Mechanical Properties of Silver Filament Produced by the Method of Glass-Coated Melt Spinning

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The mechanical properties of silver filaments produced by the method of glass coated melt spinning are studied.

In spite of a large scatter in the data obtained, it is apparent that there is a size effect on the strength of silver filaments except for the filaments spun at a winding speed of 238 m/min (sample 3). The silver filament of 4.7 μm in diameter has a tensile strength of 37 kg/mm² and an elongation of 1.5%. A large scatter in the elongation is observed for sample 3. The slip lines are observed on the fracture surface of the deformed filaments except for sample 3.

These behaviors are related to the fiber texture. The double $\langle 100 \rangle + \langle 221 \rangle$ fiber textures are observed in sample 3, and a single $\langle 100 \rangle$ fiber texture, in the other filaments. The maximum degree of orientation is observed at a winding speed of 200 m/min.

These results are explained from the point that the twin deformation occurs on the processing of melt spinning at a winding speed of 238 m/min.

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I. Introduction

In 1924, Taylor reported the method for obtaining microwires by using the glass⁽¹⁾ and later, and an automatic technique for this was developed by Ulitovskiy⁽²⁾. The melt spinning of metals by this method has been investigated in our laboratory, and it has been described that the size effect on the strength of copper and iron filaments spun at various winding speeds is observed⁽³⁾ and the degree of orientation in the filaments increases with increasing winding speed⁽⁴⁾.

In this paper, the mechanical properties of silver filaments spun under various spinning conditions will be reported.

II. Experimental

The melt spinning of silver was carried out by the same method as that done for copper⁽³⁾.

The casting apparatus used is shown in Photo. 1. About 0.7 g of 99.99% purity silver was put into a pyrex glass tube and melted by an

Photo. 1 Casting apparatus for glass coated melt spinning.

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Table 1 Spinning conditions of glass coated melt spinning of silver at about 1200°C.

Sample	Winding speed (m/min)	Winding tension (kg/mm ²)	Cross-sectional area		Percent reduction in area	Diameter of the filament (μ)	K^*
			A_0 (cm ²)	A_w (cm ²)			
1	57	3	4.3×10^{-4}	7.9×10^{-7}	99.8	10 ± 5	1.0
2	158	7	5.7×10^{-4}	2.8×10^{-7}	99.9	6 ± 2.5	1.1
3	238	10	5.0×10^{-4}	3.8×10^{-7}	99.9	7 ± 2	1.8
4	332	20	5.4×10^{-4}	2.0×10^{-7}	99.9	5 ± 1.5	2.0
5	477	40	3.8×10^{-4}	1.3×10^{-7}	99.9	4 ± 1.2	2.8

A_0 , A_w : Cross-sectional area at the bottom of the globule and at the winding drum, respectively.

K^* : The weight ratio of silver filament to coated glass.

induction heating coil. Due to the interaction between the magnetic field and the eddy current induced in the metal, the molten metal can be kept globular and suspended in a fixed position. Then the molten metal was drawn down together with the glass tube and the glass coated metal filament was coiled up to a winding drum. The glass tube is fed automatically at a rate corresponding to the rate of drawing and the position of the globule relative to the heating coil is fixed as shown in Fig. 1.

The temperature of the molten metal was $1225 \pm 25^\circ\text{C}$, which was controlled by keeping the position of the globule constant. Beyond 10 cm from the bottom of the globule, however,

Fig. 1 Schematic diagram of the glass coated melt spinning.

the temperature of the filament had dropped to room temperature. The winding tension was measured in an electronic tensiometer and the cross-sectional area of the filament was measured by the photographic method. The coated glass was finally removed by dissolving it in fused NaOH for 10 sec at about 300°C and then the filament was rinsed in water.

Tensile strengths of the filaments were measured in an Instron-type testing machine. The gauge length was 10 mm and the elongation rate was 2 mm/min. Fractographs of the deformed filaments were obtained by a scanning electron microscope. The degree of orientation was also measured by an X-ray diffraction technique to study the relation between the mechanical properties and the fiber texture. The degree of orientation was determined by the orientation function, f , defined as $f = 1/2 (\langle 3 \cos^2 \phi \rangle - 1)$, where ϕ denotes the angle between the fiber axis and a crystallographic principal axis and $\langle \cos^2 \phi \rangle$ represents the mean square of directional cosines of $\phi^{(4)(5)}$.

III. Results

The spinning conditions examined are listed in Table 1. As can be seen from the table, there was a considerable scatter in the diameter of the filament because of the temperature fluctuation of the molten filament between 1200 and 1250°C .

Figure 2 shows some typical examples of the stress-strain curves of the filament. It is shown for the filament except the filament spun at a winding speed of 238 m/min (sample 3) that

Fig. 2 Representative stress strain curves for the silver filaments.

- (1) spun at a winding speed of 158 m/min
(2) spun at a winding speed of 238 m/min

Fig. 3 The variation of the tensile strength with diameter for the silver filaments spun at various winding speeds.

- 477 m/min —▲— 158 m/min
—○— 332 m/min —△— 57 m/min
● 238 m/min

rapid hardening occurs by elongation and a maximum stress level is reached after an elongation of a few percent, as observed for copper filaments. Figures 3 and 4 show the variations of the tensile strength and elongation with the filament diameter. In spite of a large scatter in experimental data, the tensile strength increases and the elongation decreases as the diameter decreases in all filaments spun at constant winding speed except sample 3. The critical diameter which exhibits the size effect decreases as the speed of winding increases. For sample 3, a large scatter in elongation is observed. The fractographs of opposing segments of the filament are shown in Photo. 2. Many slip lines and local shrinking by elonga-

Fig. 4 The variation of the elongation with diameter for silver filaments spun at various winding speeds. The symbols used are the same as in Fig. 1.

- 477 m/min —▲— 158 m/min
—○— 332 m/min —△— 57 m/min
● 238 m/min

tion are observed on the filament except sample 3 subjected to the elongation more than 10%. In the latter case, the cup and cone type fracture, as observed for bulk metal, is found⁽⁶⁾.

The fiber texture was examined in relation to the mechanical properties of sample 3. X-ray diffraction patterns of the filament are shown in Photo. 3. The fiber axis was determined to be a single $\langle 100 \rangle$ fiber texture in the filament except sample 3 having double $\langle 100 \rangle + \langle 221 \rangle$ fiber textures. The relation between the orientation function f for the $\langle 100 \rangle$ fiber axis and the winding speed is shown in Fig. 5.

The maximum value of f is observed at a winding speed of about 200 m/min.

IV. Discussion and Conclusion

A size effect on the strength of silver filament except for sample 3 was found. As compared with the typical strength of pure silver such as a tensile strength 12.7 kg/mm² and an elongation of 48%⁽⁷⁾, a higher tensile strength and a lower elongation in the filament produced by this method were observed, for example 37 kg/mm², 1.5% at 4.7 μm in diameter. The critical diameter at which the size effect appeared decreased with the speed of winding. This dependence was not observed for copper⁽³⁾,

Photo. 2 The fracture morphology of opposing segments of the silver filaments.

- (a) (b) Spun at a winding speed of 158 m/min, fractured at 21.6 kg/mm², 3.3%
 (c) (d) Spun at a winding speed of 238 m/min, fractured at 13.5 kg/mm², 16%

which is considered due to the high winding tension in the case of silver. For sample 3, a large scatter in the elongation was observed. The slip lines and local shrinking were observed on the fracture surface of the deformed filament except sample 3 subjected to the elongation more than 10%.

These behaviors were related to the fiber texture. The double $\langle 100 \rangle + \langle 221 \rangle$ fiber textures were observed in sample 3 and a single $\langle 100 \rangle$

fiber texture in the other filaments. The degree of orientation was measured by orientation function f and the maximum value of f was observed at a winding speed of 200 m/min. As $\langle 221 \rangle$ has twin relation with $\langle 100 \rangle$ for *fcc* metal, it is considered that twin deformation has occurred on the processing of the melt spinning of silver at a winding speed of 238 m/min due to the excess winding tension over the slip deformation. Such twin deformation was

Photo. 3 X-ray diffraction patterns of the silver filaments, taken by a flat cassette camera, the distance from the sample to film being 25 mm. Cu radiation was used.

- (a) Spun at a winding speed of 57 m/min (b) Spun at a winding speed of 158 m/min
(c) Spun at a winding speed of 238 m/min (d) Spun at a winding speed of 332 m/min
(e) Spun at a winding speed of 477 m/min

Fig. 5 The orientation function f of the silver filaments spun at various winding speeds.

not observed in the melt spinning of copper at a melting temperature of about 1300°C . This is considered due to the fact that a winding tension is a few kg/mm^2 for copper due to the

low viscosity of the coated glass and the stacking fault energy of silver is smaller than that of copper^{(8)~(10)}.

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