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EFFECT OF SURFACE ROUGHNESS ON THE SHEET RESISTANCE OF CP TITANIUM FOILS

In this study, we investigated the effect of physical surface roughness on the sheet resistance (R_s) of Commercially Pure titanium (CP-Ti, Grades 1, 2, and 4) foils with varying impurity compositions. Microstructural observations revealed that the grain size of Grades 1 and 2 were 24 and 20 μm, respectively, whereas Grade 4 exhibited a very fine microstructure with indistinct grain boundaries. The surface roughness of the as-received CP-Ti foils was approximately 0.05-0.06 μm, showing no significant difference among the grades. However, the sheet resistance was determined to be 4.05, 4.60, and 4.82 mΩ/□, respectively, indicating an increase with higher impurity content. In contrast, when the surface roughness was mechanically controlled, the sheet resistance of all specimens increased with increasing surface roughness for all grades, confirming a linear correlation between surface roughness and sheet resistance.

Keywords: Surface Roughness; Sheet Resistance; Commercial Pure Titanium; Impurity; Foil

1. Introduction

Titanium has been widely used in a variety of industrial environments due to its excellent corrosion resistance and chemical stability, and it is also considered as a durable material in electrochemical conditions [1-3]. However, a TiO_2 passive film is formed naturally on titanium surfaces under ambient air and moisture exposure. While this film serves as a protective barrier that enhances corrosion resistance, it can also impede electron transport and thereby increase electrical resistance [4-6]. Therefore, for electrical applications of titanium sheets, a quantitative understanding of the factors governing its electrical behavior is essential. In general, from the perspective of Matthiessen's rule, the electrical resistance of metals can be expressed as the sum of contributions from lattice-vibration (phonon) scattering, impurity scattering, and defect-related scattering such as that from dislocations and grain boundaries [7,8]. Commercially pure titanium (CP-Ti) is classified into grades based on allowable impurity limits, such as Oxygen (O) and Iron (Fe), and the permissible impurity content generally increases with grade number [9]. Because impurity atoms act as electron scattering centers, increasing resistance, differences in CP-Ti grade may influence not only mechanical strength but also electrical properties [10,11]. Accordingly, examining grade-dependent variations in sheet resistance of CP-Ti foils provides meaningful basic information for material selection in electrically relevant applications. Moreover, electrical properties can be affected not only by composition but also by the physical surface condition, namely surface roughness [12,13]. Mechanical polishing is a representative process for controlling surface roughness, and changes in surface roughness can alter electron boundary scattering and the effective current path, leading to additional changes in sheet resistance [14]. Therefore, in this study, CP-Ti Grade 1, 2, and 4 foils were utilized to systematically evaluate the effects of composition (Grade) and mechanically controlled surface roughness on sheet resistance. Surface roughness and sheet resistance were first compared among grades in the as-received condition. Subsequently, a range of surface roughness values was obtained by varying polishing conditions, and surface roughness – sheet-resistance correlation was quantitatively analyzed.

2. Experimental

In this study, CP-Ti Grades 1, 2, and 4 foils conforming to the ASTM B265 specification were used, and the chemical composition of each grade is summarized in TABLE 1. Grade 1 contains 0.18 wt.% O and 0.20 wt.% Fe as impurities, and the

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content of O and Fe generally increases with the grade. The microstructure was examined by optical microscopy after etching for 3 s using Kroll's reagent (DI water: HNO_3: HF = 92:6:2). The thickness of the foils was 0.1 mm for all grades. For electrical characterization, the foils were cut into 20 × 20 mm specimens. To minimize measurement errors caused by surface contamination, all specimens were ultrasonically cleaned in acetone for 10 min and dried prior to testing.

TABLE 1

Chemical composition of CP titanium

ASTM B 265	Ti	H max	N max	C max	O max	Fe max
Grade 1	Bal.	0.015	0.03	0.10	0.18	0.20
Grade 2	Bal.	0.015	0.03	0.10	0.25	0.30
Grade 4	Bal.	0.015	0.03	0.10	0.40	0.50

To investigate the effect of surface conditions, the surface conditions were controlled by polishing with SiC sandpaper, varying the grit sizes from 100 to 1200 as shown in Fig. 1. The surface roughness was quantified using the arithmetic mean roughness (R_a), measured with a surface profiler (DektakXT). The electrical properties were evaluated by measuring the sheet resistance (R_s) using the four-point probe method. To accurately assess the correlation between surface roughness and sheet resistance, measurements were performed at the same location on each specimen.

3. Results and discussion

Fig. 2 shows the microstructures of as-received CP-Ti foils for Grades 1, 2, and 4. Grade 1 exhibited grains with a size of approximately 24 μm. Grade 2 showed a tendency toward reduced grain size compared to Grade 1, with a grain size of approximately 20 μm. Notably, Grade 4, which has a high impurity content, exhibited refined and elongated grain morphologies with indistinct boundaries.

Fig. 3 shows the surface roughness and sheet resistance of the as-received CP-Ti foils for each grade. The surface roughness of all specimens was approximately 0.05-0.06 μm, showing little variation attributable to the grade. However, the sheet resistance values for Grades 1, 2 and 4 were 4.05, 4.60 and 4.82 mΩ/□, respectively, demonstrating a distinct increase with higher impurity content. Consequently, the sheet resistance of as-received CP-Ti foils exhibited a clear dependence on the O and Fe impurity content. This increase in resistance is attributed to lattice distortion induced by the impurities, which enhances electron scattering within the material.

Fig. 4 shows the relationship between surface roughness and sheet resistance of CP-Ti foils, where surface roughness was controlled by varying the sandpaper grit size. For all grades, sheet resistance increased linearly with increasing surface roughness, which is primarily attributed to enhanced surface scattering. The relationship between surface roughness and sheet

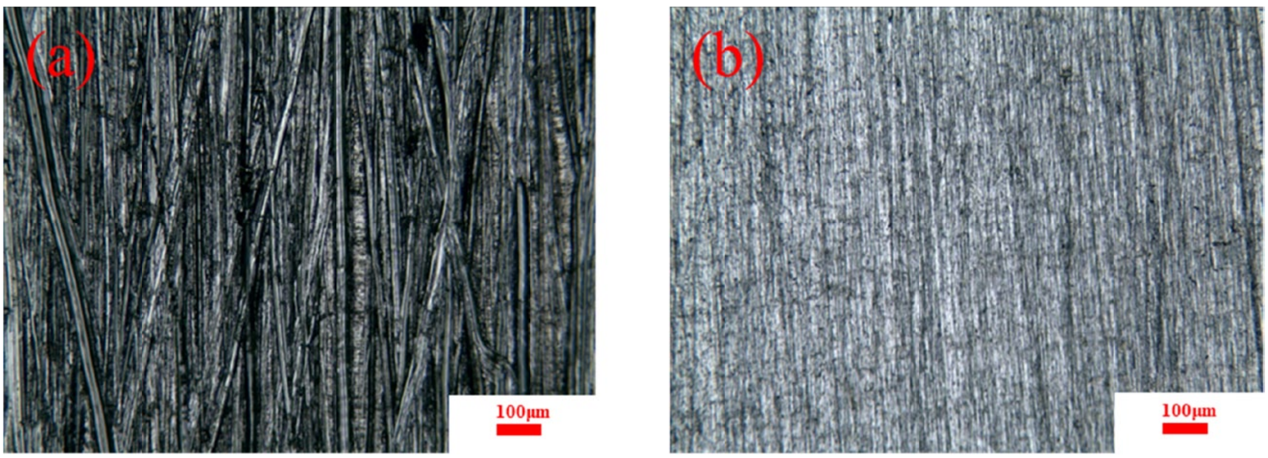

Fig. 1. OM photographs showing surface of Grade 1 CP Ti polished with (a) 100 grit and (b) 1200 grit sandpaper

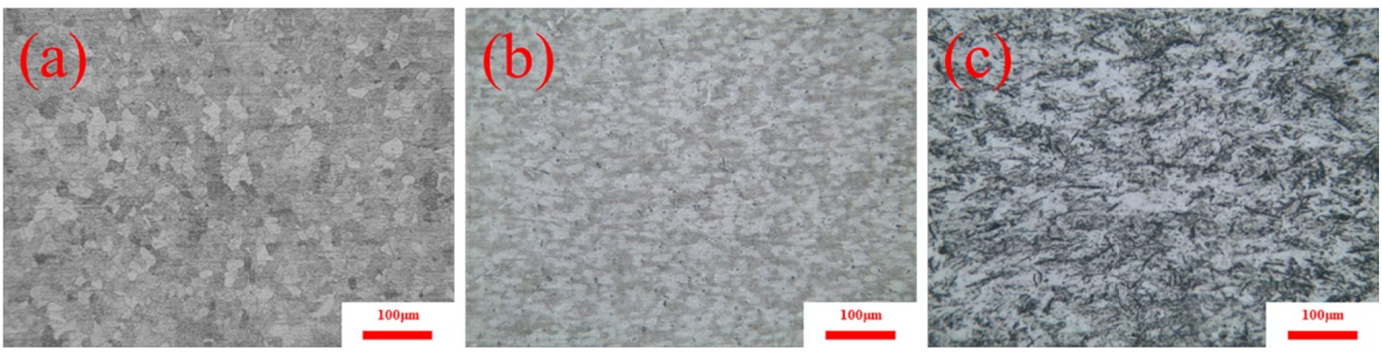

Fig. 2. Microstructures of as-received CP Ti foils: (a) Grade 1, (b) Grade 2, (c) Grade 4

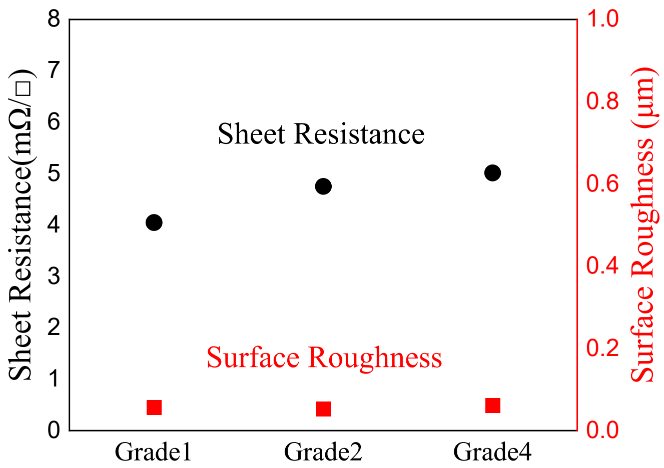

Fig. 3. Surface roughness and sheet resistance of as-received CP-Ti foils

resistance for all specimens can be described by the following linear equation.

$$R_s = R_0 + K \times R_a \tag{1}$$

where R_s is the sheet resistance, R_0 is the intrinsic sheet resistance of the material obtained by extrapolating the linear fit to $R_a = 0$, K is the slope of the linear fit, representing the sensitivity of sheet resistance to surface roughness, and R_a is the surface roughness. The linear fitting parameters for each grade, including R_0, K, and R^2, are listed in TABLE 2. The extrapolated R_0 values increased from Grade 1 to Grade 4, indicating that the intrinsic sheet resistance became higher with increasing impurity content. In addition, the calculated K values for Grades 1, 2, and 4 ranged from 0.74 to 0.82 and showed a slight decreasing trend from Grade 1 to Grade 4. This suggests that the relative contribution of surface roughness on the overall sheet resistance becomes smaller at higher grades. This may be attributed to increased electron scattering within the material associated with increased impurity content. These results indicate that the increase in sheet resistance of CP-Ti foils is primarily governed by surface roughness, whereas impurity content mainly influences the intrinsic sheet resistance.

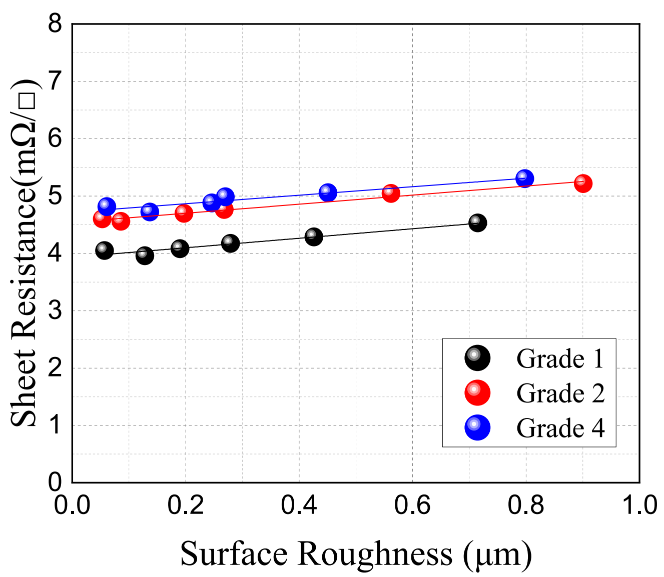

Fig. 4. Relationship between surface roughness and sheet resistance of CP-Ti foils

TABLE 2

Linear fitting parameters (R_0, K, and R^2) for CP-Ti foils of different grades

	R_0	K	R^2
Grade 1	3.93191±0.03675	0.82926±0.09904	0.94602
Grade 2	4.54147±0.02765	0.79109±0.06061	0.97706
Grade 4	4.71748±0.0449	0.74179±0.11019	0.91889

4. Conclusions

This study investigated the effect of surface roughness on the sheet resistance (R_s) of CP-Ti foils (Grades 1, 2, and 4). Microstructural analysis revealed that Grade 1 consisted of distinct equiaxed grains, whereas Grades 2 and 4 were characterized by refined and elongated grain morphologies resulting from higher impurity contents. For the as-received CP-Ti foils, R_s values were 4.05, 4.60, and 4.82 mΩ/□ for Grades 1, 2, and 4, respectively. This indicates a progressive increase with Grade, while surface roughness remained consistent across all samples. Furthermore, when surface roughness was mechanically controlled, Grade 1 maintained a lower sheet resistance compared to Grades 2 and 4 at equivalent roughness levels. The sheet resistance of the CP-Ti foils exhibited a linear increase with increasing surface roughness, irrespective of the grade. The K values decreased slightly with increasing grade, indicating that the influence of surface roughness on the total sheet resistance is gradually reduced at higher grades. Overall, surface roughness is a key factor governing the increase in sheet resistance of CP-Ti foils, whereas impurity content mainly affects the intrinsic sheet resistance.

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