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Chapter

Introductory Chapter: A Brief Introduction to Engineering Materials and Metallurgy

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1. Introduction

Materials science, also known as materials science and engineering, is a multidisciplinary field that deals with the discovery and design of new materials [1]. Always new materials open the door to new technologies, whether they are in chemical, civil, construction, nuclear, agricultural, aeronautical, biomedical, electrical, or mechanical engineering [2, 3]. The materials science engineering includes the study of the relations between the synthesis, forming, properties, structure, and performance of materials that enable an engineering function. The materials properties of interest can be electrical, mechanical, optical or magnetic; the engineering function can affect industries involved in electronics, communications, transportation, manufacturing, medicine, recreation, environment, and energy [4].

Metallurgy is the art and science of making metals and alloys in shapes and with characteristics suitable for practical use [5]. It is an applied science based on a clear understanding of the structures and properties of metals and their alloys. Metallurgy has long occupied the dominant position as the most important engineering materials; steel being by far the most important over the last few centuries. However, increasingly in many areas other materials such as ceramics, plastics and composites are challenging this position. The relatively recent development of materials science and engineering is a merger of metallurgy with others like glass and ceramic technology, mineralogy, physical and inorganic chemistry, solid-state physics, and polymer science in modern techniques to include all structural and functional materials, thus making it one of the widest of study disciplines [1].

2. What is metallurgy?

Metallurgy is the science and technology to extract metals from their ores economically, refining them and preparing them for the end use [6]. It studies the microstructure of a metal, the structural features that are control to observation under a microscope. Microstructure determines mechanical properties of the metal, including their elastic and plastic behavior when applying the force. Chemical composition is the relative content of a particular element within an alloy, usually expressed as a percent weight. Composition, as well as thermal and mechanical processing, will determine microstructure. Metals and their alloys are widely used in our daily lives. They are used for different purposes such as making machines, bridges, motor vehicles, railways, buildings structure, ships, aircrafts, agricultural tools, etc. Therefore, real economic growth can come from increasing quality and quantity of the metal production in that country [7].

Naturally, most metals occur in the combined state as minerals and they are reactive. Only a few metals like gold, silver, platinum and mercury, etc. are found as Free State in the earth's crust. Metals that have a low reaction show little convergence to air, moisture, carbon dioxide, or non-metals found in nature [8]. Materials that occurring naturally in which a metal or its compound occurs is called a mineral. A mineral from which a metal can be economically extracted is called an ore. The main active components found in nature, especially in the atmosphere are oxygen and carbon dioxide. In the earth's crust, silicon and sulfur are present in large quantities. Seawater also contains large amounts of chloride ions (obtained from dissolved salts). Most active metals are high electrically positive and therefore exist as different ions [9]. For this reason, most of the important ores of these metals occur as different components such as oxides, silicates, carbonates, and halides.

3. Metallurgy forming and processing

The importance of metals in modern technology is largely due to the ease with which it can be formed in useful shapes [10]. Hundreds of processes have been developed for specific applications of metalworking. However, these processes can be categorized into only a few classes based on the type of force applied to the workpiece when it is formed [11]. These classes are direct-compression-type processes, Indirect-compression processes, shearing processes, bending processes, and tension-type processes as shown in **Figure 1**. In direct compression processes, force is applied to the workpiece surface, and the metal flows at an angle based on the pressure direction. In indirect-compression processes, the basic applied forces are often tensile, but the indirect compressive forces are developed by the reaction of the workpiece with the die up to high values. These processes include extrusion, pipes, deep drawing of the cup and pulling wires. Therefore, the metal flows under the influence of a combined stress condition involving high pressure forces in at least one of the main directions. The best example of a tension-type forming process is the formation of expansion, where the sheet of metal is wrapped in a die contour under tensile forces. Shearing involves applying the shearing forces of sufficient size to tear the metal in the plane of shear, while bending involves applying the bending moments on the metal sheet. **Figure 1** shows these processes in a very basic way.

Metallurgy forming processes of are usually classified into hot and cold working processes. Hot working is defined as deformation under temperature and strain rate conditions so that recovery operations are performed together with the deformation. On the other hand, cold working is deformed in circumstances where recovery operations are not effective [12]. In hot working, the strain hardening and deformed grain structure caused by deformation are quickly eliminated by the formation of new strain-free grains as the result of recrystallization and grain growth. It is possible to have very large deformities in hot working because the recovery processes keep up with deformation [13]. Hot working occurs when the flow stress is essentially constant. The energy required for deformation is generally lower for hot working compared to cold working because of the flow stress decreases with increasing temperature. Since strain hardening is not alleviated in cold working, the flow stress increases with increasing the deformation. Therefore, the total plastic deformation without fracture is less for cold working compared with hot

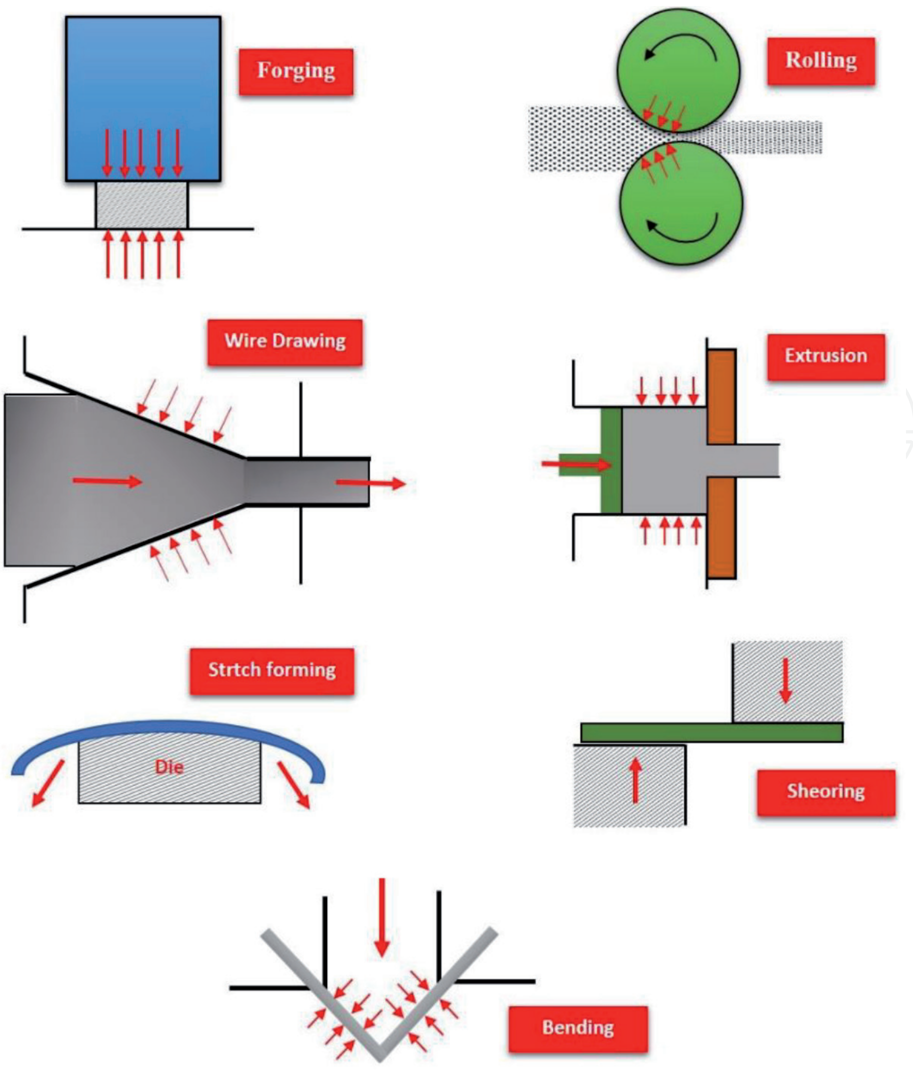

Figure 1.
Typical metallurgy forming operations.

working, unless the effects of cold work are mitigated through annealing process. It is important to understand that the difference between cold working and hot working does not depend upon any arbitrary deformation temperature. For most commercial metal alloys, hot working process should be performed at a relatively high temperature in order to obtain a rapid recrystallization rate. However, lead and tin recrystallize rapidly at room temperature after significant deformations so that the working of these metals at room temperature is like hot working. Similarly, the work of tungsten at 1093°C, in the hot work range of the steel, is a cold work because this high melting metal has a recrystallizing temperature higher than this working temperature (**Figure 1**) [14].

4. Mechanical testing and materials characterizations

Whether a material is suitable for a given application is specified by the material properties. These properties can be measured using a series of mechanical tests, such as tensile, compressive, hardness and fatigue testing (**Figure 2**) as well as physical and chemical tests. Some of the mechanical tests are easily accessible like hardness. Others are difficult to measure such as tensile or yield strength where special samples must be formed. It is difficult to determine other properties such as fatigue, toughness strength as the tests need several

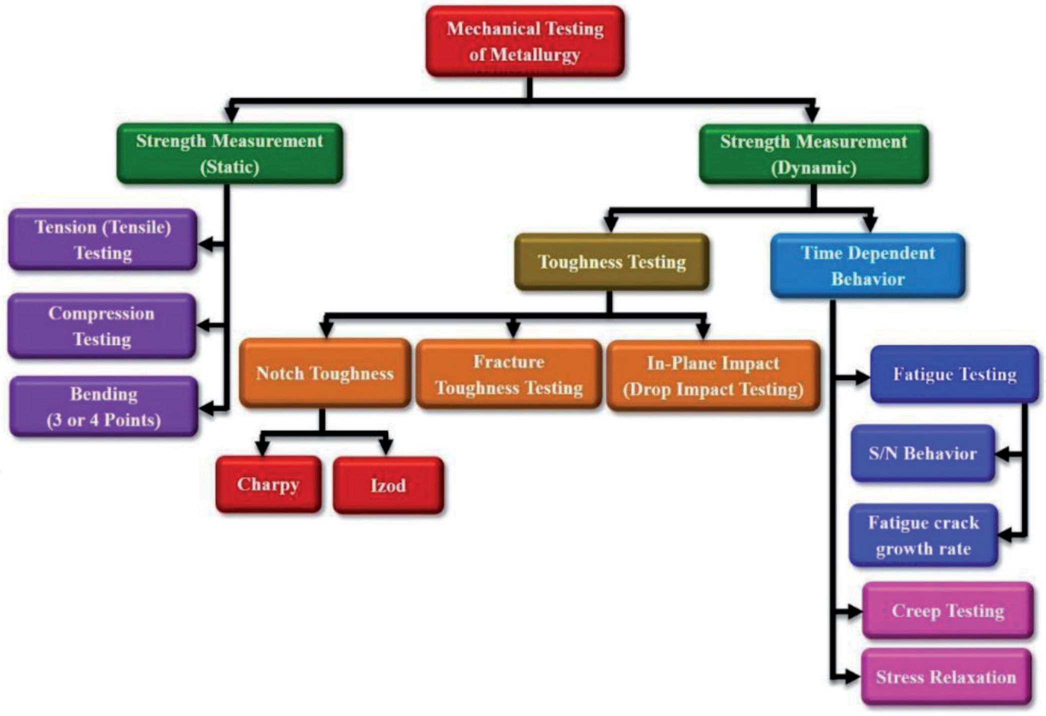

Figure 2.
Commonly used mechanical testing techniques.

samples per every case and the testing process takes a long time. Apart from the above tests, it is also possible to predict the properties of materials by determining the microscopic structure of materials, where properties are determined by the microstructure. There are a number of microstructural characterization techniques including optical microscopy, scanning electron microscopy (SEM), electron backscattered diffraction (EBSD), X-ray diffraction (XRD), transmission electron microscopy (TEM), ultrasonic sound based methods and magnetic-based methods [15]. Among these techniques, optical microscopy and electron microscopy are able to detect the morphology of microstructural features in the surface of a prepared sample. Optical microscopy has its own advantages such as low cost, ease of use on large sample areas and ease of operation. However, electron microscopy is also widely used due to its high resolution down to the nanometer scale [16].

The factors that often determine the properties of strength and toughness of pearlitic steels like interlamellar spacing, colony size, and prior austenite size can be done by examining the microstructure of these materials [17, 18]. However, measuring the size of the colony and especially the size of the prior-austenite grains is extremely difficult and requires a proficient technical examination using optical microscopy or SEM and special procedures. For multiple phases of steels, the fraction, morphology, size and distribution of the phase components are determined by the properties. XRD is an effective technique for measuring the fraction of the present phases, but cannot access the size, morphology and distribution. Image analysis techniques are also applied for this application. Unlike the XRD analysis, which is a crystallographic analysis of the bulk surface, image analysis technique extracts information directly from a microscopic image of the sample surface. So once the current features in the sample images are categorized into phases, the size, fraction, morphology and phase's distribution can easily be obtained. Most of the current image analysis-based characterization uses the histogram of the brightness (intensity) of the individual pixels that make up the image, and relies on all the pixels in one phase having intensities in a

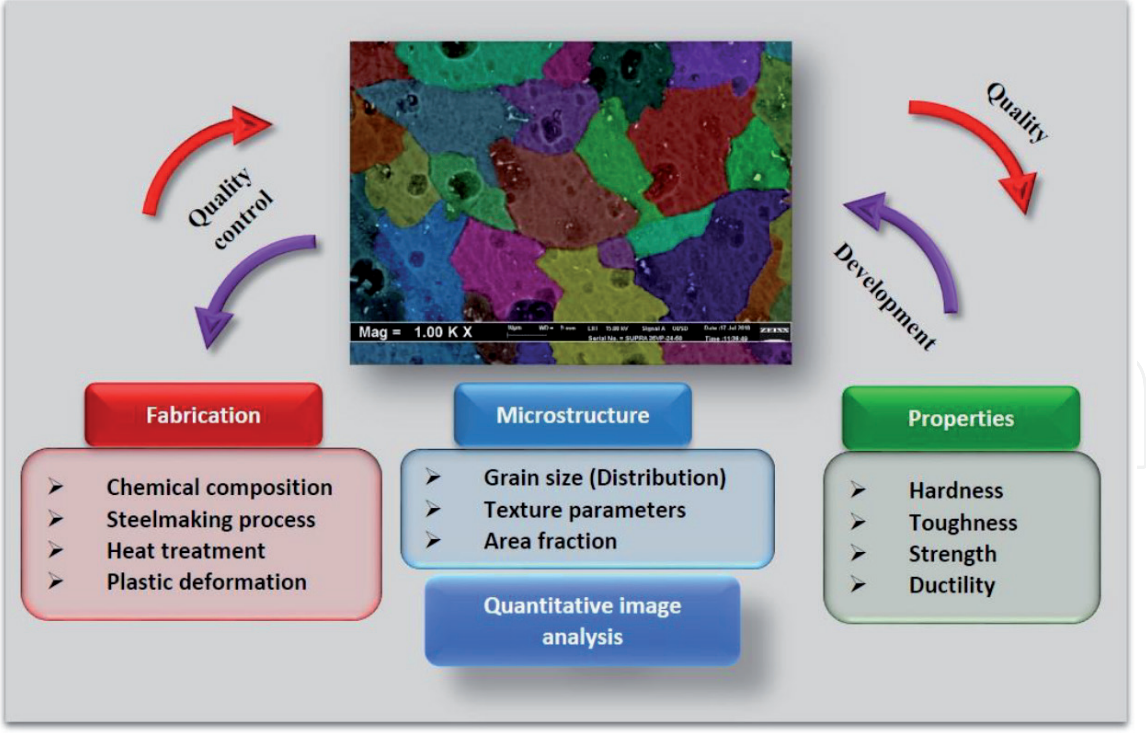

Figure 3.
Microstructure related with fabrication of components and their properties.

different range from all of those in another phase [19]. This makes it very easy to distinguish between the phases only using the threshold, and it has been shown to work with some two-phase steels characterized by high variability between phases [20]. However, the different phases in brightness levels overlap for many other steels with complex microscopic structures. In this case, the threshold of intensity is no longer able to distinguish between the phases, and instead some analysis of the spatial patterns of intensity within the phases, i.e., "texture," is required. Quantitative analysis of microstructural images allows not only a quality control examination of the treatment path, but also the possibility of establishing a reciprocal relationship between microstructure features and associated properties (**Figure 3**).

5. Steel metallurgy

Steel has been one of the most important materials used by humans for up to 4000 years due to its good combination of low cost and properties. The mechanical properties of steel have been found to be highly dependent on its internal structure at nanometers up to microns or even millimeters (its "microstructure"). The internal structure of the steel can be adjusted through composition changes, mechanical deformation or heat treatments. The metal can then be designed to meet the different requirements in a range of applications. Atoms can be arranged into steel and bonded, called phases in several ways. Different phases have various properties, which may be suitable for various applications, either singly or in groups. For example, high-strength steels have good wear and abrasion resistance as well as high tensile strength, so they are widely used as rail steels and steel wire [21]. Steel with more than one phase including two-phase steels, complex steels and transformation induced plasticity steels usually has a good mix of toughness and strength and is therefore well suited for applications that require strength and formability as in the automotive industry [22].

6. Powder metallurgy

Powder metallurgy (PM) is a term that covers a wide range of techniques by which materials or components are made of metal powders [23]. These processes are characterized by high productivity and ideal for making parts close to the complex geometry of a range of materials, increasing the use of materials, and minimizing or eliminating secondary processes such as machining. Common secondary processes of components made by liquid metal processing may lead to additional manufacturing steps that have significant cost and waste impacts [24]. However, powder metallurgy processing has obtained more attention with the advantages offered by comparison with casting and forging. In PM processing techniques, all or part of the some constituents are formed by compressing the particles with the characteristic structure, size and shape in a high-precision product. The ability of metal metallurgy powders to produce high-quality, complex parts characterized by high productivity and high durability represents significant advantages, such as potential low capital costs, with high energy efficiency. PM is widely used for a range of applications, ranging from dental restoration and implantation to bearings, transmission of automotive and engine parts across many industrial sectors (**Figure 4**).

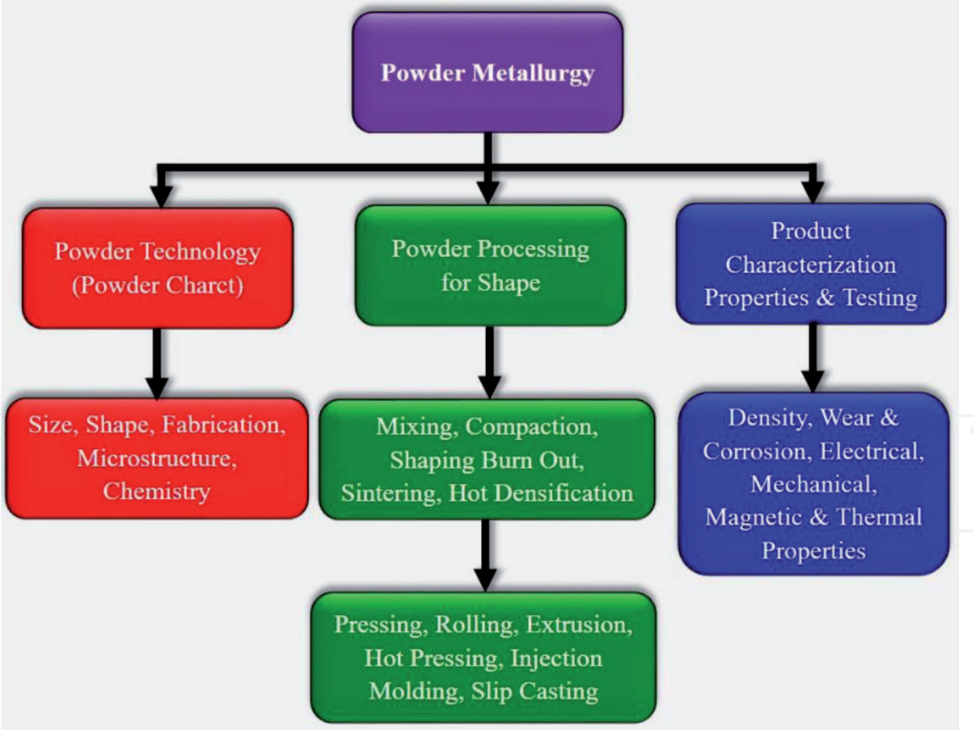

Figure 4.
Schematic of powder metallurgy.

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