Growth Kinetics of Carbon Microcoils
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Introduction
Bidirectionally grown double helical carbon nanofibers or carbon microcoils (CMCs) exhibit an intriguing morphology. CMCs are formed by unique catalytic mechanism during growth. Rotation of the catalyst was proposed by Chen et al. (Diamond Relat. Mater. 2003;12(10):1836-40).

In this study, rotation speed of growth-tip and coil growth speed were estimated using growth model fitting.

Synthesis of CMCs
CMCs were synthesized using a chemical vapor deposition method. C,H₄, H₂, Ar, H₂, and thiophene (C₅H₅S) gases were heated with Ni catalytic powder on graphite substrate. A small amount of sulfur plays an important role to form bidirectionally grown double helical shape.

Characterization
As-grown carbon material has three layers (Fig.3a)
- Top layer: CMCs
- Middle layer: Carbon nanotubes and nanofibers
- Bottom layer: Dense and shiny carbon materials including nickel

CMCs obtained at 740 °C
- Average coil diameter (d₀) = 2.86 µm
- Average fiber size (w × h) = 0.59 × 0.94 µm²
- Volumetric density (ρ) = 1.7 g/cm³
- The number of CMCs (N₀) = 3.31×10⁵ cm⁻²

Fig. 2. Optical microscope image of CMCs embedded in epoxy. To measure the number of CMCs (N₀), as-grown carbon material was embedded in epoxy, and then the cross section was polished.

Growth Kinetics of CMCs
Fig. 3. CMC images after 150 min reaction: (a) cross-section of as-grown carbon deposition and (b) representative CMCs.

Growth of the Double Helix
Fig. 1. Bidirectionally grown double helical carbon nanofiber

Growth Kinetics of CMCs
Fig. 4. Weight of carbon deposition obtained at 740 °C for each layer as a function of the reaction time.

Growth Mechanism
Factors for rotation of growth tip
- Growth of two curved nanofibers from one catalyst
- Fixation of bottom of coil by middle or bottom layer

Carbon deposition rate of each fiber (Fig. 6a)
- Half of carbon deposition (k₂/2) from one catalyst was used to form one side of carbon fiber.

Rotation and growth speed at 740 °C (Fig. 6b)
Based on the CMC size, density (ρ) and carbon deposition rate per catalyst (k₂), growth speeds were calculated.

- Rotation speed of catalyst >>> 41.5 rpm
- Growth speed of coil length >>> 78.1 µm/min

Fig. 6. Schematic top view illustration of (a) CMC growth and (b) growth-tip rotation.

Conclusion
The growth mode of CMCs was bidirectional double helical growth. Exponential decay model was well fitted to weight gain of CMCs. Catalyst or growth tip was rotated by the formation of two curved carbon filaments and the fixation of the bottom part of the coil in carbon deposition. Rotation speed was calculated using parameters obtained from the experiments and curve fitting.