Session Number: F2D2

Teaching Mechanical Engineering Undergraduates about Nanomaterials

Malur N. Srinivasan and Yavuz S. Tunc

Department of Mechanical Engineering
Lamar University, Beaumont, TX 77710

ABSTRACT

Nanomaterials have attracted enormous attention in the recent years. They have small feature size (crystallite size) in the range of 1-100 nm and are structurally quite distinct from traditional crystalline materials whose feature size may extend from several micrometers to several millimeters, and traditional amorphous materials, which are essentially featureless in bulk. Therefore it is reasonable to postulate that their behavior is influenced by factors that lie in between those affecting atomic and quantum phenomena and those affecting bulk phenomena [1]. Products from nanomaterials may be produced from metals, polymers, ceramics and composites made from some combination of the first three. It is again reasonable to postulate that the background mechanical engineering students already have in the design and manufacture of bulk engineered products made of metals, polymers, ceramics and composites would be helpful in generating interest in studying methods for producing nanostructured products.

This paper is intended to serve as a preamble for the development of a course on nanomaterials for mechanical engineers. As the course should cover not only the science of nanomaterials but the characterization and the methods of manufacture and applications such as sensors and nanocomposites that are of interest to mechanical engineers, an outline of these topics is provided in the paper.

Introduction:
As noted above, nanomaterials possess distinct properties and behavior in view of their small (1-100 nm) feature size. Research in the area of nanomaterials grew exponentially in the 1990's as evident in a very comprehensive report published in 1999 [2]. The growth is still very rapid as evidenced by enormous amount of publications in recent times [3]. Needless to say, the amount of information available on nanomaterials is very vast and it would be overwhelming for students to study everything that is known about nanomaterials. A sensible approach would be to focus upon selected topics consistent with the background of the students as an introductory measure and encourage them to recognize that there are abundant opportunities to expand their horizon by taking part in interdisciplinary projects later. Such an exposure would help the students to be initiated into the world of nanoscience and nanotechnology.

The three areas of specialization in a traditional mechanical engineering program, like the one at Lamar University in Beaumont, Texas are thermal science, mechanical systems and design and, materials and manufacturing. Nanomaterials suitable for structural and sensor applications may be considered to be important to be studied in such a setting, as well as the mechanical behavior of bulk form nanostructured objects. Also, the students traditionally focus on the science of materials at a feature level exceeding, in general, well over1000 nm and therefore there is a need for them to be introduced to the concepts of quantum mechanics as many nanomaterials and their products may be strongly affected by atomic level behavior. In what follows an outline of these topics is provided as a preamble for developing an introductory course on nanomaterials to traditional mechanical engineering students.

Quantum Mechanics

The principle and importance of quantum mechanics is succinctly described in Todd's Quantum Intro [4]. Quantum mechanics was developed because classical physics could not explain some experimental results obtained at the atomic level. As opposed to classical physics, quantum mechanics can describe the discreteness of energy, the wave-particle duality of light and matter, quantum tunneling, the Heisenberg uncertainty principle and the spin of a particle. No doubt the mechanical engineering students will have been exposed to these topics in elementary physics courses, but in general, will not have had the opportunity to apply quantum mechanics in engineering situations. Demonstrating how quantum mechanics can help understand the behavior of nanomaterials, particularly at the low nanorange, will generate interest in reviewing this subject more objectively. For instance the properties and behavior of a nanomaterial or its product may be better explained by considering that the atomic orbitals are probabilistic rather than deterministic (the latter assumption may be quite appropriate for materials with conventional feature size). For example, it may be possible to better explain inverse Hall-Petch relationship observed at low feature sizes of nanomaterials.

Mechanical Properties of Bulk Nanomaterials

Koch [5] has provided a comprehensive account of bulk nanostructured materials. As stated by him, compared to their counterparts with conventional structure, nanostructured materials have 30-50% lower elastic modulus, very high hardness and strength, negative Hall-Petch relationship, high ductility at low homologous temperatures. It is suggested that the intrinsic elastic modulus of conventional materials and nanostructured materials should be the same, but at very low feature sizes (< 5 nm), the modulus is lowered by the fact that the number of atoms associated with grain boundaries and triple junctions becomes very large. In regard to deformation-related behavior, it has been noted by Darken [5, 6] there is a lack of dislocations in confined spaces such as single crystal whiskers. It may therefore be argued that as the crystallite size decreases in nanomaterials, the dislocation activity decreases because of the above tendency and the difficulty for stress-activated dislocation multiplication. Eventually, at very low feature sizes, the dislocations may be absent and the deformation may be diffusion-controlled. Quantum mechanics may assume particular importance under these circumstances. Koch [5] has specifically pointed out towards the need for better understanding the plastic deformation and fracture in nanomaterials.

Application of Nanostructured Materials

Tungsten Carbide Parts
The manufacture of nanostructured tungsten carbide (WC-Co) powder has attained maturity [7] following pioneering research by Kear [8]. The consolidated part showed hardness values about twice that of its counterpart made with conventional structure. Similar results have been obtained by Srinivasan, et al [9] who used mechanical alloying and equal channel angular extrusion to make WC-Co billets. Work done at Stevens Institute of Technology and Royal Institute of Technology, Sweden has shown that the fracture toughness of nanostructured WC-Co equals or exceeds that of conventional WC-Co [5].

Sensors
It has been reported that the nanotechnology sensor market will generate revenue of $2.8 billion in 2008 and it will reach $17.2 billion by 2012 [10]. As stated in reference [11] sensors made with nanomaterials employ their high sensitivity to changes in various parameters they are designed to measure. The measured parameters include electrical resistivity, chemical activity, magnetic permeability, thermal conductivity and capacitance. Sensors made with nanocrystalline materials are extremely sensitive to change in environment. Typical applications which take advantage of this feature are smoke detectors, ice detectors on aircraft wings, automobile engine performance sensors and others.

Nanocrystalline sensors are made with several materials of different compositions. Szewczyk, et al [12] have examined the compressive stress characteristics of a sensor of FINEMET type [$Fe_{7.5}Si_{13.5}Nb_3CuB_9$]. This study is important to assess he magnetoelastic Villari effect which deals with the change in the magnetization of a soft magnetic material due to mechanical stress. Osterloh and his associates at the University of California in Davis [13] discovered that nanowires made of lithium, molybdenum and selenium atoms show changes in electrical resistance up to 200 % when exposed to vapors of organic solvents. By attaching chemical groups to the nanowires they could modify the sensor to measure the acidity of a solution. A nanomaterials research and development company [14] is involved in using nanostructure in sensors made with conventional materials such as tin oxide, to enhance the performance of the sensors. It is also involved with federal government agencies in developing nanomaterial sensors based on novel conducting polymers and several other sensors. Another company is developing nanoelectronic sensors that integrate carbon nanotube electronics with silicon microstructures [15]. It is therefore clear that sensors made with nanomaterials have huge potential for development and application.

Nanocomposites
Nanocomposites may be defined as those class of composites where the dispersed phase is a nanomaterial. Considerable development has occurred in producing mineral (usually clay) filled polymers [16] but in recent times the addition of carbon nanotubes to polymers has attracted attention [17]. The addition of the nanomaterials can significantly improve the properties of the matrix. For instance, the addition of relatively small amounts (<10%) of clay can enhance the mechanical and thermal properties of the matrix and improve flame retardancy [16]. A company

[18] has developed polymer matrix nanocomposites that show increased thermal stability and over ten-fold improvement as a barrier to oxygen and water vapor compared to conventional polymer resins. The present application of nanocomposites is mainly in the automotive field [19], the technology having been developed by first by a leading Japanese automobile manufacturer around 1990 [16]. It is again evident that nanomaterials have a significant role to play in the development of new generation composites.

Processing of Nanomaterials

There are basically two approaches to produce nanomaterials, the "bottom-up" approach and the "top-down" approach [20]. In the "bottom-up" approach, the building blocks are first formed and then assembled to get the final nanomaterial. An example of this approach is the formation of powder through aerosol techniques [20, 21] and then the compaction of the powder into the final material. Chemical synthesis using thin film techniques also belong to this category. In the "top-down" approach the principle is to start with a relatively bulky product with conventional microstructure and then "sculpt" it into the nanomaterial [20]. Examples of this technique are lithography/etching and mechanical attrition (ball milling). To form the final product with nanostructure the assembly and synthesis may be done sequentially, such as ball milling and sintering, or in by integrating assembly and synthesis [20, 22].

Characterization of Nanomaterials

Sophisticated techniques are necessary to characterize nanomaterials. These include X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning tunneling electron microscopy (STEM) and others, with which many mechanical engineering majors may not be familiar.

Planning and Teaching the Course

A course containing the above topics may be taught as an elective for senior-level undergraduate and graduate students in mechanical engineering with traditional curriculum. There are text books available on this subject [e.g. 23, 24] but it would be advisable to expose the students to relevant information available in current literature. This is perhaps best done by offering lectures over half the period of the semester and keeping the other half for student seminars involving study of the current literature. The seminars could include subtopics such as lithography, mechanical alloying, XRD, TEM, STEM, etc., in the context of nanomaterials.

The planned schedule for teaching this course as a mechanical engineering elective (3 credit hours, one semester) is shown in Table-1 below.

Table-1 – Schedule for Teaching Nanomaterials*

Item No	Topic	Number of hours
1	Introduction to Quantum Mechanics	6
2	Processing of Nanomaterials	9
3	Characterization of Nanomaterials	9
4	Mechanical Properties of Bulk Nanomaterials	9
5	Application of Nanostructured Materials: Tungsten Carbide Parts Sensors Nanocomposites	 3 3 6

*The number of hours shown includes the time allotted for lectures and seminars

No laboratory program is planned for the present, but once experience is gained in teaching this course, time will be made available for some simple demonstration experiments as typically discussed in reference [25].

Summary

An outline of chosen topics and their importance in the context of teaching a course on nanomaterials for traditional mechanical engineering students is presented in this paper. The topics are by no means exhaustive but should be adequate to give the students a good introduction to the nanoworld.

References

1. K. Hickmann, http://www.csa.com/hottopics/nano/overview.html
2. "Nanostructure Science and Technology, A Worldwide Study", R.W. Siegel, E. Hu and M.C. Roco (eds), Sept.1999, http://www.wtec.org/loyola/nano
3. http://www.azom.com/
4. http://www-theory.chem.washington.edu/~trstedl/quantum/quantum.html
5. C.C. Koch in Ref. 2, 113-
6. L.S. Darken, Transactions of American Society of Metals, 1961, vol. 54, 599
7. "Description of Tungsten Carbide Technology- Superfine Tungsten Carbide for Bulk Hardmetal Applications", http://www.Inframat.com/wcdetail.htm, 1-7
8. ibid., Reference to B.H. Kear's work at Rutgers University, 1
9. M.N. Srinivasan, K. Ramakrishnan, X. Kaculi and K.T. Hartwig, "Mechanical Properties of Mechanical Alloyed and Equal Channel Angular Extruded Tungsten Carbide", Proceedings of the International Conference on Advanced Materials, Munich, Sept. 25, 2000

10. http://www.techweb.com/wire/networking/55300270
11. http://www.nanomat.com/services_applications_05.html
12. R. Szewczyk, et al., "The Influence of Microstructure on Compressive Stress Characteristics of the FINEMET-type Nanocrystalline Sensors", Journal of Optoelectronics and Advanced Materials, vol .5, no.3, Sept.2003, 705-708
13. http://www.azom.com/news.asp?newsID=1873
14. http://sbir.gsfc.nasa.gov/SBIR/successes/ss/files/Jsc09/ss-9-010.ppt
15. http://www.nano.com/main-homeb-content.html
16. http://www.principiaconsulting.com/industryreports_nanocomp.cfm
17. http://www.azom.com/details.asp?ArticleID=1291
18. http://www.csa.com/hottopics/nano/biblio13.html
19. http://www.sae.org/automag/material/10-2001
20. E.L. Hu and D.T. Shaw in Ref.2, 42
21. M.K. Wu, et al., "Controlled synthesis of nanosized particles by aerosol processes", Aerosol Science and Technology, 1993, vol. 19, 527
22. C.B. Murray, et al., Journal of American Chemical Society, 1993, vol. 115, 8706
23. G. Cao, Nanostructures and Nanomaterials, http://www.worldscibooks.com/nanosci/p305.html
24. A.I. Gusev and A.A. Rempel, Nanocrystalline Materials, Nauka Publishing House, Moscow, 2000, 2001
25. http://www.thenanotechnologygroup.org/id97_m.htm

Acknowledgment
Sireesha Gummadi is sincerely thanked for her help in preparing this paper.

Biographical Information
Dr. Malur Srinivasan earned a Ph.D. in mechanical engineering at the Indian Institute of Science in 1971. He was a member of the mechanical engineering faculty for 20 years at the Indian Institute of Science and 10 years at Texas A&M University in College Station. He has been a faculty in the Department of Mechanical Engineering at Lamar University for 9 years. He has been the Department Chair at Lamar since 1999. His teaching interest is in the area of materials and manufacturing.