Reliable Young's modulus Value of High Flexible Treated Rolled Copper Foils Measured by Resonance Method

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Abstract

Smartphones and tablets require very high flexible and sever bending performance to the Flexible Printed Circuits (FPCs) to fit into their thinner and smaller body designs. In these FPCs the extraordinary highly flexible treated rolled annealed (RA) copper foils are recently used instead of regular RA foil and electro deposited (ED) foils. It is very important to measure the Young's moduli of these foils predicting the mechanical properties of FPCs such as capabilities of fatigue endurance, folding and so on. Even though the manufacturers use IPC TM-650 2.4.18.3 test method for measuring Young's modulus of copper foils over many years, where Young's modulus is calculated from stress-strain curve, it is quite difficult to obtain the accurate Young's modulus of metal foils by this test method. The S-S curves of copper foils always exhibit a large degree of scattering. In order to cope with the issue, 'Resonance method' using the resonance frequency of a specimen is proposed to measure the much accurate Young's modulus. The comparison is made between IPC TM-650 2.4.18.3 and the resonance method in view of calculation of Young's modulus, accuracy. It is found that Young's modulus values measured by the resonance method were close to theoretical values than those measured by the conventional method. In addition, the experimental data of fatigue life are utilized to support the accuracy of Young's modulus values measured by the resonance method.

Key words: *copper foil, Young's modulus, Resonance Method, Tensile method, crystallographic orientation, fatigue*

1. Introduction

The mechanical behavior of the copper foils in flexible printed circuits (FPCs) is a key factor determining the long-term service life of electronic devices. The copper foils are largely divided into rolled copper foils and electrodeposited (ED) copper foils. In general, rolled copper foils annealed via a copper clad laminating process are used when the FPCs are required to endure cyclic deformations. In recent highly miniaturized devices, rolled copper foils, which are softer and much more highly flexible than conventional copper foils, are widely used to enhance the devices' reliability [1].

Several methods have been developed for measuring the Young's modulus of materials. The simplest method is to measure it from stress–strain curves acquired from tensile tests, as specified in standard IPC TM-650 2.4.18.3, even though this standard was developed for organic films instead of copper foils. The Young's modulus E is well described by

$$E = \frac{\sigma_e}{\varepsilon_e} \tag{1}$$

where σ_e and ε_e are the stress and strain of elastic deformation, respectively. However, the Young's modulus of metals is usually tens to hundreds of times larger and the range of elastic deformation of metals is tens of times shorter than those of polymers such as polyimide and epoxy, i.e., the σ_e values of metals substantially change with a slight change in ε_e; thus, accurately measuring the Young's modulus of thin metal foils is difficult. Consequently, the Young's moduli of copper and copper alloy sheets for connector materials, which range in thickness from approximately 0.1 mm to 0.65 mm, are commonly measured using a cantilever beam test [2]. The Young's modulus measured using a cantilever beam test is given by

$$E = \frac{4W}{b} \cdot \left(\frac{L}{b}\right)^3 \cdot \frac{1}{f} \tag{2}$$

where W, b, L, and f are a given load, the width of the sample, the length from the loading point to a fixed point, and the deflection amount, respectively. However, this method cannot be applied to metal foils because the copper foils used in FPCs range in thickness from approximately several micrometers to 0. 1 mm; i.e., significant deflection occurs not only under the applied given load but also under the foil's own weight, at which the assumption of equation (2) cannot work.

Several methods have been developed to investigate the Young's modulus of thin metal foils, including the indentation method [3] and the bulge method [4], among others. However, those methods are not practical for industrial use because specialized apparatus and techniques are required to obtain accurate E values for metal foils.

The Young's modulus can be also obtained from the characteristic vibrations of materials because the resonant frequency of a bending vibration of a material is a function of its Young's modulus, density, and dimensions. Details of this method are presented in the Experimental Procedure section. The aim of this work was to obtain an accurate Young's modulus using a resonance frequency measurement to accurately measure the Young's modulus of copper foils, and compare the results with the tensile Young's modulus. On the basis of the experimental results, the accuracy of measuring the Young's modulus of copper foils was discussed.

2. Experimental Procedure

2.1 Materials

Two kinds of commercial as-rolled copper foils with especially high flex property even though they are classified as grade 8 according to the copper foil specification sheet in standard IPC-4562A-WAM1 and two kinds of ED foils classified the grades 3 and 11 were prepared. The thickness t of each foil was 18 μm. For tensile tests, specimens 12.7 mm in width and 76.2 mm in length were cut from the 18μm thick foils using a Thwing-Albert JDC precision cutter such that their longitudinal axis was parallel to the machine direction (MD) and perpendicular to the transverse direction (TD). For the measurements of the Young's modulus by the resonance frequency, specimens 3.2 mm in width and 15.0 mm in length using the Thwing-Albert JDC precision cutter was prepared such that the longitudinal axis was parallel to the MD and perpendicular to the TD. Some of the samples were annealed at 180 °C for 1 h to enable data to be obtained both before and after annealing.

Annealed copper foils were subjected electron backscatter diffraction (EBSD) analysis to investigate their crystallographic orientation.

2.2 Measurement

The tensile tests were performed using a tensile tester with a 0.2-kN load cell under a grip separation rate of 5.08 mm/min at 23 °C. The Young's moduli were calculated according to standard IPC TM-650 2.4.18.3.

The resonance frequency of a beam is given by

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \cdot \frac{\lambda^2}{l^2} \sqrt{\frac{EI}{\rho A}} \tag{3}$$

where ω, l, ρ and A are the natural angular frequency, the length of the beam, the density of the beam, and the cross-sectional area of the beam, respectively, I is the moment of inertia of area that is here expressed by $bt^3/12$, and λ is a dimensionless constant that is determined by the boundary condition and the vibration mode. In the case of vibration tests of copper foils, cantilever mode is the best option; this mode can avoid deflection under the sample's own weight because small-sized foils are positioned such that the thickness direction of the foil is horizontal, as illustrated in Figure 1. The test based on this principal was performed using a vibration device manufactured by Nihon Techno-Plus Corp, Japan. "TE-RT".

3. Results and Discussion

3.1 Young's modulus

Elucidating the crystallographic orientation of the foils is important for understanding the measurement results of E because E is strongly influenced by the crystallographic orientation. Figure 2 shows EBSD images of the four copper foils after the foils were annealed. The corresponding inverse pole figures are also shown in figure 3. Note that the EBSD image of the grade 3 foil differs in magnitude from the images of the other foils because the grade 3 foil has a much smaller grain size. The grains of the grade 8 foils with high flex property show a very strong cubic texture. The symmetry of the cubes indicates that most grains have <100> orientations in the normal direction (ND), in the MD, and in the TD. By contrast, the ED foils do not exhibit the clear texture. (Note that the magnitude of the isocline is very low in the inverse pole figures of the foils.) A weak <113> texture in the ND is observed for the grade 11 foil. However, the grains do not have texture in the MD or in the TD; i.e., the grains are randomly oriented. In the case of the grade 3 foil, a weak <101> texture in the MD and a random orientation in the TD are observed. The textured orientation to the MD and the TD, which is the load direction of the tensile tests, and its density level (times random) are summarized in Table 1.

The Young's moduli measured by tensile tests and vibration tests are summarized in Table 2. These numbers are the averages for 10 specimens. The Young's modulus of the resonance method is approximately two times greater than that of the tensile method. Even though the moduli of the grade 8 foils of the high flex type and the grade 11 foil after annealing are approximately the same in the case of the values measured using the tensile method, the moduli of the grade 8 foil is approximately two times greater than that of the grade 11 foil in the case of the values measured using the resonance method. These facts indicate that a clear difference exists between the two methods; a correlative relationship was not observed.

The authors of previous studies [5, 6] discussed the influence of size effects, i.e., the thickness dependence of E. Armstrong et al. [5] elucidated that the E of microscale copper agrees well with the values for bulk copper. Therefore, the experimentally measured values were compared with the literature data for bulk copper. Here, the results after annealing are focused because annealing eliminates the effects of the residual stress that causes a change in distance among Cu atoms. The distance among Cu atoms, which is crystallographically anisotropic, is a primary reason for determining the Young's modulus. Hence, the Young's modulus varies with crystallographic orientation, and numerous studies of the anisotropic Young's modulus have been reported. The values for the Young's moduli of Cu reported in the literature values from 55 GPa to 77 GPa in the <100> direction, from 160 GPa to 202 GPa in the <111> direction, and from 121 GPa to 138 GPa in <110> direction as shown in Figure 4 [5]. The value for bulk polycrystalline Cu with randomly oriented grains is approximately 100-130 GPa, which is the representative value reported for Cu in a reference book [7]. In the studies, cantilever beam, ultrasonic pulse-echo, X-ray and ultrasonic interference method were adapted.

Even though these authors investigated the Yong's moduli with different methods, the similar results were obtained. When the strongly textured grains in the <100> direction of the grade 8 foils is taken into account, the Young's modulus determined by the resonance method in both the MD and the TD of the foils is approximately 70 GPa, which is in good agreement with previously reported values. In addition, the result of approximately 110 GPa for ED foils, which have a very weak texture, is a reasonable value (see Figure 5). By contrast, the values determined using the tensile method are not only too small, but they cannot also detect the anisotropy of the Young's modulus. Thus, it is noted that an accurate value for the Young's modulus of copper foils can be obtained using the resonance method.

3.2 Effective utilization of the accurate Young's modulus

In addition, the importance of obtaining an accurate Young's modulus for understanding the underlying mechanism of flex property is here demonstrated. The Coffin–Manson relation is a well-known relation for fatigue life:

$$\frac{\Delta\varepsilon}{2} = \sigma_f \cdot \frac{(2N_f)^b}{E} + \varepsilon_f \cdot (2N_f)^c \tag{4}$$

where $\Delta\varepsilon$, σ_f, and N_f are total strain of cyclic deformation, the fatigue strength, and the fatigue life, respectively. The equation for the Young's modulus is clearly included in this equation. Since the mode of cyclic deformation usually bends on FPC uses, the maximum bending strain in absolute value on copper foils should be adapted to the $\Delta\varepsilon$. The bending strain is expressed as

$$\varepsilon \approx z/\rho \tag{5}$$

where ρ is curvature radius which is the bending radius at the neutral plane and z is the distance from the neutral plane. Assuming most bending deformation is elastic in the test, the relation that total stress of the bent specimen is zero is given by

$$\int_A \sigma \, dA = \int_A E \frac{z}{\rho} dA = 0 \tag{6}$$

Because FPCs are laminated specimens of several layers as shown in figure 6, equation (6) is expressed as

$$\sum_{i=0}^{n} \int_{hi}^{hi+1} Ei \, \frac{z}{\rho} dy = 0 \tag{7}$$

From equations (5) - (7) and construction of FPC specimen (thickness and position of each layer in FPC), the maximum strain on copper foils in FPC can be obtained. Thus, the accurate E is necessary to characterize the fatigue property by equation (4).

Figure 7 shows the fatigue test configuration according to standard IPC-TM-650, 2.4.3 and Figure 8 shows the results for flexural endurance of the test. The grade 8 foils with high flex property exhibit much longer fatigue lives than the grade 11 foils. Several factors affect fatigue life, including changes induced by the active slip system via crystallographic orientation, grain boundaries, and grain size, among other factors. On the basis of equation (4) and the Young's moduli measured by the resonance method, the Young's modulus is reasonably assumed to be one of the key factors governing fatigue life.

4. Conclusions

Young's moduli of Cu foils using the resonance method were measured and compared the results with those obtained according to standard IPC TM-650 2.4.18.3. The Young's modulus obtained via the resonance method was approximately two times greater that obtained using the tensile method. It was found that the Young's modulus values measured by the resonance method were quite similar to the theoretical values and that the resonance method could detect the crystallographic orientation dependence of the Young's modulus. The resonance method is recommended for measuring Young's modulus at foil thicknesses.

Reference

[1] T. Hatano, Y. Kurosawa and J. Miyake, J. Electron. Mater. 29 (2000) 611-616.

[2] JAPAN COPPER BRASS and ASSOCIATION standard; JCBA T312:2001.

[3] S.H. Hong, K.S. Kim, Y.M. Kim, J.H. Hahn, C.S. Lee and J.H. Park, Compos. Sci. and Tech. 65 (2005) 1401-1408.

[4] N. Takano, S. Hirose and S. Nanayama, The Society of Materials Science, Japan 40 (1991) 161-163.

[5] D. E. J. Armstrong, A. J. Wilkinson and S. G. Roberts, J. Mater. Res. 24 (2009) 3268-3273.

[6] S. Zhang, T. Ando, Z Yuan, K. Kobayashi, K. Terada and M. Sakane, Transactions of the JSME 77 (2011) 190-200.

[7] JAPAN COPPER BRASS and ASSOCIATION, Data book (2009).

Table 1 Summary of main crystallographic orientations and its density.

(a) MD

Grade 8, sample1		Grade 8, sample2		Grade 11		Grade 3	
Direction	**Density**	**Direction**	**Density**	**Direction**	**Density**	**Direction**	**Density**
<001>	35.90	<001>	31.40	<338>	1.30	<101>	2.50
<225>	2.13	<225>	2.37				
<535>	1.57	<535>	1.73				
<102>	1.20	<102>	1.40				

(b) TD

Grade 8, sample1		Grade 8, sample2		Grade 11		Grade 3	
Direction	**Density**	**Direction**	**Density**	**Direction**	**Density**	**Direction**	**Density**
<001>	35.7	<001>	31.00	<338>	1.42	<101>	2.53
<225>	2.35	<225>	2.38				
<535>	1.52	<535>	1.73				
<102>	1.20	<102>	1.40				

Table 2 Summary of Young's modulus measured by resonance method and tensile method.

(a) MD

Before annealing

	Grade 8, sample1	Grade 8, sample2	Grade 11	Grade 3
Resonance method	116 GPa	110 GPa	113 GPa	95 GPa
Tensile method	68 GPa	67 GPa	56 GPa	53 GPa

After annealing

	Grade 8, sample1	Grade 8, sample2	Grade 11	Grade 3
Resonance method	70 GPa	78 GPa	120 GPa	120 GPa
Tensile method	32 GPa	39 GPa	44 GPa	49 GPa

(b) TD

Before annealing

	Grade 8, sample1	Grade 8, sample2	Grade 11	Grade 3
Resonance method	123 GPa	121 GPa	107 GPa	93 GPa
Tensile method	65 GPa	66 GPa	44 GPa	45 GPa

After annealing

	Grade 8, sample1	Grade 8, sample2	Grade 11	Grade 3
Resonance method	67 GPa	68 GPa	123 GPa	95 GPa
Tensile method	26 GPa	20 GPa	23 GPa	47 GPa

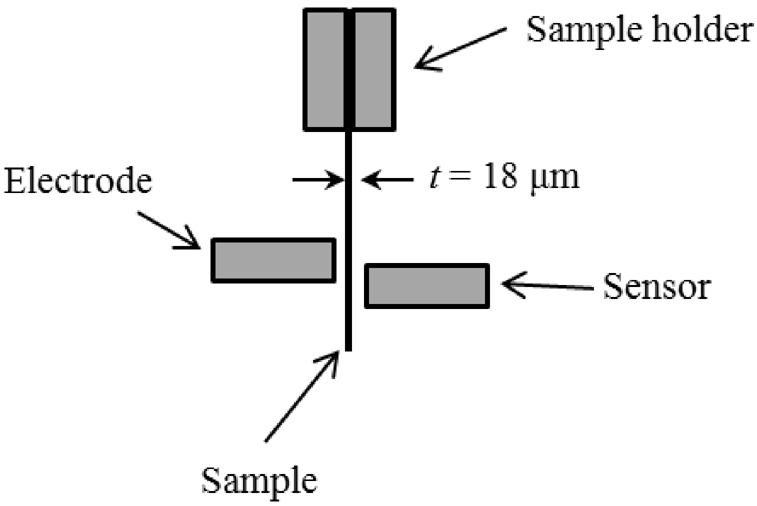

Figure 1 Schematic illustration of resonance method.

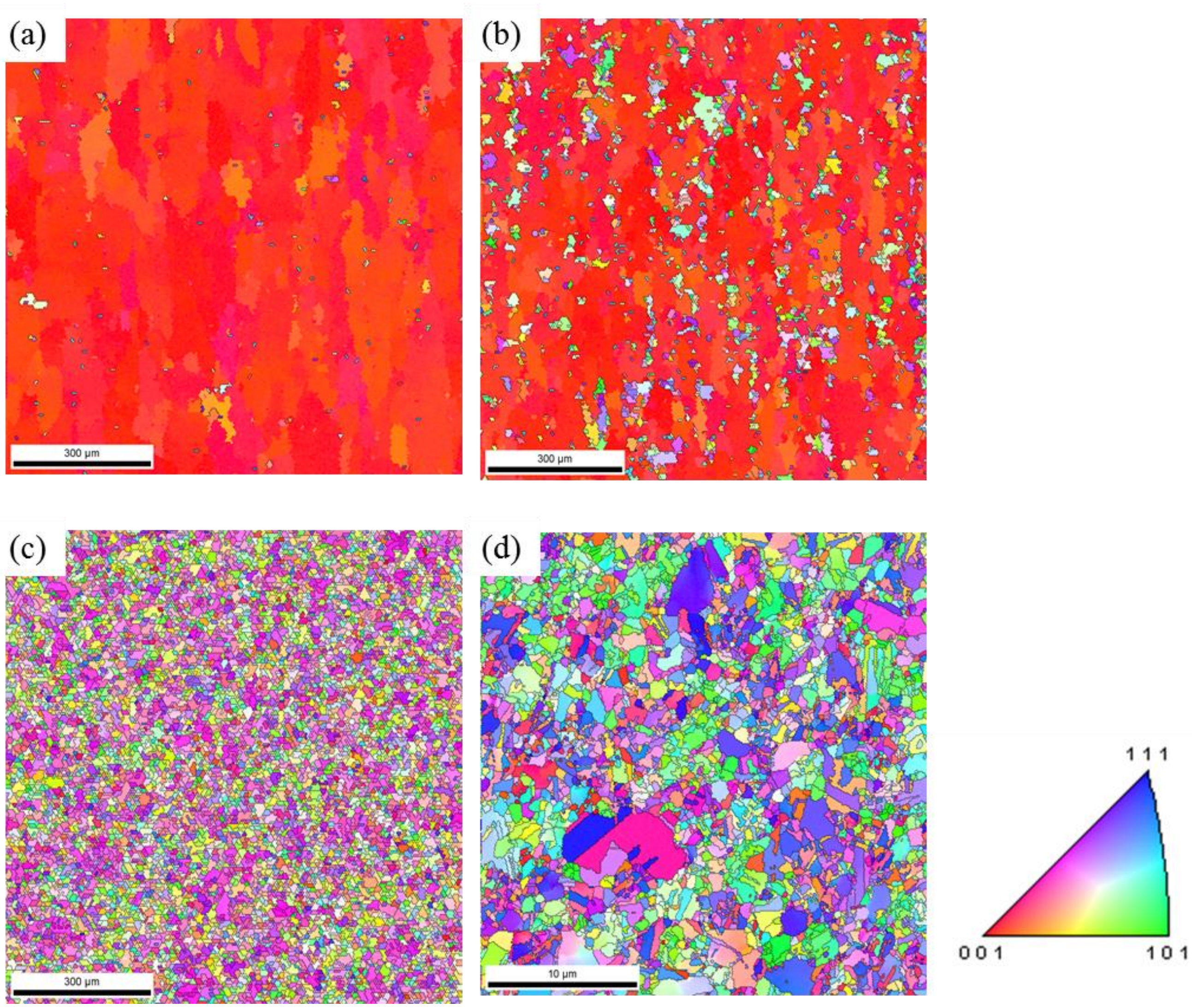

Figure 2 EBSD images of copper foils after annealing: (a) grade 8, sample 1; (b) grade8, sample2; (c) grade11; (d) grade3.

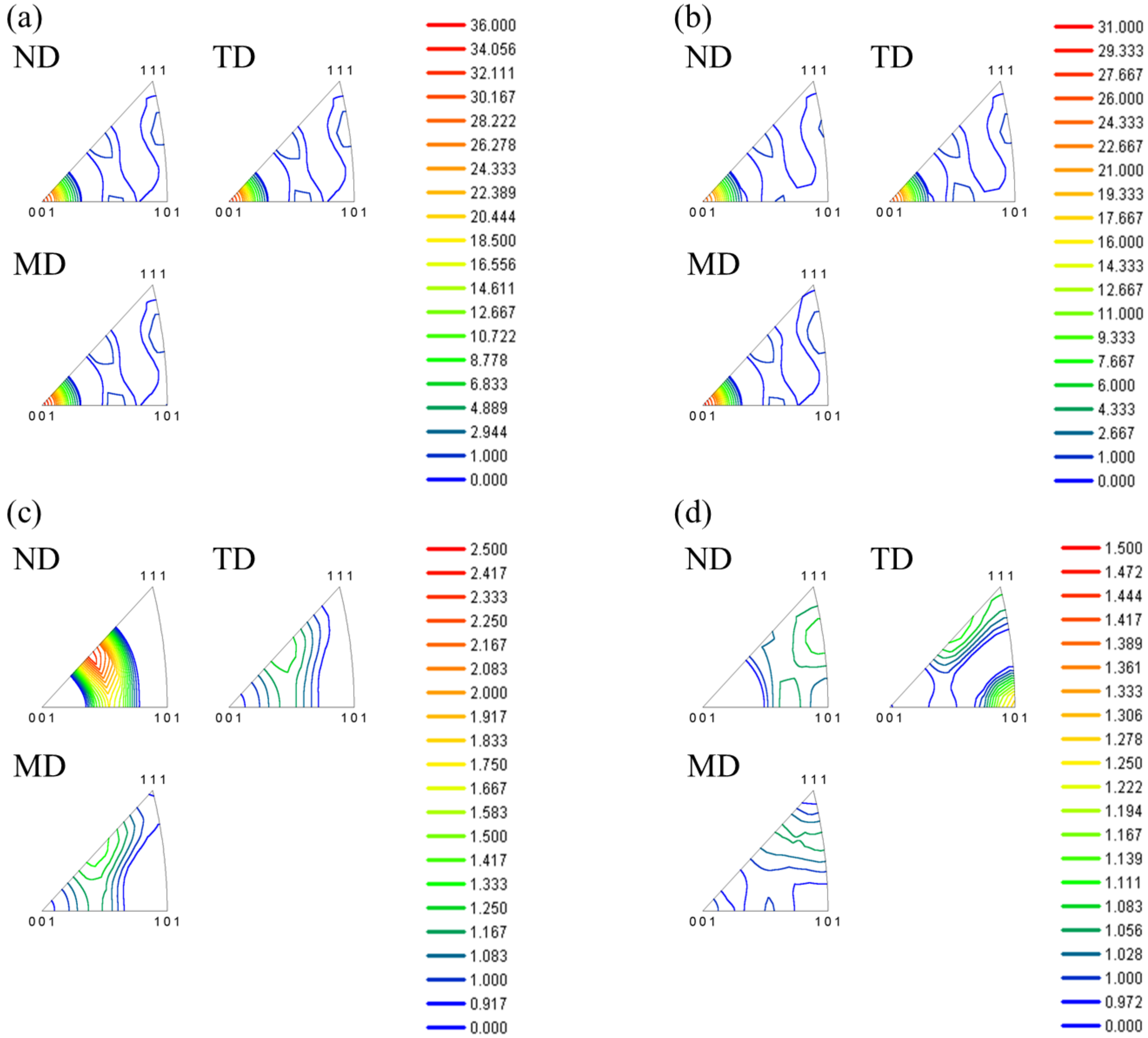

Figure 3 IPF maps of copper foils after annealing: (a) grade 8, sample 1; (b) grade8, sample2; (c) grade11; (d) grade3.

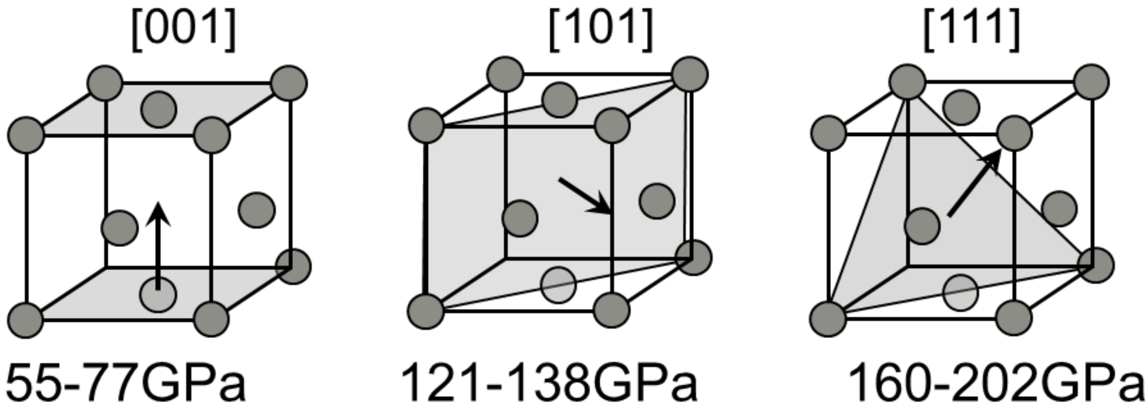

Figure 4 Anisotropy of the Young' modulus on copper crystal [5].

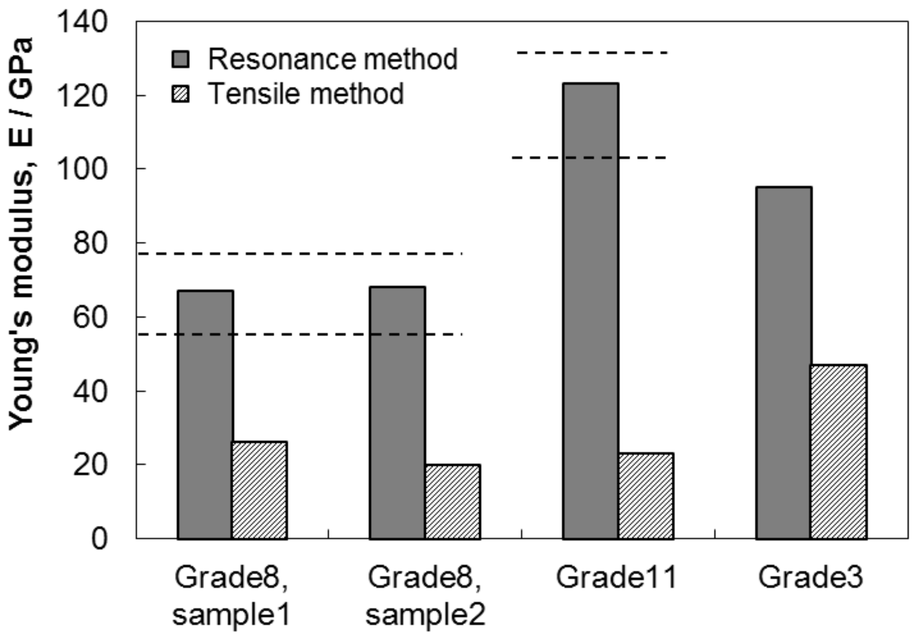

Figure 5 The Young's modulus of TD after annealing by resonance method and tensile method. Break lines means the results of the past studies [5, 7].

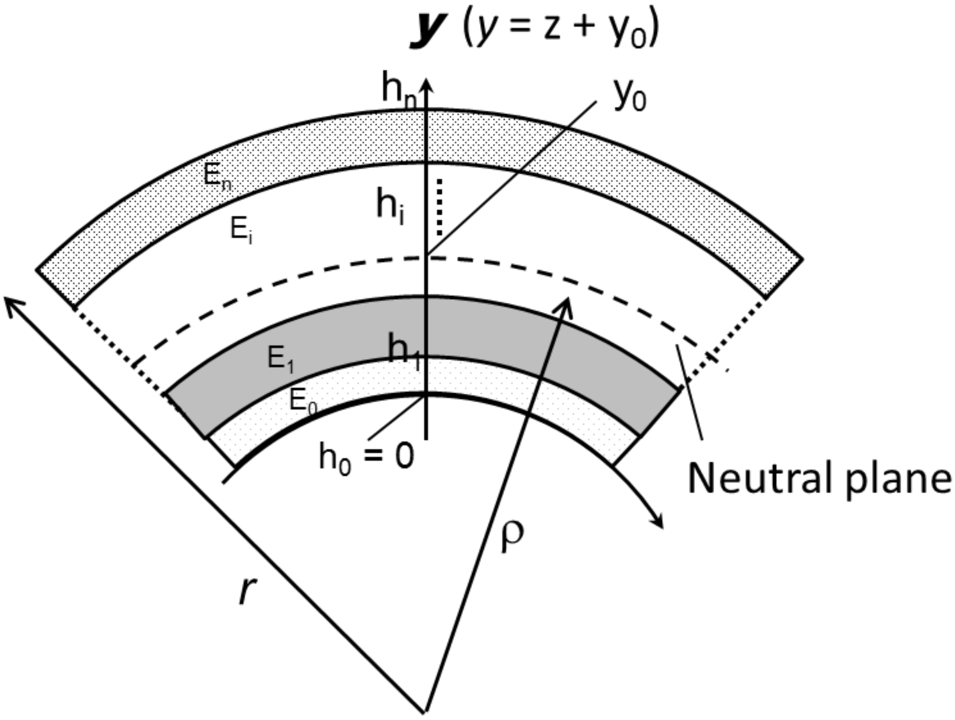

Figure 6　Coordinate system for analysis of bending on FPC.

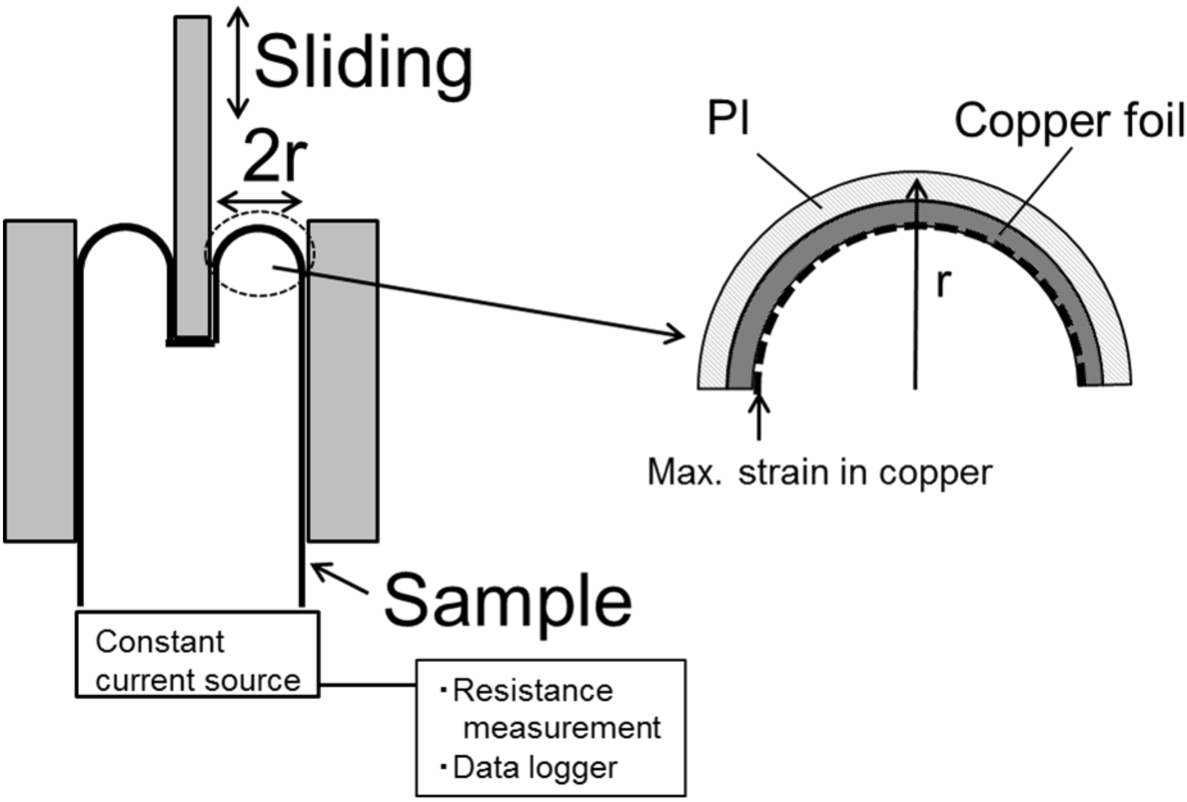

Figure 7　Schematic configuration of fatigue test of IPC-TM-650, 2.4.3.

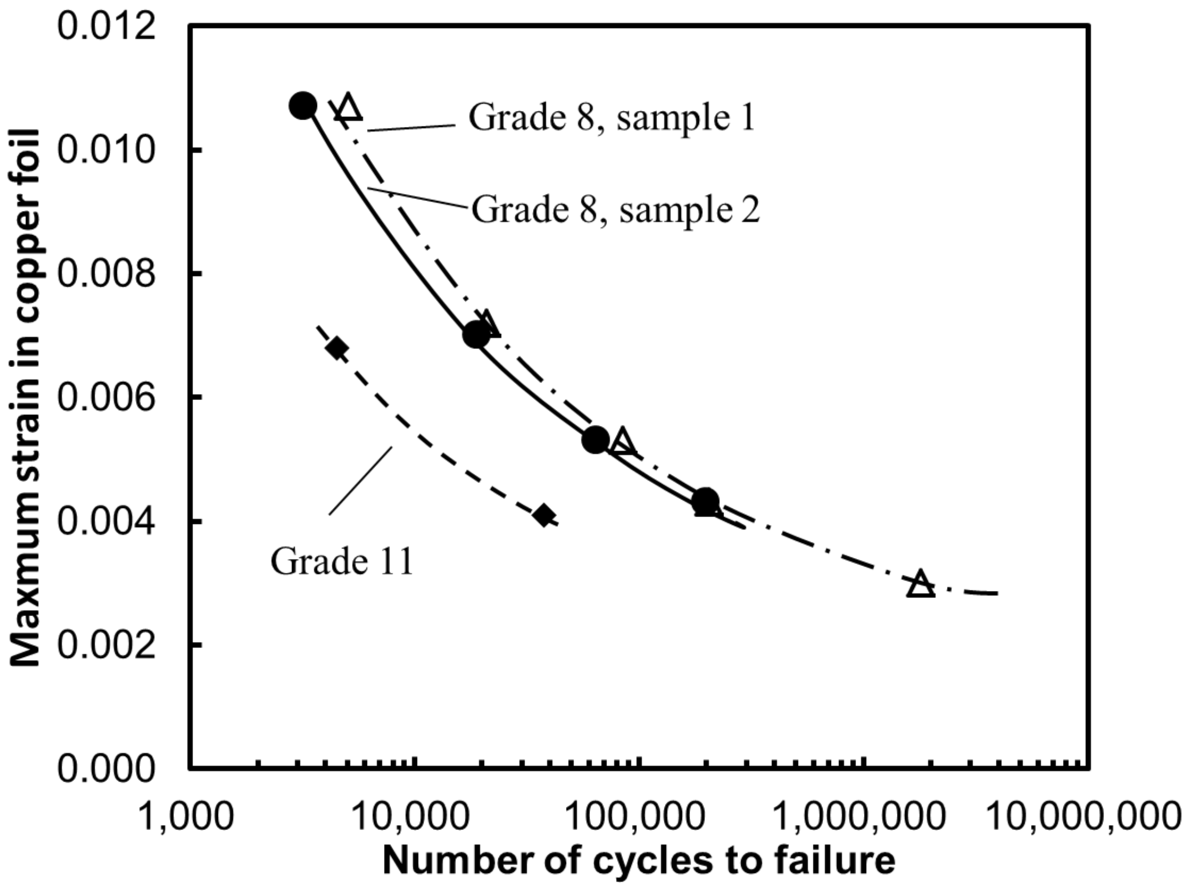

Figure 8 Flexural endurance, as measured according to standard IPC-TM-650, 2.4.3.

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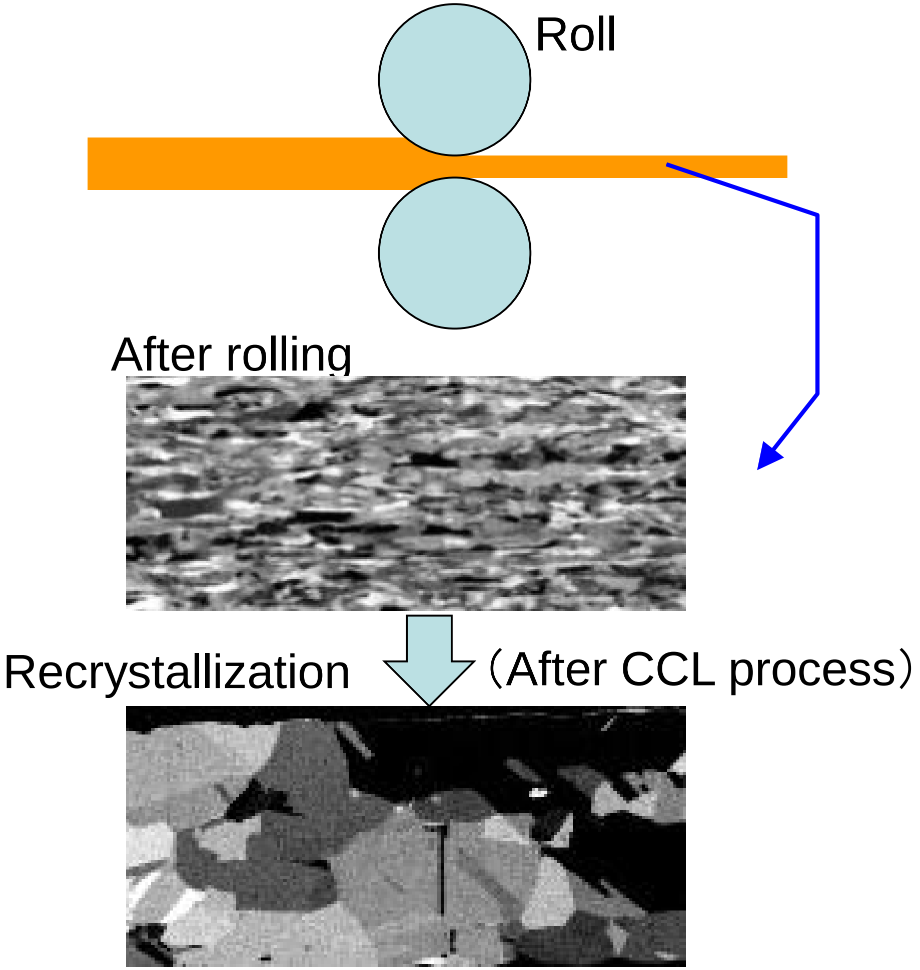
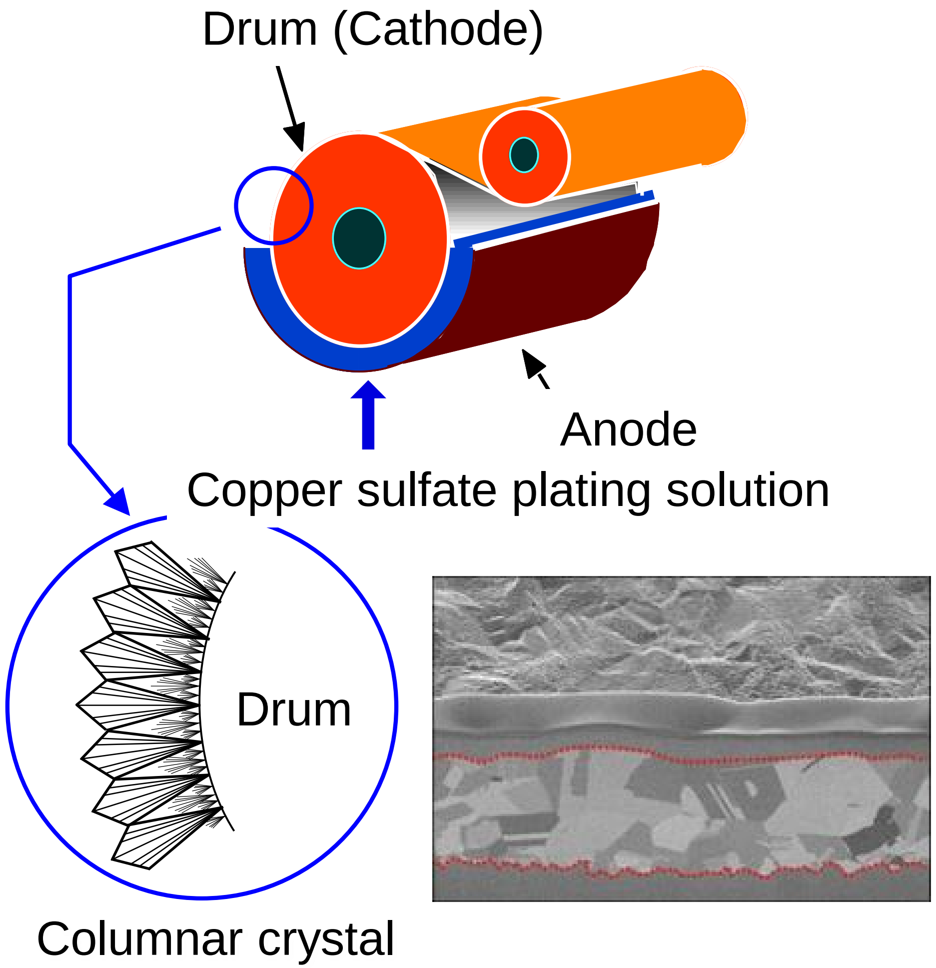
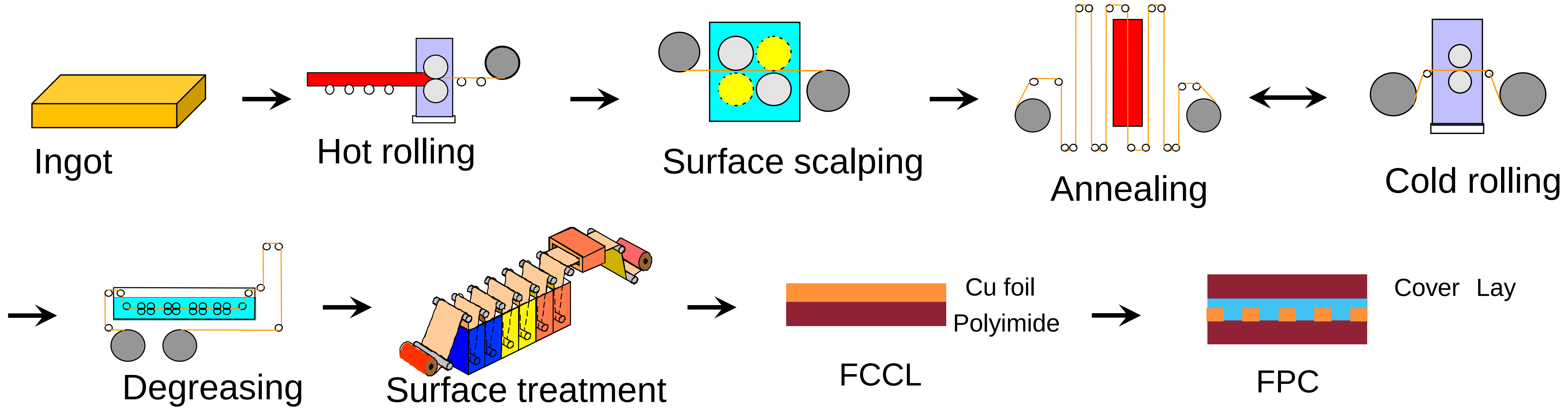
Copper Foils (Rolled Foil and Electro Deposited Foil)

【Rolled copper foil / Grade 8】

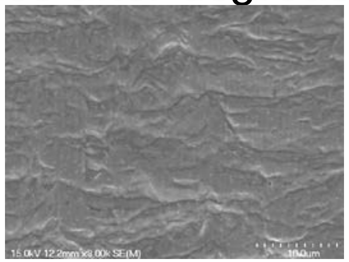


【Electro-deposited copper foil】

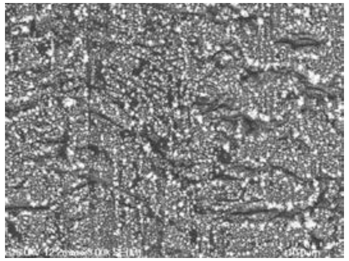




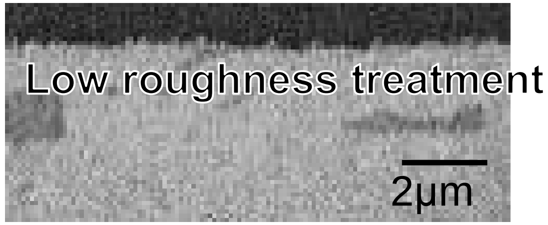
Surface after degreasing



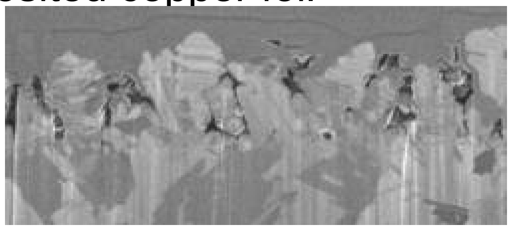
Surface after treatment



Cross section of rolled copper foil after surface treatment



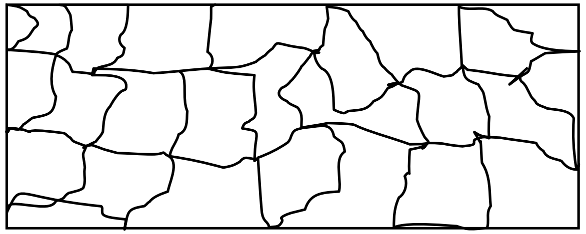
(cf.)Cross section of special electro-deposited copper foil



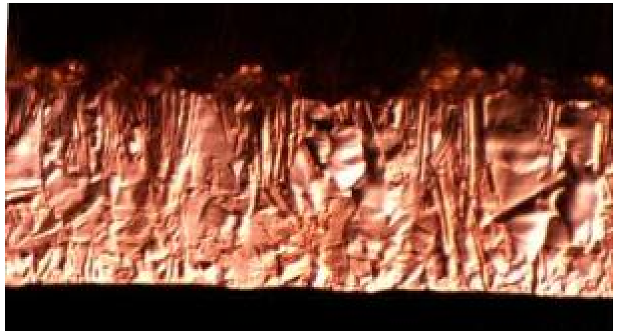
Difference of Microstructure among Copper Foils

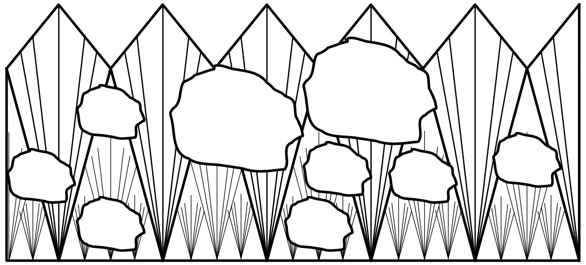
Cross-sectional images after annealing (after FCCL process)

Grade 8
As rolled-wrought-low temperature annealable (Rolled annealed foil, RA)

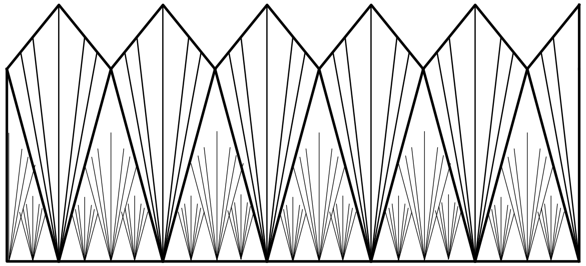


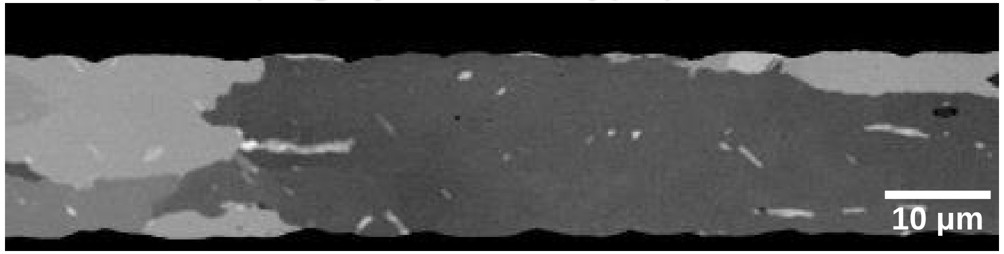
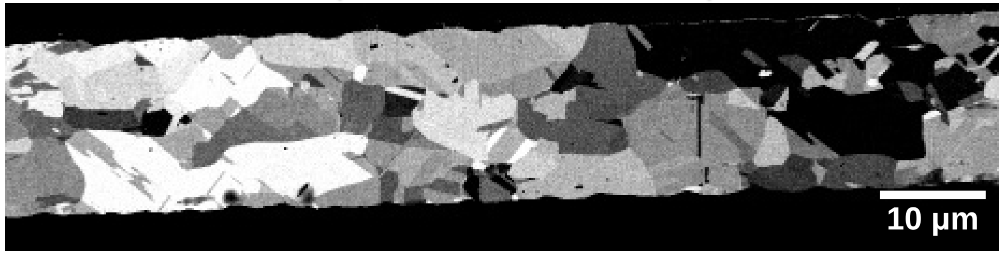
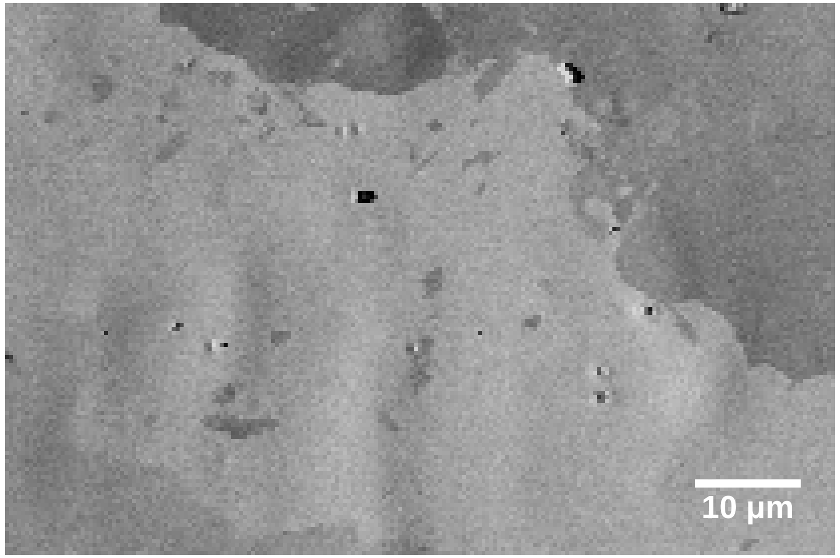
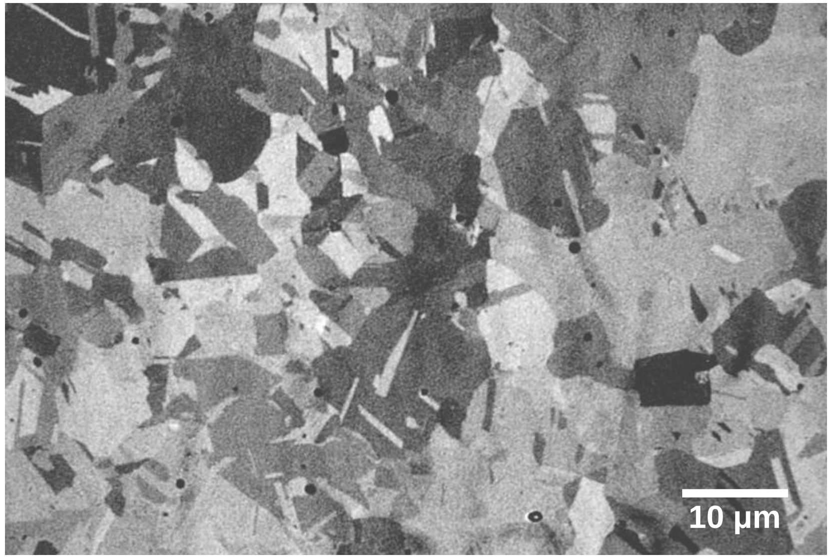
Grade 11
Electrodeposited annealable (Special ED)





Grade 3
High temperature elongation (HTE, ED)

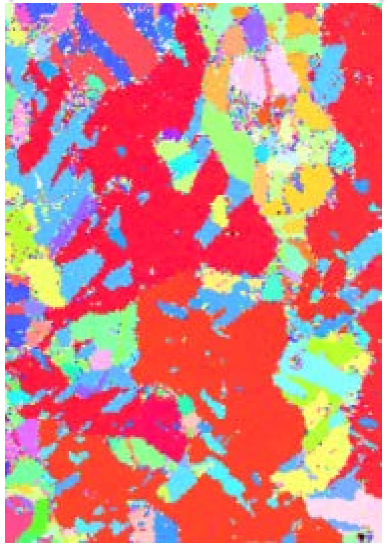


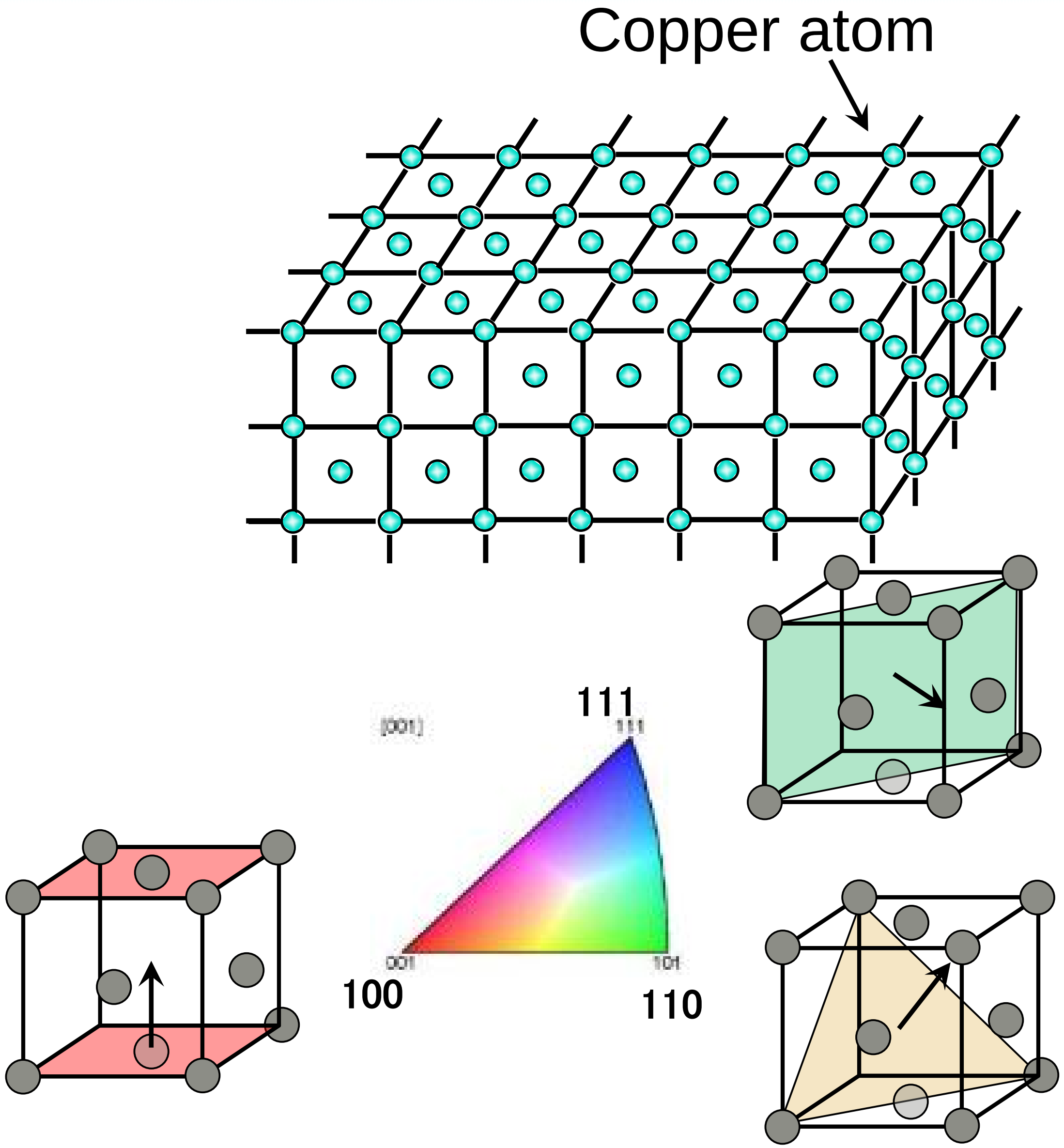
	Grade 8 (Highly flexible type)	Grade 8 (Conventional RA)
Cross section		
Surface		

Larger grain size

Grade 8
(Highly flexible type)

Grade 8
(Conventional RA)





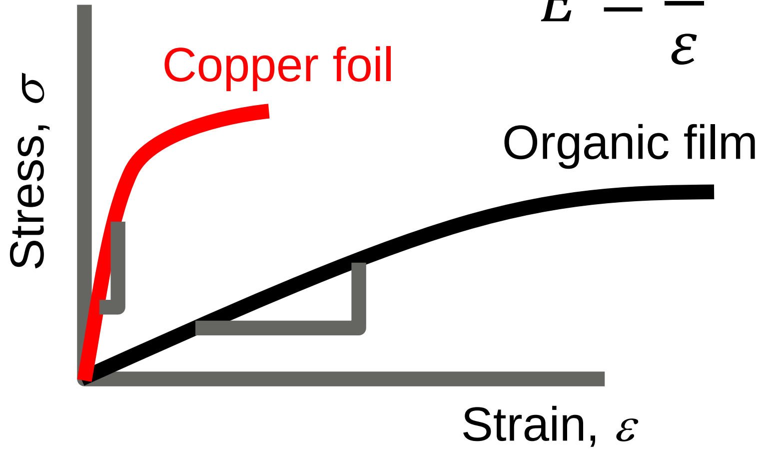
Young's modulus

- IPC does not specify how to measure the Young's modulus for copper foils

Tensile method

IPC TM-650 2.4.18.3
(For organic film)

$$E = \frac{\sigma}{\varepsilon}$$



The Young's modulus

Copper foil >> Organic film

The range of elastic deformation

Copper foil << Organic film

Resonance method

Natural Frequency of cantilever beam

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \cdot \frac{\mathrm{l}^2}{l^2} \sqrt{\frac{EI}{\rho A}}$$

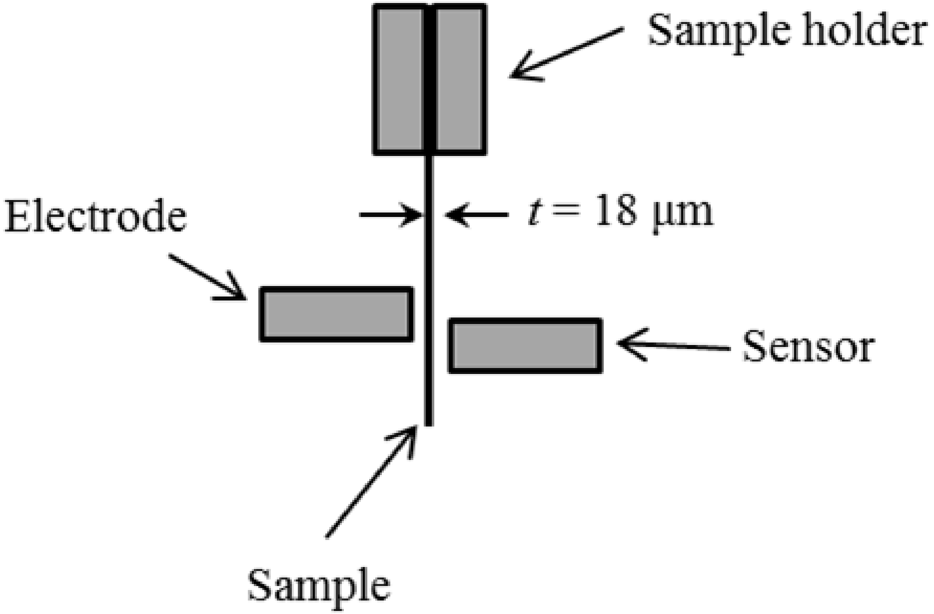
ω : Natural angular frequency
l : Length of the beam
ρ : Density of the beam
A : Cross-sectional area of the beam
I : Moment of inertia of area

$I = bt^3/12$

b : Width of the beam

t : Thickness of the beam

Top view



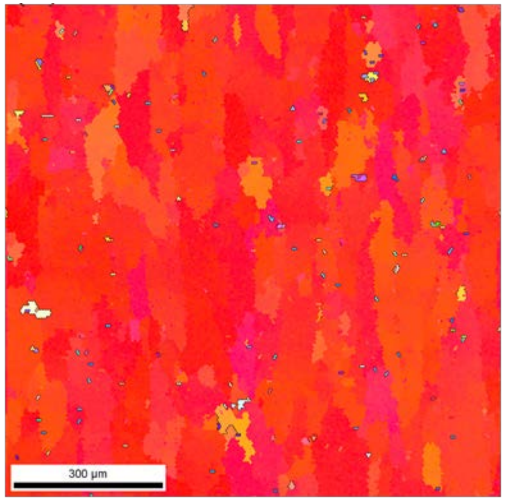
b = 3.2mm, l = 10 mm, t = 18 µm

Specimens

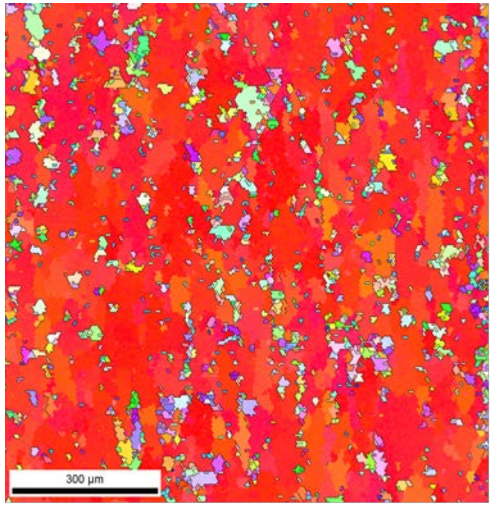
Copper foils were annealed at 180 ° C x 1h

Rolled annealed foil

Grade 8, sample1 (Highly flexible type)

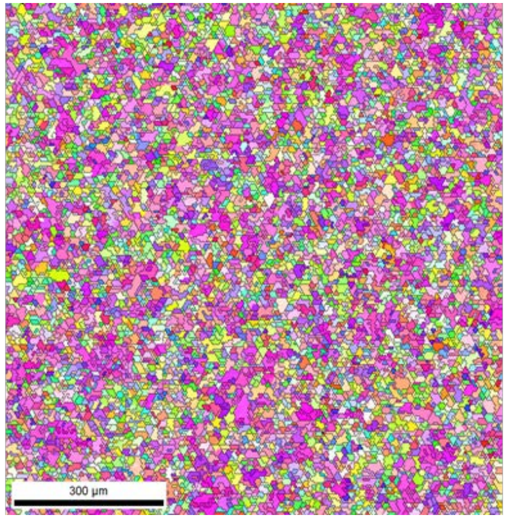


Grade 8, sample2 (Highly flexible type)

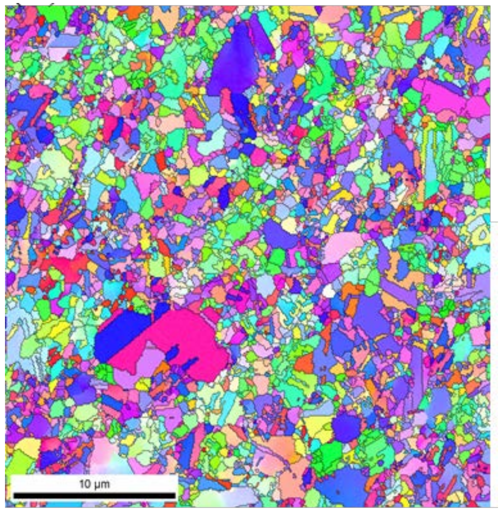


Electrodeposited foil

Grade 11



Grade 3

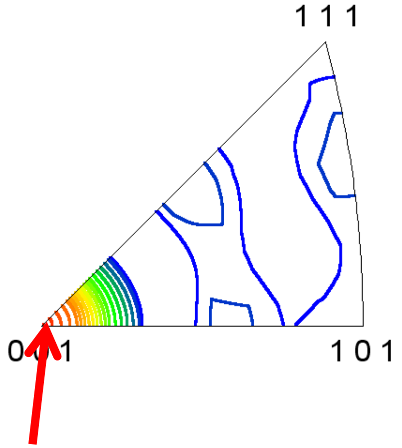


(High magnification)

The crystallographic orientation of TD (Stress axis)

Rolled annealed foil

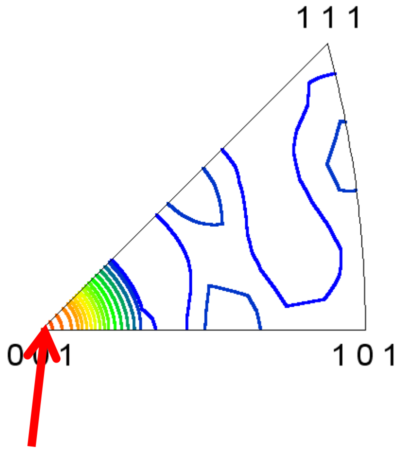
Grade 8, sample1
(Highly flexible type)



Maximum intensity

35.9 times
higher than random

Grade 8, sample2
(Highly flexible type)



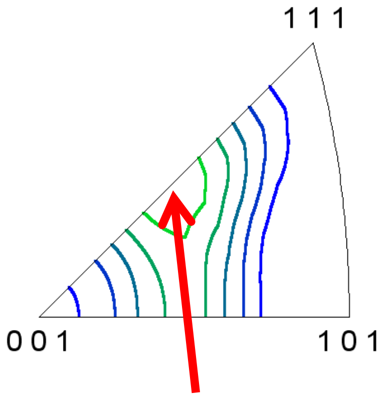
Maximum intensity

31.4 times
higher than random

Highly cubic texture

Electrodeposited foil

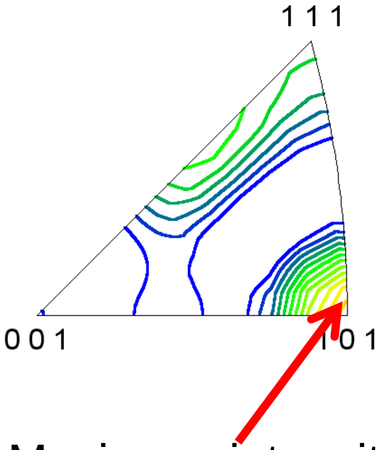
Grade 11



Maximum intensity

1.3 times

Grade 3

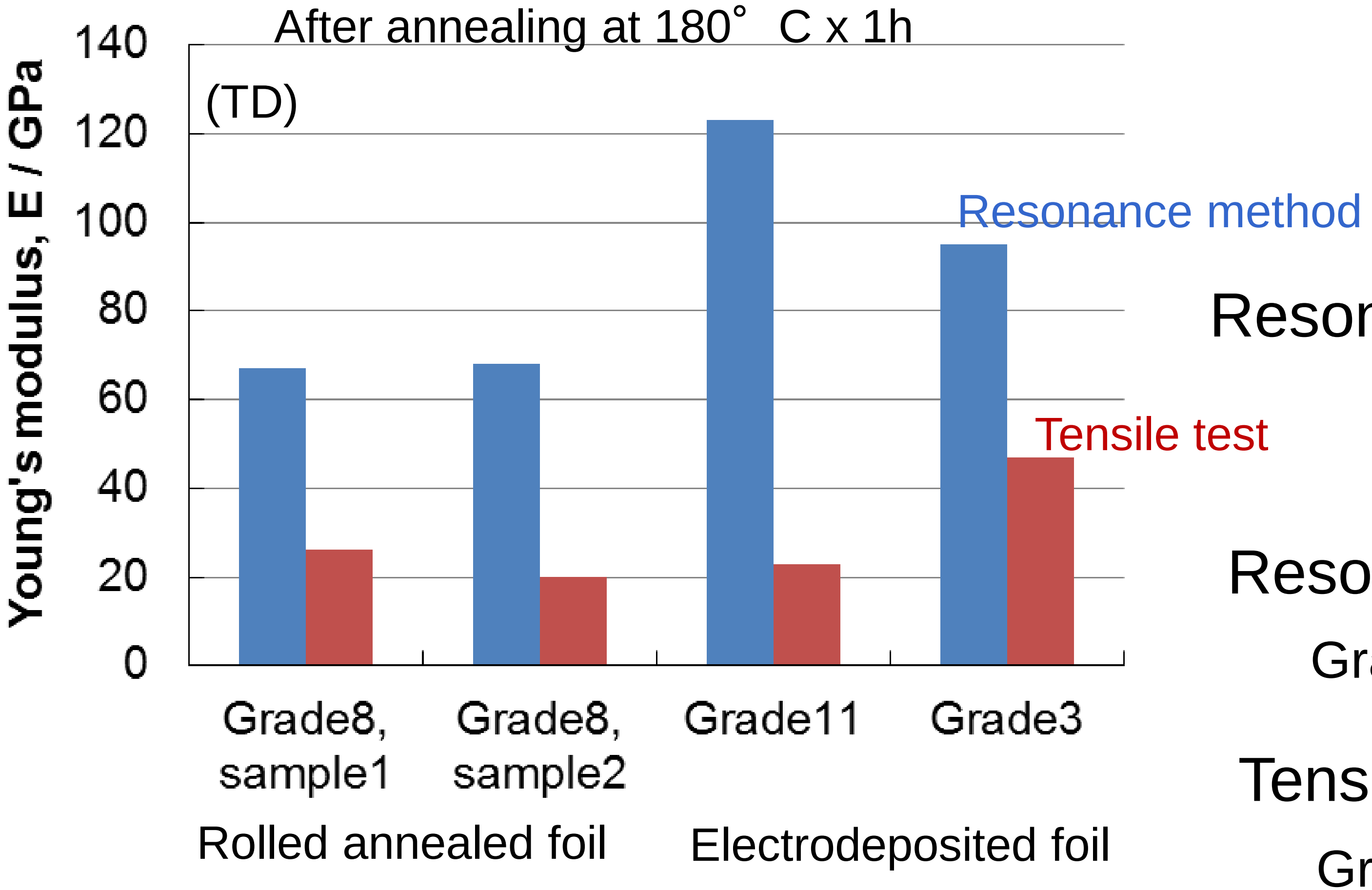


Maximum intensity

2.5 times

Almost random

Comparison of the Young's Modulus between the Resonance Method and Tensile Method



Resonance method > Tensile method

Resonance method

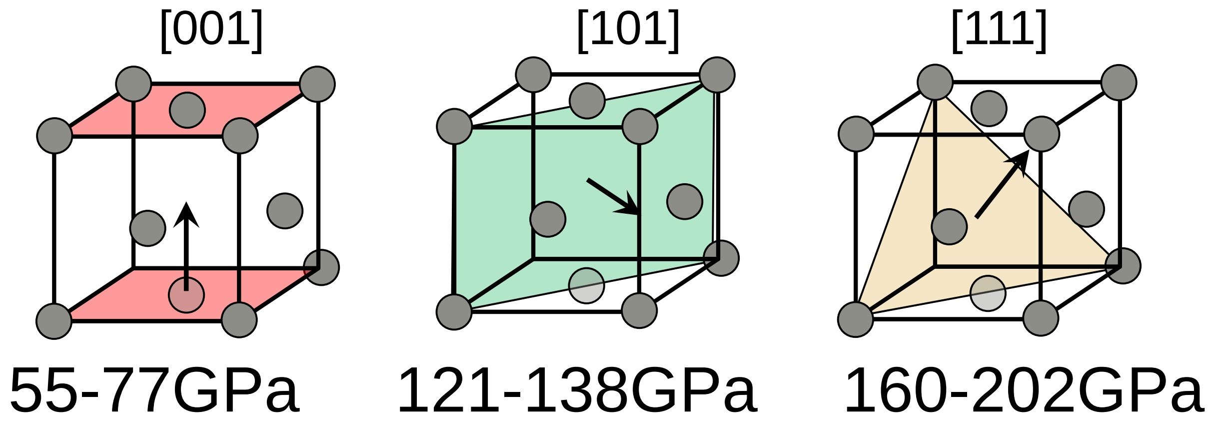
Grade 8 (Highly Flex) < Grade 11

Tensile method

Grade 8 (Highly Flex) ≈ Grade 11

Previous studies

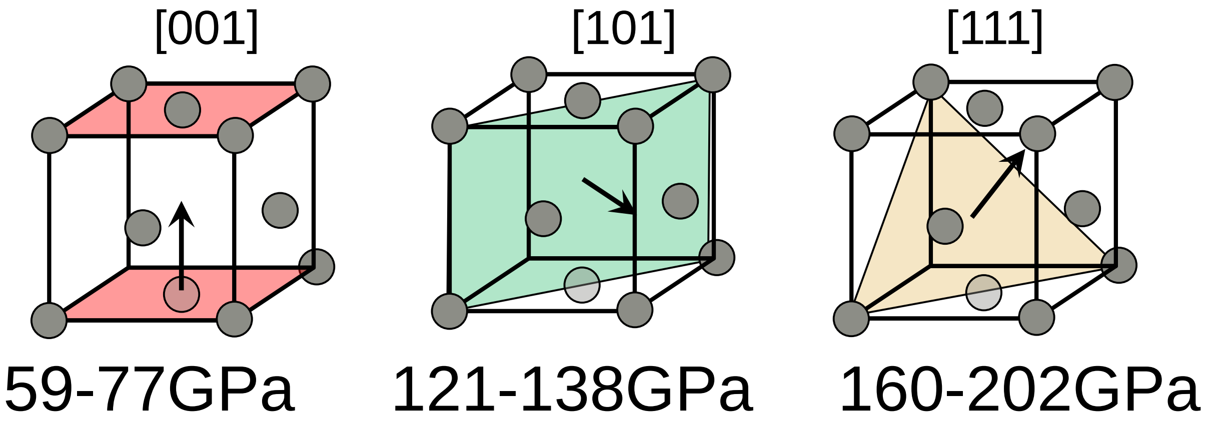
- Crystallographic anisotropy in Young's modulus



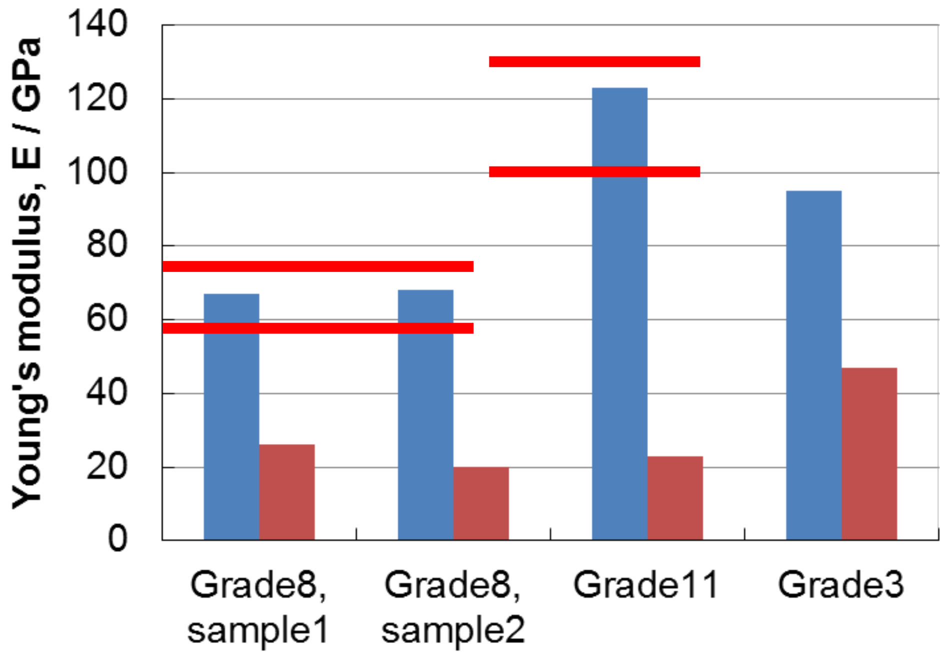
- Polycrystalline, Random 100-130GPa

- Armstrong et al. (2009)
  Cantilever beam method (thin film)
- Epstein et al. (1965)
  Ultrasonic pulse-echo technique
- Ledbetter et al. (1974)
- Jacobsen et al. (1954)
  X-ray method
- Hiki et al. (1966)
  Ultrasonic interference method
- JCBA Data book
  Unknown

- Crystallographic anisotropy in Young's modulus



- Polycrystalline, Random 100-130GPa



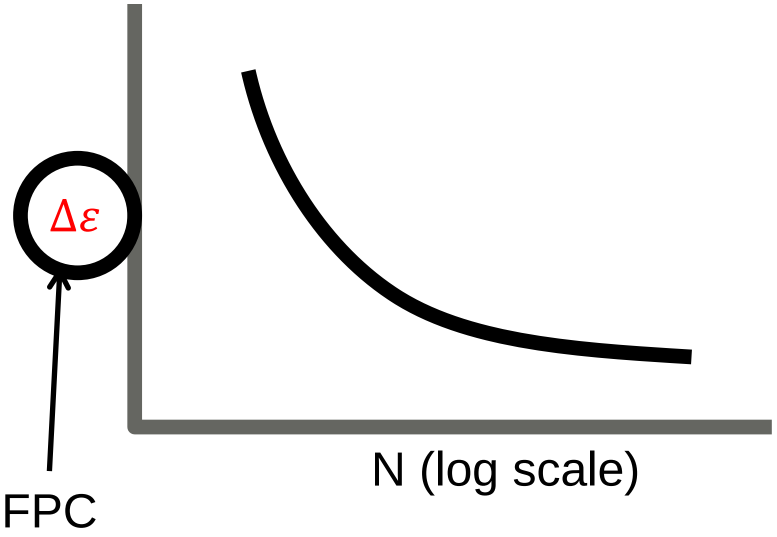
The values of resonance method are reasonable taking into account the microstructure of copper foil.

Effective Utilization of the Accurate Young's Modulus

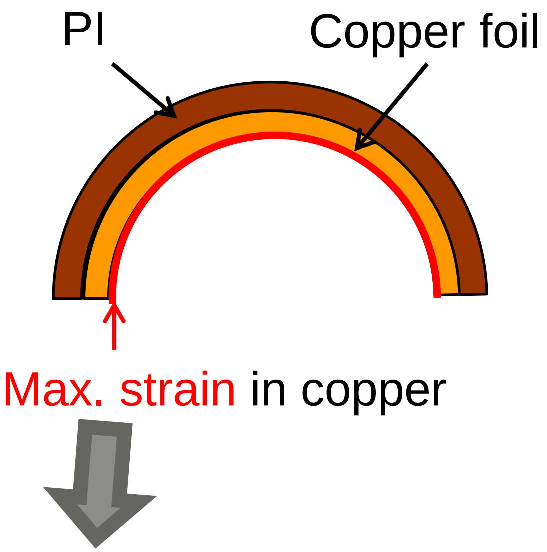
The relationship between strain and fatigue life

Coffin–Manson relation

$$\frac{\Delta\varepsilon}{2} = \sigma_f \cdot \frac{(2N_f)^b}{E} + \varepsilon_f \cdot (2N_f)^c$$



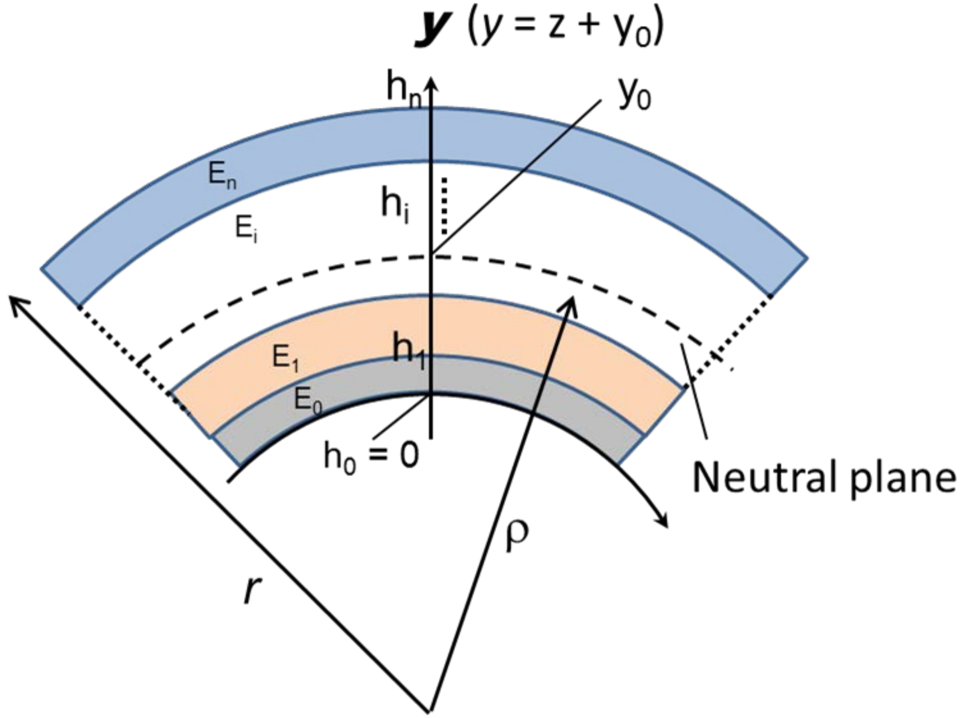
In general, Bending strain is received



To obtain the strain,
the Young's modulus is necessary

- FPCs are laminated specimens of several layers.

- Knowing max. strain in copper is necessary to determining the reliability of electronic devices.

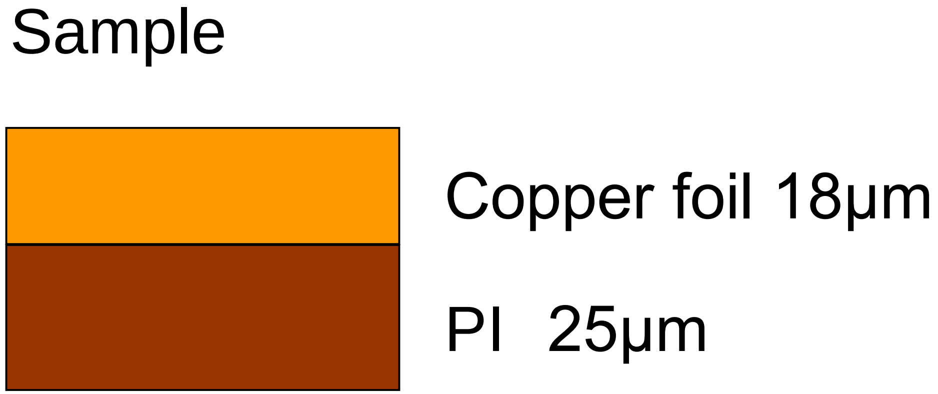


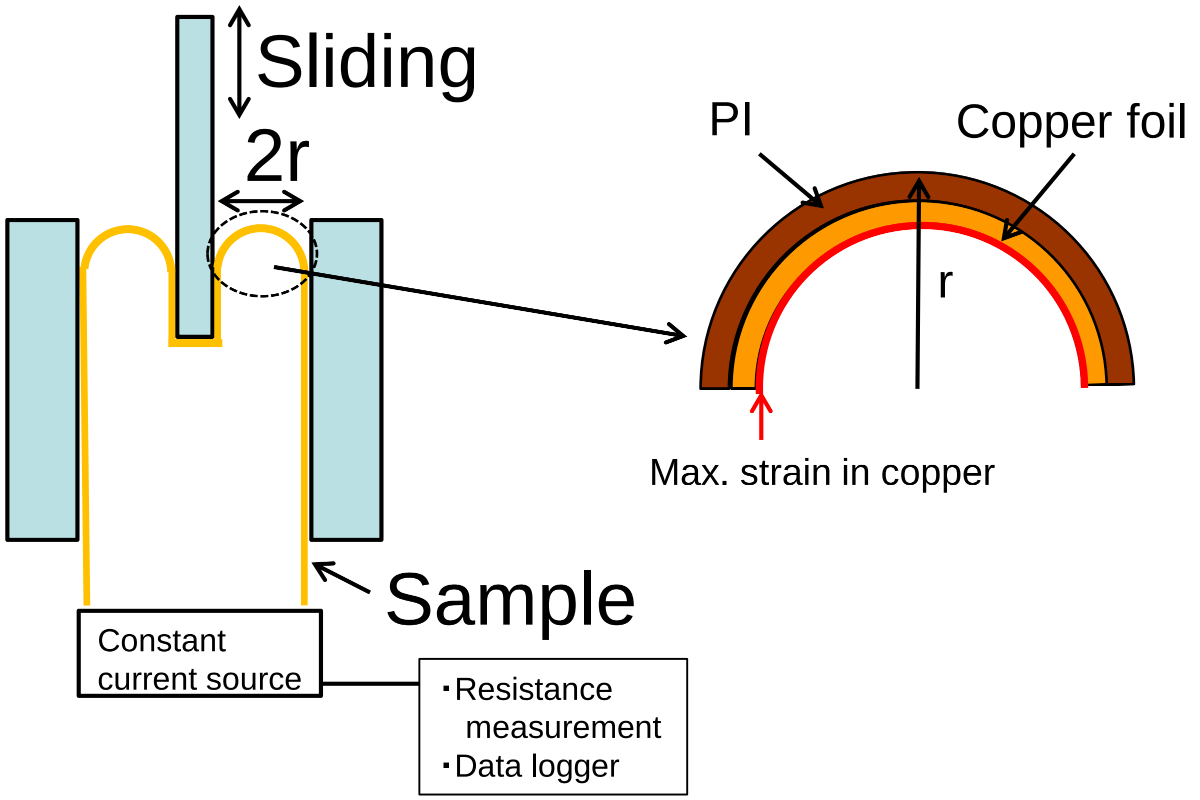
$$\varepsilon \approx \frac{y - y_0}{\rho}$$

$$\int_A \sigma \, dA = 0, \quad \sigma = E\frac{y - y_o}{\rho}$$

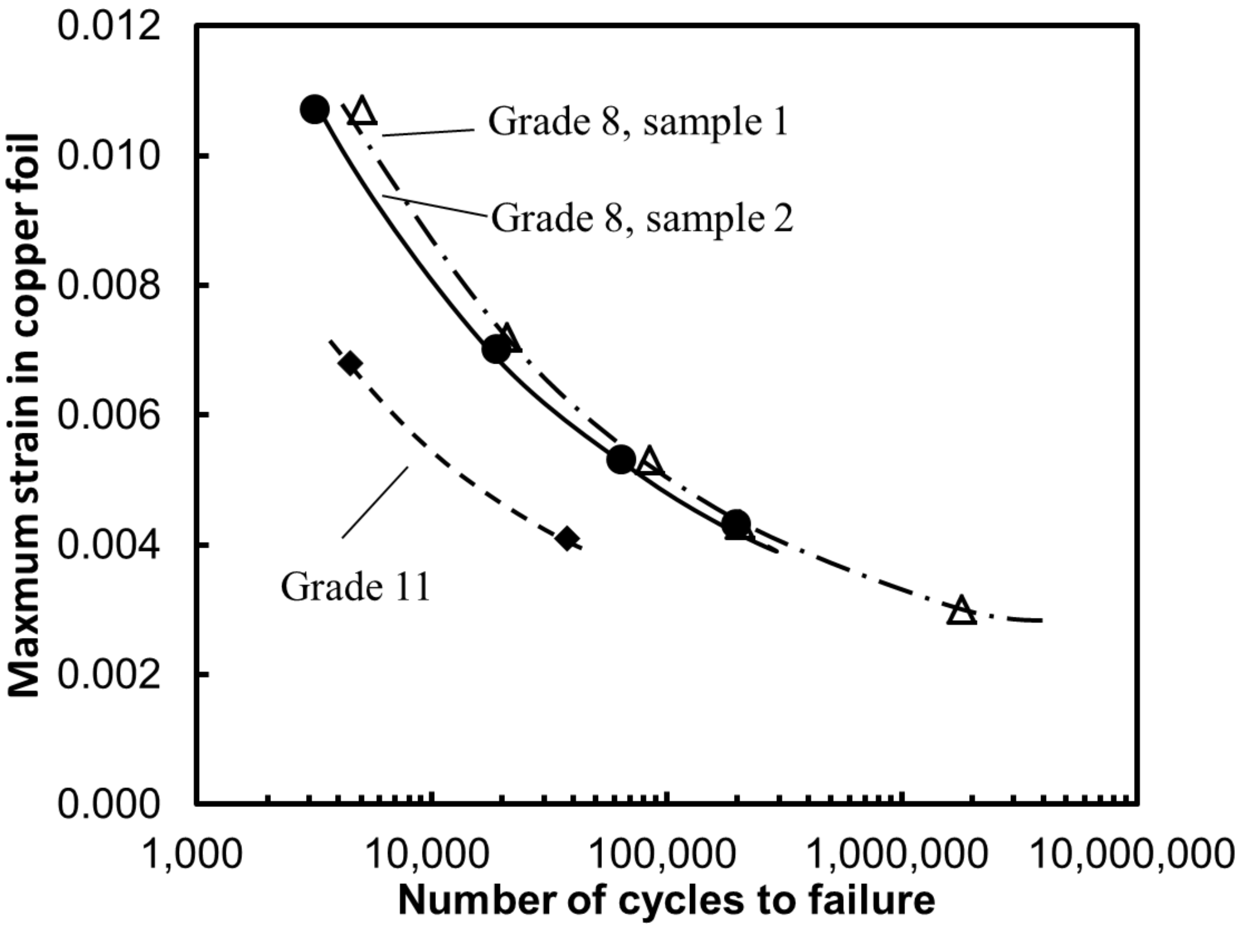
$$\sum_{i=0}^{n} \int_{hi}^{hi+1} Ei \, \frac{y - y_o}{\rho} dy = 0$$

Cyclic bend test (IPC-TM-650,2.4.3)





Cyclic bend test (IPC-TM-650,2.4.3)



Coffin–Manson relation

$$\frac{\Delta\varepsilon}{2} = \sigma_f \cdot \frac{(2N_f)^b}{E} + \varepsilon_f \cdot (2N_f)^c$$

Summary

Young's moduli of copper foils using the resonance method were measured and compared with those obtained according to the IPC TM-650 2.4.18.3 test method.

- The Young's modulus obtained via the resonance method was approximately two times greater than that obtained using the tensile method.
- It was found that the Young's modulus values measured by the resonance method were quite similar to the theoretical values.
- The resonance method could detect the crystallographic orientation dependence of the Young's modulus.

The resonance method is recommended for measuring Young's modulus at foil thicknesses.

THANK YOU!

Any Questions?