---|---|---|---|
| ULCB | 7.8 | 300 | 575 | 291 |
| AISI1045 | 7.8 | 300 | 453 | 204 |

### 2.3 Test conditions

Powder-type lubricant is usually used when the diameter of wire is less than 8 mm. Since the diameter of specimen was 7.8 mm in this test, the powder lubricant was chosen. We employed two kinds of lubricants which have different lubrication: '$\beta$-type' lubricant (particle size: 4.3 μm avg.) is generally used for the wire-drawing of carbon steel as well as alloy steel; '$\delta$-type' (particle size: 1.0 μm avg.) is a high grade lubricant used for stainless steel which requires more strict surface condition than other materials.

Three different reduction ratios were designed to distinguish the amount of deformation. Fig.3 shows the geometries of die with different reduction ratios. The entrance diameter of die is 7.8 mm which is same with that of specimen. Since the conical angles of the three dies are same but the inclined length is different, the reduction ratios vary.

## 3 Finite element analysis

We performed a series of finite element analyses (FEA) to calculate the friction coefficient between wire specimens and dies during drawing. To find the actual friction coefficient during drawing, FE simulations are iteratively performed with changing estimated friction coefficient until the difference between the calculated drawing force and the measured one is very small. For the FE simulation, a commercial FE code, ABAQUS® which has a good capability in the analysis of the non-

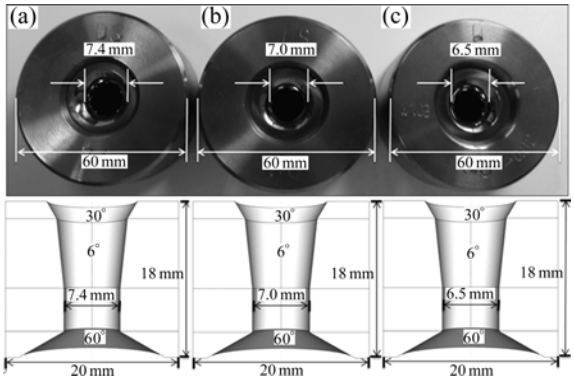



**Fig.3** Actual appearance and dimensions of die for three different reduction ratios: (a) Reduction ratio of 10%; (b) Reduction ratio of 20%; (c) Reduction ratio of 30%

linear behavior with severe elastic-plastic deformation is employed.

Fig.4 shows the mesh and boundary conditions of the specimen to analyze the wire drawing. The geometries of die and specimen as well as the drawing speed coincide with the pilot drawing test condition. The specimen section was taken as the analysis domain and the die was treated as the rigid body

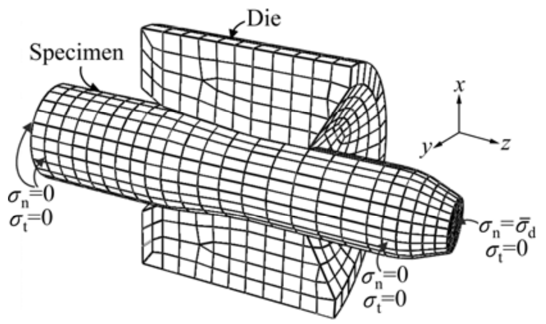



**Fig.4** FE meshes and boundary conditions used in wire drawing analysis (Symbolic parameters $\sigma_n$, $\sigma_t$ and $\sigma_d$ represent normal surface traction, tangential surface traction and drawing pressure on top cross section of specimen, respectively)

## 4 Results and discussion

Fig.5 shows the variation of drawing force measured at the different specimen types, reduction ratios and lubricants. The drawing force was measured by the load cell with time. When the top of specimen is deformed first, the drawing force is rapidly increased. The drawing force knocks down as the tail of specimen leaves the die. In Fig.5, solid line represents the drawing force when $\delta$-type lubricant is covered on the surface of specimen. The drawing force by $\beta$-type lubricant is symbolized by dashed line. The reason why the starting point of drawing force is different for each specimen is that the length of tapered part of each specimen is different.

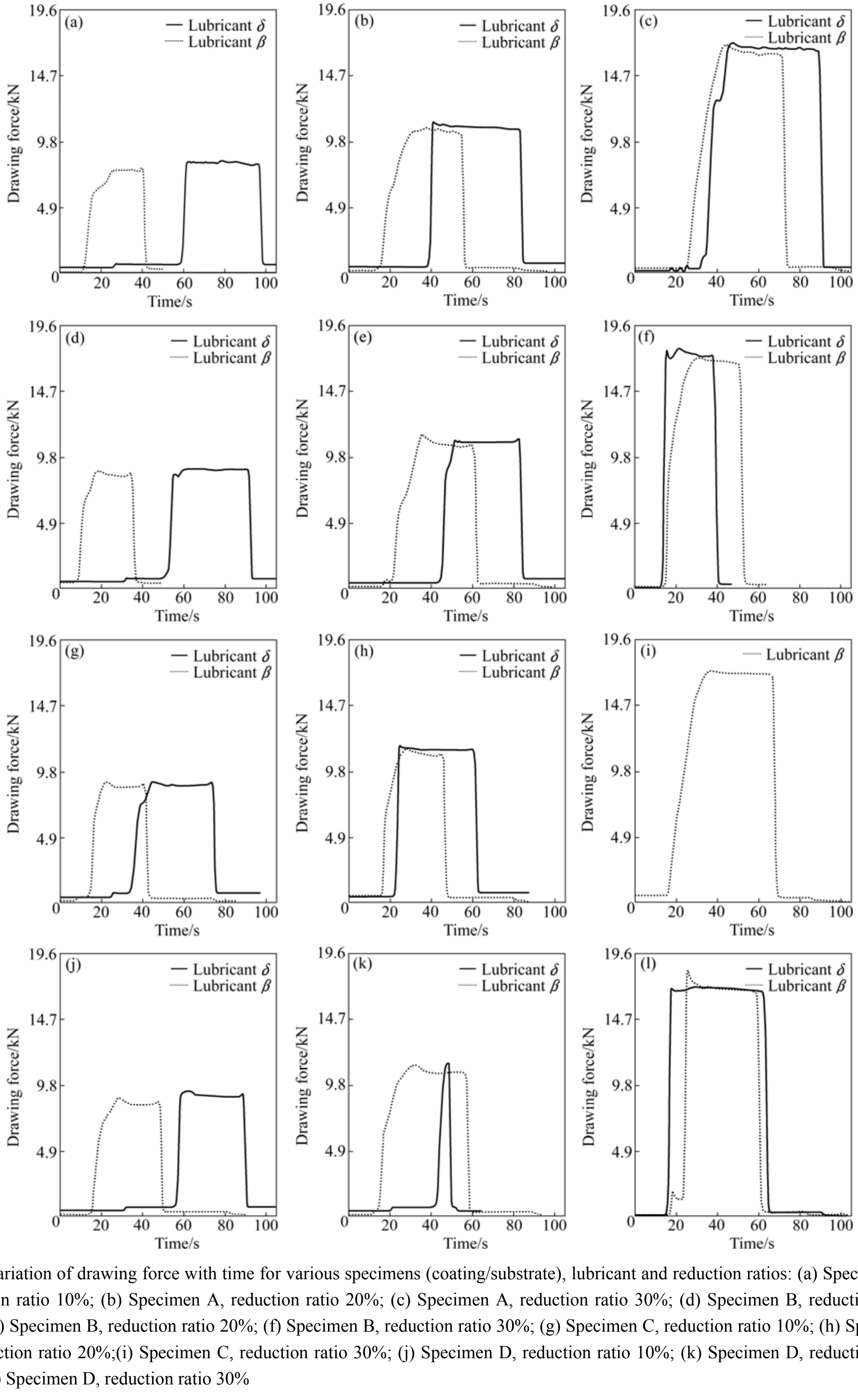



**Fig.5** Variation of drawing force with time for various specimens (coating/substrate), lubricant and reduction ratios: (a) Specimen A, reduction ratio 10%; (b) Specimen A, reduction ratio 20%; (c) Specimen A, reduction ratio 30%; (d) Specimen B, reduction ratio 10%; (e) Specimen B, reduction ratio 20%; (f) Specimen B, reduction ratio 30%; (g) Specimen C, reduction ratio 10%; (h) Specimen C, reduction ratio 20%;(i) Specimen C, reduction ratio 30%; (j) Specimen D, reduction ratio 10%; (k) Specimen D, reduction ratio 20%; (l) Specimen D, reduction ratio 30%

It is noticeable that the behavior of drawing force remarkably varies with lubricant type. The drawing force of the specimen covered with $\delta$-type lubricant jumps up and directly reaches the steady state as the top of specimen passes the die, whereas the one covered with $\beta$-type lubricant gradually reaches the steady state with several slopes. This is because that the particle size of $\delta$-type lubricant is smaller than that of $\beta$-type lubricant. As the size of a particle is small, the adhesion of a lubricant powder is high. It is deduced that the $\delta$-type lubricant is fully covered on the entire surface of specimen due to a fair adhesion characteristics as soon as the one passes through a lubricant box. The $\beta$-type lubricant, however, is not so adhesive that the $\delta$-type lubricant does.

The variation of the drawing force with reduction ratio is observed. In the case where wire specimen is covered with $\delta$-type lubricant, the progressive shape of drawing force does not vary with reduction ratio. For the $\beta$-type lubricant, however, the multi-step slop of the shape at the initial stage of drawing is transformed to one-slope curve as the reduction ratio increases. This indicates that the high contacting pressure due to the high reduction ratio makes the roughness of tapered part of specimen blunt and leads to the uniform contact between the specimen and the die. The drawing force of the specimen C covered with $\delta$-type lubricant (Fig.5(i)) was not measured because of the breakage caused by the over-pulling beyond the yield stress.

To analyze the friction characteristics of coating, we should transform the measured drawing forces to the friction coefficients. Since the die geometry and the material parameters are given, we can inversely calculate the friction coefficient by the finite element analysis. Fig.6 shows the friction coefficients for the different specimen-type, lubricant and reduction ratio. These are calculated on the basis of the average drawing force under steady-state deformation condition.

The flow or yield stress of the specimen A is lower than that of the specimens B, C or D, as shown in Table 2. The drawing force of the specimen A, however, is similar with the others in magnitude (Fig.5), which means that the friction coefficient of the specimen A is higher than the others. This fact is clearly represented in Fig.6. For the specimen A, the variation of the friction coefficient with the lubricant-type is the largest among all specimen types whereas the other specimens have a similar magnitude of the friction coefficient regardless of the lubricant-type. Based on these observations, we may deduce that the friction coefficient is dependent on the flow stress of the substrate of specimen. That is, the contact pressure increases as the flow stress increases, and this leads to tighter adhesion with the powder-typed lubricant between the specimen and the die. Consequently,

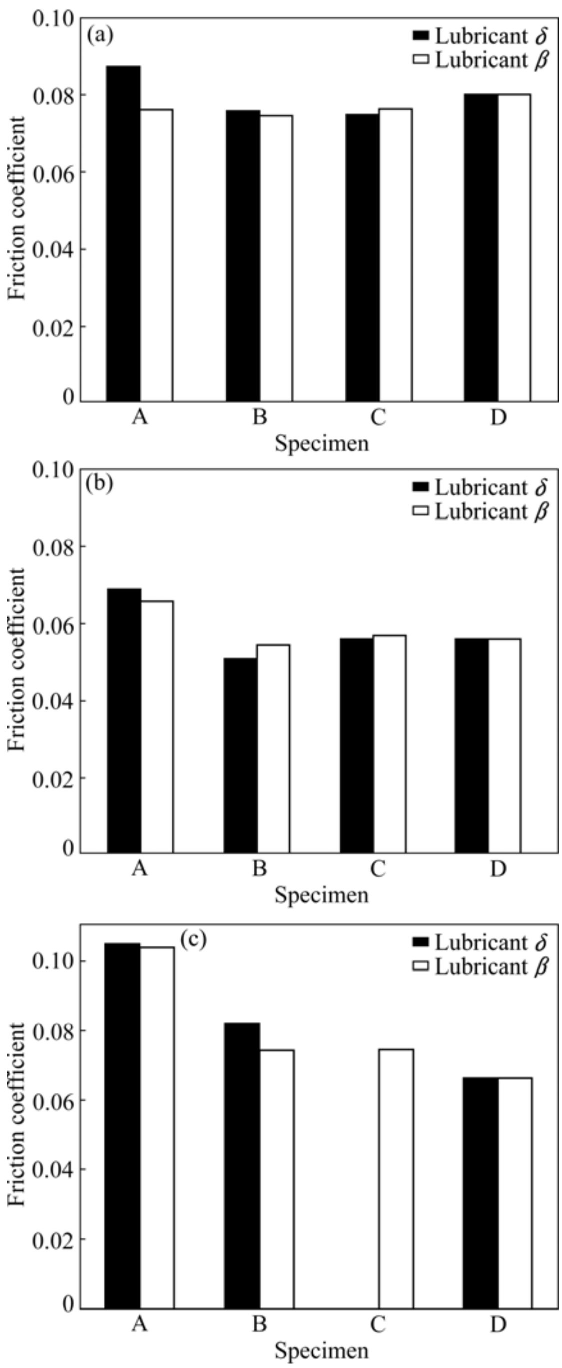
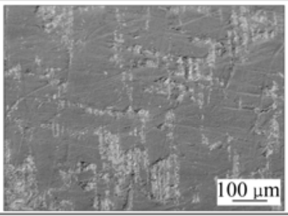
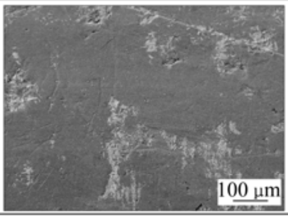
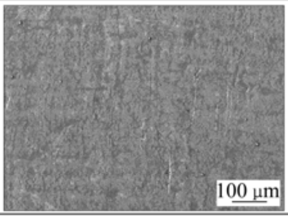
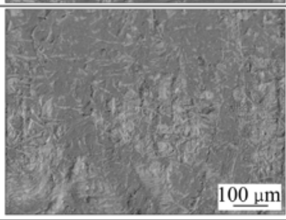
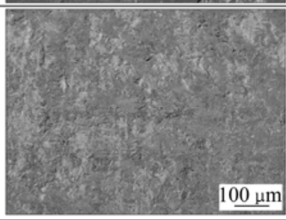
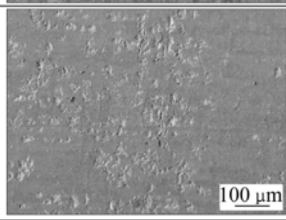
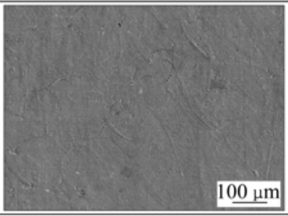
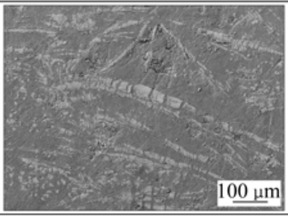
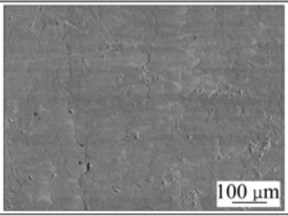
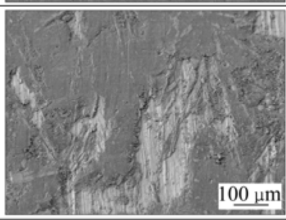
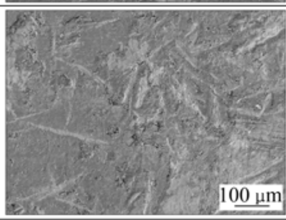
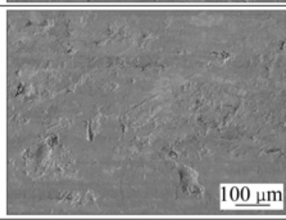
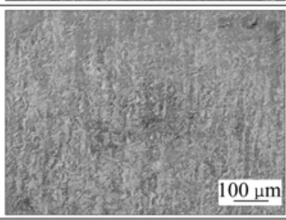
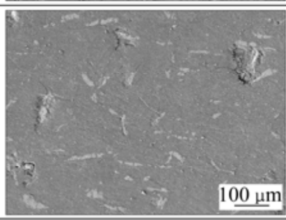
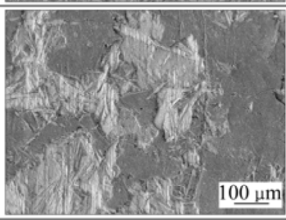
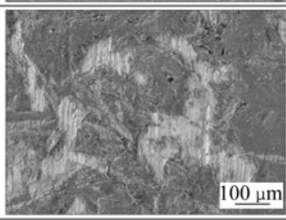
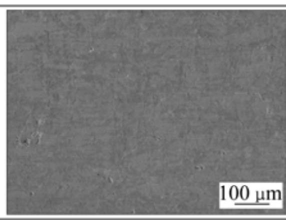
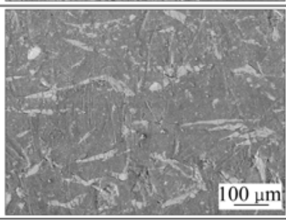
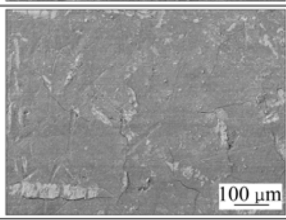
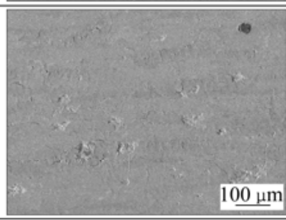
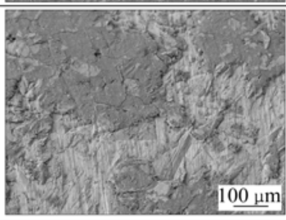
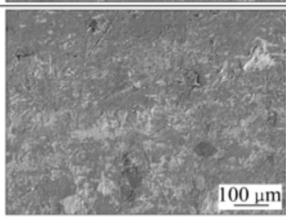
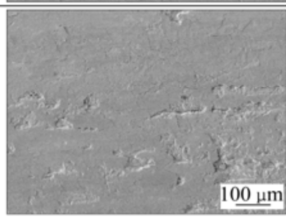



**Fig.6** Friction coefficients calculated by finite element method for various specimens (coating/substrate), lubricants and reduction ratios: (a) Reduction ratio of 10%; (b) Reduction ratio of 20%; (c) Reduction ratio of 30%

the friction coefficient in the specimens B, C or D is lower than that in the specimen A. In the case of relatively loose contact such as the specimen A at 10% reduction ratio, the friction coefficient is more dependent on the particle size of the powder-typed lubricant.

Table 3 shows the surface states of the specimens after wire drawing test, which are taken by SEM (Scanning electron microscope). Table 3 represents the

**Table 3** Inspection results of drawn wire surface by SEM for various specimens (coating/substrate), lubricants and reduction ratios (Dark part represents original surface covered with phosphate coating and light part represents substrate without coating)

| Specimen | Lubricant | Reduction ratio | | |
|---|---|---|---|---|
| | | 10% | 20% | 30% |
| A | δ |  |  |  |
| | β |  |  |  |
| B | δ |  |  |  |
| | β |  |  |  |
| C | δ |  |  | |
| | β |  |  |  |
| D | δ |  |  |  |
| | β |  |  |  |

effect of a coating/substrate, lubricant and reduction ratio on the surface defects. It is obviously observed that the lubricant-type gives a great effect on the difference in the surface state of specimen. The difference in the specimen A is minor, but the one in the specimens B, C, and D is remarkable. When the $\beta$-type lubricant is used in wire-drawing of the specimens B, C, and D, the surface defects occur as a form of local or wide galling.

Since the friction coefficient of specimen A is higher than the others, as shown in Fig.6, the surface defects is not caused by the steady-state deformation behavior. Then, we may deduce that the non-steady state deformation behavior brings about those defects. Considering the surface defects are dominant in wire-drawing used with $\beta$-type lubricant, we may conclude that the multi-slope behavior of drawing force at the initial stage of drawing is main cause of those defects. This fact might point out that the cause of the surface defect is not the magnitude of the friction coefficient but the variation of the friction coefficient with drawing time. The reason why those defects occur in specimens B, C and D is that the normal pressure between the specimen and the die owing to the flow stress of substrate is so high that the marks occur on the surface of wire.

## 5 Conclusions

1) The crucial factor to give an effect on the surface defect of wire is the lubricant-type at the initial stage of drawing. As the size of powder particle is smaller, the lubrication between wire and die is more fully formed around the entire contact surface without a local dry contact.

2) The lubricant with a large particle causes the retardation of the full lubrication and the local delamination of coating layer. This coating defect is more significant as the flow stress of the substrate increases.


## Acknowledgement

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