

## Experimental Measurement of Young's Modulus from a Single Crystalline Cementite

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Cementite, known to be the hard phase maintaining the high strength in carbon steel, is one of the most important phases in steel performance and much research has been conducted on its mechanical, electrical, and thermal characteristics [1-8]. It is required to measure elastic properties from a single crystalline cementite to predict the mechanical properties of steel, but experimental measurement from a single crystalline cementite has not been done yet. Considering the anisotropy, most of the studies so far have used the polycrystalline phase due to the difficulty in preparing a single crystalline cementite. In order to measure the mechanical properties from a single crystalline cementite, three major experimental hurdles should be considered. First, single crystalline cementite sheets with specific crystallographic orientation in the lamellar structure of pearlitic steel should be extracted. Second, the geometrical arrangement of the extracted cementite sheets must pass the bending test that considers the anisotropic elastic constants of a single crystalline cementite. Finally, the bending test should have stress quantification in a small scale.

In this study, we experimentally measured the Young's modulus of a single crystalline cementite along two different orientations in the [100] and [001] directions and compared the results with the theoretically calculated value from the reported elastic constants provided by the first principle calculation. Pure Fe-C pearlite was heat-treated and selectively etched to extract [001]- and [100]-oriented single crystalline cementite sheets, as shown in Figure 1. The elastic properties of the shaped cementite were measured in a simple, home-built in-situ bending test system set up inside the scanning electron microscope (SEM) using a micro-newton ( $\mu\text{N}$ ) range force sensing probe, as shown in Figure 2(a). Loading force and strain measurement was carried out from the force sensor with linear movements and snapshots of in-situ recording SEM images, as shown in Figure 2(b).

The calculated Young's modulus from the theoretical elastic constants [9] obtained in this study is 286.90 GPa for [100]-oriented and 220.62 GPa for [001]-oriented cementite. The average experimental Young's modulus of the single crystalline cementite sheet along the [100] direction is 262.21 ( $\pm 31.75$ ) GPa and along [001] is 212.66 ( $\pm 45.38$ ) GPa. When the experimental values are compared with the theoretical value, the experimental numbers were 8.6 and 3.6% lower than the theoretical values for [100]- and [001]-oriented cementite, respectively. The experimental value of Young's modulus obtained from real samples is believed to provide meaningful numbers and can be applied in the design of structural materials. Additionally, the technique employed in this study can evaluate the elastic properties of a small-scale single crystalline second-phase precipitate in the metal matrix.

### References

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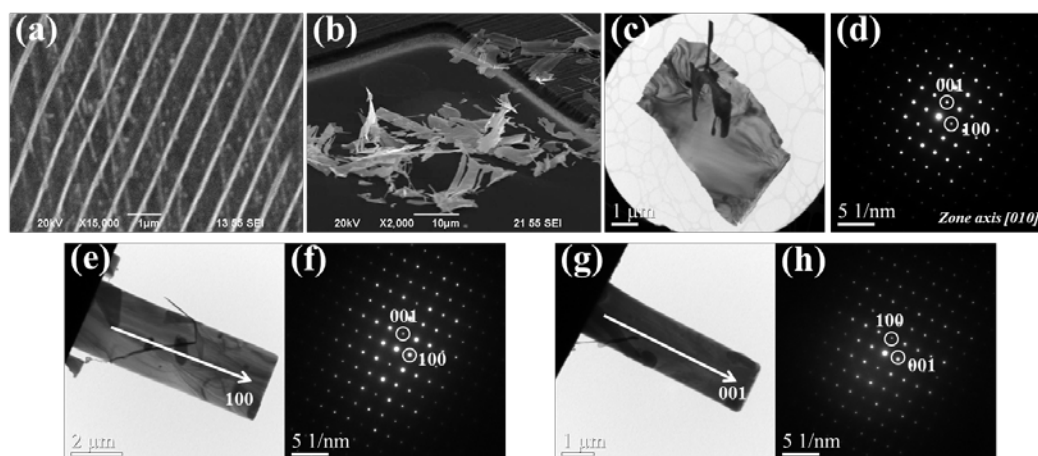


Figure 1. (a) SEM image of pearlitic microstructure of nital-etched sample. (b) SEM image of extracted cementite sheets on a lacey carbon film grid. (c) Bright field (BF) TEM image (d) selective area diffraction pattern (SADP) of individual extracted cementite sheet. (e) BF TEM image (e) SADP of cementite sheet along  $[100]$  orientation with  $[010]$  zone axis. (g)-(h) Cementite sheet along  $[001]$  orientation.

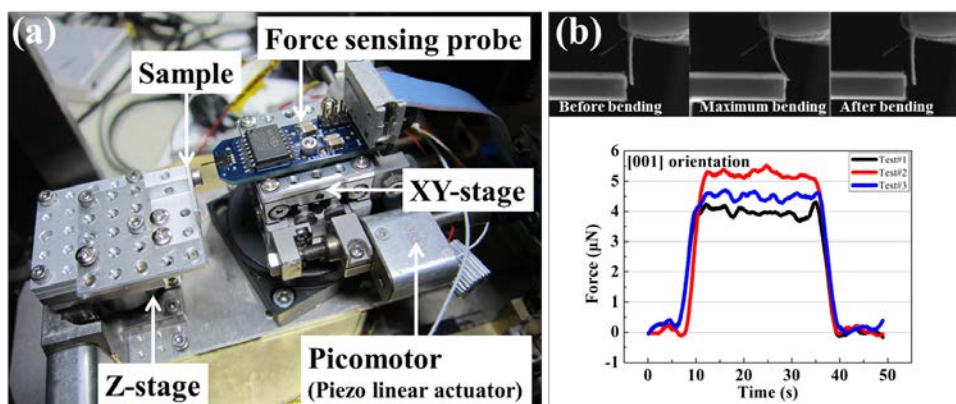


Figure 2. (a) Home-built in-situ bending test system. (b) Snapshot images of recorded SEM images during in-situ bending test of the cementite sheet along  $[001]$  orientation and measured force versus time curve.