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極低温引抜きによるアルミニウムワイヤの引抜き性改善

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Improvement Drawability of Advanced Aluminum Alloy Wire by Using Cryogenic Drawing Method

by

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Abstract

Improvement of drawability aluminum A6061 alloy wire in the conventional wire drawing and cryogenic wire drawing was examined. In two wire drawing methods, we clarified the mechanical properties and surface properties of the drawn wire as well as drawability. The drawn aluminum A6061 alloy wire has high strength but low workability. Cryogenic drawing has good lubricity and is convenient for improving drawability of aluminum A6061 alloy wire. For the purpose of this research, the best temperature annealing condition for wire drawing and drawing condition were established. In addition, the effect of half-die angle on drawability was discussed using FEM (Finite Element Method) and slab method. By cryogenic wire drawing, it is clarifying that high strength aluminum wire could be easily drawn to a total reduction of area 80%, and the surface properties were very good. The effectiveness of the cryogenic drawing method for advanced aluminum alloy wire was confirmed.

Keywords: Drawability, Aluminum Alloy Wire, Finite Element Method (FEM), Cryogenic Drawing.

1. Introduction

Even though the aluminum alloys wire has useful mechanical properties like high strength, they are very hard to manufacture due to their low workability. In this study, we will improvement on drawability aluminum A6061 alloy wire in two wire drawing method. The conventional wire drawing and cryogenic wire drawing of advanced aluminum alloy wire was examined. The mechanical properties and surface properties of aluminum A6061 alloy wire on the drawn wire as well as drawability[1]. Cryogenic drawing has good lubricity and is convenient for improving drawing of aluminum A6061 alloy wire[1,2]. Cryogenic drawing was performed by using liquid nitrogen. Liquid nitrogen has a boiling point below -320°F (-196°C)[3,4].

The purpose in this study is the best temperature annealing condition for aluminum A6061 alloy wire drawing and drawing condition were established. In addition, the effect of half-die angle on drawability was discussed using FEM (Finite Element Method) and slab method. And by using cryogenic wire drawing, it is clarify that high strength aluminum wire could be easily drawn to a total reduction of area 80%, and the surface properties were very good. The results in two wire drawing methods will be compare. The effectiveness of the cryogenic drawing method for advanced aluminum alloy wire was confirmed.

2. Tested Wire and Experimental Condition

2.1 Material condition

In this study, the tested wire was an aluminum A6061 alloy wires. The diameter of mother wire is φ7.6mm. Annealed aluminum A6061 alloy wire at 400°C, 500°C and 600°C were prepare. Table 1 shows the chemical composition of tested this wire[5].

Table 1 Chemical composition of tested aluminum A6061 alloy wire (%)

A6061	**Al**	**Cr**	**Cu**	**Fe**	**Mg**
	Bal.	0.35	0.40	0.7	1.2
	Mn	**Si**	**Ti**	**Zn**	
	0.15	0.8	0.15	0.25	

2.2 Wire drawing condition

The conditions for drawing wire for the lubrication Petroleum-based hydrocarbon was used. a tungsten carbide dies with a die half-angle α of 5°, 6°, 7°, 9°, 11° and 13° were used for the drawing process and the reduction per pass was about 20%, the explanation of the drawing process and the staging of the process is shown in Figure 1.

The definitions of reduction per pass (R/P) and total reduction (R_t) are shown in Figure 1 also the equation (1), (2) respectively[6].

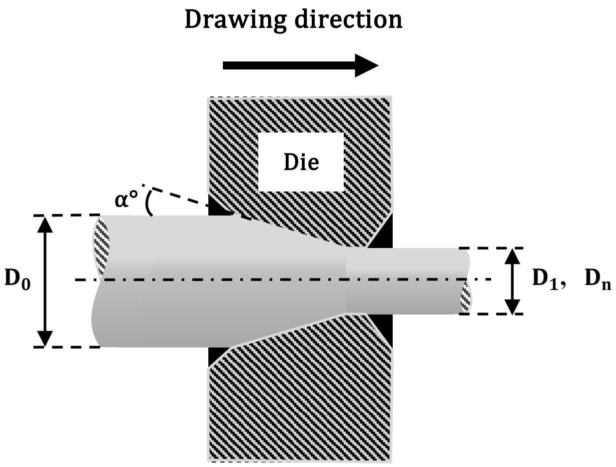

Fig. 1 Definition of wire drawing

$$R/P = \left[1 - \left(\frac{D_1}{D_2}\right)^2\right] \times 100[\%] \qquad \dots (1)$$

$$R_t = \left[1 - \left(\frac{D_n}{D_0}\right)^2\right] \times 100[\%] \qquad \dots (2)$$

3. Result and Discussion

3.1 Effect of viscosity of drawing lubricating oil on drawability in conventional wire drawing

We prepared lubricating oils with viscosities of 110, 2000, 6000 and 10000 for wire drawing. The drawing limit was examined under the drawing condition that the die half angle was 6° and reduction per pass was 20% and the result is shown in Figure 2. Figure 3 shows SEM observation of drawn wire surface after 7-pass drawing.

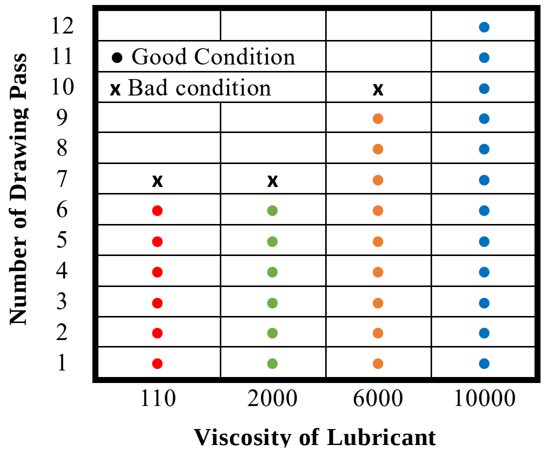

Fig. 2 Effect of viscosity of lubricant on drawability

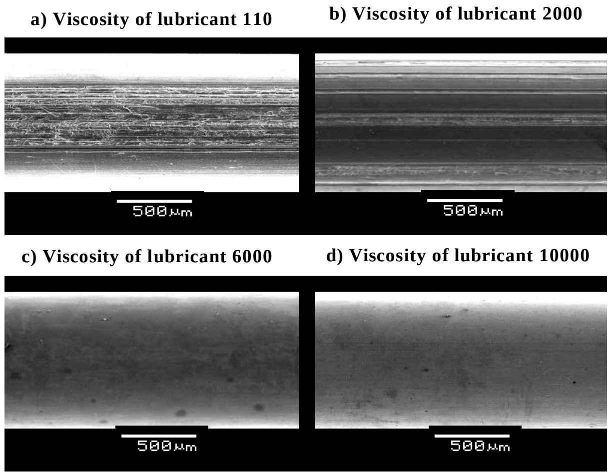

Fig. 3 Scanning Electron Microscope (SEM) images of the surface of drawn wire at 7-pass drawing

From the SEM results show, when the viscosity of lubricant was 110 and 2000, that the lubricant was not drawn sufficiently between the dies and the wire during drawing, it was found that a die mark was formed on the wire surface after 7-pass drawing.

In the drawing of the aluminum alloy wire, it showed different drawability depending on the viscosity of the lubricant. When the viscosity of the lubricant was 110 and 2000, the drawability are not good, the viscosity become high such as 6000 or 10000, the drawability was improved. It is possible to draw, 12 pass and without occurrence of breakage resulting in a wire with a good wire surface. The result of drawing stress at that time is shown in Figure 4.

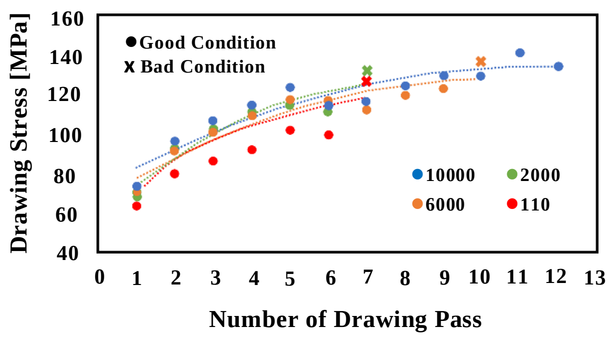

Fig. 4 Effect of viscosity of lubricant on drawing stress

Until the 6 passes, the drawing stress was low when the viscosity was low, but the drawing stress rapidly increased at 110 and 2000 at the seventh pass and the wire broke, but at the viscosity of 6000 and 10000 it was found that it can be drawn without large fluctuation of drawing stress. We also investigated whether the viscosity of the lubricant affects the surface properties, and the results are shown in Figure 5 and Figure 6.

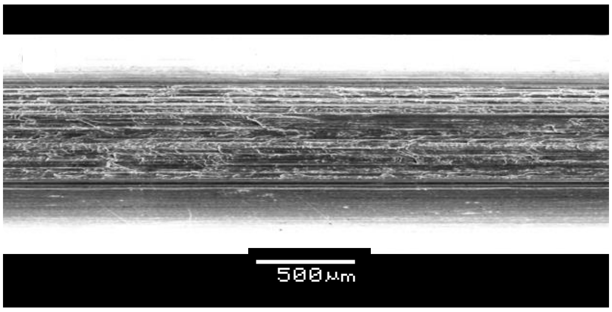

Fig. 5 SEM image of the drawn wire surface
by using lubricant with low viscosity

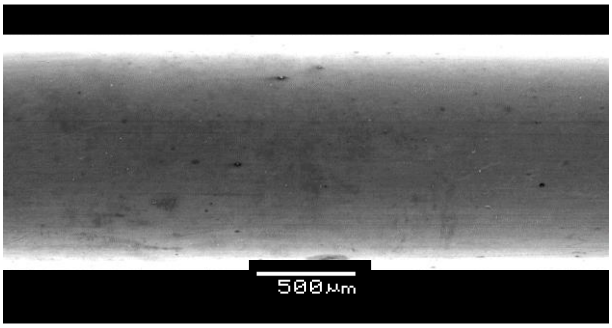

Fig. 6 SEM image of the drawn wire surface
by using lubricant with high viscosity

When the viscosity of the lubricant was low, and the lubricant was not drawn sufficiently between the dies and the wire during drawing, it was found that a die mark was formed on the wire as shown in Figure 5.

From the viewpoint of improving the strength of the wire and manufacturing cost, it is preferable to draw without conducting intermediate annealing. Therefore, it can be said that the optimum lubricant for aluminum A6061 alloy wire has a viscosity of lubricant 10000.

3.2 Optimum drawing condition using FEM analysis and Slab method

It was found that drawing work can be performed by setting the viscosity of the lubricant to 10000. Therefore, by using FEM analysis and formula of Körber and Eichinger equation (3), find the optimum die half angle when using a lubricant with a viscosity of lubricant 10000.

$$F = YA_1\left\{\left(1+\frac{1}{B}\right)\left[1-\left(\frac{A_1}{A_0}\right)^B\right]+\frac{4\alpha}{3\sqrt{3}}\right\} \quad \dots (3)$$

The definition equation (3) F is Force, Y is Averages Deformation Resistance, μ is Friction Coefficient, α is die half-angle $B = \mu \cot \alpha$[7]. The result is shown in Figure 7.

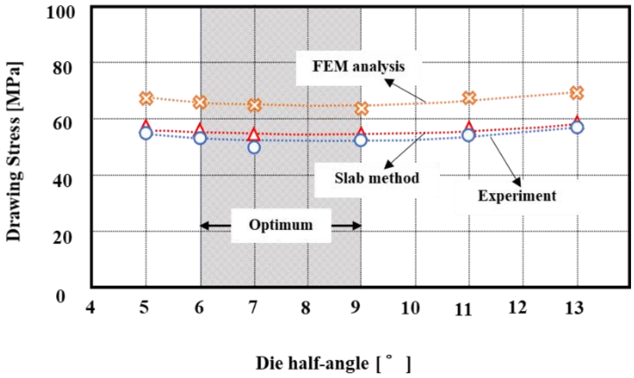

Fig. 7 Optimum die half angle condition by FEM analysis and calculation equation

From the results calculated by FEM analysis and calculation by equation (3), the drawing stress is lower from 6 ° to 9 °, the drawing stress increases from 9 ° to 13 °, the friction of coefficient is 0.08. In addition, the stress inside the wire due to the difference in die half angle was confirmed by FEM analysis, and the result is shown in Figure 8 and Figure 9.

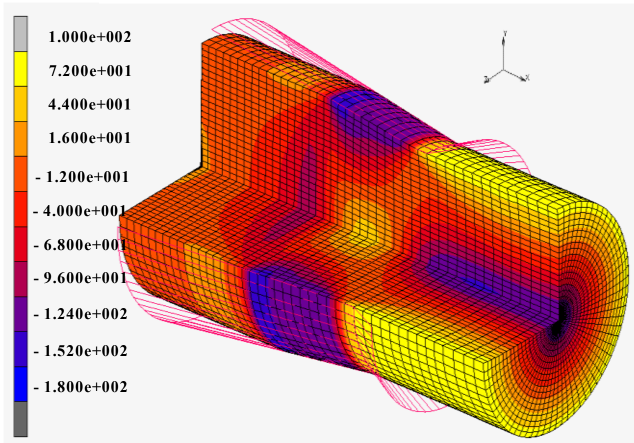

Fig. 8 Distribution of hydrostatic stress with low die half-angle α of 7° by FEM

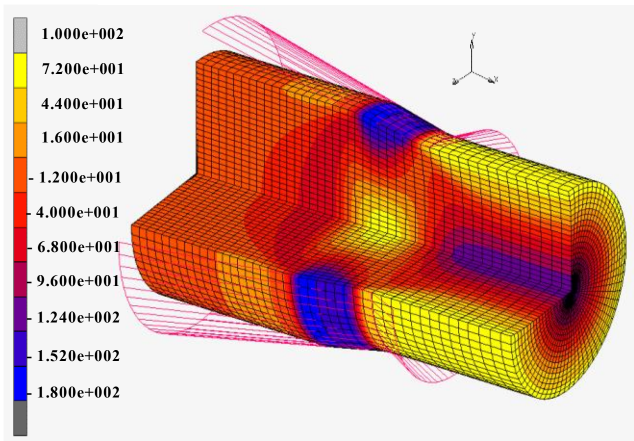

Fig. 9 Distribution of hydrostatic stress with high die half-angle α of 11° by FEM

By increasing the die half-angle, a large tensile stress is generated in the center portion of the wire and the possibility of occurrence of internal defect is high. In addition, the experimental values, analytical values and calculated values all show close values, indicating that the coefficient of friction is between 0.05 and 0.08.

Therefore, when the viscosity of the lubricant is 10000, the coefficient of friction is 0.05 to 0.08, prediction of the drawing stress by FEM analysis and calculation by equation (3) is possible, and the drawn stress decreases at 6 ° to 9 ° of die half angle, it can be said that it is the optimal die half angle.

3.3 Effect of annealing temperature on drawability

Following this the optimum heat treatment of the wire rod is studied. Before the drawing process, the wire was annealed to improve drawability. Therefore, in order to investigate the optimum annealing temperature of the aluminum alloy wire, the annealing was carried out at 400 °C, 500 °C. and 600 °C, and the mechanical properties of the annealed wire were investigated, and the results are shown in Table 2 and Figure 10.

Table 2 Tensile strength and elongation in tensile test of annealed wire with various temperature

Aluminum A6061 Alloy Wires			
Temperature [°C]	400	500	600
Tensile strength [MPa]	145	148	146
Elongation [ε]	23	23	25

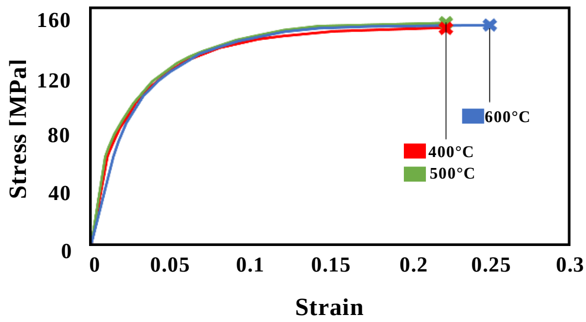

Fig. 10 Stress-strain curve of annealed aluminum A6061 alloy wire with various temperature

By changing the annealing temperature, there was no significant difference in tensile strength. However, ductility improvement of about 2% could be confirmed at annealing temperature 600 °C compared with other temperatures. More specifically, in order to investigate the effect of annealing temperature, the annealed wire at each temperature was drawn to the drawing limit, and the result is shown in Figure 11.

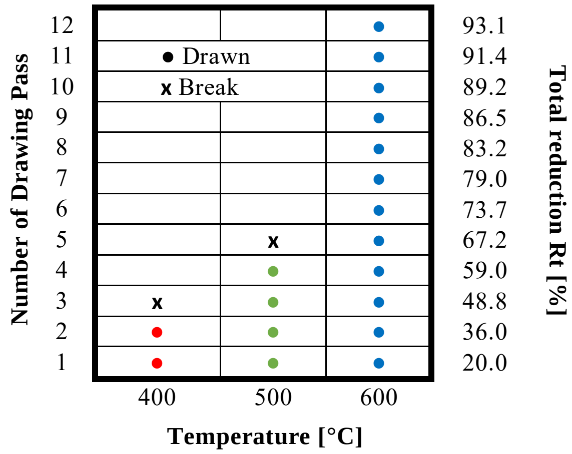

Fig.11 Effect annealing temperature on drawability

In drawing of all annealed wires, at 600°C, wire was drawn limit up to 93.1% that is the highest drawability, 500°C was drawn up to 59.0% and drawn annealed wire at 400°C was drawn up to 36.0% respectively. These reasons are relative to the result of Figure 11. Therefore, suitable annealing temperature of aluminum A6061 alloy wire is 600°C. Because at temperatures of 400°C and 500°C a wire break occurs at the maximum drawing limit respectively. The results are shown in Figure 12.

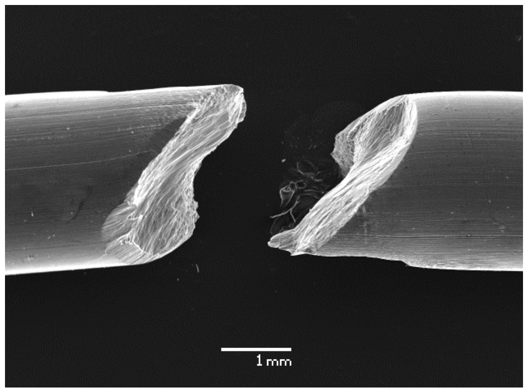

Fig.12 SEM images of wire break during drawing

4. Cryogenic Drawing Method

Liquid nitrogen (LN2) is most commonly used in cryogenics due to its widespread availability worldwide. Liquid nitrogen has a boiling point below -320°F (-196°C)[3,4]. By cryogenic wire drawing with high strength aluminum wire could be easily drawn without using oil. Cryogenic drawing was performed by using liquid nitrogen for at least 60sec before starting the process wires annealed at temperature 600 °C. The explanation of the cryogenic wire drawing process and the staging of the process is shown in Figure 13.

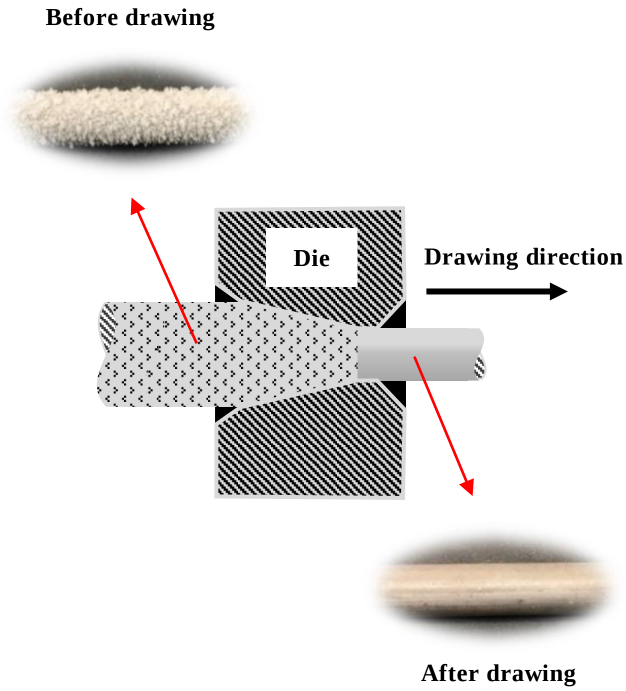

Fig. 13 Cryogenic wire drawing process

The drawability and drawing stress in each pass in the cryogenic drawing and the conventional drawing are shown in Figure 14 and Figure 15.

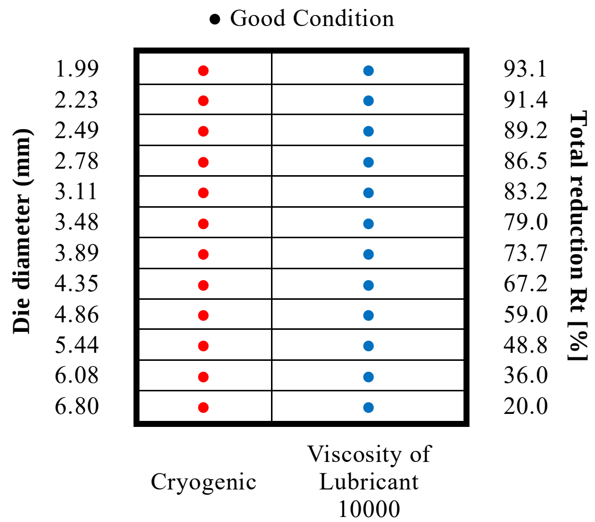

Fig. 14 Drawing possibility in wire drawing by using cryogenic and lubricant

From the result of wire drawing by using cryogenic drawing and viscosity of lubricant 10000. The diameter of the mother of the aluminum A6061 alloy wire is φ7.6mm drawn to the drawing limit with a diameter φ 1.99mm, 12 passes were drawing without occurrence of breakage with the total cross-section reduction rate was as 93.1% respectively.

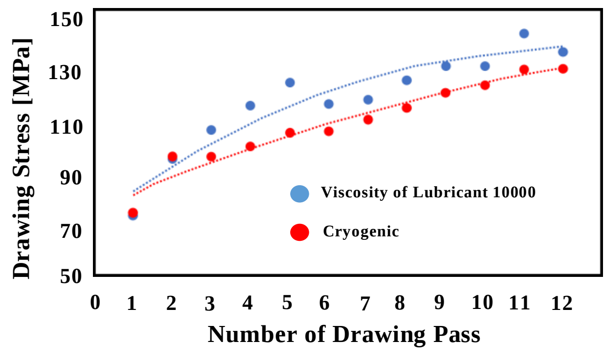

Fig. 15 Drawing stress by using cryogenic and lubricant

Figure 15 shows the results of drawing stress in the cryogenic drawing and the conventional drawing. Vertical line is drawing stress while horizontal line is drawing pass. The drawing stress using the liquid nitrogen are lower than the viscosity of lubricant 10000.

After that we examined the mechanical properties in the cryogenic drawing and the conventional drawing with tensile strength in every 2-pass wire drawing pass. The results are shown in Figure 16 and Figure 17.

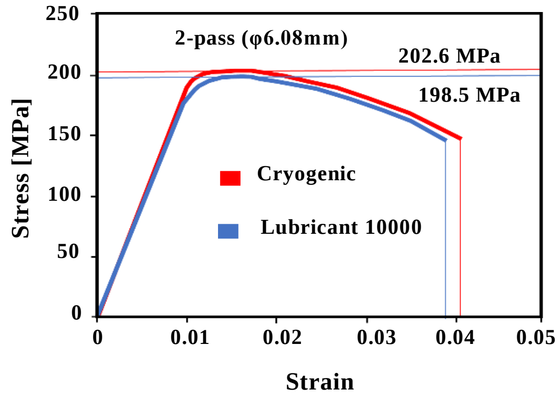

Fig 16. Stress-strain curve of drawability by cryogenic and viscosity of lubricant 10000

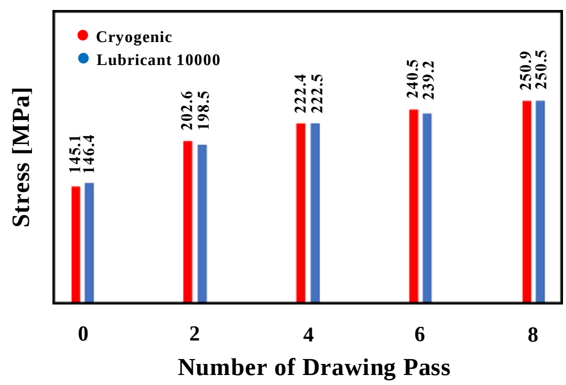

Fig 17. Compression stress-strain curve between cryogenic and lubricant 10000 on every two passes

From the result of Figure 16 shows at 2-pass with φ 6.08mm that 202.6MPa was little highest tensile strength by cryogenic, while 198.5MPa by viscosity of lubricant 10000 and also were considered on percent of elongation, 4.1% by cryogenic longer than 3.8% by viscosity of lubricant 10000. As the result of stress-strain curve shown in Figure 17, there was no significant difference in tensile strength. The mechanical properties of a wire drawn in the cryogenic drawing and the conventional drawing are similar.

In two methods wire drawing has been done. After that we also investigate whether the cryogenic drawing and the conventional drawing affect the surface properties of aluminum A6061 alloy wire on 12-drawing passes by SEM. The surface image is shown in Figure 18 and Figure 19.

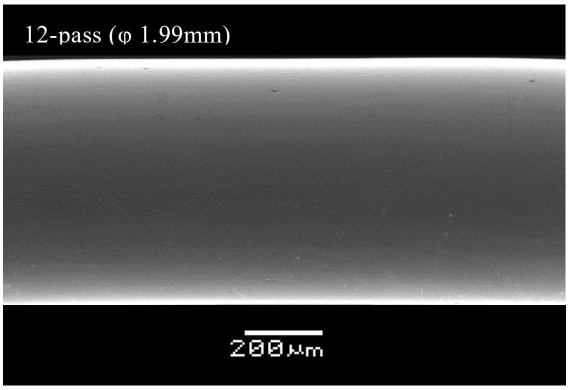

Fig. 18 SEM images of drawn wire aluminum A6061 alloy by using cryogenic

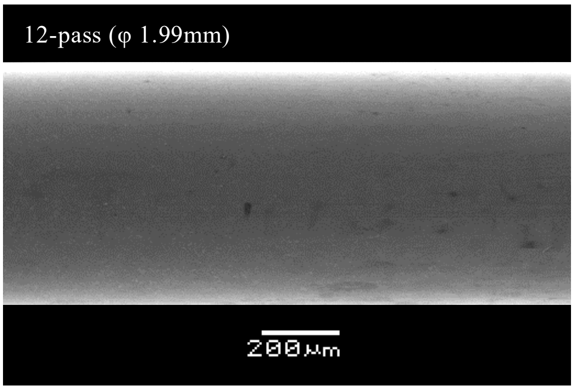

Fig. 19 SEM images of drawn wire aluminum A6061 alloy by using viscosity of lubricant 10000

Scanning Electron microscope (SEM) image is shown in Figure 18 and Figure 19. Although the total cross-section reduction rate was as 93.1% with a diameter φ 1.99mm, a wire surface property without defects was obtained. It was determined that the wire drawn by the cryogenic wire drawing had a very good surface like in the conventional drawing method.

5. Conclusions

Research on improvement drawability of aluminum A6061 alloy wire has done. We examined the annealing condition, drawing condition and lubricant selection by conventional drawing also propose cryogenic drawing and examined the drawability.

1) The annealing temperature of mother aluminum A6061 alloy wire for improving the drawability is 600 °C.
2) The higher the viscosity of lubricant, the better for the drawability in conventional drawing process.
3) The optimal drawing conditions for aluminum A6061 alloy wire are R/P 20% and the optimal die half-angle (α) is between 6° to 9°.
4) By using cryogenic drawing, even aluminum alloy wire with poor formability can be easily drawn. A drawn wire with a good surface, properties was obtained.

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