Trends in Advanced Manufacturing

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ABSTRACT
Some recent trends and developments in advanced manufacturing of advanced materials from macro- to nanoscale subjected to impact and shock loading, with industrial applications to net-shape manufacturing, bioengineering, safety, transport, energy and environment, an outcome of the very extensive, over 45 years, work on this field performed by the author and his research international team, are briefly outlined. The benefits of such advanced materials, manufacturing and loading techniques, products and applications in many technological areas are significant, since their impact will make the manufacturing/machine tool sector, communications, transportations, data storage, health treatment, energy conservation, environmental and human-life protection and many other technological applications better, faster, safer, cleaner and cheaper.

1. INTRODUCTION

In manufacturing technology six main elements may be identified, see Figure 1(a), with the central one being the enforced deformation to the material, i.e. the processing itself, brought about under consideration of the interface between tool and workpiece, introducing interdisciplinary features for lubrication and friction, tool materials properties and the surface integrity of the component. The as-received material structure is plastically deformed through the deformation processing, therefore, materials testing and quality control before and after processing are predominantly the areas of interest to the materials scientist. The performance of the machine tools together with the tool design are very important, whilst, the techno-economic aspects, e.g. manufacturing systems, automation, modeling and simulation, rapid prototyping, process planning and computer integrated manufacturing, energy conservation and recycling as well as environmental aspects are also important in manufacturing engineering [1].

Dimensional and shape accuracy, surface integrity as well as the functional properties of manufactured parts mainly determine their quality. Therefore, advanced manufacturing is related to the tendency to miniaturization and is accompanied by the continuous increasing of the accuracy of the manufactured parts. Precision/ultraprecision engineering, carried out by machine tools with very high accuracy, and nanotechnology processing, defined as the fabrication of devices with atomic or molecular scale precision by employing new advanced energy beam processes that allow for atom manipulation, constitute the two main trends towards product miniaturization, see Figure 1(b). Therefore, manufacture of nanostructured materials (carbon nanotubes and nanoparticles), having every atom or molecule in a designated location and exhibiting novel and significantly improved optical, chemical, mechanical and electrical properties, is made possible Note that, nanoparticles have larger

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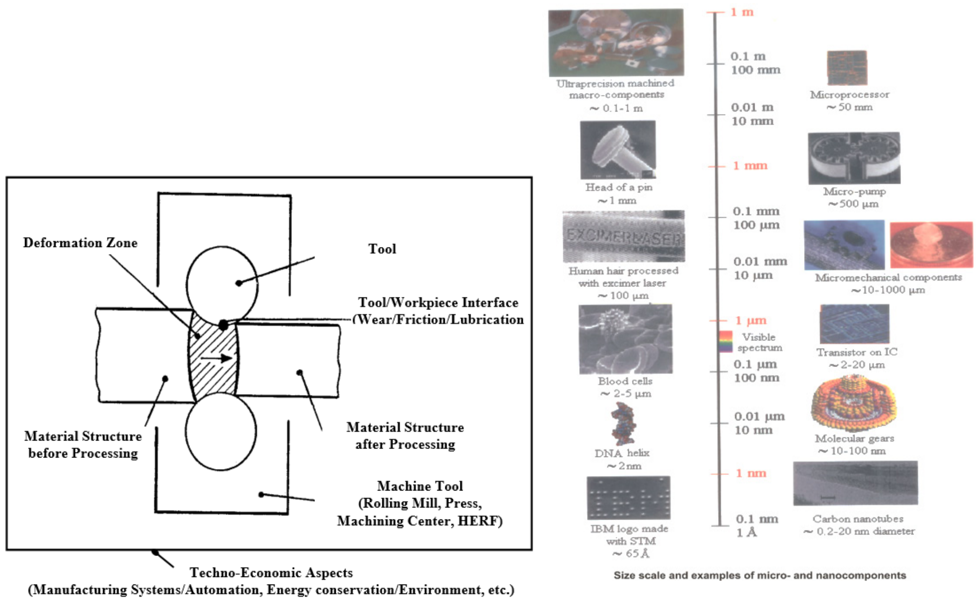


(a) (b)

1. Fabrication	1.1	Electrodynamic techniques
	1.2	Plasma chemical synthesis
	1.3	Explosive techniques
	1.4	Glass crystallization methods
	1.5	Sol-gel technique
	1.6	Mechanical milling
2. Consolidation and Processing	2.1	Electrodynamic compaction
	2.2	Explosive compaction
	2.3	Die pressing
	2.4	Injection molding
	2.5	Microwave sintering
	2.6	Nanomachining
3. Coating	3.1	Electrodeposition
	3.2	Microwave
Characterization		

(c)

Figure 1: (a) Principle of manufacturing technology; (b) Precision / Ultraprecision manufacturing – Nanotechnology; (c) Nanomaterials manufacturing

active surfaces per unit volume and mass, exhibiting greater chemical activity and, therefore, they can be used as catalysts, whilst nanostructured materials can also be built in such a way that they will be biocompatible for implants. The manufacturing sequence of nanomaterials is usefully classified in Figure 1(c) [2].

Recent trends and developments in advanced manufacturing from macro- to nanoscale in the important engineering topics nowadays from industrial, research and academic point of view: nanotechnology/ultraprecision engineering and advanced materials under low/high speed impact and shock loading, with industrial applications to net-shape manufacturing, bioengineering, safety, transport, energy and environment, an outcome of the very extensive work, over 45 years, on these fields performed by the author and his research international team, are briefly outlined in the present Invited Lecture of the Multiphysics 2017.

2. SHOCK LOADING AND PROCESSING

Explosive and/or electromagnetic compaction/cladding methods as well as high temperature/high pressure die techniques are employed for the production of ultrafine materials (metals, ceramics, mixtures) from macro- to nanoscale, see Figure 2(a). During shock compaction, a longitudinal, P-shockwave, with a real shockwave profile (pressure, P vs time, t), is initiated, travelling into the body at high speed, calculated from the corresponding state of the material under shock conditions, i.e. its Hugoniot curve (pressure, P - specific volume, V relationship), defined as the loci of all shock states and essentially describing the material properties, see Figure 2(b). The particles are accelerated into the pores at high velocities, impacting each other, which results in the development of shear S-waves in the powder particles due to jet impact at a point on the particle surface, travelling inside the particle and reflected at its surface resulting in jet formation due to spalling, with subsequent loading of the already formed jet moving between the interparticle voids in the same direction as the shock. The frictional energy release results, therefore, in melting at the surface regions with the associated bonding once the material is solidified. In the consolidation of brittle materials, particle fracture also occurs, leading to the filling of the gaps, whilst reactive elements can also be added to help the bonding process. The high-pressure state creates numerous lattice defects and dislocation substructures leading very often to localise shearing and microcracking. The energy dissipation modes due to shockwaves, see Figure 2(a), and the mechanisms, leading to the final consolidated material, are related to the shock released energy, E

$$E = ½ P (V - V_0) \quad (1)$$

where P is the peak shock pressure, V_0 the initial specific powder volume and V the volume of the solid material. This analytical model of the shock compaction mechanism, validated by the consolidation of spherical copper powders using the explosive cladding/compaction technique, has been proposed by the author; see Ref. [3] for details. It may be noted that, the powders, synthesized by shock, and mixtures on their basis can be utilized as basic materials or as modifying additives at the manufacturing of sintered powdery ceramics, superhard materials (diamonds, CBN), hard-alloy and ceramic composites, nanoparticle reinforced metal and polymeric matrix composites, abrasive pastes and polishing ones, chemical catalysts and sorbents. Subsequent forming (extrusion, rolling, etc.) and metal removal processing result in manufacturing various components (billets, rods, wires, bimetallic foils etc.).

Crushing of brittle materials grains for producing materials of micro- and nanoscale grains can be achieved by shock loading. By applying properly calculated and directed high speed shockwaves with high energy content, created by explosion (explosive compaction) or by discharging electric capacitors (electromagnetic compaction), Al_2O_3, MgO, ZrO_2, Mo, Ti, W, as well as metal MgB_2 low-Tc superconductors and ceramic YBCO/BSCCO high-Tc superconductors are treated for reducing their grain size into nanoscale. Compaction of such materials by shockwaves has the advantage that, during the compaction, phase grain growth does not occur. Note, also, that, in successfully consolidated products, molten and rapidly solidified interparticle regions are usually observed, which are more profound in metals than in ceramics. The main defect of compacted ceramics is the presence of cracks, propagating through the whole component, which may be eliminated by novel compaction techniques and powder preheating or by employing reactive mixtures to produce heat by exothermic reaction, triggered by the shockwave passage [3].

Shock production of nanodiamonds doped with boron is obtained by detonating high explosives, at detonation velocities up to 7 km/s, in an explosive chamber, see Figure 3(a). The main mechanical, thermal and magnetic characteristics of the produced nanoparticles, are usefully classified in the same Figure.

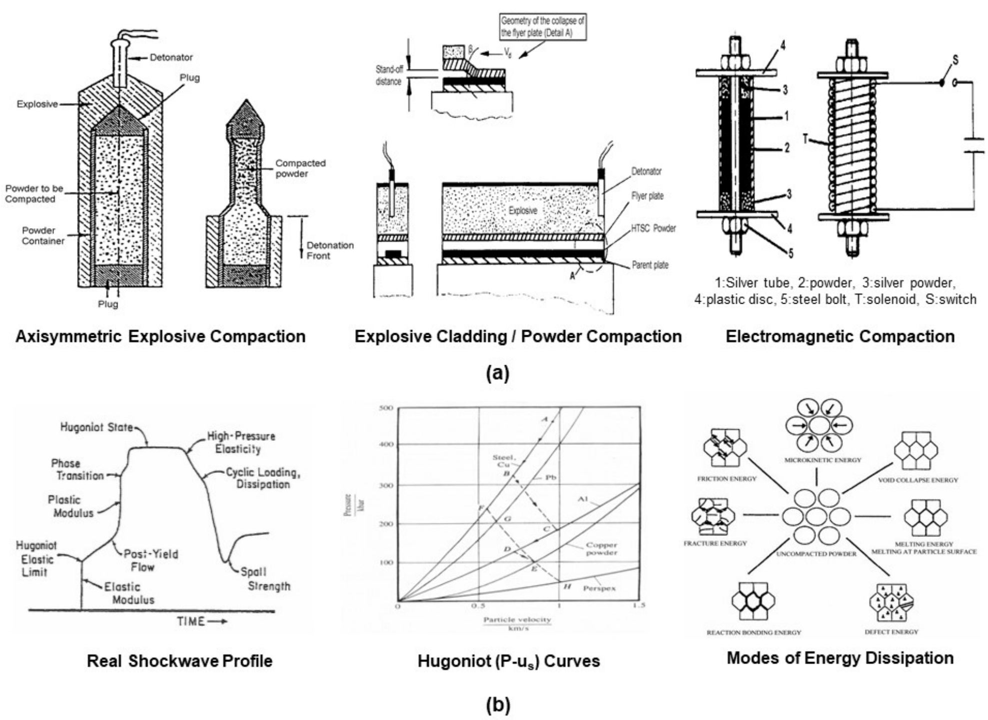


Figure 2: (a) Shock processing; (b) Powders / nanoparticles under shock loading

Applications of these nanodiamonds are related to ultraprecision nanoprocessing / nanolithography, where nanodiamonds are used as multifunctional Scanning Tunneling Microscope tips, shaped as Berkovich pyramid, for surface nanomachining and tribo-nanolithography, see Figure 3(b), as well as to biomedical engineering, with diamond nanoplatforms employed for targeted delivery of diagnostic and therapeutic agents in oncology, see Figure 3(c), [4].

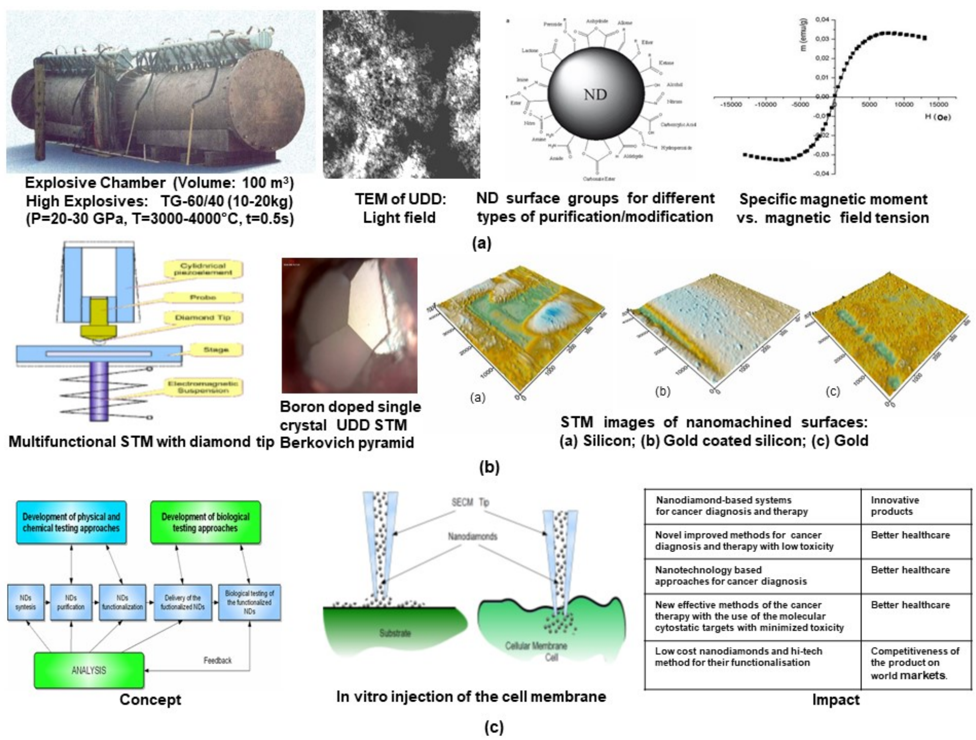


Figure 3: Shock processed nanodiamomds: (a) Production by detonation of explosives; (b) STM tips for surface nanomachining and tribo-nanolithography; (c) Diagnostic and therapeutic agents in oncology

3. SAFETY

Investigations towards the detection of explosives are of high priority in recent years for counter-terrorism, since explosives are the chosen weapons for terrorist attacks targeting any populated area. In this case, three processes are necessary: collectivity, consisting of front-end collection and pre-concentration; separation, providing selectivity of the threat; detection for of threat sensitivity. In that respect, a three-channel explosive detection sensor with different sets of sorbents that provide separation of various groups of explosives, consisting of carbon nanotubes in combination with various monomers-organic compounds effectively interacting with certain nitro-aromatics, has been designed, see Figure 4(a). The first channel, a photoluminescence detector, is a robust connection between nanotubes and diamond substrate without additional bounding layer, whilst, the second one, the mash sensitive sensor, is a tunneling-nanocantilever to improve the selectivity of the detection system; in this case, no additional layers are used in the compounds of monomers, with the carbon nanotubes attached to a flexible diamond plate, connected to the tunnelling deflection sensors, whilst, the deflection of the cantilevered beam, fixed at one end, is registered by tunneling current between a semiconducting diamond plate and an STM tip. For the third, the chemiresisting sensor, a combined, conductive and non-conductive, diamond plate is used as a substrate for the deposition of nanotubes, without metal contacts chemically interacting with the analyser, improving, therefore, the accuracy and sensitivity of the sensor, due its chemical inertness, stable physical/mechanical characteristics and high electromagnetic radiation efficiency from the UV to the g-ray and radioactive particles range.

The development of new methods to better understanding the weakness of current defenses against improvised explosive devices (IEDs) and home-made explosives (HMEs) and the improvement of existing facilities by creating the next generation systems for early detection and neutralization of person-borne or vehicle-borne IEDs, in order to enable faster, more sensitive and less expensive explosive detection, constitute the overall objectives of the Integrated Network for the Detection of Explosives (INDEX) concept, see Figure 4(b), [5].

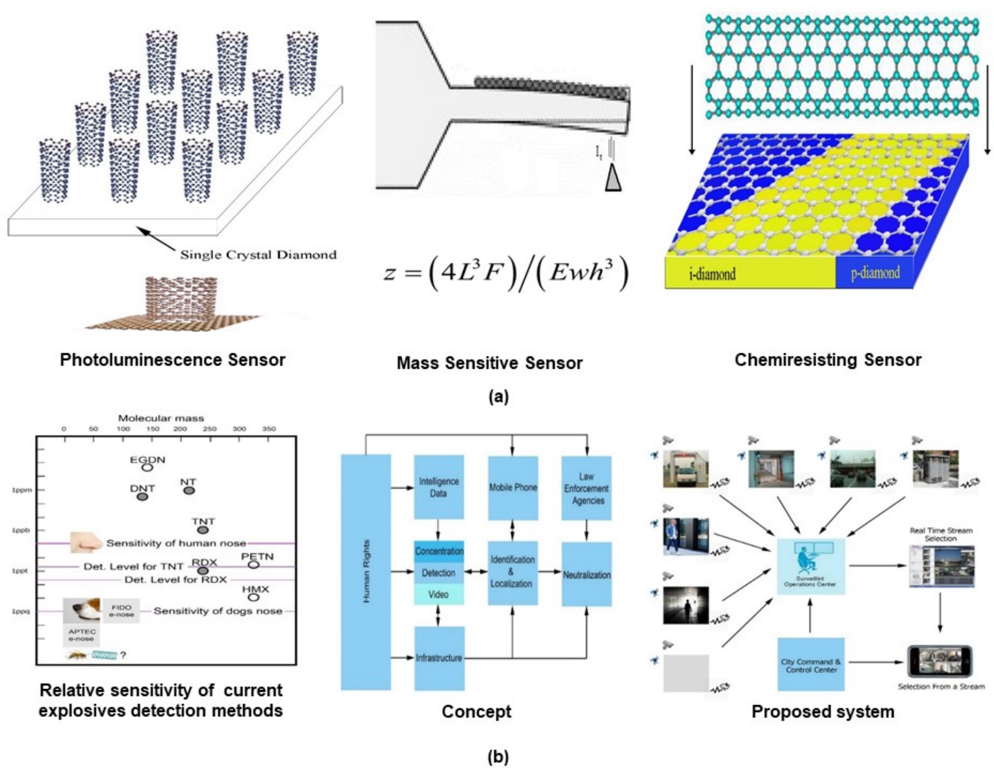


Figure 4: Detection of explosions: (a) Three-channel explosive detection sensor; (b) Integrated Network for the detection of explosives

4. TRANSPORT / CRASHWORTHINESS OF VEHICLES

Crashworthiness studies provide with the mechanism by which a proportion of impact energy is absorbed by the collapsing structure, whilst a small amount is transferred to the passenger in order to improve the crash resistance of the vehicle. To obtain effective crashworthy behavior, associated with the passive safety, a Crashworthiness study must be carried out in the very early design stages, considering analytical and numerical modeling and experimental in situ and at laboratory scale of thin-wall structural components subjected to various loading conditions, in particular, low and high speed impact. Note, also, that, active safety is associated with the passengers and cargo protection during crash. For passengers, it is mainly related to biomedical engineering, with the hip-joint endoprostheses being an important crash biomechanics application. A brief outline of my, over 40 years, extensive work on the crash mechanism of metals, polymers, composite materials and advanced hybrid composite structures, related to surface transport and aeronautics is presented in Figures 5-7(i), respectively [6, 7].

In relation to transport, mainly aeronautics, and energy requirements, a novel design of fifth generation gas turbine engines, using ceramic blades in a diskless gas turbine, reducing, therefore, the effect of thermo-mechanical and dynamic loading on it, is proposed, see Figure 7(ii)(b). High strength ductile nanocomposite refractory compound structural

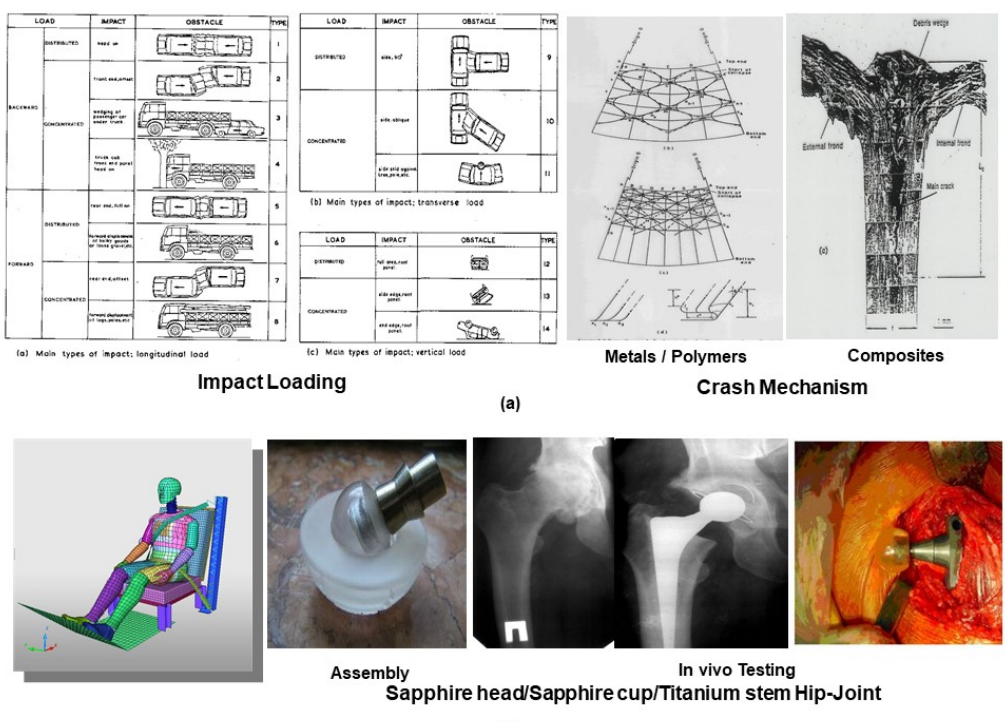
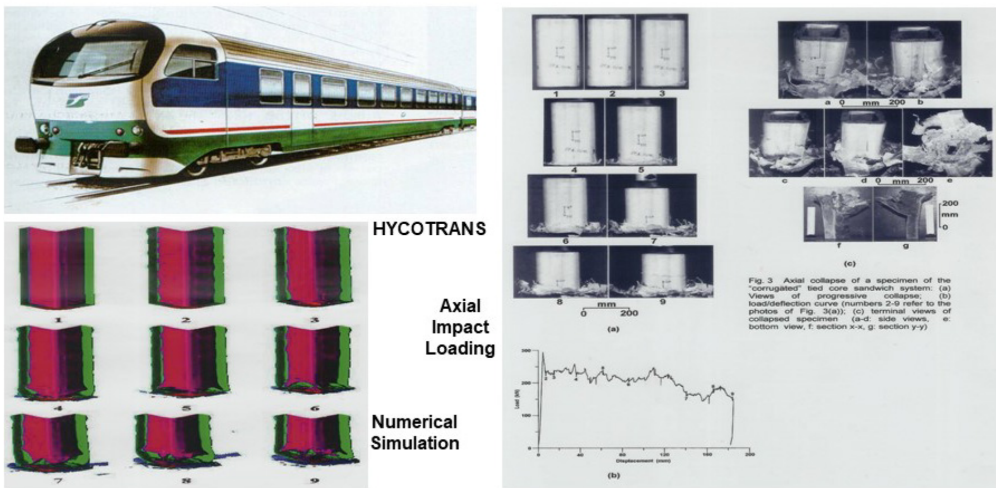
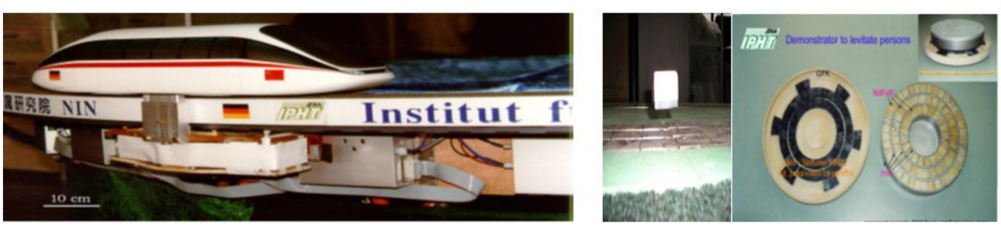


Figure 5: Automotive surface transport: (a) Crashworthy behavior of motorcars subjected to impact loading; (b) Crash biomechanics.

ceramics, with significantly higher rates of heat resistance, raising the turbine operating temperature of the gasifier to a level of 1670°C, are employed Such materials are replacing the expensive and of inadequate performance heat-resistant nickel-chromium alloys, operating at temperatures of 980°C, currently used for manufacturing the fourth generation gas turbine engines. A new technology of manufacturing such ceramic blades of high physical and mechanical properties, namely the self-propagating high-temperature synthesis (SHS) of nanopowder monocarbide tungsten and electrochemical dimensional processing, is also proposed [8].



(a)



(b)

Figure 6: Railway surface transport: (a) Crashworthy behavior of hybrid FRP / foam composite structures subjected to impact loading; (b) Levitation devices and MAGLEV transport

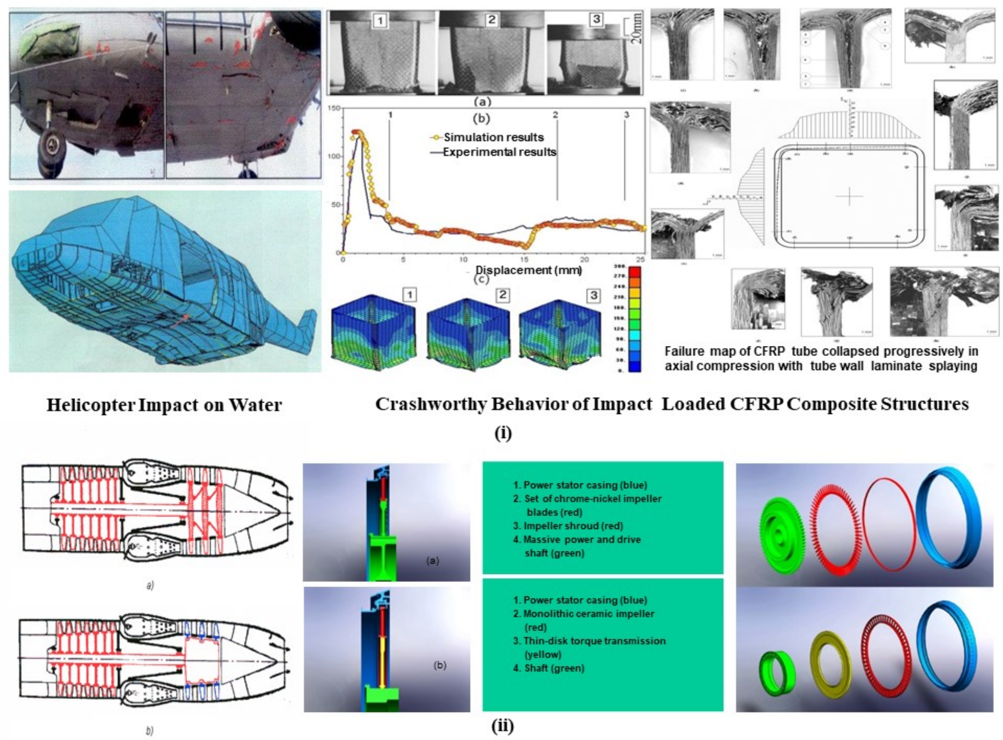


Figure 7: (i) Crashworthiness of helicopters ditching on water and subjected to impact loading; (ii) Design of fifth generation gas turbine engines: (a) existing and (b) novel model

4. ENERGY

Materials that present zero resistance at a certain critical temperature above the absolute zero are named superconductors and the related phenomenon superconductivity, see Figure 8(a), [9].

High-temperature (high-Tc) superconducting materials of the YBCO and BSCCO compounds at critical temperatures, Tc=77-93K, are fabricated by various physicochemical techniques (solid state reaction, sol-gel, etc.) in the form of powders, whilst shockwave powder compaction/cladding techniques, e.g. explosive and electromagnetic, are employed to produce superconductive ceramics with unique properties, see Figure 8(b). The shockwaves originated from explosive detonation and propagated through the porous media, can create high shock pressures and high temperatures that result in fracturing the original grains and in sintering, with the compacted solid containing various primarily line defects that would provide flux pinning centers in Type II superconductors.

The hydrogen technologies development, for replacing the combustion fuel of airplanes, automobiles and submarines by hydrogen, requires the transfer of liquid hydrogen for long distances using pipes and, at the same time, the electric power by superconductive cables disposed in these pipes, so that the liquid hydrogen is simultaneously working as a cooling agent for the superconductor. This makes the use of low-temperature (low-Tc) MgB_2-based

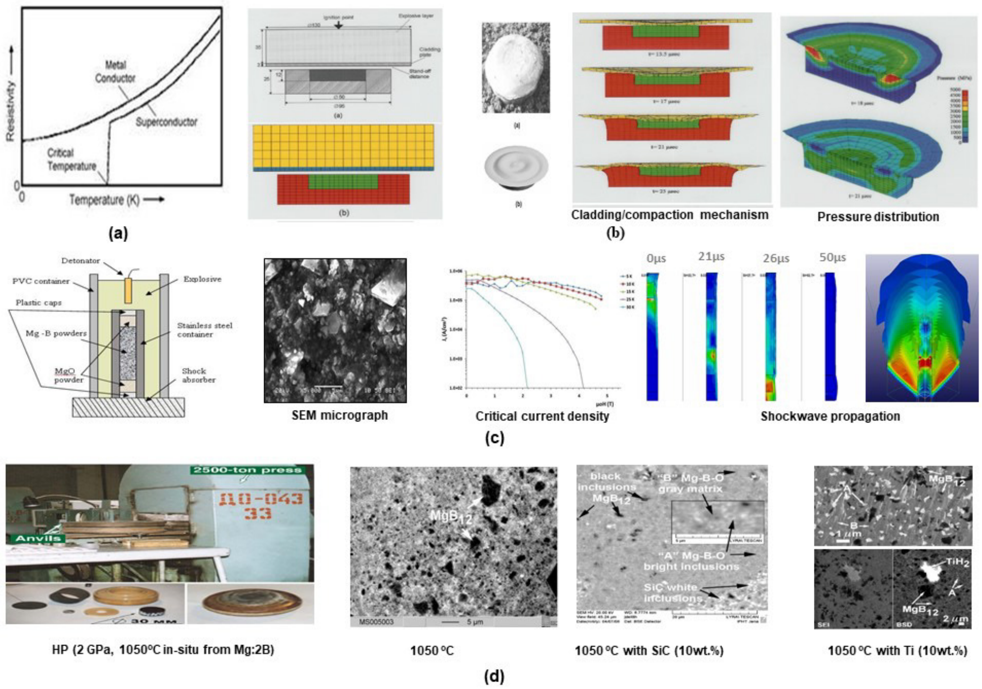


Figure 8: (a) Principle of superconductivity; (b) Explosive cladding/compaction of YBCO high-Tc; (c) Axisymmetric explosive compaction of PIT MgB_2 low-Tc; (d) High temperature/high pressure synthesis of bulk MgB_2 low-Tc superconductors

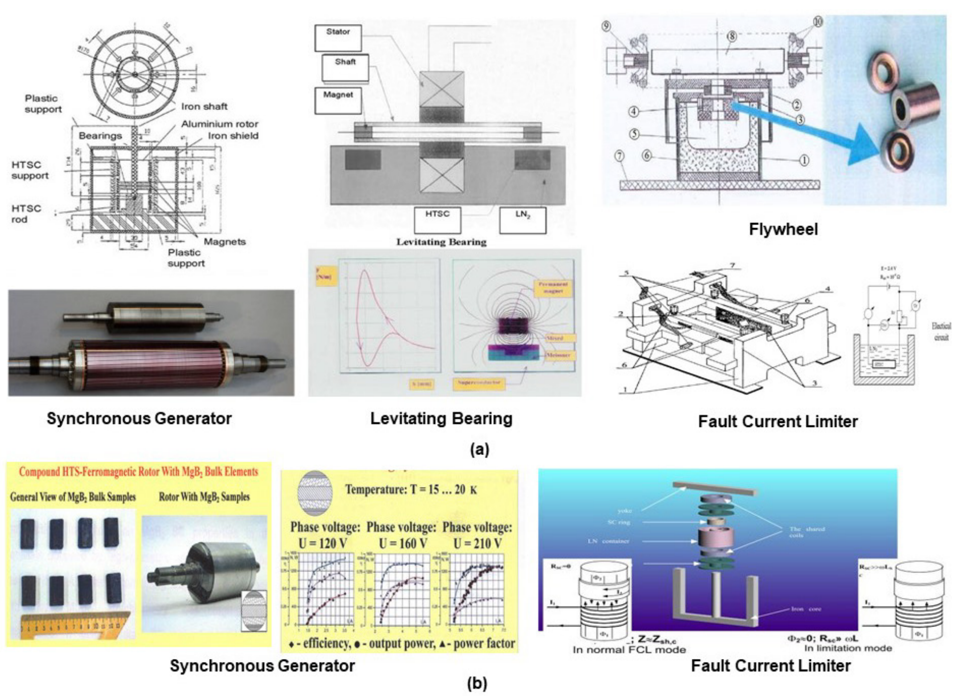


Figure 9: Electromagnetic applications of: (a) High-Tc YBCO superconductors; (b) Low-Tc high pressure synthesized nanostructured MgB_2 superconductors

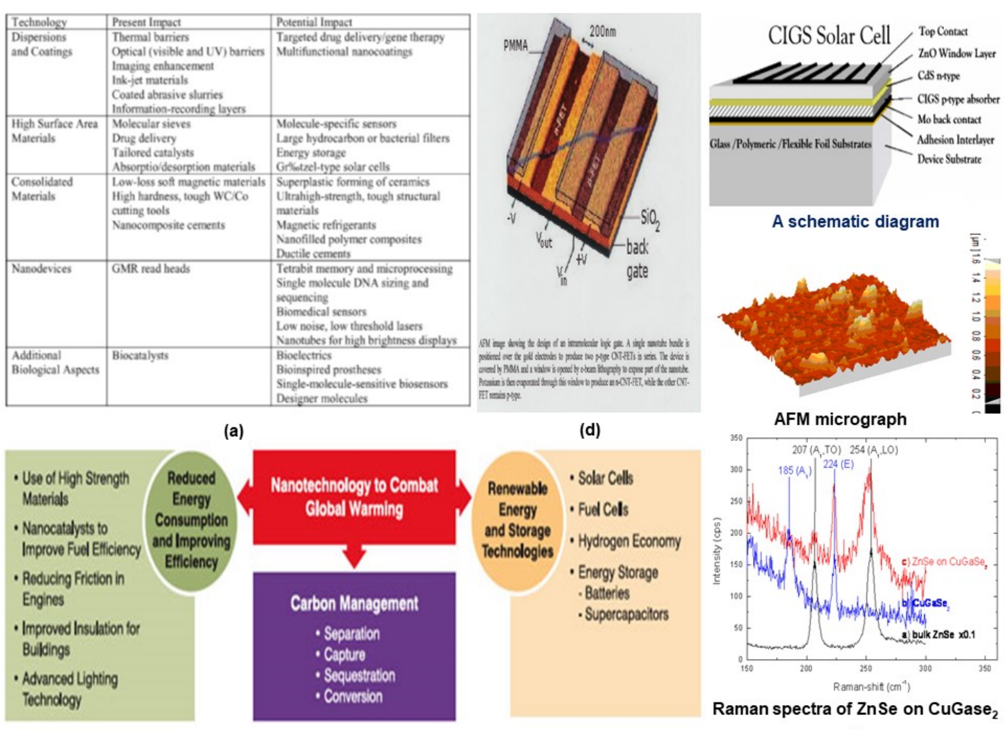
superconductors (brittle intermetallic compounds with working critical temperatures near to the boiling point of liquid hydrogen, Tc=20-49K) promising for the fabrication of cryogenic devices, like liquid-gas-transfer pumps, electromotors, generators, levitating bearings, flywheels and fault current limiters. Similar high-energy rate techniques (explosive / electromagnetic compaction, high temperature/high pressure) and subsequent material processing are employed to produce low-Tc MgB_2 superconductors, see Figures 8(c) and (d).

Applications of such high-Tc and low-Tc superconducting cryogenic components, fabricated by high-energy rate techniques and subsequent forming and metal removal processing, to electricity and transportation (synchronous generators, levitating bearings, flywheels, fault current limiters) are presented in Figure 9 [10-12].

5. ENVIROMENTAL ASPECTS

5.1 The Effect of Nanotechnology on Climate Change

Nanotechnology is best described as a "platform technology", having itself not a dramatic impact on climate change, however, being incorporated into larger systems, such as the hydrogen based economy, solar power technology or next generation batteries, it potentially could have a profound impact on energy consumption and hence greenhouse gas emissions (GHG).



Technology	Present Impact	Potential Impact
Dispersions and Coatings	Thermal barriers Optical (visible and UV) barriers Imaging enhancement Ink-jet materials Coated abrasive slurries Information-recording layers	Targeted drug delivery/gene therapy Multifunctional nanocoatings
High Surface Area Materials	Molecular sieves Drug delivery Tailored catalysts Absorptio/desorption materials	Molecule-specific sensors Large hydrocarbon or bacterial filters Energy storage Gr%tzel-type solar cells
Consolidated Materials	Low-loss soft magnetic materials High hardness, tough WC/Co cutting tools Nanocomposite cements	Superplastic forming of ceramics Ultrahigh-strength, tough structural materials Magnetic refrigerants Nanofilled polymer composites Ductile cements
Nanodevices	GMR read heads	Tetrabit memory and microprocessing Single molecule DNA sizing and sequencing Biomedical sensors Low noise, low threshold lasers Nanotubes for high brightness displays
Additional Biological Aspects	Biocatalysts	Bioelectrics Bioinspired prostheses Single-molecule-sensitive biosensors Designer molecules

Figure 10: Nanotechnology impact on climate change: (a) Technological impact; (b) Strategies to combat Global Warming; (c) CIGSs Solar-cell; (d) Intramolecular logic gate

The technological impact of nanotechnology on climate change as well various strategies to combat it are presented in Figures 10(a) and (b). In fact, by following the energy supply chain (renewable energies; photovoltaics and solar energy, see Figure 10(c); wind energy, fuel cells and hydrogen economy; energy storage, batteries, supercapacitors; thermoelectric conversion efficiency in combustion and electric engines; weight reduction by using lighter, stronger and stiffer nanocomposite materials with the potential to significantly reduce dead weight and promote energy efficiency in transportation), observing the ways in which clean nanotechnologies supplant old technologies based on the carbon fossil fuel cycle, and, furthermore, by utilising the more mature nanotechnology applications invariably involving use of bulk and surface nanomaterials (nanocoatings, nanoparticles, nanotubes, aerogel etc.), as well as nanoengineering surfaces associated with microscopic phenomena (nanocatalysts, nanomembranes, miniaturisation of functions observed in MEMS/NEMS applications, see Figure 10(d)) and nanomaterials of biological origin or interacting with living organisms, it may be helpful in discerning the synergy effects of multiple technologies applied in parallel, inside a comprehensive conservation reuse and reduction global climate change mitigation effort. In general, nanomanufacturing has higher environmental demands than conventional materials [14].

5.2 The Effect of Automotive Industry and Its Supply Chain on Climate Change

The relation between CO_2 emissions for the whole transport system including emissions from road vehicles, trains, ships and aircrafts, attributed to each sector of the human activity,

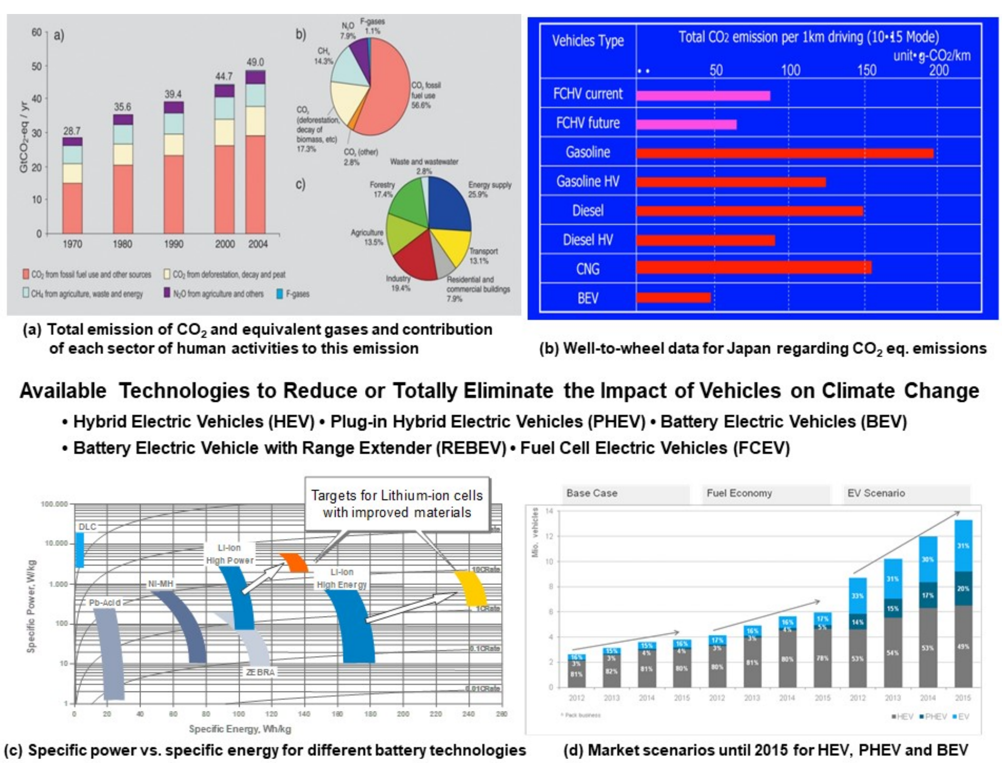


Figure 11: Automotive industry impact on climate change

and the climate change is established, see Figures 11(a) and (b). Electric and hybrid cars have the potential to dramatically reduce emissions resulting in both global warming and air pollution locally, whilst, in addition, they would help curb the world's dependence on oil. The available technologies that have already been or will be introduced into the market to reduce or totally eliminate the contribution of vehicles in the climate change are: Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), Battery Electric Vehicle with Range Extender (REBEV), Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV).Vehicle with Range Extender (REBEV), Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV). Note, that, battery technology is the first key-one to BEV, as documented by the data of Figure 11(c).

Nanotechnology is promising to improve the performance and life-times of the Li-ion batteries, to enhance their energy and power density, shorten the recharge time, as well as decrease their size and weight while improving safety and stability, through optimised electrode materials and electrolytes, i.e. polymer electrolytes and thin-film ceramic separators for increasing safety. By combining supercapacitors with Li-ion batteries as a next generation energy storage system for their electric hybrid vehicles and, although the energy density of capacitors is quite low compared to batteries, due to their excellent power characteristics, they can be used to provide short bursts of power and can assist highway acceleration, hill climbing, braking or cold starting, thereby preserving the battery's life. The addition of supercapacitors can help the new generation of cars to accelerate at comparable or better rates than traditional petrol-only engine vehicles, while achieving significantly reduced fuel consumption. Consequently, implementation of new technologies in the automotive industry is technologically possible and will depend on the price of batteries with respect to the oil price. The three alternative scenarios for the battery industry considered are usefully summarized in Figure 11(d) [13].

6. CONCLUSION

From the above mentioned remarks, it may be concluded, that the benefits of such advanced materials, manufacturing and loading techniques, products and applications in many technological areas are significant. The impact of these technologies in every day's life is considered to be great, since it will make the manufacturing / machine tool sector, communications, transportations, data storage, health treatment, energy conservation, environmental and human-life protection and many other technological applications better, faster, safer, cleaner and cheaper. Moreover, it may be emphasized that, industry is conducted both for profit-making and supplying goods to the mass of the people at minimum economic prices, with the primary concern being the manufacturing cost, whilst defence industries or requirements are concerned with a product to fulfil a certain task and cost tends to be secondary. These two functions can be carried out efficiently with international research cooperation between Research Centers, Universities and Industry.

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