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Helices in micro-world: Materials, properties, and applications

Gaoshan Huang [a,b], Yongfeng Mei [a,*]

[a] *Department of Materials Science, Fudan University, Shanghai 200433, People's Republic of China*
[b] *Key Laboratory of Inorganic Coating Materials, Chinese Academy of Sciences, Shanghai 200050, People's Republic of China*

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Abstract

The demand for equipments with small dimensions and high performance as well as the development of micro-/nano-fabrication has stimulated intensive researches related to micro-/nano-structures. As a new member in the micro-world with three-dimensional geometry, micro-helices made from various materials possess unique properties and meanwhile present challenge in fabrication. This overview reviews recent progresses in micro-helices related researches, especially fabricated by rolled-up nanotechnology. The fabrication approaches with respective advantages and limitations are summarized and categorized, and the underneath mechanisms are explained. The important properties related to the helical geometries in the disciplines of mechanics, electrics, magnetics, and optics are discussed in detail. The results summarized here suggest that micro-helices may have great potential in micro-devices and systems like micro-electro-mechanical system and lab-on-a-chip.

Keywords: Micro-helix; Materials; Fabrication; Properties; Applications

1. Introduction

Mathematically, an ideal helix curve has the property that the tangent line at any point makes a constant angle with a fixed line called the axis [1]. One should notice that the nature has already built plenty of sophisticated helical structures, although the structures may not as perfect as the definition from mathematics. Seashells, horns, plant tendrils, and seed pods are macroscopic examples [2]. The important genetic material-DNA molecule, which consists of two helical chains each coiled round the same axis, is a representative in the micro-world. Helix-related structures can also be frequently noticed in the ordinary life. For instance, a helical spring with structural flexibility, is a mechanical device used to store energy due to resilience and release, and therefore can be engaged to absorb shock, or to maintain a force between contacting surfaces [3]. Another example is the screw. The thread on its body surface is obviously a helix-like structure, which has the ability to transfer the rotation into the motion along the axis direction. Nowadays, fabrication of artificial helices with different materials in the macro-world may not be very difficult due to the rapid development of industrial technique; however, producing a helix in micro- or nano-world is more challenging.

Recently, it is increasingly demanded for equipments with small dimensions and high performance. The typical example is the well-known Moore's law. Similar demands also motivate the researches in the interdisciplinary fields such as micro/nano-electro-mechanical systems (MEMS/NEMS) and lab-on-a-chip. The enormous progresses in the miniaturization of those electronic, optical and mechanical devices have led to intense studies of fabrication methods and physical properties of the corresponding building blocks, i.e. micro-/nano-structures and materials. The helices in micro-/nano-scale are still a three-dimensional structure although the dimensions are much smaller than their macro counterparts. This three-dimensional geometry certainly implies difficulty in manufacturing,

* Corresponding author.
E-mail address: yfm@fudan.edu.cn (Y. F. Mei).
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because the structures are too big to be made by well-established molecular synthesis, and too small to be constructed by the tools and methods used in the macro case [4]. On the other hand, the unique geometry in small dimension may give birth to a lot of new properties, and may find advantageous applications in electronics, optoelectronics, sensing and actuating, and electromechanically coupled devices [4]. More and more interest has been attracted, while the number of the publications in the related disciplines increases rapidly.

From the viewpoint of practical applications, the helices in the micro-scale (typical dimension from ~100 nm to ~100 μm) are important and interesting. For instance, due to their relative larger size, their incorporation into MEMS is direct and the characterization can be carried out in a convenient way, since most micro-structures are visible in normal optical microscope. The devices sometimes can even be built up by hand. The helices in nano-scale, on the contrary, are even difficult to be fabricated and investigated, although the new sciences in such small scale may suggest even significant potentials in the future. Based on this consideration, here, we mainly focus on the fabrications of the helices and related structures with the diameter from ~100 nm to ~100 μm. The fabrication of micro-helices from different materials will be categorized and their novel properties and applications will be summarized and reviewed. Given limited space, priority will be given to new and unique approaches and properties. Our emphasis is artificial helical micro-structures, the helicity from the molecules and their arrangement like in liquid crystal [5] will not be covered.

2. Fabrication techniques and mechanisms

There are a few methods commonly used in micro-fabrications, and they are classified to two groups: "top-down" and "bottom-up". The top-down approaches create micro-structures by shaping the larger materials into the desired structures while the bottom-up approaches try to make smaller components built up into complex assemblies. Generally, a specific method can be evaluated according to its generality, tunability, and controllability. In this section, we will summarize the methods used in producing micro-helices. Both "top-down" and "bottom-up" approaches will be discussed.

2.1. Self-assembly in vapor phase deposition

Vapor phase deposition generally consists of vapor transport and vapor reaction at suitable temperature and pressure [6]. There are actually different mechanisms and reactions taking place in the processes, making the method capable of produce abundant microstructures.

Carbon nanotube (CNT) is an important nanomaterials and its discovery in 1991 inspires researches in carbon-related materials [7,8]. CNT and carbon nanowire (CNW) can be produced by chemical vapor deposition (CVD) via a vapor−liquid−solid (VLS) process: the carbon formed in the gas phase is dissolved in a molten catalyst droplet (liquid) and reaches oversaturation. The liquid nucleates at lower temperature to form CNT or CNW (solid) at the droplet/substrate interface. Under certain experimental conditions, CNT or CNWs with helical geometry were obtained. Publications based on individual results reported carbon-related helices with different dimensions and crystallinity [4,9,10]. A typical scanning electron microscopy (SEM) image of an array of highly aligned helical CNTs with nearly identical diameter and pitch is shown in Fig. 1(a) [11]. The mechanism for this curved growth process is believed to be connected with the growth front, i.e. the carbon/catalyst interface. Several models have been proposed but no consistence has been achieved. The first model suggests the regular insertion of pentagon−heptagon pairs at the interface and the stress introduced cause the unique geometry [12−15]. The second model invokes the localized stresses and anisotropic deposition rates on

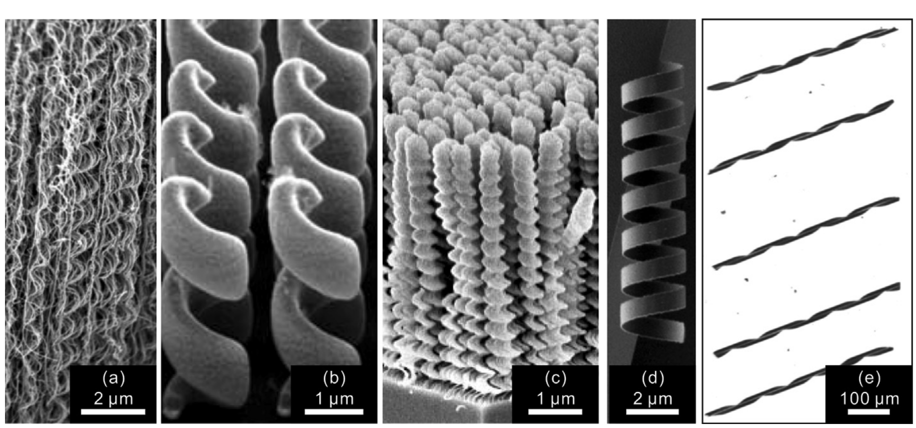

Fig. 1. (a) SEM image of an array of helical CNTs with identical diameter and pitch. Adapted with permission from Ref. [11]. (b) Oblique view of the helical structures after removal of the template. Adapted with permission from Ref. [28]. (c) Morphology of MgF_2 micro-helices on glass with 15 turns. Adapted with permission from Ref. [37]. (d) Micro-helix fabricated by rolling SiGe/Si/Cr multi-layered nanomembrane. Adapted with permission from Ref. [63]. (e) Optical image of an array of grating-structured micro-helices.