PHYSICS SCHOOL

PHYSICS OF MATERIALS

Mechanical Properties and Crystal Defects in Solids

Dr. Thomas La Grange

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INTRODUCTION

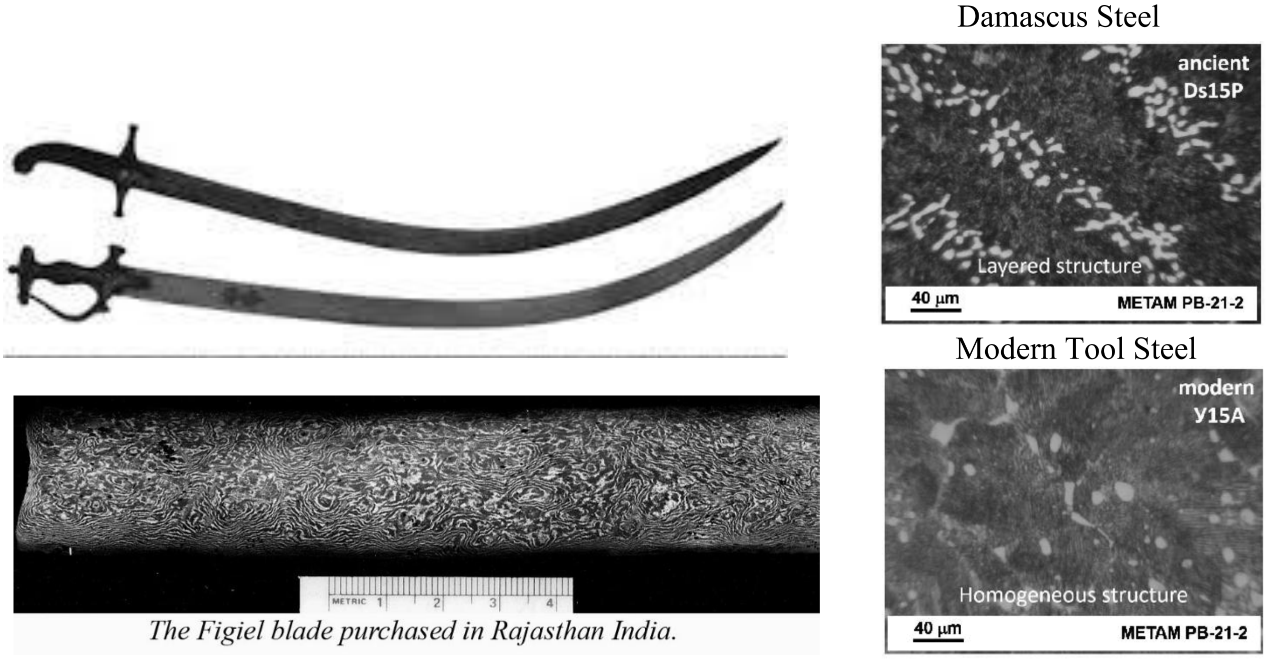
The discovery and mastery of new materials and technologies have marked every significant stage of human history. Prehistoric ages are even named after them: Stone, Bronze, and Iron Ages. The development of tools, structures, and machines has always relied on our ability to shape materials into stronger, sharper, lighter, or more durable forms. Today, some describe our era as the information and quantum age, enabled by the development of semiconductors, superconductors, and advanced alloys. As in the past, the properties of these materials define the frontiers of technology.


Stone Age
Copper Age
Iron Age

Figure 1: Man has learned to harness nature and progress through material science and energineering and the development of new materials and technologies.

For millennia, progress in metallurgy and materials processing relied more on chance and empirical observation than on scientific understanding. The discovery of quenching steel illustrates this: when iron, heated in a coal fire, absorbed carbon from the soot and was rapidly cooled, it transformed into a hard phase known as martensite. Another legendary example is Damascus steel, renowned for its exceptional sharpness, resilience, and toughness in swords. They would not bend or shatter under extreme forces, possessing extraordinary properties compared to iron swords of the period. Ancient blacksmiths achieved this through repeated heating, folding, and quenching of steel, unknowingly creating a layered microstructure comparable to modern tool steels. Folklore attributed mystical powers to these weapons, although their superiority stemmed from microstructural control — specifically, the diffusion of carbon, phase transformations, and controlled cooling rates. Perhaps the famed Excalibur was a sword made of Damascus steel.

Only in the 20th century did metallurgy evolve from craftsmanship into a science. Systematic research on atomic bonding, crystal structures, defects, and phase transformations established Materials Science and Engineering as disciplines. For a long time, the discovery of new materials has been driven more by chance and empirical knowledge than by a systematic pursuit of specific properties. Modern tool steel used for cutting and other manufacturing applications has a similar phase distribution and mechanical properties, which are more performant than Damascus steel and are produced by well-defined processing steps guided by **phase transformation kinetics** and **continuous cooling curve analysis** (see Chapter XII), which emerged from the metallurgical research of the 20th century, producing these desired microstructures.


Damascus Steel

Modern Tool Steel

The Figiel blade purchased in Rajasthan India.

Figure 2: The layered microstructure of a Damascus steel sword of antiquity that gives its superior mechanical properties is comparable to those of modern tool steel used in manufacturing.

Previously, every advancement in use and the discovery of new materials had essentially been technological in nature. Only within the past century has the production of new materials left empiricism to become an engineering science. English uses the term "Materials science and engineering" to highlight how fundamental research supports the design of new materials. Materials science is thus a common field for physical engineers. In practice, the term "Materials science and engineering" has been in use since the 1950s, and materials science is a very young discipline. Only in the post-war years did the interest in the effect of impurities in solid conductors pave the way for transistors. Those were the times when a more explicit link between structural defects and the mechanical properties of metals was finally drawn. For example, the very peculiar arrangement of carbon within iron gives the steel its characteristic high hardness. Moreover, due to dislocation glide (motion), steel can be deformed and shaped into different forms without shattering due to brittle fracture. As R.W. Cahn noted, a decisive turning point occurred when scientists began studying “dirty” matter — real solids with impurities and defects — rather than focusing exclusively on pure substances. This shift led to fundamental discoveries:

- The link between **defects in crystals** and **mechanical properties**.
- The role of **impurities** in semiconductors, paving the way for **transistors**.
- The relationship between **dislocation motion** and the ductility of metals.

These insights connected atomic-scale structure to macroscopic performance, laying the foundation of much of modern theoretical understanding in materials science.

The 21st century has ushered in remarkable advancements in materials science, focusing on the development of materials with superior performance and properties optimized for specific applications. The current century has introduced a new paradigm: **materials-by-design**. Instead of relying on decades of empirical trial and error, scientists use computational modeling, artificial intelligence, and high-throughput experiments to design alloys, composites, and nanomaterials with tailored properties. Applications are broad:

- **Aerospace**: high-strength, lightweight alloys for extreme environments.
- **Nanotechnology**: nanocomposites in electronics, energy, and sports.
- **Shape memory alloys**: medical devices, robotics, and actuators.
- **Renewable energy**: steels for wind turbines, materials for solar cells, and advanced battery components.
- **Biomedicine**: biocompatible metals for implants and prosthetics.

At the same time, metallurgy faces new challenges: **sustainability**, **resource scarcity**, and the demand for **eco-friendly processes**. The advent of advanced manufacturing techniques, such as additive manufacturing and 3D metal printing, is further revolutionizing the field by enabling the production of complex metal components with enhanced properties and reduced waste. Moreover, incorporating artificial intelligence in material discovery accelerates innovation, allowing for more efficient design and development of new materials.. Despite these advancements, challenges such as sustainability, resource scarcity, and environmental concerns persist. Materials science research remains essential, with a continued emphasis on developing stronger, lighter, and more environmentally friendly materials and processes. Green metallurgy, recycling, and circular materials economy are now as critical as mechanical performance.

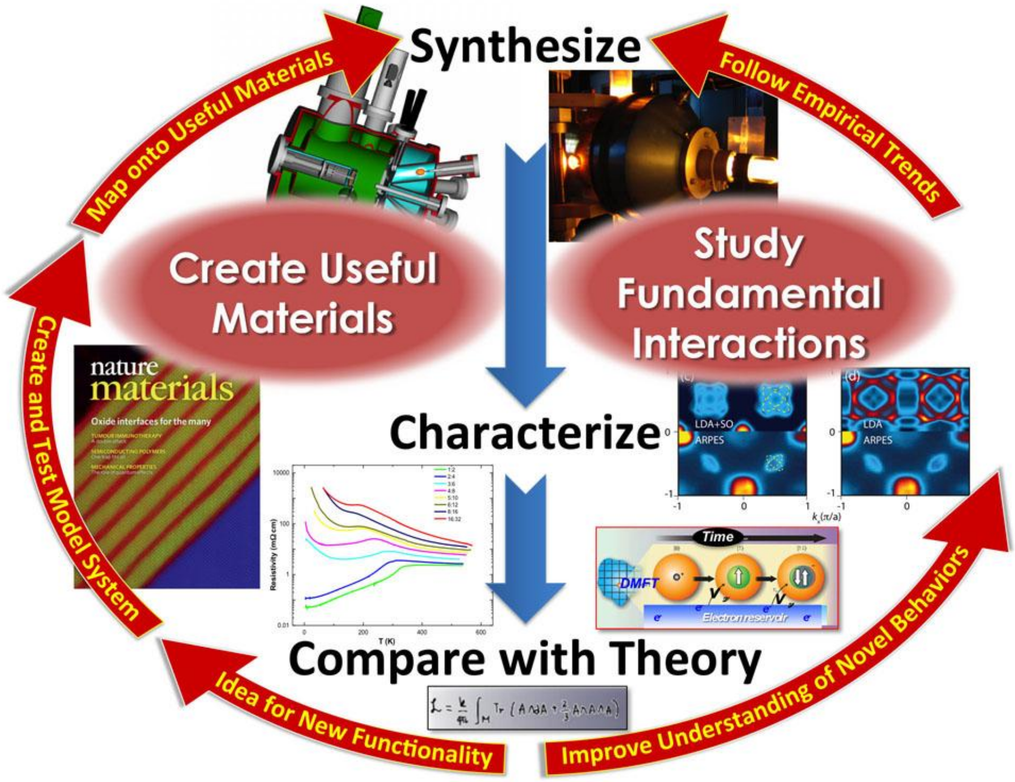


Figure 3: The Materials-by-Design Concept.

The 21st century of material physics also marks a paradigm shift away from empirical research, making explicit links between applications and specific alloys or compounds. The empirical research method takes decades to develop new materials for applications, which is far too slow. The Material by Design concept was formed from large-scale initiatives and the need to design new materials with tailored properties for specific applications. Researchers employ materials-by-design strategies to enhance fundamental understanding and develop tools for addressing critical materials issues. These efforts help identify gaps and improve material characterization tools and models at various length scales, from the atomic level to bulk properties, thereby advancing computational tools for designing better materials. This new modality of materials design is essential for developing nanotechnology and quantum materials and technologies.

This course builds a bridge from atomic-scale structure to macroscopic properties:

- **Chapters I–II**: Foundations — atomic bonds and crystal structures.
- **Chapter III**: Theory of elasticity, linking atomic interactions to macroscopic deformation.
- **Chapters IV–X**: Defects in crystals, defect diffusion kinetics, dislocation theory, and experimental characterization, explaining how imperfections govern plasticity, strength, and toughness.
- **Chapters XI–XII**: Phase transformations — solidification, martensite, and recrystallization — showing how processing controls microstructure and performance.

By the end of this course, students will be able to interpret the **mechanical behavior of solids** from their **atomic structure**, understand the role of **defects and microstructure**, and appreciate the central role of materials in technology and innovation.