Bogdan Viorel NEAMȚU

LEARNING MATERIALS PROCESSING

THE TECHNOLOGY BEHIND EVERYDAY PRODUCTS

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Preface

This book has been written especially for students, with the goal of helping you build a strong foundation in materials processing technologies, a field that is central to modern engineering and manufacturing. Materials processing is the vital link between natural resources and the products we rely on every day. From the steel beams that hold up skyscrapers to the microscopic circuits in smartphones, the way we process materials shapes innovation, technology, and economic growth.

At its core, materials processing technology refers to the methods and techniques used to transform raw materials into products with specific properties and functions. Whether working with metals, polymers, ceramics, or composites, the primary objectives remain the same: to enhance performance, ensure reliability, and optimize costs while maintaining quality.

The roots of this field stretch deep into history. Early humans discovered how to control fire, extract metals, and craft simple tools, laying the groundwork for centuries of progress. The Bronze Age and Iron Age marked significant leaps, as new materials and processing techniques revolutionized both daily life and warfare.

Today, materials processing has evolved into a highly interdisciplinary and technologically advanced field. Modern breakthroughs such as 3D printing (additive manufacturing), nanotechnology, and smart materials are opening doors to applications that were once unimaginable. These innovations are reshaping industries ranging from aerospace and healthcare to renewable energy and environmental protection. 3D printing, for example, allows engineers to create complex geometries directly from digital models with minimal material waste. This approach is transforming aerospace design by reducing component weight and is revolutionizing healthcare with custom implants and prosthetics tailored to individual patients. Nanotechnology operates at an even smaller scale, manipulating atoms and molecules to create materials with extraordinary properties. This field enables advances like targeted drug delivery systems, ultra-strong coatings, and next-generation electronics. The concept of nanotechnology, first envisioned by physicist Richard Feynman in his iconic 1959 lecture

“There’s Plenty of Room at the Bottom”, has evolved from a bold idea into a driving force behind modern materials science.

As we look to the future, sustainability has become one of the most important challenges in materials processing. The environmental impact of extracting, manufacturing, and disposing of materials demands eco-friendly solutions. Researchers are working on recyclable composites, bio-based polymers, and strategies inspired by the circular economy where materials are continuously reused rather than discarded.

In this book, we will explore the fascinating world of materials processing, examining both the fundamental principles and the cutting-edge technologies that define the field. This introduction is just the beginning of a journey that will help you, as students and future engineers, understand not only how materials are processed but also why these processes matter in shaping a sustainable and innovative future.

Cluj-Napoca, 2025 Bogdan Viorel Neamţu

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Chapter I

MANUFACTURING AND EXTRACTIVE METTALURGY

1.1. Introduction to manufacturing

1.1.1. Evolution of manufacturing

The term manufacture originates from the Latin words *manus* (hand) and *facere* (to make), initially referring to items created entirely by hand [1]. For centuries, production relied on the skills of artisans and craftsmen, who shaped raw materials into tools, household objects, and weapons using simple manual techniques. This form of manufacturing was slow, labor-intensive, and highly dependent on individual craftsmanship, which made mass production nearly impossible.

A dramatic shift occurred during the 18th and 19th centuries with the rise of the Industrial Revolution. Innovations such as the steam engine, mechanized textile machines, and advancements in metallurgy revolutionized production methods. Manual labor was progressively replaced by machine-based processes, enabling products to be manufactured faster, in larger quantities, and at lower costs. Factories emerged as centers of production, introducing division of labor and assembly line techniques that significantly increased efficiency.

By the mid-20th century, manufacturing entered a new era driven by automation and computer-controlled machinery. The development of programmable logic controllers (PLCs), computer numerical control (CNC) machines, and robotics allowed manufacturers to achieve levels of precision and consistency that were previously unattainable. Mass production became the norm, with industries like automotive and electronics leading the way in implementing automated assembly lines.

Today, we are in the era of Industry 4.0, which represents the fusion of digital technologies with manufacturing. Smart factories integrate the Internet of Things (IoT), artificial intelligence (AI), machine learning, and big data analytics to optimize production in real time. Additive manufacturing (3D printing), advanced robotics, and nanotechnology are transforming the way products are designed, prototyped, and manufactured. These innovations not only improve efficiency but also enable customization, reduce waste, and support sustainable practices, marking a significant leap from the early days of handcrafting to fully intelligent production systems.

Ancient manufacturing of pottery

Modern manufacturing of pottery

Figure 1. Comparison of ancient manufacturing of pottery and modern manufacturing pottery [2, 3].

1.1.2. Understanding the manufacturing process

A manufacturing process involves a structured series of operations designed to convert raw materials, parts, or components into finished products ready for distribution or sale. This transformation often includes several key activities such as product design, engineering, prototyping, production, assembly, quality testing, packaging, and delivery.

The process generally begins with the design and engineering phase, where detailed plans and specifications are created. This stage defines the product's dimensions, materials, functionality, and production methods.

Once the design is complete, the next step is prototyping and testing. A prototype, or sample version of the product, is manufactured and tested to ensure it meets all required performance and quality standards. Adjustments are made as necessary before moving into large-scale production.

The production stage follows, which includes sourcing raw materials, fabricating parts, and assembling the components into the final product. During this phase, quality control measures (such as inspections, performance checks, and other verification processes) are essential to ensure that the final goods meet established standards and customer expectations.

After production, the goods are packaged and prepared for shipping to customers or distribution centers. In many cases, the manufacturing cycle also includes after-sales support, such as warranty, maintenance, and repair services.

The concept of manufacturing is often explained in two ways: as a technological operation and as an economic activity [4]:

- ***Technological View***

From this perspective, the manufacturing is defined as the application of physical and chemical processes to modify the shape, structure, or properties of a raw material to create a product. These processes are typically carried out in a sequence of operations, with each step bringing the material closer to its desired final form.

- ***Economic View***

From this perspective, the manufacturing is the creation of value by transforming materials into products with greater utility and worth. For instance, extracting bauxite and refining it into aluminum adds value, when this aluminum is shaped into aircraft parts or beverage cans, its value increases substantially. Similarly, raw clay can be transformed into ceramic tiles or porcelain, greatly enhancing its utility and market worth. Crude oil derivatives can also be processed into synthetic fibers, which are then woven into textiles for use in clothing or industrial applications—adding both functional and economic value.

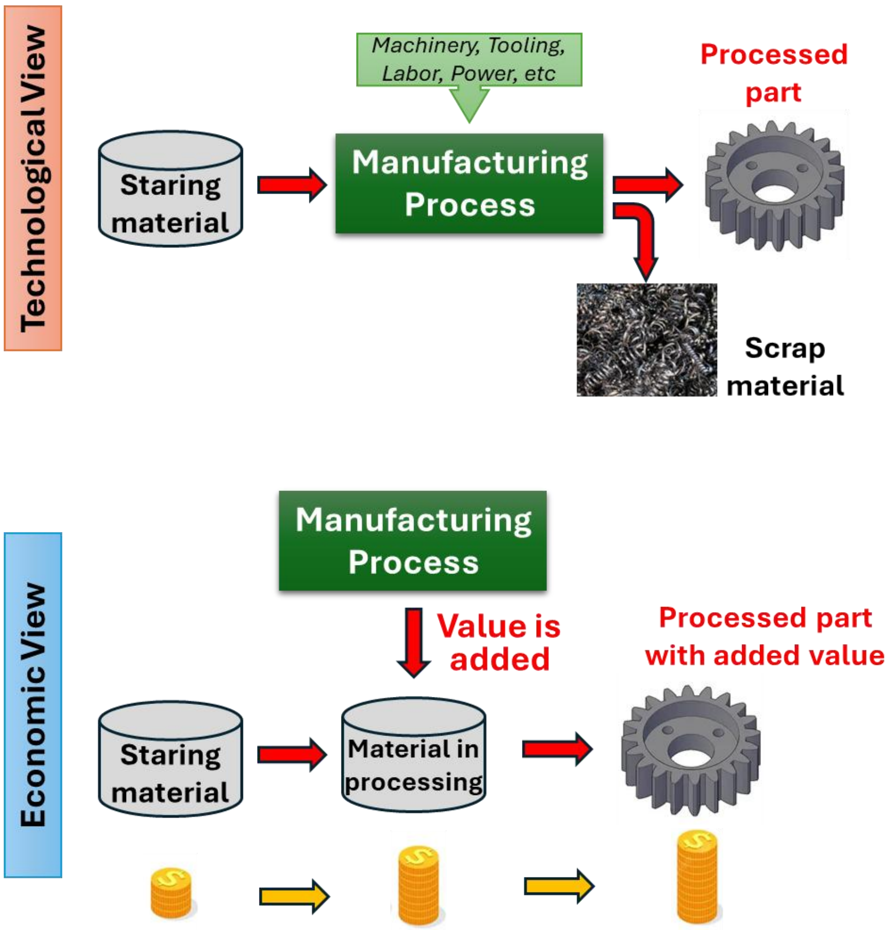


Figure 2. The concept of manufacturing as a technological operation and as an economic activity [4].

The term industry refers to all enterprises, organizations, and economic activities involved in the production of goods or the provision of services. Industries play a central role in any economy and can be broadly grouped into three major categories: primary, secondary, and tertiary sectors.

Primary Industries:

These industries are focused on the extraction and harvesting of natural resources. They include activities such as agriculture, fishing, forestry, and mining, which provide the raw materials required by other sectors. For example, mining produces minerals and ores used in manufacturing, while agriculture supplies food and raw fibers.

Secondary Industries:

Secondary industries transform the raw materials from the primary sector into finished or semi-finished goods. This category covers manufacturing, construction, energy production, and chemical processing. For instance, steel plants convert iron ore into usable steel, which is then used in building structures, vehicles, and machinery. This sector is often seen as the backbone of industrial development because it adds value to raw materials.

Tertiary Industries:

The tertiary sector focuses on providing services rather than physical products. Examples include healthcare, education, finance, retail, transportation, information technology, and hospitality. These industries support both the primary and secondary sectors by ensuring distribution, financial systems, communication, and customer service.

1.1.3. Materials in the manufacturing process

Materials form the foundation of any manufacturing activity, serving as the starting point for creating finished products. The selection of appropriate materials is a critical step because it influences the quality, performance, cost, and lifespan of the final product. Factors such as mechanical, thermal, electrical properties, manufacturing methods, and raw material availability all play an essential role in the selection process.

The main classes of materials used in manufacturing are metals, polymers, ceramics, and composites, each offering unique characteristics and advantages.

Metals are widely used in manufacturing for producing machinery, automotive parts, appliances, and structural components. They are known for high strength, toughness, durability, electrical and thermal conductivity, as well as resistance to wear and corrosion. Most metals used in manufacturing are alloys that are defined as a mixture of two or more elements, with at least one being metallic. Metals and alloys can be divided into two basic groups: (1) ferrous (steel and cast iron) and (2) nonferrous (alloys based on Cu, Al, Ti, Zn, Mg, etc).

A polymer is a compound made of repeating molecular units called mers, typically based on carbon with additional elements such as hydrogen, oxygen, nitrogen, or chlorine. Polymers include plastics and elastomers, which are valued for their lightweight nature, flexibility, corrosion resistance, low cost, and ease of shaping into complex forms. They are extensively used in packaging, consumer products, toys, medical devices, and electronics. The main types of polymers are:

- Thermoplastics – can be reheated and reshaped multiple times (e.g., polyethylene).
- Thermosetting polymers – harden permanently after being processed (e.g., epoxy resins).
- Elastomers – have rubber-like elasticity (e.g., natural rubber, silicone).

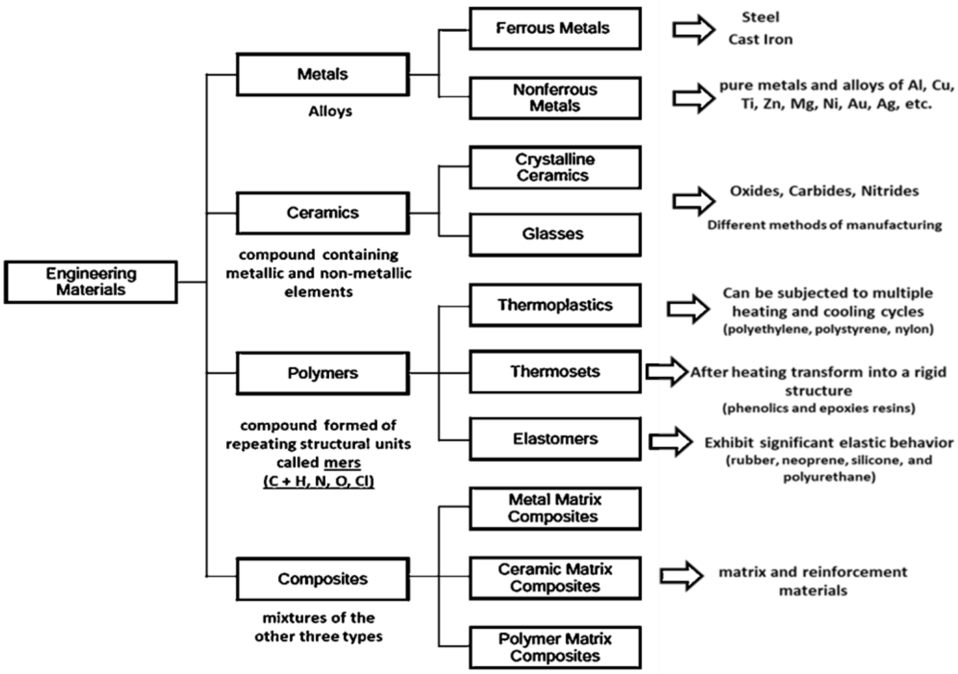


Figure 3. The main classes of materials used in manufacturing.

Ceramics are known for their high hardness, compressive strength, and ability to withstand high temperatures, but they are often brittle. Common applications include tiles, bricks, cutting tools, glass products, and electrical insulators. A ceramic is typically a compound consisting of metallic or semimetallic elements combined with non-metals such as oxygen, nitrogen, or carbon. Examples of ceramics: oxides (e.g., alumina), carbides (e.g., tungsten carbide), nitrides (e.g., silicon nitride).

Composites are engineered materials made by combining two or more distinct materials to create a new material with enhanced or unique properties. Typically, they consist of reinforcing fibers or particles embedded in a matrix material. These materials are commonly found in aerospace (carbon-fiber composites), automotive components, construction materials (fiber-reinforced concrete), and sporting equipment.

Choosing the right material is vital for the success of any product. It affects manufacturability, performance, durability, environmental impact, and cost-effectiveness. Engineers and designers evaluate factors such as strength, toughness, corrosion resistance, weight, and thermal properties to select materials that best meet the requirements of a given application.

1.1.4. Manufacturing processes and operations

A manufacturing process is a planned and controlled set of steps designed to produce physical and/or chemical changes in a raw material with the goal of increasing its value. Through manufacturing, a basic material is transformed into components or finished goods that meet specific design and functional requirements. Manufacturing operations are broadly divided into two categories:

- ***Processing operations:*** these operations transform a raw or semi-finished material into a product that is closer to its final desired form. Value is added by modifying the geometry, surface quality, properties, or overall appearance of the starting material.
- ***Assembly operations:*** In this case, two or more parts are joined or connected to create a new structure, often referred to as an assembly or subassembly. Depending on the method, connections can be permanent (e.g., welding, soldering, brazing, adhesive bonding) or semi-permanent (e.g., screws, bolts, threaded fasteners).

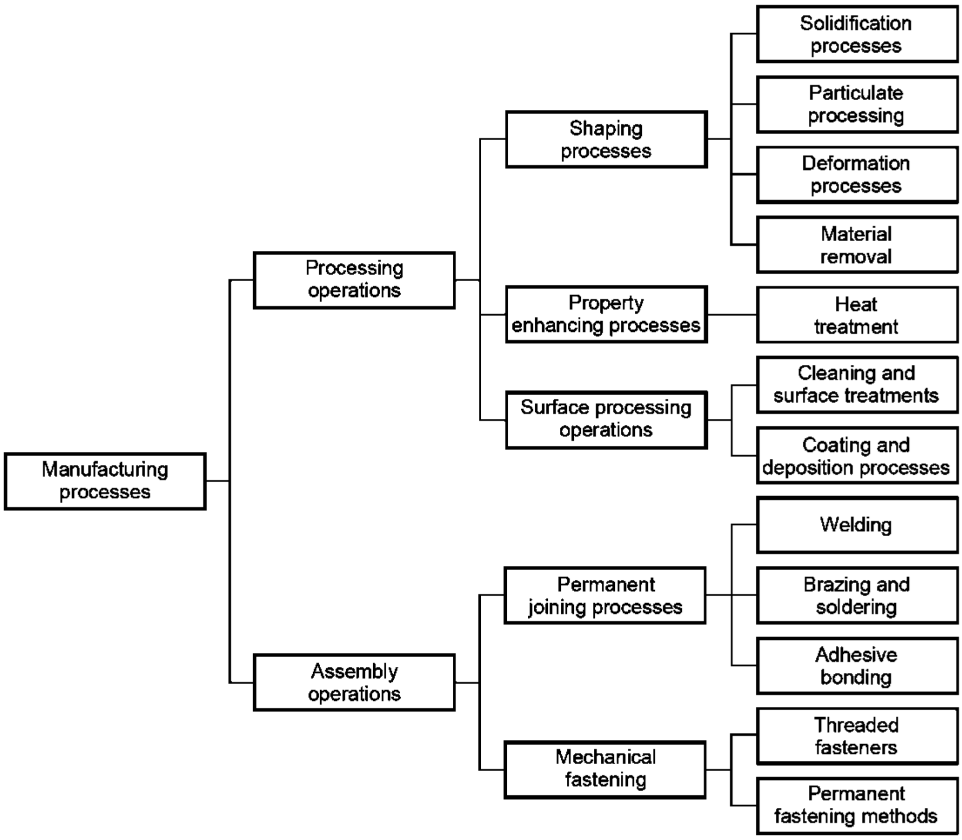


Figure 4. Manufacturing operations [4].

Processing operations are further classified into three main groups:

- *Shaping operations*, these methods change the geometry of the workpiece. Examples include casting, forging, rolling, extrusion, machining, and molding.
- *Property-enhancing operations*, these processes improve the mechanical, thermal, or chemical properties of a material without altering its shape. Heat treatment of metals (e.g., hardening or tempering) is a common example.
- *Surface processing operations*, these techniques are used to clean, coat, or modify the outer surface of a material to improve appearance, corrosion resistance, or functionality. Common examples include plating, painting, polishing, or anodizing.

Assembly processes create a new functional unit by joining components together. The two main joining approaches are:

- *Permanent methods*: Welding, brazing, soldering, and adhesive bonding.
- *Semi-permanent methods*: Mechanical fastening systems, such as screws, rivets, nuts, bolts, or snap-fit components.

In short, manufacturing processes are the backbone of today's industry, turning raw materials into useful products with added value. Whether it is through processing operations that shape and improve materials or through assembly operations that bring parts together into complete systems, every stage has a direct impact on the quality, performance, and cost of the final product. A good understanding of these processes helps engineers and manufacturers choose the most effective methods, minimize waste, and increase productivity.

1.2. Extractive metallurgy

Extractive metallurgy is a key discipline within materials and metallurgical engineering that deals with obtaining metals from naturally occurring mineral sources. It encompasses both the science of understanding chemical and physical processes involved in metal extraction and the engineering required to design and optimize industrial-scale operations. The ultimate goal of extractive metallurgy is to efficiently and economically recover metals while minimizing environmental impact and energy consumption.

An essential concept in this field is the ore, that is a naturally occurring material from which a mineral or a combination of minerals can be extracted at an economically viable cost. Ores typically contain one or more valuable minerals, such as metals or rare earth elements, that can be processed to extract the desired material. Ores often occur as a mixture of the desired metal-bearing minerals and unwanted materials, known as gangue, which must be separated during processing. Examples of common ores include bauxite (the primary source of aluminium), hematite and magnetite (sources of iron), chalcopyrite (a copper ore), and gold-bearing quartz.

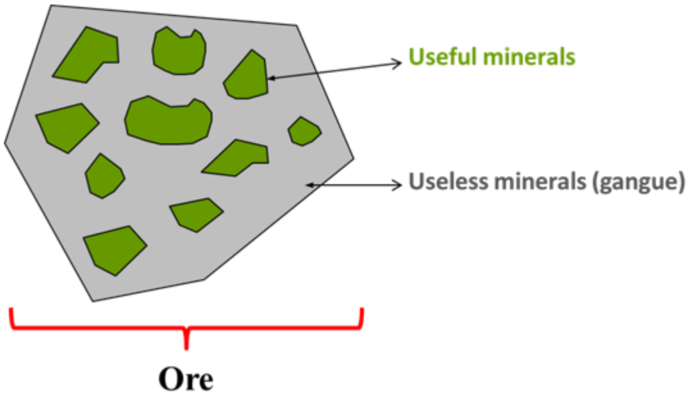
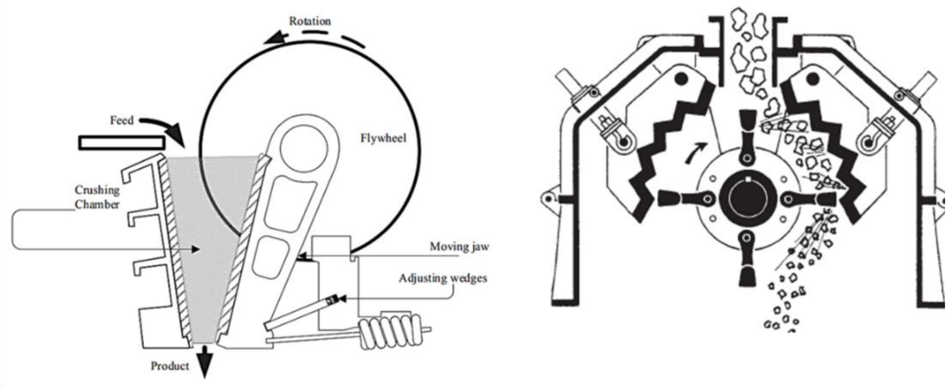


Figure 5. Schematic representation of ore.

In order to economically extract the metal for its ore, the ore must be subjected to several operations: Comminution, Sizing, Concentration and Agglomeration.

1.2.1. Comminution process

Comminution is the process of reducing the size of the ore by crushing and grinding. Large chunks of ore extracted from mines are broken down into smaller, manageable pieces to increase the surface area, making subsequent processing steps more efficient. Smaller particles are the desired product either because of their large surface or because of their shape, size, and number. The energy efficiency of the operation can be related to the new surface formed by the reduction in size. In the comminution process, ore is first reduced in size by mechanical means such as jaw crushers, cone crushers, or gyratory crushers. After that, the ore is further reduced in size through grinding using ball mills or rod mills.



Jaw crusher Hammer crusher

Figure 5. Schematic representation of jaw crusher and hammer crusher.

A jaw crusher is a type of primary crusher used in mines and ore processing plants. Jaw crushers are designed to crush large rocks into smaller pieces for further processing. The working principle of a jaw crusher is simple: the jaw crusher uses a motor to drive the belt and flywheel, making the movable jaw move up and down through the eccentric shaft. When the movable jaw rises, the angle between the toggle plate (fix jaw) and the movable jaw becomes larger, which pushes the movable jaw towards the fixed jaw, and the material is crushed or smashed between the two jaws. The crushed material falls from the discharge opening at the bottom of the crusher.

A hammer crusher, also called hammer mill crusher, is a machine that crushes materials by the impact of a high-speed hammer. The material is fed into the hammer crusher from the top. As the rotor rotates, the hammerhead on the rotor rotates and strikes the material with a high-speed impact. The material is then broken into small pieces and falls through the sieve plate at the bottom of the crusher

A ball mill crusher works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell.

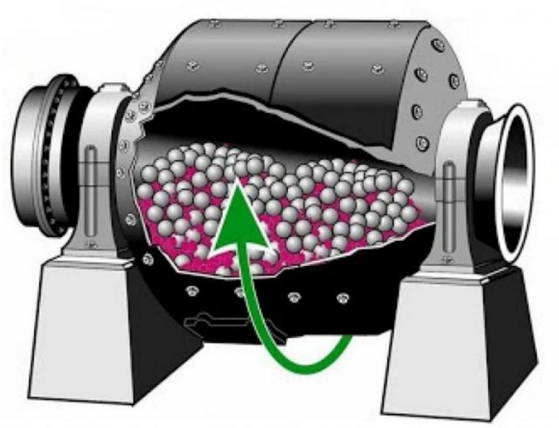


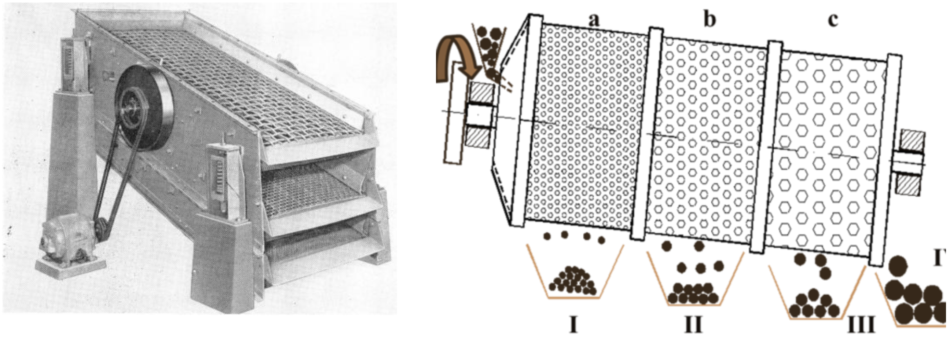
Figure 6. Schematic representation of a ball mill crusher [5]

The ball mill crusher consists of a hollow cylindrical shell rotating about its axis. The axis of the shell may be either horizontal or at a small angle to the horizontal. The cylindrical shell is partially filled with grinding media, such as steel or ceramic balls, which are used to grind the material as the mill rotates. As the mill rotates, the grinding media and the material inside the mill are lifted up and then dropped back down onto the material, causing it to be ground into smaller particles.

1.2.2. Sizing process

Sizing is the general term for separating minerals according to their size by screening. The sizing of ore is typically done after the comminution process, as the particle size distribution of the ore can affect the efficiency of downstream processing steps. Several equipment for sizing are described bellow:

A vibrating screen is a machine used to separate materials by particle size. It consists of a vibrating device that vibrates a screen or sieve surface to separate different sized particles. The vibrating screen operates by imparting a vibration to the screens or sieves, causing the particles to move along and through the screen or sieve surface. The movement of particles is influenced by factors such as vibration frequency, amplitude, and direction of vibration.



Vibrating screen　　　　　　　　Revolving screens

Figure 6. Schematic representation of vibrating screen and revolving screens

Revolving screens consist of a cylindrical drum that rotates around its axis, with screens or sieves attached to the interior of the drum. The materials to be separated are fed into the drum at one end, while smaller particles pass through the screens and are collected at the other end. The drum is designed with a slight slope or angle, allowing the materials to move along the length of the drum as it rotates. Smaller particles that pass through the screens fall through the bottom of the drum and are collected in a hopper or conveyor, while larger particles that are retained on the screens are carried along by the rotation of the drum and eventually exit at the other end.

1.2.3. Concentration process

Ore concentration refers to the process of separating and extracting valuable minerals from the ore. The goal of ore concentration is to increase the concentration of the desired mineral(s) and remove the unwanted gangue minerals (useless minerals). There are several methods used for ore concentration, including physical separation techniques such as gravity separation, magnetic separation, and froth flotation, as well as chemical processes such as leaching and smelting.

Gravity separation involves the use of differences in the density of minerals to separate them, while magnetic separation uses differences in magnetic properties to separate minerals.

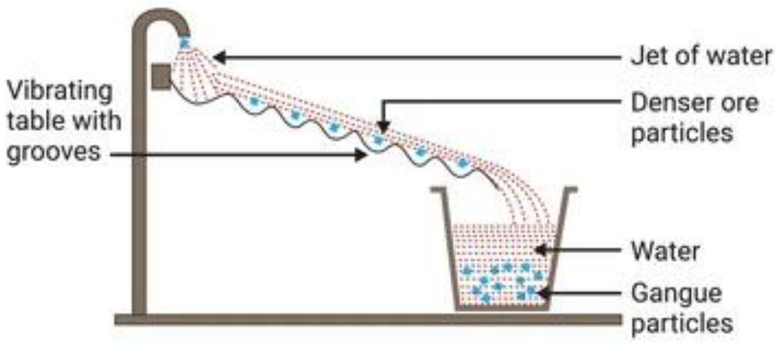


Figure 7. Schematic illustration of ore concentration by gravity separation [6].

Froth flotation is a process where minerals are separated by their surface properties, with the use of chemicals that selectively attach to the desired mineral(s) and cause them to float to the surface of a froth layer.

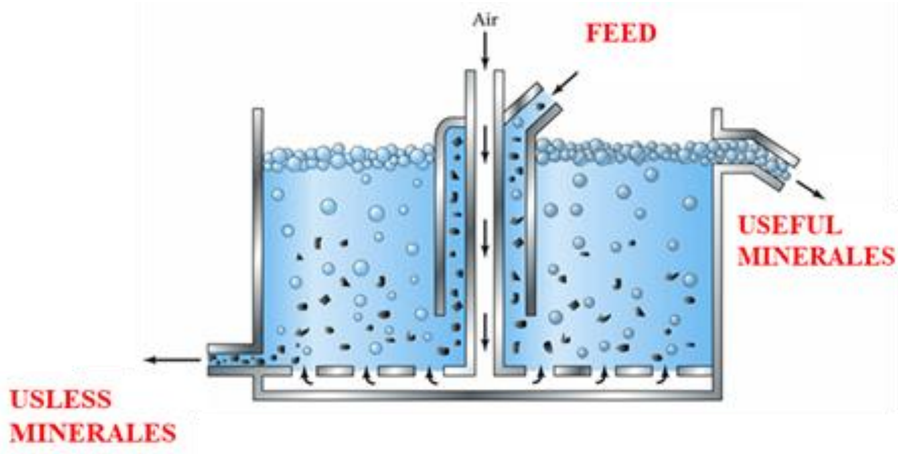


Figure 8. Schematic illustration of forth flotation process [6].

The process of magnetic separation involves the use of a magnetic field to attract and separate magnetic materials from non-magnetic ones. The magnetic field can be created by a magnet or an electromagnet. When a mixture of magnetic and non-magnetic materials is placed in the magnetic field, the magnetic materials are attracted to the field and are separated from the non-magnetic materials.

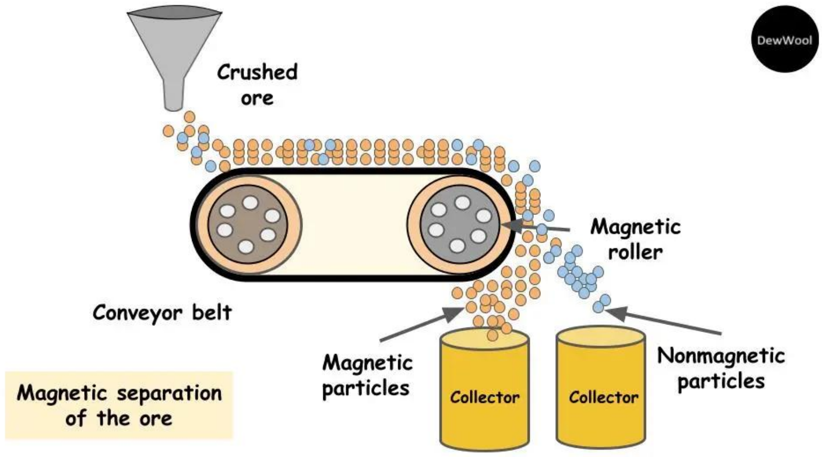


Figure 9. Schematic illustration of ore concentration by magnetic separation [6].

Leaching is a process in which chemical solutions (usually acids, bases, or other solvents) are used to dissolve valuable minerals from the ore. The desired metal is transferred into the solution, leaving behind the unwanted gangue material. For example, cyanide leaching is commonly used to extract gold from gold ore.

Smelting is a process that involves heating the ore to a high temperature, often in the presence of a reducing agent (like carbon), to separate the metal in its molten form. It also involves the addition of fluxes (such as limestone) to remove impurities and form slag. For example, iron is extracted from its ore (hematite or magnetite) in a blast furnace through smelting, where heat and chemical reduction transform the ore into molten iron.

1.2.4. Agglomeration process

Agglomeration of the ore refers to the process that transforms fine particles of concentrate ore into pellets or brickettes, allowing a more efficient extraction. The agglomeration process can involve different techniques such as briquetting, pelletizing, or nodulizing, depending on the properties of the ore and the desired end product. Regardless of the used technique, prior compaction, the fine particles of concentrate are mixed with a binding agent such as water, cement, or chemicals. The resulting agglomerates can be of various sizes and shapes and are typically more uniform in size and composition than the original fine particles.

Figure 10. Briquetting process and different types (shapes and sizes) of briquets.

The three primary approaches used to extract metals from their ores after mineral processing are: Pyrometallurgy, Hydrometallurgy, and Electrometallurgy.

Pyrometallurgy involves high-temperature treatments, such as smelting and roasting, to chemically reduce and separate metals from their oxides or sulfides. It is commonly applied in the production of metals like iron, copper, and lead.

Hydrometallurgy, in contrast, uses aqueous chemical solutions to dissolve valuable metals from the ore through processes like leaching. Once dissolved, the metals are recovered by precipitation, solvent extraction, or ion exchange. This method is widely used for gold, silver, and uranium extraction.

Electrometallurgy employs electrical energy for metal recovery and refining, often through electrolysis, as in the extraction of aluminum, copper, and zinc.

The choice of method depends on the nature of the ore, the target metal, and the economic and environmental factors involved.

Chapter II

IRON AND STEEL PRODUCTION

2.1. Introduction to iron and steel production

The production of iron and steel has played a fundamental role in the progress of human civilization, shaping culture, politics, and technology throughout history. Iron and steel are well-known for their special mechanical, thermal, and electrical properties, which make them suitable for a wide variety of applications. Today, these materials are essential in industries such as construction, automotive manufacturing, heavy machinery, energy, and transportation.

Steel is especially popular because of its high strength, durability, flexibility in design, and relatively low cost compared to other engineering materials. Its abundance in nature and the efficiency of modern steelmaking processes have further contributed to its widespread use. In addition, steel is crucial for many industrial technologies, such as tool and die production, forging, and casting, most of which rely heavily on steel components. Therefore, steel is not just a basic material but a key factor in the development of modern industry and the global economy.

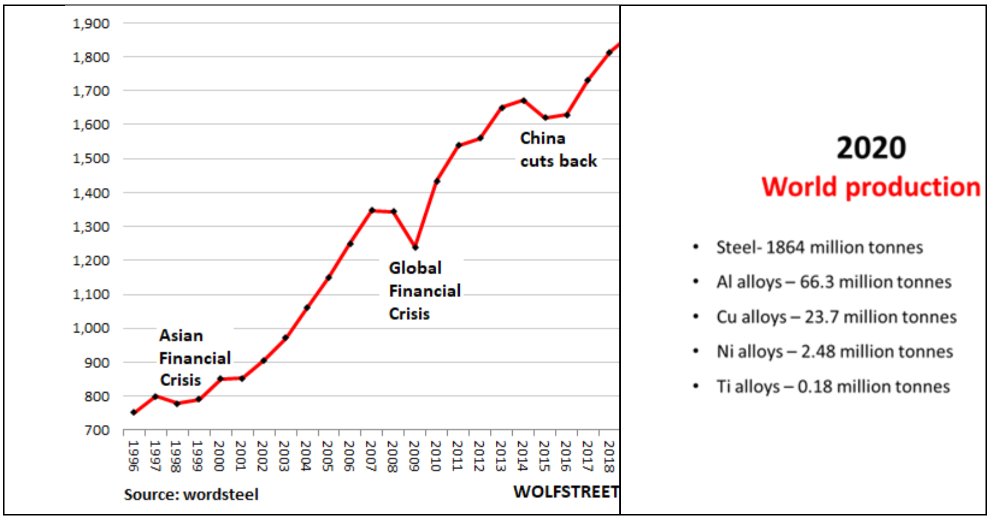


Figure 1. Evolution of the global steel production and comparison with other alloys [7].

The global production of steel has increased significantly over the last several decades. According to data from the World Steel Association, global steel production grew from 851 million metric tons in 2000 to 1.86 billion metric tons in 2020. This represents a nearly 120% increase in production over a 20 years period.

China is currently the world's largest steel producer, accounting for more than half of global steel production. According to data from the World Steel Association, China produced 1.05 billion metric tons of crude steel in 2020, which was more than 56% of global steel production for the year. Other major steel producing countries include:

- India – 149.4 million metric tons in 2020
- Japan – 84 million metric tons in 2020
- United States - 79.5 million metric tons in 2020
- Russia – 71 million metric tons in 2020

The steel industry in Romania has undergone significant changes in recent decades, with production decreasing very much and shifting towards higher value-added products such as special steels and steel products for the automotive industry. The production of crude steel in Romania fluctuates between 2.9 to 3.4 million metric tons.

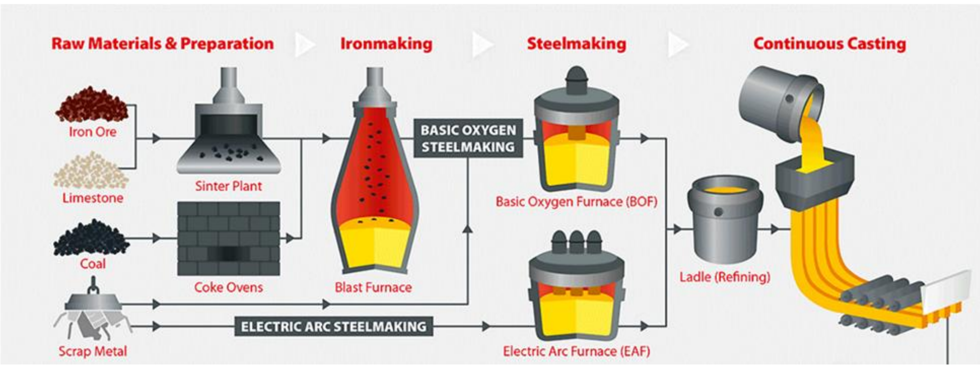


Figure 2. Schematic overview of the steelmaking process [8].

The first stage in steelmaking involves producing iron from either iron ore or recycled steel scrap. This is typically achieved in a blast furnace (BF) when using iron ore, or in an electric arc furnace (EAF) when melting steel scrap. Once molten iron (or liquid steel from scrap) is obtained, it undergoes refining to become steel. This step is performed in either a basic oxygen furnace (BOF) where oxygen is blown into the molten iron to reduce its carbon content or in an electric arc furnace (EAF), which can both melt scrap and refine it into high-quality steel.

To achieve the desired chemical composition and purity, the steel is further treated through secondary refining processes such as ladle refining, vacuum degassing, or argon oxygen decarburization. These techniques help remove remaining impurities (such as sulfur, phosphorus, or dissolved gases) and enhance the steel's quality.

Finally, the purified liquid steel is solidified through continuous casting, where it is shaped into semi-finished forms such as billets, blooms, or slabs. These semi-finished products are later rolled or forged into final shapes used in various industries.

2.2. Blast furnace - Pig Iron production

Around 70% of the world's steel is produced using blast furnace technology. A blast furnace is a large, refractory-lined structure, typically 9–11 m wide at its largest point and about 40 m high. In its lower part, hot air is injected at high pressure to ensure the combustion of coke and the reduction of iron oxides. The result of this process is pig iron, obtained through the combined actions of reduction and carburization of iron ores.

The main raw materials charged into the furnace are iron ore, coke, limestone, and preheated air (the oxidizing agent).

The most common **iron ore** used in blast furnaces is hematite (Fe_2O_3). Hematite is a reddish-brown mineral containing about 55–65% iron. It is relatively easy to mine and process, yielding a high-grade concentrate suitable for ironmaking. Another important ore is magnetite (Fe_3O_4), a black mineral with a higher iron content of 60–70%. Although harder to process compared to hematite, magnetite results in a higher-quality iron concentrate. Less frequently used ores include:

- Siderite ($FeCO_3$) – 35–46% Fe,
- Pyrite (FeS_2) – 45–60% Fe,
- Limonite ($Fe_2O_3 \cdot xH_2O$) – 42–58% Fe.

Coke is a synthetic carbon-rich fuel produced by heating bituminous coal to 1000-1300 °C in a low-oxygen environment. In the blast furnace, coke has two key roles:

1. provides the necessary heat for the chemical reactions.
2. generates carbon monoxide (CO), which acts as a reducing agent.

Main properties of coke include:

- Carbon content: 90–95%
- Ash content: $< 10\%$
- Moisture content: $< 5\%$
- High mechanical strength: 180–250 MPa
- Low sulfur and phosphorus content: $< 1\%$

Limestone is mainly composed of calcium carbonate ($CaCO_3$). In the furnace, it acts as a flux, combining with impurities from the iron ore and forming slag, which floats on top of the molten metal.

The air, also called the oxidizing blast, is preheated to about 1200 °C and injected into the furnace through tuyeres (special nozzles) near the bottom. When this hot air meets the coke, it produces carbon monoxide that is the main reducing gas responsible for converting iron oxides into molten iron.

The working principle of a blast furnace is divided into four stages based on different temperature zones. The highest temperature is found at the bottom of the furnace, while the temperature gradually decreases towards the top. The mixture of iron ore, coke, and limestone (called the charge) is introduced from the top of the furnace. The four zones and their main reactions are: **preheating zone, reduction zone, carburization zone, and melting zone.**

Preheating Zone (200–400 °C)

In this uppermost part of the furnace, the charge materials are preheated by the ascending hot gases. Any moisture is removed, and organic contaminants may burn off.

Reduction Zone (400–800 °C)

As the charge moves downward, it enters the reduction zone, where the chemical reduction of iron oxides begins. This process is known as **indirect reduction**, as it is carried out by carbon monoxide (CO) gas formed from the combustion of coke. In this reaction, CO captures the oxygen from the iron oxides, forming carbon dioxide (CO_2) while reducing the ore to metallic iron through intermediate steps. The main sequence of reactions can be summarized as:

$$\begin{aligned}
3\,Fe_2O_3 + CO &\rightarrow 2\,Fe_3O_4 + CO_2 \\
Fe_3O_4 + CO &\rightarrow 3\,FeO + CO_2 \\
FeO + CO &\rightarrow Fe + CO_2
\end{aligned}$$

If the iron ores that are not yet fully reduced continue to move downward in the blast furnace, they reach a zone with higher temperatures where carbon from the coke directly reduces the iron oxides. In this process, carbon reacts with the oxygen from the ore, forming carbon monoxide (CO). This is called direct reduction, and it occurs in the temperature range of approximately 800–1200 °C.

Carburizing Zone

In this zone, the metallic iron formed in the reduction stages absorbs carbon either from carbon monoxide (CO) gas or from solid coke. This leads to the formation of iron carbide (Fe_3C, also known as cementite).

$$3Fe + 2CO \rightarrow Fe_3C + CO_2$$
$$3Fe + C \rightarrow Fe_3C$$

The absorption of carbon has an important effect: it lowers the melting point of iron from 1536 °C to around 1200 °C, as shown in the iron-carbon phase diagram.

Melting Zone

This is the hottest part of the blast furnace. Here:

- Coke combustion, supported by the hot blast from the tuyeres, generates very high temperatures.
- The reduced and carburized iron melts to form pig iron.
- Impurities combine with the flux (limestone) to form slag, which is also liquid but less dense than pig iron and therefore floats on its surface.

The molten pig iron collects at the bottom of the furnace in the hearth (or crucible). Due to the density difference, pig iron can be removed separately from the slag. The removal process, known as tapping, is done 4 - 6 times per day to extract both molten iron and slag for further processing.

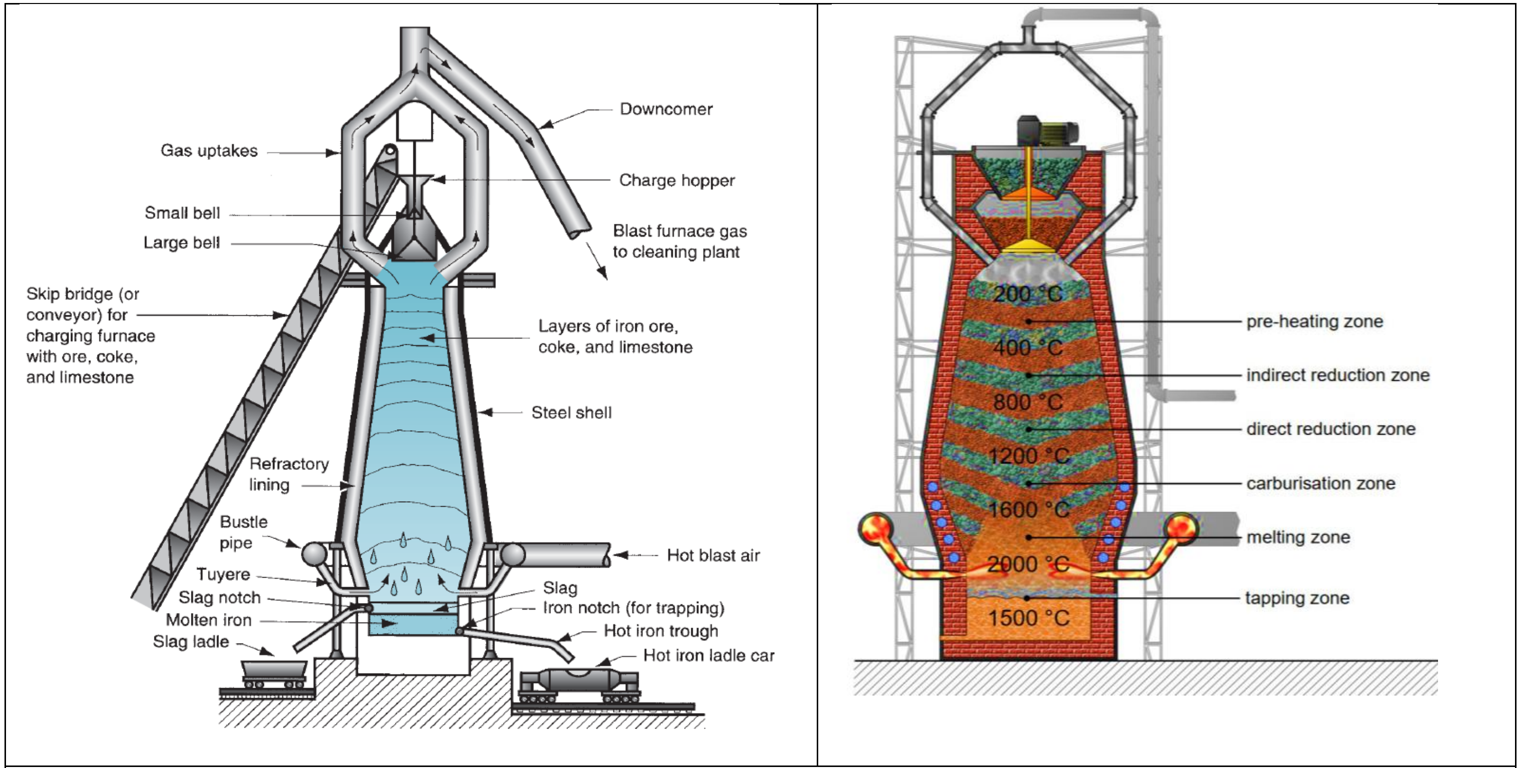


Figure 3. Cross-sectional view of a blast furnace illustrating the main components and the temperature zones associated with the ironmaking process [4].

2.3. Blast furnace products

The main products obtained from a blast furnace are **pig iron**, **blast furnace gas**, and **slag**.

Pig iron is the primary product of the blast furnace, but it is considered an intermediate material because it contains a high percentage of carbon (typically 2.0–4.5%) and other impurities. Its composition can vary depending on the furnace operation, but it generally includes:

- Carbon (C): 2.0–4.5%
- Silicon (Si): 0.5–3.0%
- Manganese (Mn): 0.1–1.0%
- Phosphorus (P): 0.1–1.0%
- Sulfur (S): 0.1–2.0%

Pig iron is mainly used as a feedstock for steelmaking or for the production of cast iron. Depending on the size of the blast furnace, the output of pig iron can range from several hundred to several thousand tons per production cycle.

Blast furnace gas (BFG) is an important by-product. After cleaning (by passing through dust-capturing filters), this gas can be reused for:

- Power generation and heating,
- Injection back into the blast furnace as an auxiliary fuel,
- Chemical production (e.g., ammonia, methanol, hydrogen).

On average, 1,800–2,500 m^3 of blast furnace gas are produced for every ton of pig iron.

Slag is the non-metallic by-product of the blast furnace, consisting of various oxides and minerals. Its typical composition includes:

- Silicon dioxide (SiO_2): 30–50%
- Calcium oxide (CaO): 10–20%
- Magnesium oxide (MgO): 5–15%
- Aluminum oxide (Al_2O_3): 5–15%
- Iron oxide (FeO): 5–15%

Slag is often processed and used as a construction material, with applications such as road building, cement production, soil stabilization, decontamination, and abrasives. Typically, 200 - 250 kg of slag are generated for every ton of pig iron produced.

2.4. Steelmaking processes

Steel is mainly produced by two methods: **Basic Oxygen Steelmaking (BOS)** and the **Electric Arc Furnace (EAF)** process. BOS is the dominant method, accounting for approximately 70% of global steel production, and is best suited for large-scale steelmaking due to its speed and efficiency. In contrast, EAF is often used for smaller batches and specialty steels. One key advantage of EAF is its use of recycled scrap steel as the primary raw material, making it more environmentally friendly compared to BOS, which relies on pig iron obtained from blast furnaces and iron ore.

2.4.1. Basic Oxygen Steelmaking (BOS)

The central piece of equipment in BOS is the basic oxygen furnace (BOF), which is a pear-shaped vessel lined with refractory materials to withstand high temperatures. A typical BOF can process between 150 and 200 tons of molten metal per batch and is mounted on pivots to allow tilting during charging and tapping. The main objective of BOS is to reduce the carbon content of pig iron (from 2–4.5% to less than 0.05%) and to remove impurities such as phosphorus, manganese, sulfur, and silicon.

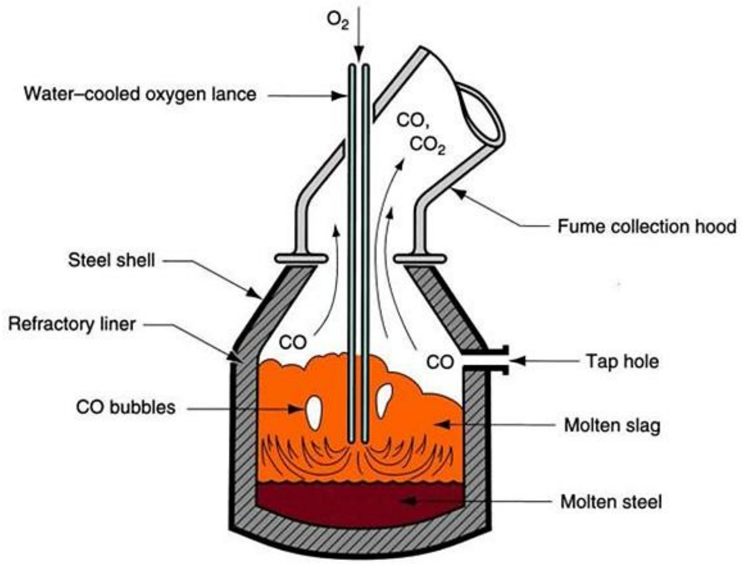


Figure 4. Basic oxygen furnace (BOF) vessel during steelmaking operations [adapted after 4].

The process begins by charging the converter with molten pig iron from the blast furnace. Up to 20% scrap steel may also be added to cool the process and recycle steel. Once charged, pure oxygen is blown into the furnace at supersonic speeds using a water-cooled copper lance positioned approximately 1.5 meters above the molten metal. Modern BOS converters also include bottom-blowing nozzles, which inject oxygen from below, improving mixing and reducing processing time by about three minutes.

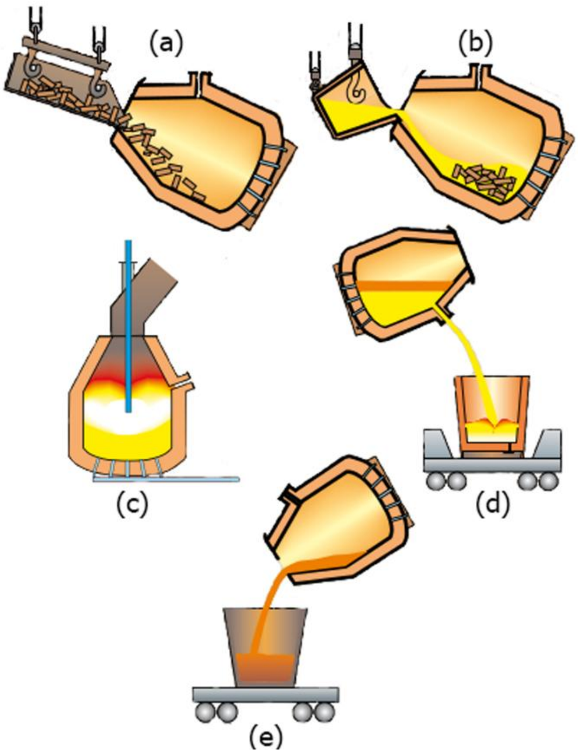


Figure 5. BOF processing sequence: (1) charging with scrap, (2) adding molten pig iron, (3) oxygen blowing, (4) tapping the molten steel, and (5) removing the slag [9].

The oxygen reacts exothermically with the carbon and impurities, raising the temperature of the molten metal from around 1250 °C to more than 1600 °C. Carbon is oxidized to carbon monoxide gas, while silicon, manganese, phosphorus, and sulfur are oxidized and absorbed into the basic slag formed with limestone and dolomite fluxes.

$$2C + O_2 \rightarrow 2CO \text{ } (CO_2 \text{ is also produced})$$
$$Si + O_2 \rightarrow SiO_2$$
$$2Mn + O_2 \rightarrow 2MnO$$
$$4P + 5O_2 \rightarrow 2P_2O_5$$

Iron is also partially oxidized to FeO, which further oxidizes other elements due to their higher oxygen affinity.

$$\begin{aligned} FeO &+ C &\rightleftharpoons Fe &+ CO \\ 5\,FeO &+ 2\,P &\rightleftharpoons 5\,Fe &+ P_2O_5 \\ FeO &+ Mn &\rightleftharpoons Fe &+ MnO \\ 2\,FeO &+ S &\rightleftharpoons 2\,Fe &+ SO_2 \\ 2\,FeO &+ Si &\rightleftharpoons 2\,Fe &+ SiO_2 \end{aligned}$$

After about 20 minutes of oxygen blowing, the molten metal becomes crude steel with a much lower carbon content. To remove excess oxygen dissolved in the steel, ferroalloys such as ferrosilicon or ferromanganese are added. These bind the oxygen to form oxides that float into the slag.

$$[FeO] + [Fe\text{-}Si] \rightarrow [Fe] + (SiO_2)$$
$$[FeO] + [Fe\text{-}Mn] \rightarrow [Fe] + (MnO)$$
$$[FeO] + [Fe\text{-}Al] \rightarrow [Fe] + (Al_2O_3)$$

At this stage, additional alloying elements such as nickel, chromium, or molybdenum may be added to adjust the chemical composition of the steel.

The refined steel is then poured into ladles and typically cast using continuous casting, where the molten metal solidifies into semi-finished shapes such as slabs, billets, or blooms.

2.4.2. Electric Arc Furnace (EAF)

The Electric Arc Furnace (EAF) process is a steelmaking method that primarily uses recycled steel scrap as the raw material, which is melted by the intense heat of an electric arc.

During operation, the graphite electrodes of the furnace are raised to the top position, and the roof of the furnace is swung open to allow charging. The EAF is then filled with recycled steel scrap, which is often preheated to reduce energy consumption and shorten melting time. Once charged, a high electrical current is passed through the electrodes, creating an electric arc between the electrodes and the steel scrap. The distance between the electrodes and the scrap is typically 200–300 mm, and the arc's heat melts the scrap into a pool of molten steel.

Some modern EAFs are equipped with burners or oxygen injectors, which can enhance the melting process, accelerate reactions, or adjust the composition of the molten metal. Chemical samples of the molten steel are taken during the process to monitor and control its composition. Ferroalloys are commonly added to deoxidize the molten steel, while alloying elements are introduced to achieve the required steel grade.

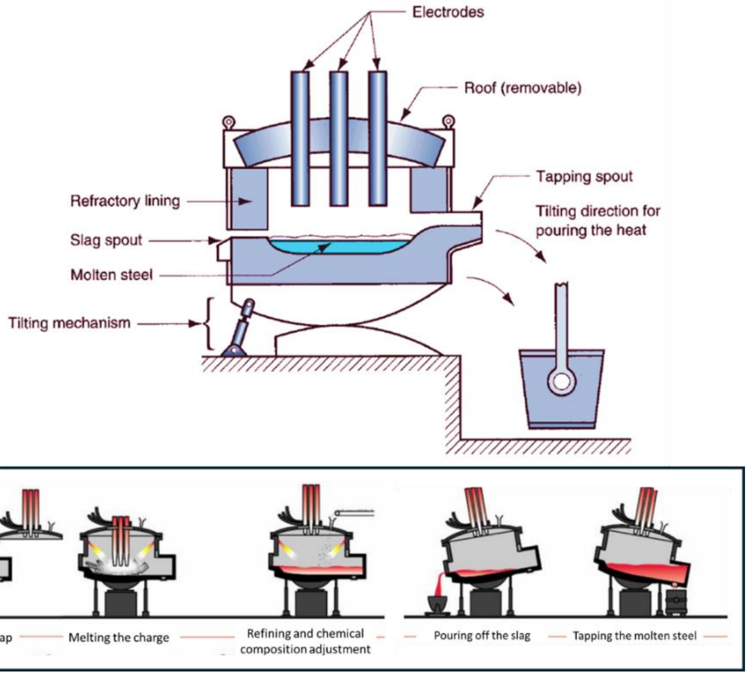


Figure 6. Electric arc furnace for steelmaking and processing sequence [adapted after 4].

Once the steel is refined to the desired composition, the EAF is tilted to pour the molten steel into a ladle or directly into a continuous casting machine, where it solidifies into semi-finished products such as billets, slabs, or blooms.

Key Features of EAF Steelmaking:

- Melting time: Complete melting takes approximately 2 hours, while the tap-to-tap cycle (from one batch to the next) is about 4 hours.
- Capacity: Electric arc furnaces typically range from 30 to 200 tons per heat, with 50–60 tons being the most common capacity.
- Quality vs. cost: EAFs produce high-quality steel, including alloy steels, tool steels, and stainless steels, but the cost per ton is generally higher than that of BOS.
- Environmental benefit: EAFs rely largely on scrap recycling, which significantly reduces CO_2 emissions compared to traditional steelmaking routes.

2.5. Continuous casting process

Once the desired steel quality has been achieved, whether by the BOS or EAF route, the molten steel is transferred to continuous casting machines using large casting ladles. Historically, steel was poured into permanent molds (a process called ingot casting), which was discontinuous and time-consuming. However, since its industrial introduction in the late 1960s, continuous casting has become the dominant method. Today, about 97% of EU steel production and approximately 90% of global steel output are produced using this technique.

Continuous casting is a highly automated process that ensures consistent quality and efficiency. It begins with molten steel being poured from the ladle into a tundish, that is a refractory-lined container that acts as a buffer and controls the flow of molten steel to the molds.

From the tundish, the steel enters in a water-cooled copper mold, which initiate the solidification process. As the molten steel flows downward through the mold, a thin solid shell forms around the outer surface. This shell is supported and guided by rolls and rollers, which maintain the desired shape and dimensions of the product (slab, bloom, or billet).

Upon exiting the mold, the steel is only partially solidified and passes through a secondary cooling zone, where intense water sprays and controlled cooling help complete solidification. The cooling rate in this zone is crucial, as it influences the final microstructure and mechanical properties of the steel.

The fully solidified product is then straightened and cut to length using high-speed torches or flying saws. After cutting, these semi-finished products undergo further processing such as hot rolling, heat treatment, or surface finishing.

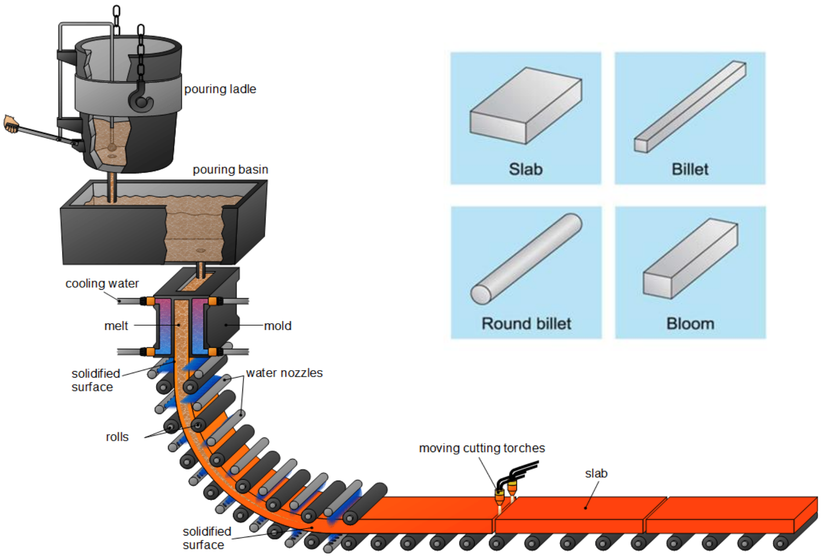


Figure 7. Continuous casting process and the resulting semi-finished steel products (slabs, billets, blooms) [10].

Continuous casting offers significant advantages over traditional ingot casting. It allows for the production of large volumes of steel in a shorter time, increasing efficiency and reducing downtime. The products obtained by this method have fewer internal defects, such as shrinkage cavities or segregation, which leads to improved mechanical properties and higher overall quality. Moreover, the process ensures better dimensional precision and surface finish, reducing the need for extensive downstream processing. From an energy standpoint, continuous casting is more efficient because the direct conversion of molten steel into semi-finished products minimizes reheating requirements. Additionally, this method is more environmentally friendly, as it produces less waste and lowers CO_2 emissions due to its reduced energy consumption.

In Romania, the Călărași steel plant, part of Tenaris Silcotub, is equipped with an Electric Arc Furnace and continuous casting units producing round bars (Ø 148–260 mm) and rectangular blooms (350×260 mm). Its annual production capacity is approximately 470,000 tons of steel, powered by electric arc melting and continuous casting technology

Chapter III

METAL FORMING PROCESSES

3.1. Introduction to metal forming processes

Metal forming refers to a broad range of manufacturing techniques where plastic deformation is used to modify the shape of metal workpieces without removing material. These processes are fundamental in modern manufacturing due to several key advantages [11-13]:

- *Enhanced mechanical properties:*

Techniques such as forging, rolling, and extrusion improve the strength, toughness, and ductility of metals. These improvements result from microstructural changes induced by plastic deformation, including grain refinement, texture development, and an increased density of dislocations.

- *High material efficiency:*

Unlike machining processes, which often generate significant waste, metal forming operations allow near-net-shape manufacturing with minimal material loss.

- *Design versatility:*

Forming methods enable the production of components with complex geometries that would be difficult or expensive to achieve by machining. For instance, extrusion allows for intricate cross-sectional profiles, while forging can create three-dimensional shapes with excellent structural integrity.

- *Reduction of manufacturing steps:*

A single forming operation can replace several machining steps. For example, a forged part often requires little or no additional machining due to its near-final shape and improved surface quality.

- *Wide applicability to different metals and alloys:*

Plastic deformation methods are effective for a large variety of materials, ranging from highly ductile metals (such as aluminum or copper) to alloys that are less ductile but can still be shaped under controlled conditions.

In materials science, **plastic deformation** describes the permanent change in shape or dimensions of a material when the applied stress exceeds its elastic limit. Initially, when a force is applied to a metal, it deforms elastically, meaning the material returns to its original shape when the force is removed. However, beyond the yield point, the metal undergoes irreversible deformation.

Plastic deformation processes are designed to intentionally exceed this elastic limit, reshaping the material without causing fracture. The ability of metals to deform plastically is directly linked to their crystalline structure and the movement of dislocations.

3.2. Classification of metal forming processes

Metal forming processes are commonly divided into two main categories:

1. Bulk deformation processes

These involve shaping a large volume of material using compressive, tensile, or shear forces. Common examples include:

- Forging – compressing the metal between dies to obtain the desired shape.
- Rolling – passing the metal between rollers to reduce thickness or change cross-sectional shape.
- Extrusion – forcing the metal through a die to create a specific profile.
- Drawing – pulling the metal through a die to reduce its cross-sectional area.

Bulk deformation often requires high forces and heavy machinery, such as presses or rolling mills. Depending on the material and the final properties required, these processes can be performed hot (above recrystallization temperature) to enhance ductility or cold (at room temperature) to achieve better surface finish and strain hardening.

2. Sheet metalworking processes

These focus on shaping thin sheets of metal into desired forms using operations such as bending, stretching, deep drawing, cutting, and stamping.

Unlike bulk deformation, sheet metal forming usually involves smaller tools such as dies, punches, or press brakes, and is most often performed at room temperature (cold working). This allows for precise dimensions and a good surface finish but may require additional treatments to relieve residual stresses.

3.3. Cold, Warm and Hot Working

Temperature is a critical factor in metal forming processes because the mechanical properties of metals, such as strength, ductility, and toughness, are strongly influenced by temperature. Depending on the temperature relative to the recrystallization temperature (Tr) of the metal, forming processes are classified into three categories: cold working, warm working, and hot working.

3.3.1. Cold working

Cold working refers to the plastic deformation of metals at temperatures well below their recrystallization temperature, typically at or near room temperature. During cold working, the metal's grains become elongated and distorted in the direction of the applied force. The degree of elongation depends on the amount of deformation and the initial grain orientation. As deformation increases, the metal becomes harder and stronger, but its ductility and toughness decrease due to the accumulation of dislocations. This phenomena is known as strain hardening or work hardening.

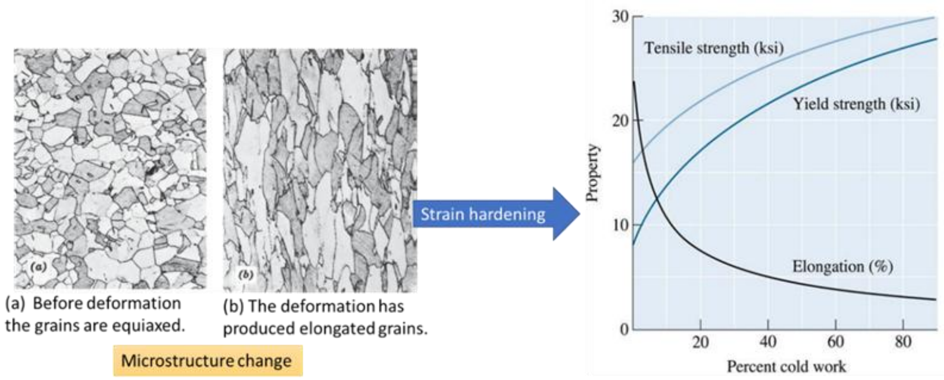


Figure 1. Evolution of the microstructure and mechanical properties of metals during cold working [adapted after 14].

To restore ductility, a heat treatment called recrystallization is applied. This involves heating the metal to a temperature below its melting point and allowing new equiaxed grains to form, replacing the deformed grain structure. Recrystallization removes dislocations and restores the mechanical properties lost during cold working.

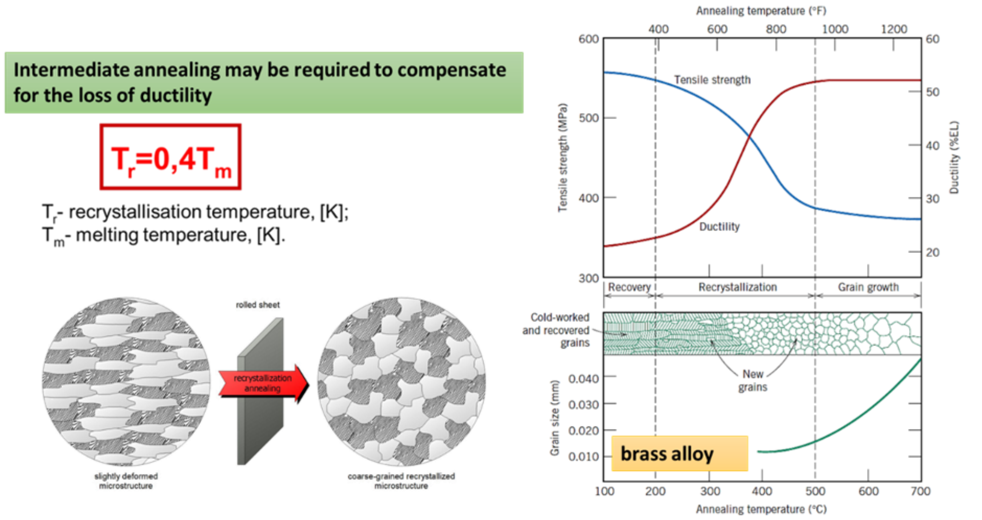


Figure 2. The effect of recrystallization on the microstructure and mechanical properties of cold-worked metals [adapted after 14].

Advantages of cold working:

- No heating is required, which reduces energy costs.
- Produces superior surface finish and high dimensional accuracy (no thermal expansion issues).
- Parts exhibit better reproducibility and interchangeability.
- Strength, fatigue resistance, and wear resistance are improved through strain hardening.
- Directional properties (anisotropy) can be tailored.
- The absence of high temperatures reduces contamination risks.

Disadvantages of cold working:

- Requires high forces to initiate and sustain deformation.
- Heavier and more powerful equipment (presses, rolls, dies) is needed.
- Reduced ductility can lead to cracking if deformation is excessive.
- Metal surfaces must be clean and free from oxide scales.
- Intermediate annealing is often required to restore ductility in multi-step processes.
- Residual stresses may develop, leading to dimensional instability.
- Directional properties (anisotropy) may sometimes be unfavorable.

3.3.2. Warm working

Warm working is performed at temperatures above room temperature but below the recrystallization temperature, typically in the range of 0.3 Tm (where *Tm* is the melting temperature of the alloy in Kelvin).

Advantages over cold working:

- Lower forces and power requirements.
- More complex shapes and intricate geometries can be produced.
- May reduce or eliminate the need for annealing.
- Offers a compromise between improved ductility (compared to cold working) and better dimensional accuracy (compared to hot working).

Warm working is especially useful for metals and alloys that are difficult to deform at room temperature, such as certain high-strength steels and titanium alloys.

3.3.3. Hot working

Hot working (or hot forming) involves metal deformation at temperatures above the recrystallization temperature, usually in the range of 0.5–0.75 Tm. At these temperatures, recrystallization occurs simultaneously with deformation, continuously removing strain hardening effects. As a result, metals remain soft and ductile, allowing large plastic deformations without fracture.

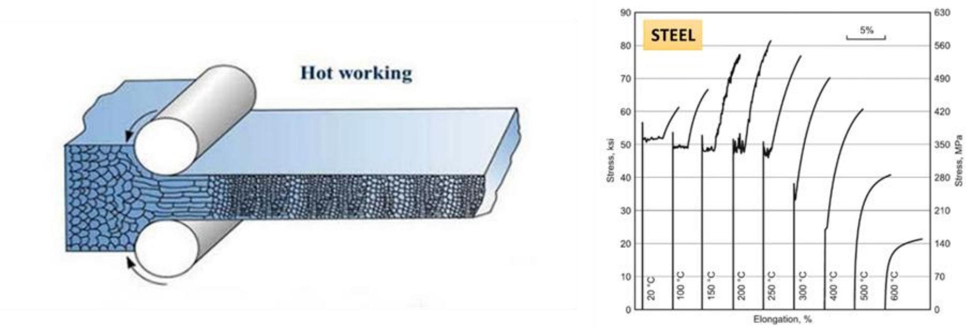


Figure 3. Evolution of the microstructure of materials during hot working and typical stain-elongation curve at different temperature for steel [15].

Alloy	Start Temperature °C	End Temperature °C
Aluminium alloys	400°C to 550°C	200°C to 350°C
Copper alloys	650°C to 1000°C	400°C to 600°C
Steel alloys	1000°C to 1300°C	800°C to 1000°C
Titanium alloys	800°C to 1100°C	500°C to 800°C
Nickel alloys	900°C to 1200°C	900°C to 1100°C
Magnesium alloys	350°C to 500°C	200°C to 300°C
Zinc alloys	350°C to 425°C	200°C to 250°C

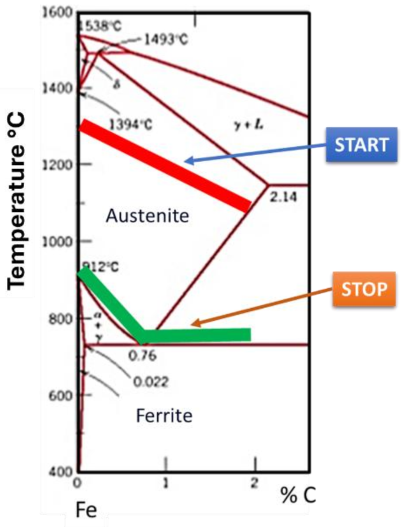


Figure 4. Temperature ranges for hot working of the main alloy classes used in industry, along with the start and stop temperatures for steels, as represented on the Fe–Fe_3C phase diagram.

Advantages of hot working:

- Metals can be deformed extensively with relatively low forces.
- The stress-strain curve is nearly flat beyond the yield point, simplifying forming operations.
- Diffusion is enhanced, which helps eliminate chemical segregation and close internal porosity.
- Particularly advantageous for steels, which transform to the soft and ductile austenite phase at elevated temperatures, making them easier to shape.

Disadvantages of hot working:

- High temperatures may cause undesirable reactions (oxidation, scaling) with the environment.
- Dimensional accuracy and tolerances are poorer due to thermal expansion and contraction.
- Final grain structure may be non-uniform, depending on deformation history, final temperature, and cooling rate.

3.4. Laws/Principles of plastic deformation

3.4.1. The principle of volume constancy

The principle of volume constancy, states that the volume of a material undergoing plastic deformation remains constant. This means that the material is incompressible and the total volume of the material remains constant throughout the deformation process.

This law is based on the fact that plastic deformation is a result of the rearrangement of material within the structure of the material, rather than the creation or destruction of material. When a material undergoes plastic deformation, the material is compressed or stretched in some regions, while it is expanded or relieved in others, resulting in an overall change in shape but no change in volume.

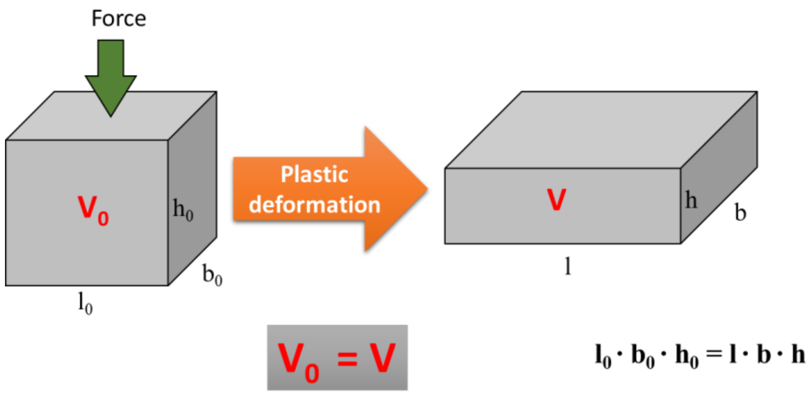


Figure 5. Exemplification of the volume constancy principle in plastic deformation.

The law of constant volume is an important principle in understanding the behavior of materials undergoing plastic deformation, and it has important implications for the design of structures and components that are subjected to plastic deformation.

3.4.2. The law of superposition

The law of superposition states that when a material undergoes plastic deformation, the total deformation (ε_{tot}) can be considered as the sum of two components: elastic deformation (ε_e) and plastic deformation (ε_p).

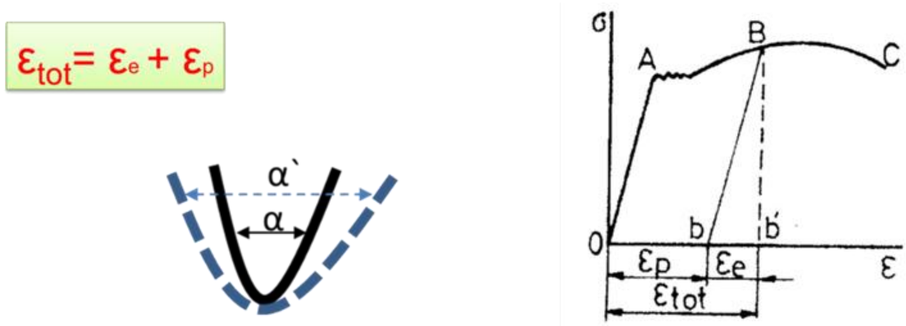


Figure 6. Illustration of the law of superposition; the left side demonstrates the spring-back effect observed during the bending of a metallic wire.

This law is important in understanding the behavior of materials during plastic deformation (especially for cold working), as it allows engineers to estimate the total deformation of a structure or component undergoing plastic deformation, and to design structures and components that can withstand the expected deformation without failure.

3.4.3. The principle of least resistance

The principle of least resistance states that a material undergoing plastic deformation will tend to deform in the direction of least resistance or with minimum stress, all other factors being equal.

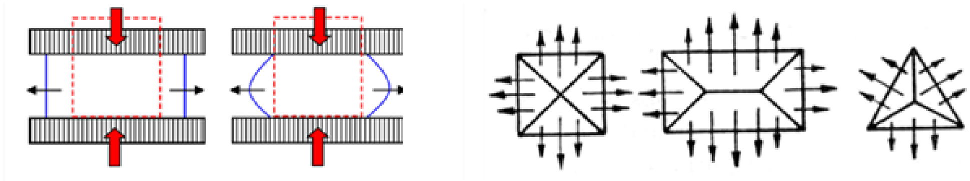


Figure 7. Illustration of the principle of least resistance [16].

This principle arises from the fact that materials are anisotropic, meaning that they have different mechanical properties and strengths in different directions. Therefore, when a material is subjected to external forces that cause deformation, it will tend to deform in the direction of least resistance, where the stress required to cause deformation is the lowest.

3.4.4. The principle of similarity or scaling law

If two objects made of the same material and with similar shapes but different sizes are subjected to the same ratio of stresses to yield strength, they will experience similar plastic deformation behavior.

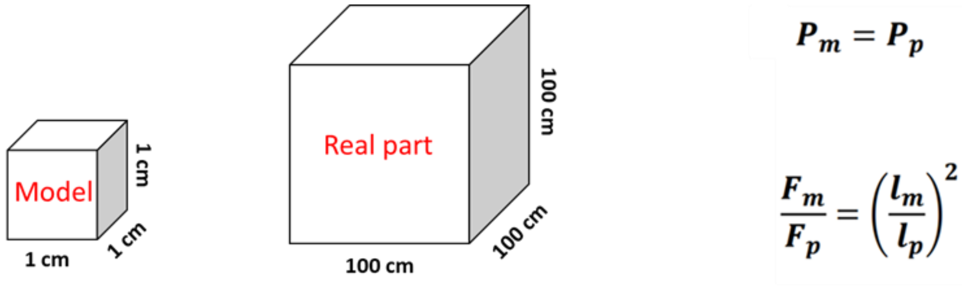


Figure 8. The principle of similarity or scaling law.

This principle is based on the concept of similarity in physics, which states that objects with similar geometric shapes and physical properties will exhibit similar behavior when subjected to similar conditions. The law of similitude is particularly important in testing and evaluating the behavior of materials, as it allows engineers to scale up or down the size of specimens and test structures while still accurately predicting their behavior under various loading conditions.

3.5. Bulk deformation processes

Bulk deformation processes involve shaping large volumes of metal through compressive, tensile, or shear forces, with common methods including forging, rolling, extrusion, and drawing. These processes improve mechanical properties, reduce material waste, and enable the creation of complex geometries. Bulk deformation is widely used in industries such as automotive, aerospace, and construction for manufacturing critical parts like shafts, gears, pipes, and structural components. Due to its ability to improve both the internal structure and surface quality of metals, bulk deformation is essential for producing strong, reliable, and cost-effective components.

3.5.1. Forging process

Forging is a metal forming process in which a workpiece is compressed between dies to achieve the desired shape, using either impact (dynamic) or gradual increasing (static) pressure. It is widely used in modern industries, especially automotive and aerospace, for manufacturing high-strength components such as engine crankshafts, connecting rods, gears, aircraft structural parts, and turbine blades. In the steel industry, forging is often employed to produce the basic shapes of large components before they undergo final machining. Forged parts are known for their superior mechanical properties, with strength-to-weight ratios typically about 20% higher compared to cast or machined parts.

Forging operations are often classified by working temperature:

- Hot or warm forging is the most common, as elevated temperatures lower the material's strength and improve ductility, allowing for significant deformation.
- Cold forging, although less common, is used for specific products, offering the advantage of strain hardening, which increases the strength of the final component.

The equipment used includes forging hammers (impact load) and forging presses (gradual pressure). Forging processes are also classified based on the degree to which metal flow is restricted by the dies, resulting in three main types: Open-die forging, Closed-die forging, and Flashless forging.

3.5.1.1. Open-die forging

In open-die forging, the workpiece is compressed between two flat (or nearly flat) dies, allowing the metal to flow laterally without complete constraint. Since the dies are not shaped, the operator must carefully orient and reposition the workpiece between blows to achieve the required form. The process is called "open-die" because the dies do not enclose or confine the material.

Basic steps of open-die forging:

- The raw material (usually a bar or billet) is heated above its recrystallization temperature to improve deformability.
- The hot workpiece is placed on the lower flat die.
- The upper die strikes or presses the workpiece, causing it to flatten and flow outward.
- The workpiece is rotated or shifted between successive blows.

- The sequence is repeated until the desired dimensions are achieved.

Open-die forging is particularly advantageous for producing custom or non-standard shapes that are difficult or impossible to achieve with other manufacturing techniques. Several specific open-die forging operations are used to obtain desired geometries or to enhance the properties of the metal.

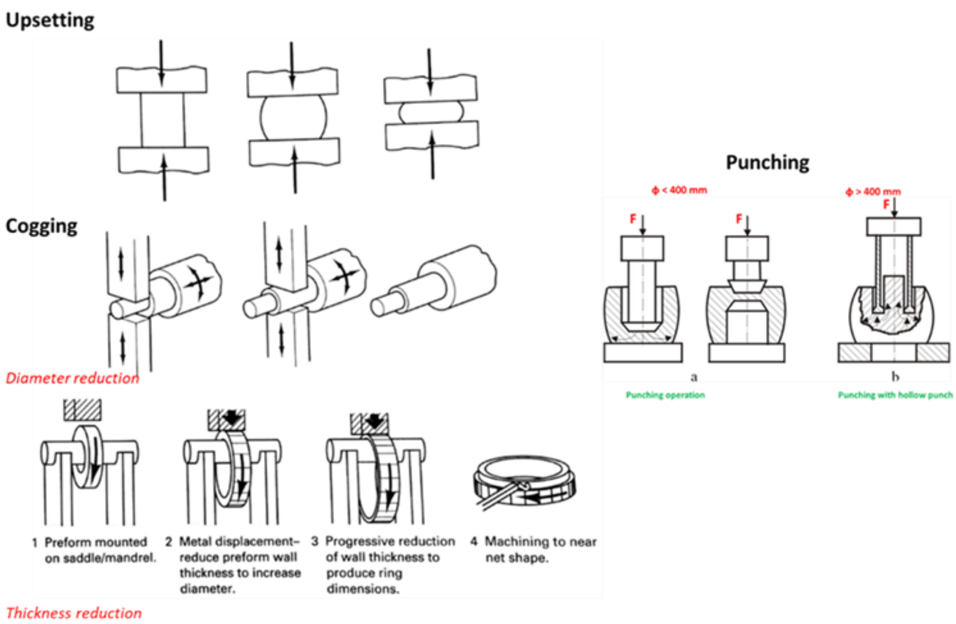


Figure 9. Illustration of primary open-die forging operations: upsetting, punching and cogging [17].

The most common operations include:

- **Upsetting:** In this process, the workpiece is compressed between flat dies, resulting in a reduction in height and a corresponding increase in width or cross-sectional area. Multiple upsetting steps may be performed to reach the required dimensions.
- **Punching:** This involves creating a hole through the workpiece using a punch and a supporting die. The punch is driven through the metal, and the hole can be further shaped or enlarged in subsequent steps.

- **Cogging:** In cogging, the workpiece is compressed repeatedly along its length to reduce its diameter while increasing its overall length, commonly used to prepare billets or bars for subsequent processing.

3.5.1.2. Closed-die forging

Closed-die forging, also called impression-die forging, is a metal forming process in which a heated workpiece is compressed between two precisely shaped dies (molds) that fit together to form the desired geometry. As the dies close, the metal flows to fill the cavity, and any excess material is squeezed out as flash in the narrow gap between the die plates. This method is ideal for producing complex shapes with high strength, excellent surface finish, and tight dimensional tolerances.

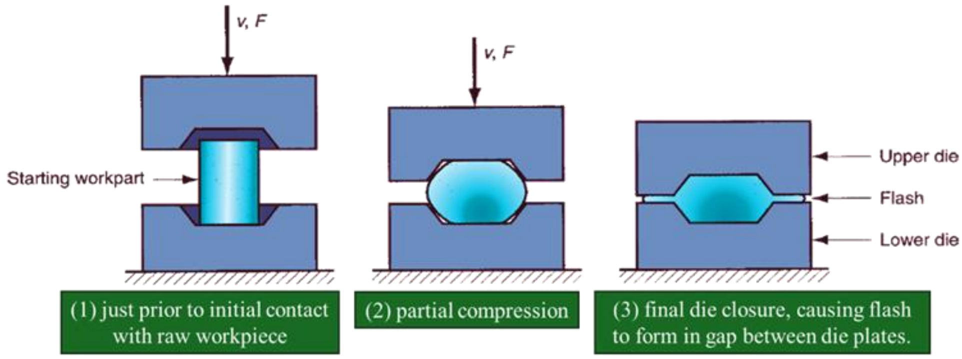


Figure 10. Illustration of the main steps in closed-die forging.

Main steps in closed-die forging include:

1. Heating: The metal is heated to a temperature that provides good ductility and reduces required forming forces.
2. Positioning: The preheated billet is placed on the lower die, which is fixed to a hammer or press.
3. Applying pressure: The upper die is driven down with great force, causing the metal to flow and fill the die cavities.
4. Shaping (multiple steps): For intricate shapes, the metal may be reheated and forged in several stages.
5. Trimming: After forming, the flash (excess material) is cut away to achieve the final part shape.

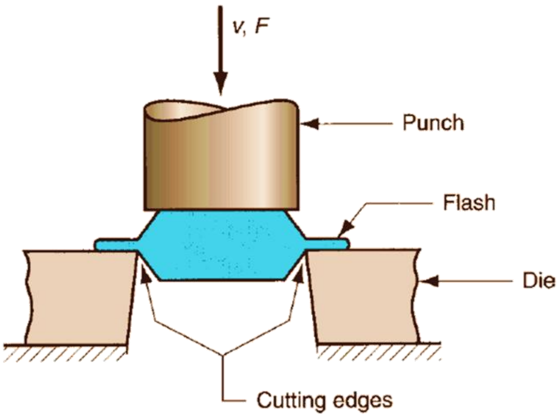


Figure 11. Illustration of the trimming operation [adapted after 4].

Closed-die forging is widely used in aerospace, automotive, and heavy industries for producing high-performance components such as gears, crankshafts, connecting rods, and turbine blades.

3.5.1.3. Flashless forging

Flashless forging, also referred to as true closed-die forging, is a precision forging process where the metal workpiece is shaped entirely within the die cavity without the formation of flash. This technique requires exceptionally accurate control over the process parameters, particularly the volume of the starting billet, which must closely match the die cavity volume.

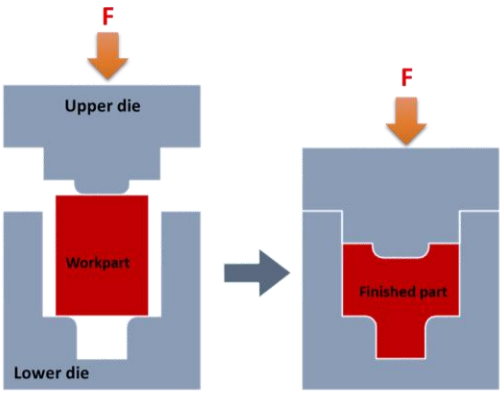


Figure 12. Principle of flashless forging [18].

Any deviation can lead to significant issues:

- Oversized blanks can generate excessive pressures during forging, risking damage to the dies or the press.
- Undersized blanks result in incomplete filling of the cavity, leading to dimensional inaccuracies and defective parts.

To ensure accuracy, flashless forging often relies on precisely machined billets and may require lubrication and careful temperature control to facilitate complete material flow. The process typically uses hydraulic presses or other equipment capable of applying steady, high forces.

Flashless forging is best suited for simple, symmetrical shapes (e.g., discs, rings, or gear blanks). It is commonly applied to lightweight, ductile materials, especially aluminum, magnesium, and their alloys, due to their excellent formability. This technique produces near-net-shape components, reducing or eliminating subsequent machining operations and is frequently employed in industries such as automotive, aerospace, and defense, particularly for high-performance or lightweight components where precision is critical.

3.5.2. Rolling process

Rolling is a metal forming process where the thickness of a workpiece is reduced by compressive forces generated between two rotating rolls. The rolls rotate in opposite directions, simultaneously pulling the metal into the gap and squeezing it to reduce its thickness. The distance between the rolls is always set slightly smaller than the initial thickness of the incoming metal. As a result of this compression, the metal elongates to compensate for the reduction in cross-sectional area.

Rolling operations can be classified based on the temperature at which they are performed:

- Hot rolling (above recrystallization temperature),
- Warm rolling (at intermediate temperatures),
- Cold rolling (below recrystallization temperature).

Flat rolling (as commonly illustrated) is used for workpieces with a rectangular cross-section, where the width is significantly larger than the thickness, such as slabs, strips, sheets, and plates.

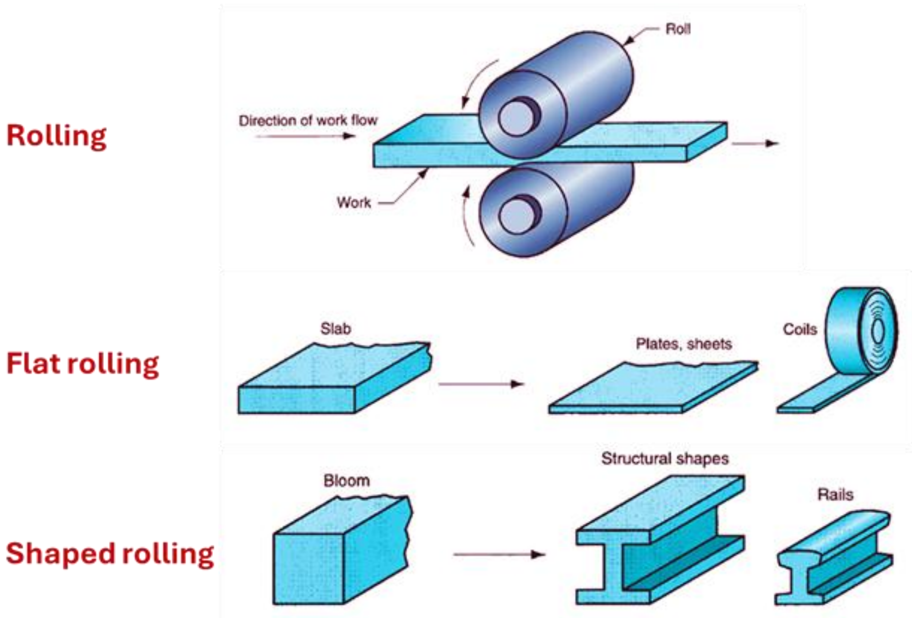


Figure 13. The rolling process and typical products of flat and shaped rolling [adapted after 4].

In shaped rolling, the rolls are designed with contours to produce parts with specific cross-sections, such as I-beams, L-beams, U-channels, railroad rails, and round or square bars and rods. This process is widely used in the steel industry for producing construction and structural components.

In flat rolling, the reduction in thickness is called the draft, defined as:

$$d = t_o - t_f$$

where t_0 – initial thickness, t_f – final thickness after rolling.

Draft can also be expressed as a fraction of the original thickness, known as the reduction ratio:

$$r = \frac{d}{t_o}$$

Typical values for thickness reduction vary:

- Cold rolling: 5–50% reduction per pass, due to higher strength of the material at lower temperatures.
- Hot rolling: 20–90% reduction, as high temperatures increase ductility and reduce required rolling forces.

For large total reductions, multiple passes are often needed, with smaller reductions per pass to avoid excessive forces or defects.

There is a limit to the amount of deformation in a single pass as it depends on the friction conditions along the interface. Too much deformation may skid the rollers on the material. The material must advance in the space between rollers without the need of being push or pull. This condition is fulfilled if the axial component of the deformation force (N_0) is smaller than the axial component of the friction force (T_0) (friction between material and rollers).

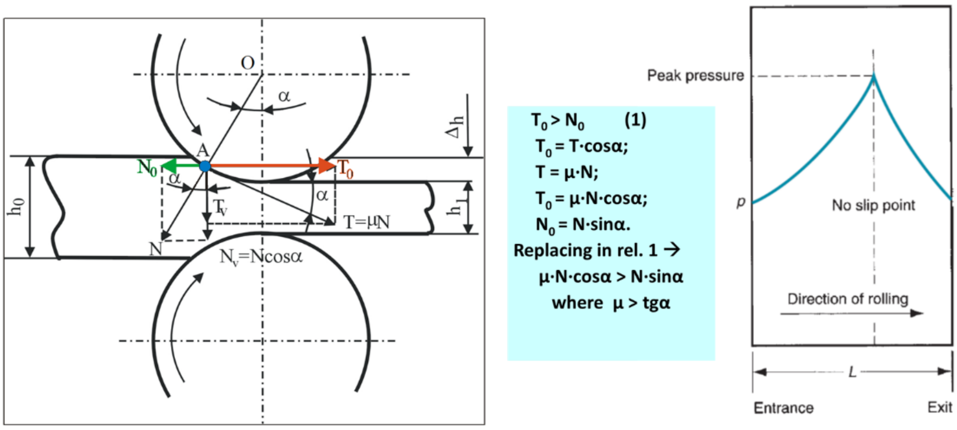


Figure 14. Diagram of the forces acting on a material during rolling and the pressure distribution along the contact length in flat rolling.

The diameter of the rolls also affects rolling forces and energy requirements:

- Smaller rolls have a shorter contact length with the workpiece, reducing the required force and energy.
- However, smaller rolls are less stiff and prone to elastic bending, which can cause uneven thickness. To counteract this, backup rolls are often used to support smaller work rolls and maintain uniform deformation.

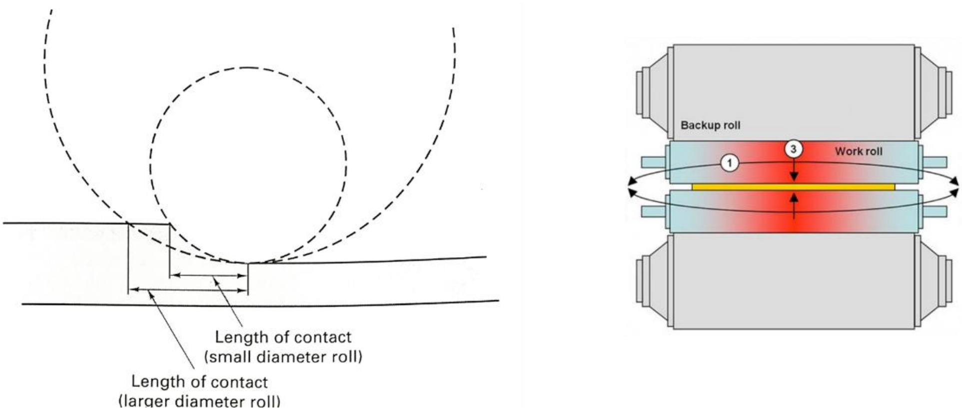


Figure 15. Relationship between contact length and roll diameter, and the use of backup rolls to prevent deflection of small-diameter rolls [17].

3.5.2.1. Rolling mills

To accommodate various applications and technical challenges in rolling, several rolling mill configurations have been developed. The simplest arrangement, known as a two-high rolling mill, consists of two opposing rolls, typically with diameters ranging from 0.6 to 1.4 m. Two-high mills can operate in two modes:

- Non-reversing: The rolls rotate in a fixed direction, and the workpiece always enters from the same side.
- Reversing: The rolls can change direction, allowing the workpiece to pass back and forth through the same rolls for multiple reductions, eliminating the need to return the strip to its starting position manually.

A three-high rolling mill consists of three rolls arranged vertically. The rolls rotate in fixed directions, and by raising or lowering the workpiece, it can pass through the rolls in both directions to achieve successive reductions without reversing roll rotation.

In a four-high rolling mill, two smaller-diameter rolls are in direct contact with the workpiece, while two large backup rolls provide support. The smaller rolls reduce the required rolling force, but they would otherwise deflect elastically under the load, so backup rolls are essential to maintain roll stiffness and dimensional accuracy.

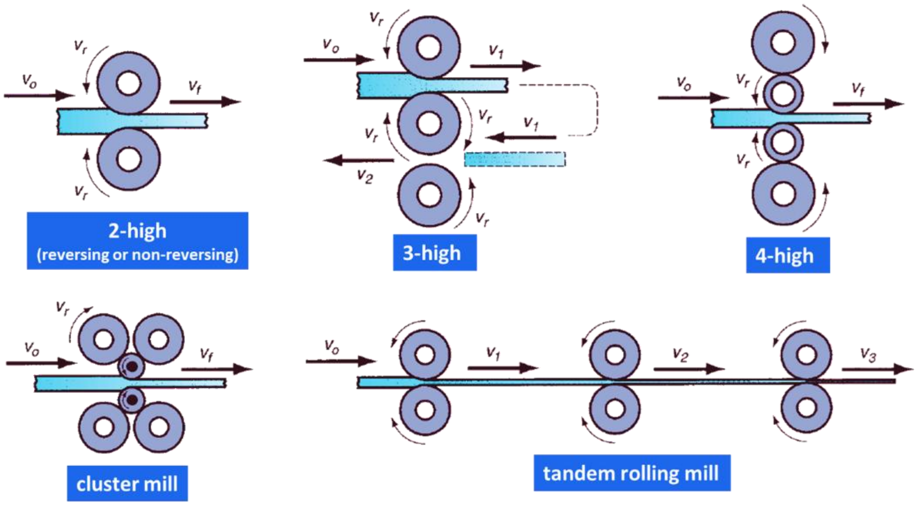


Figure 16. Common rolling mill configurations: two-high, three-high, four-high, cluster and tandem rolling mill [adapted after 4].

For further improvements, a cluster rolling mill uses multiple backup rolls to support smaller working rolls, enabling the production of thinner sheets while minimizing roll deflection.

To achieve high production rates for standard products, tandem rolling mills are used. A tandem mill consists of a series of rolling stands (commonly 8–10), each performing a small reduction in thickness or refinement of shape. As the material passes through consecutive stands, its speed increases, requiring precise synchronization of roll speeds across all stands to ensure uniform reduction and surface quality. Modern tandem rolling mills are often supplied directly by continuous casting operations as depicted bellow.

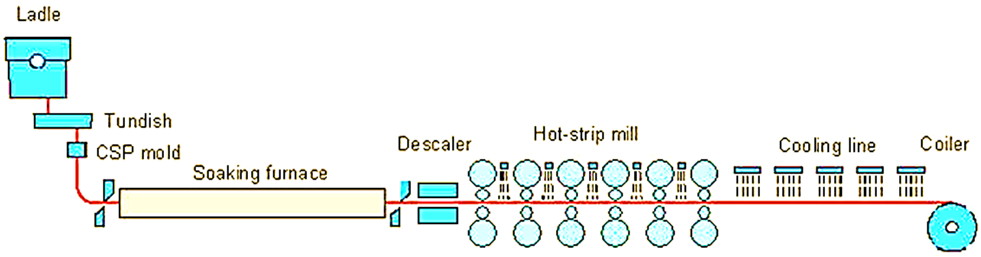
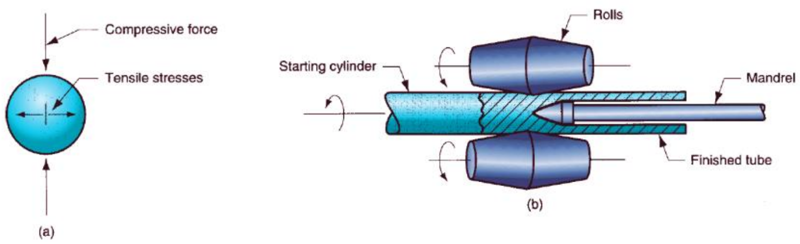


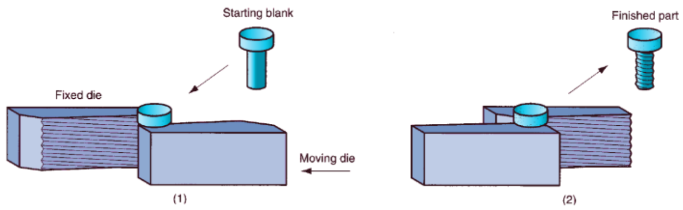
Figure 17. Illustration of a modern tandem rolling mills supplied directly by continuous casting operations [19].

3.5.2.2. Other deformation processes related to rolling

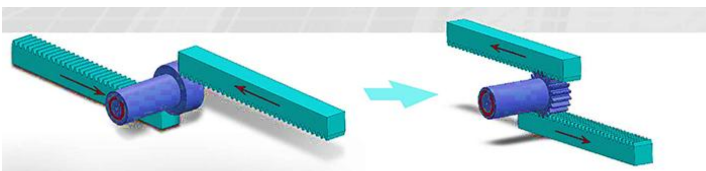
Roll piercing is a metal forming process used primarily for producing seamless, thick-walled tubes. The process is based on the principle that when a solid cylindrical billet is subjected to strong compressive forces along its circumference, tensile stresses are generated at the core. If the compression is sufficiently high, these internal tensile stresses cause the formation of an axial cavity (internal crack) inside the billet. In Romania, Tenaris Silcotub, located in Zalău, uses this process to manufacture seamless thick-walled tubes.



To ensure precise control of the hole diameter and surface finish, a mandrel (a hardened cylindrical tool) is inserted into the billet during the piercing operation. The billet is typically rotated between two skewed rolls, which not only compress but also elongate the billet, assisting in the uniform formation of the hollow section.



Thread rolling is a cold forming process used to produce threads on cylindrical parts by pressing the workpiece between two or more dies with threaded profiles. As the dies rotate or reciprocate, the material of the workpiece is plastically displaced (not cut), causing the threads to form with the exact shape and size defined by the dies.



Gear rolling is a cold working process to produce certain gears, the setup is similar to thread rolling

3.5.3. Extrusion process

Extrusion is a metal forming process in which a billet, either hot or cold, is pushed through a specially designed die using high hydraulic pressure. As the metal flows through the die cavity, it takes on the shape of the die's opening, resulting in a continuous product with a uniform cross-sectional profile. The output material is called the extrudate.

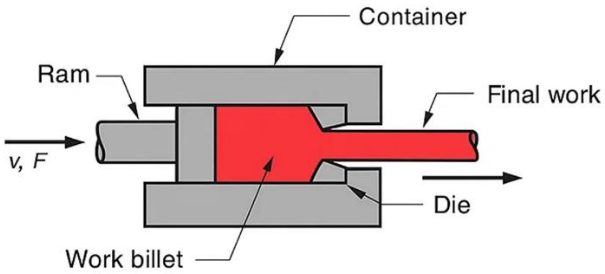


Figure 18. Principle of extrusion process and examples of products obtained from extrusion process.

During extrusion, the metal is subjected mainly to compressive and shear stresses, which help in shaping it effectively. This method is widely applied in producing components like rods, tubes, and complex profiles used in industries such as construction, automotive, and aerospace. The resulting products typically feature high mechanical strength, dimensional accuracy, and consistent quality.

A wide range of metals and alloys can be processed by extrusion, including:

- Aluminium and its alloys
- Copper and copper-based alloys
- Steel and stainless steel
- Brass and bronze
- Magnesium and its alloys
- Titanium and titanium alloys

Key advantages of metal extrusion:

1. High Strength – The extrusion process refines the grain structure of the material, which increases the mechanical strength and durability of the final product.

2. Precision – It allows for the creation of components with tight dimensional tolerances and excellent surface finish.
3. Versatility – A wide variety of simple or complex profiles can be manufactured.
4. Efficiency – High production rates make extrusion suitable for mass production.
5. Material Flexibility – Compatible with a broad spectrum of metals and alloys.
6. Eco-Friendly Process – Produces minimal waste; leftover material can be recycled easily.
7. Reduced Post-Processing – Often, extruded parts require minimal machining or finishing.

Main steps of the extrusion process:

- Billet Preparation: The metal billet is cut to the required size and, if necessary, cleaned and coated with a lubricant to reduce friction during extrusion.
- Heating: Depending on the material, the billet is heated (in an electric furnace or in an induction furnace) to improve plasticity and ease deformation.
- Extrusion: The softened billet is placed into a chamber and pressed through the die by a hydraulic ram. The die determines the cross-sectional shape of the final product.
- Cooling: The extrudate is cooled, usually by air or water, to stabilize its structure.
- Finishing: Final processing steps, such as cutting to length, surface treatment, or machining, are applied as needed.

Types of metal extrusion:

The extrusion process can be classified in several ways, depending on factors like flow direction, temperature, or force application method:

- Direct Extrusion
- Indirect Extrusion
- Hydrostatic Extrusion
- Lateral Extrusion
- Hot Extrusion
- Cold Extrusion

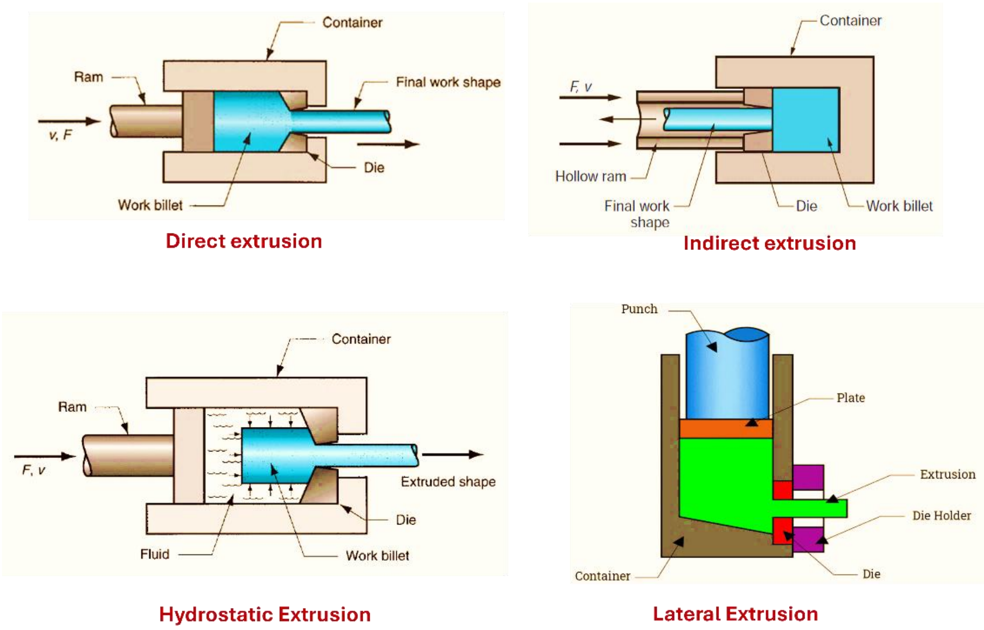


Figure 19. The main types of extrusion processes [adapted after 4].

3.5.3.1. Direct extrusion

In direct extrusion, the die remains fixed while the ram applies pressure to the metal billet, forcing it through the die opening. Since the material flows in the same direction as the ram movement, this process is also referred to as forward extrusion.

This is the most commonly used type of extrusion due to its simplicity and efficiency. However, one of its main disadvantages is the high friction between the billet and the inner walls of the container. As the billet moves forward, this friction increases the ram force needed to push the metal through the die. When hot extrusion is used, the friction issue can become more severe due to the formation of an oxide layer on the surface of the billet. This oxide layer not only increases resistance but can also lead to surface defects in the final extruded product.

A typical diagram comparing ram pressure versus ram stroke for both direct and indirect extrusion shows higher pressure values for direct extrusion. This is mainly caused by the friction mentioned earlier. At the beginning of the stroke, pressure builds up rapidly, especially when using dies with a steep angle, which increases flow resistance.

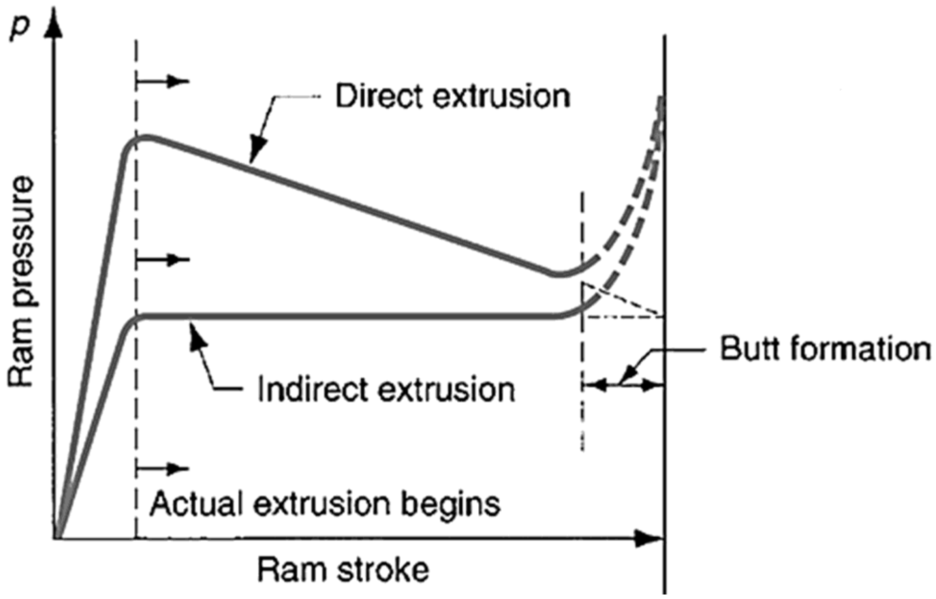


Figure 20. Typical curves illustrating how ram pressure changes during the ram stroke in both direct and indirect extrusion

Near the end of the stroke, pressure rises again. This is due to two factors:

- The formation of a butt (a small leftover piece of the billet that cannot be pushed through the die).
- A drop in billet temperature, which makes the metal harder to deform.

3.5.3.2. Indirect extrusion

In indirect extrusion, the die is mounted on the ram itself. As the ram moves forward, it compresses the stationary billet, forcing the metal to flow in the opposite direction, away from the die. Because of this reverse material flow, the process is also called backward extrusion.

A major advantage of indirect extrusion is the significantly reduced friction between the billet and the container walls, since the billet remains stationary during deformation. As a result, less power is required compared to direct extrusion. This efficiency is clearly reflected in the lower ram pressure shown in the figure above.

Indirect extrusion can be used in both hot and cold conditions, making it suitable for a wide range of materials and applications.

However, this method also presents some limitations:

- The extruded product (extrudate) can be difficult to support, especially when long lengths are produced, which may lead to instability or deformation.
- The ram must be hollow to allow metal to flow through the die. This design reduces the mechanical strength of the ram, which can limit the maximum applicable load.

Despite these drawbacks, indirect extrusion remains a valuable technique for producing high-quality profiles with reduced energy consumption.

3.5.3.3. Hydrostatic extrusion

In hydrostatic extrusion, the metal billet is enclosed in a chamber filled with a high-pressure fluid, and the extrusion force is applied through this fluid rather than by direct contact between the ram and the billet. This method minimizes friction between the billet and the container walls, resulting in lower required extrusion forces and a reduced risk of surface defects. It is especially advantageous for extruding brittle materials, as the surrounding fluid provides uniform pressure that helps prevent cracking. Hydrostatic extrusion can be carried out at room or elevated temperatures, depending on the material and desired properties.

3.5.3.4. Lateral extrusion

Lateral extrusion, also known as side extrusion, is a variation in which the material flows at a right angle to the direction of the applied force. In this process, the billet is compressed by a punch or ram, and the metal is forced to exit through a die positioned perpendicular to the punch axis. This configuration is useful when axial space is limited or when producing parts with non-standard geometries. Lateral extrusion is typically employed for specialized applications, such as creating T-shaped or angular profiles.

Universal Alloy Corporation (UAC) Europe, based in Dumbrăvița, Maramureș, and Alu Menziken SRL, located in Satu Mare, are two major players in the field of aluminum billet casting and extrusion in Romania. Both companies operate fully integrated facilities that include billet casting lines, hot extrusion presses, and advanced heat treatment and machining systems. UAC Europe focuses primarily on high-strength aluminum alloys (2xxx and

7xxx series), supplying precision extruded profiles for the aerospace industry, where components such as fuselage frames, seat tracks, and structural reinforcements are required. Alu Menziken, a member of the Swiss Montana Tech Components Group, also casts its own billets and extrudes lightweight profiles tailored for automotive, railway, defense, and industrial applications, where weight reduction and mechanical performance are critical.

3.5.4. Drawing process

Drawing is a metal forming process used to reduce the cross-sectional area of a bar, rod, or wire by pulling it through a die. Unlike extrusion, which pushes material through a die, drawing involves tensile forces, and it is most commonly performed cold, especially in industrial manufacturing. Before the drawing operation begins, the material usually undergoes preparation steps. These include annealing (to relieve internal stresses), cleaning (often through shot blasting or acidic solutions), and surface conditioning to improve lubricant adhesion. Conditioning agents help ensure that the workpiece surface can retain the lubrication needed for smooth drawing. Once cleaned and conditioned, one end of the bar or wire is pointed to allow insertion through the die and is then gripped mechanically to begin the drawing process.

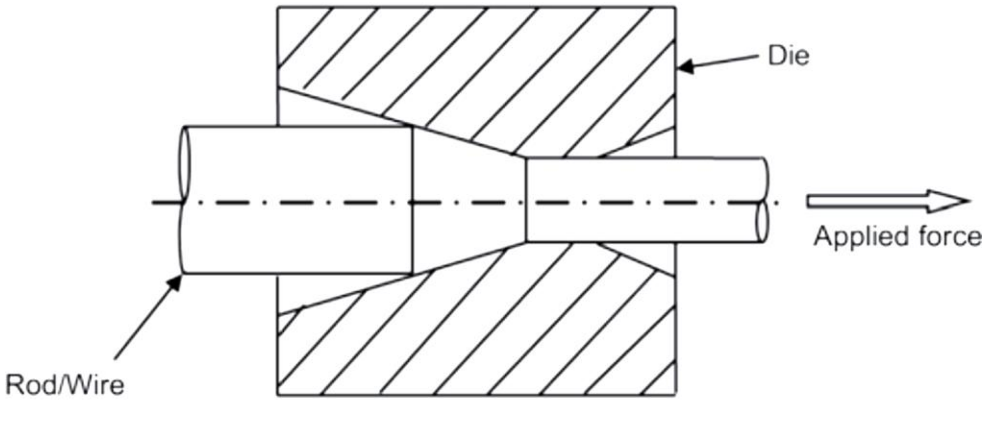


Figure 21. The principle of drawing process [20].

The amount of cross-sectional area reduction is limited by the tensile strength of the material. Theoretically, the maximum reduction possible in a single pass without failure is about 63%, but in practice, industrial reductions usually range from 15% to 45%. For greater reductions, the material can be passed through multiple dies in series, each performing a partial reduction.

The drawing speed depends on several factors, including material type, initial geometry, lubrication, and machine setup. Speeds must be carefully controlled to maintain quality and avoid material damage. General speed ranges for different materials are:

- Carbon Steels: 10–100 m/min
- Stainless Steels: 10–60 m/min
- Copper and Copper Alloys: 50–200 m/min
- Aluminum and Aluminum Alloys: 100–500 m/min
- Nickel and Nickel Alloys: 10–60 m/min
- Titanium and Titanium Alloys: 1–20 m/min

A key distinction in terminology relates to the initial size of the stock:

- Bar drawing is used for larger diameters, such as bars and rods.
- Wire drawing refers to smaller diameters, often down to 0.03 mm.

Although both processes are mechanically similar, bar drawing typically uses single-die equipment, while wire drawing is performed on continuous drawing machines. These systems contain multiple drawing dies arranged in sequence, with capstans (motor-driven drums) between them. Each capstan provides pulling force and maintains tension on the wire as it moves through the series of dies.

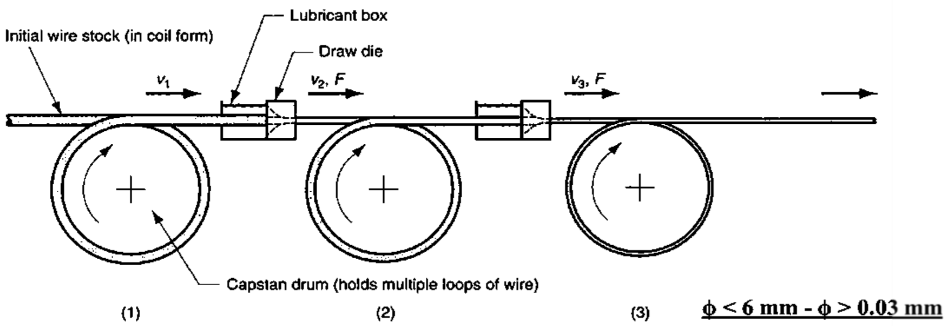


Figure 22. Schematic of the continuous wire drawing process using multiple dies and capstans

The total reduction is distributed across several stages, and in some cases, intermediate annealing is required to restore ductility before continuing the drawing process.

A typical draw die used in metal drawing operations consists of four distinct regions: Entry, Approach angle, Bearing surface (land) and Back relief.

The entry region, often shaped like a bell mouth, serves to guide the workpiece smoothly into the die and to help channel lubricant into the working zone. It does not come into direct contact with the metal and helps prevent surface damage to both the die and the workpiece.

The approach angle is the conical section where the actual drawing takes place. The metal is plastically deformed as it is pulled through this zone. The half-angle of the cone typically ranges from 6° to 20°, depending on the material being processed. A correct angle selection is important to balance deformation efficiency and avoid defects.

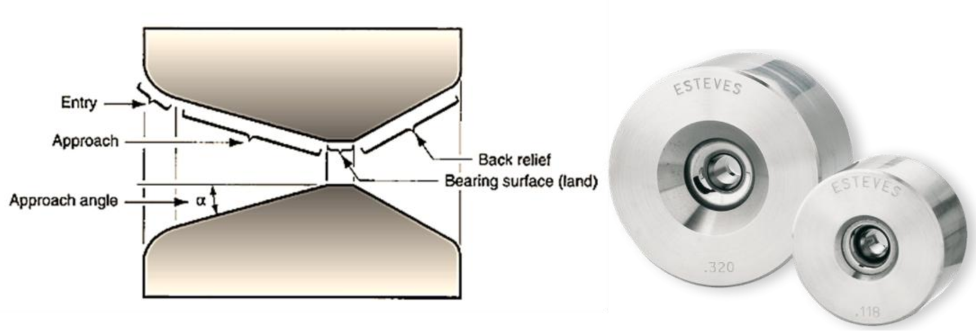


Figure 23. Cross-sectional schematic of a drawing die, showing its four main regions, alongside an image of actual drawing dies.

The bearing surface, also called the land, is a short cylindrical section that defines the final diameter of the drawn product. It ensures dimensional accuracy and stabilizes the shape of the extrudate.

The back relief is the exit portion of the die and includes a relief angle, usually around 30° (half-angle). This area helps reduce friction and allows the drawn product to exit smoothly from the die.

Draw dies are usually made of tool steels or cemented carbides due to the high wear conditions they are exposed to. For high-speed wire drawing, especially when working with hard materials or fine diameters, diamond inserts (natural or synthetic) are often used in the die's working zones to ensure high durability and performance.

3.5.4.1. Tube drawing

Tube drawing is a process used to reduce the diameter and/or wall thickness of seamless metal tubes after they have been initially formed using methods such as extrusion or the Mannesmann process. Drawing improves dimensional accuracy and surface finish. This operation can be performed with or without a mandrel, depending on the desired result.

In its simplest form, tube drawing is done without a mandrel, and is mainly used for reducing the outer diameter. This method is sometimes referred to as tube sinking. However, when no mandrel is used, there is limited control over the inner diameter and wall thickness, which may vary depending on the material flow and die geometry.

To improve precision, various types of mandrels are introduced. One option is a fixed mandrel, which is attached to a long support bar. It helps define both the internal diameter and wall thickness during drawing. However, this setup has practical limitations: the length of the support bar restricts how long the tube can be.

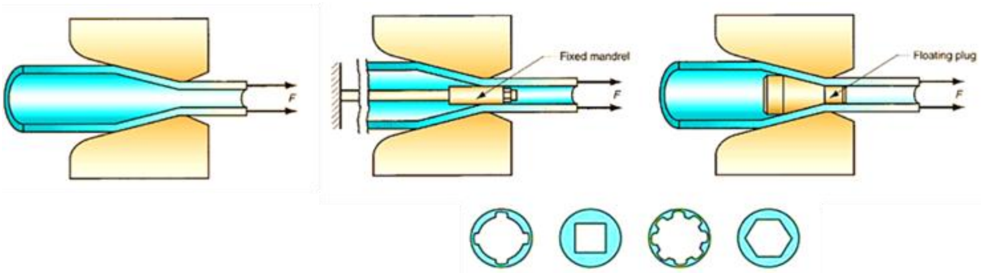


Figure 24. Tube drawing methods: without mandrel (left), with fixed mandrel (center), and with floating plug (right) [adapted after 4].

An alternative method uses a floating plug, which is not mechanically fixed but instead aligns itself naturally within the reduction zone of the die. The shape of the plug helps control the internal dimensions of the tube while allowing for longer tube lengths to be processed. This method removes the length constraints present with fixed mandrel systems.

In Romania,Tenaris Silcotub Zalău, Romania, operates one of the most advanced cold-drawing facilities in Eastern Europe for the production of seamless steel tubes. At the Zalău facility, tubes undergo cold drawing through dies, allowing for precise control of diameter, wall thickness, and surface finish.

3.6. Sheet metalworking

Sheet metal refers to thin, flat pieces of metal, typically rectangular in shape, produced by processes such as rolling, where a metal billet or ingot is passed through rollers to reduce its thickness. These sheets can then undergo various secondary operations, including cutting, bending, forming, and welding, to create a wide range of parts and structures. Sheet metal is widely used in industries such as construction, automotive, electronics, and manufacturing.

Sheet metal is available in numerous materials, thicknesses, sizes, and surface finishes, making it highly adaptable to both industrial and commercial applications. Common materials include steel, aluminium, copper, and stainless steel.

Sheet metal can be classified according to several criteria [21-23]:

1. *By material composition*
   - Steel Sheets: Mostly composed of iron and carbon, often alloyed with elements like manganese, chromium, or nickel for enhanced properties.
   - Aluminium Sheets: Lightweight and corrosion-resistant, with good thermal and electrical conductivity.
   - Copper Sheets: Known for excellent electrical and thermal conductivity.
   - Stainless Steel Sheets: Made from iron and chromium, sometimes with nickel or molybdenum, offering superior corrosion resistance.
2. *By manufacturing process*
   - Cold-Rolled Sheets: Rolled at room temperature, resulting in better surface finish and dimensional precision.
   - Hot-Rolled Sheets: Rolled at high temperatures, which allows greater formability but leaves a rougher surface.
   - Galvanized Sheets: Steel sheets coated with zinc to protect against corrosion.
3. *By thickness*
   - Thin Sheets: Usually defined as having thicknesses below 6 mm.

- Thick Sheets: Typically considered to be thicker than 6 mm.

4. *By application*
   - Roofing Sheets: Used for covering buildings, often made from galvanized steel or aluminium.
   - Automotive Sheets: Used in car bodies, structural parts, and frames.
   - Construction Sheets: Applied in walls, façades, or structural panels.
   - Electrical Sheets: Used in electrical enclosures or transformer components, often made from electrical steel or aluminium.

The most widely used sheet metal is low carbon steel (typically 0.06%–0.15% carbon), due to its low cost, good formability, and adequate strength for general applications.

Most sheet-metalworking operations are carried out at room temperature, a process known as cold working. Exceptions include cases where the sheet is thick, the metal is brittle, or the deformation is extensive, such conditions may require warm working instead.

There are three main categories of sheet metal processes:

1. Cutting – separating the material by shearing or punching;
2. Bending – deforming the sheet along a straight axis;
3. Drawing – forming the sheet into a three-dimensional shape, such as a cup or a box.

3.6.1. Cutting operations

Cutting in sheet metalworking is achieved through a shearing action that occurs between two sharp edges: a moving punch and a stationary die. As the punch moves downward past the die, it compresses and deforms the metal, initiating plastic deformation at the surface. As the punch penetrates further, the material is pushed into a fracture zone, which begins at both cutting edges. When properly aligned, these fracture lines meet, resulting in a clean separation of the material into two distinct parts. The penetration depth before fracture typically reaches about one-third of the sheet's thickness.

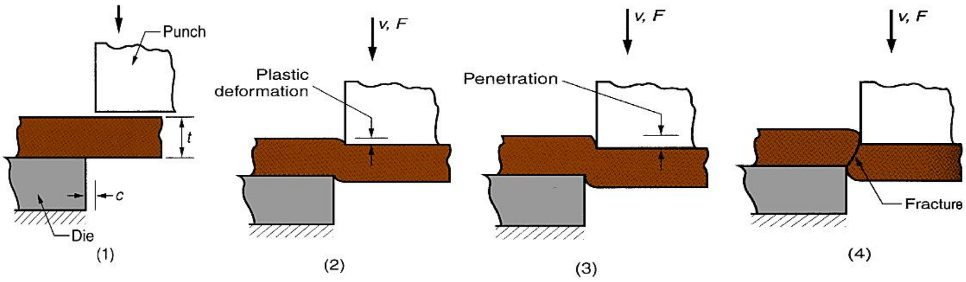


Figure 25. Stages of sheet metal shearing between two cutting edges: (1) punch approaches the workpiece; (2) initial contact causes plastic deformation; (3) punch penetrates the sheet, forming a smooth cut surface; and (4) fractures initiate from both edges, leading to complete separation of the material.

A key factor influencing cut quality is the clearance (c) between the punch and the die, which is the lateral gap separating their edges. The correct clearance ensures controlled fracture and reduces tool wear or burr formation.

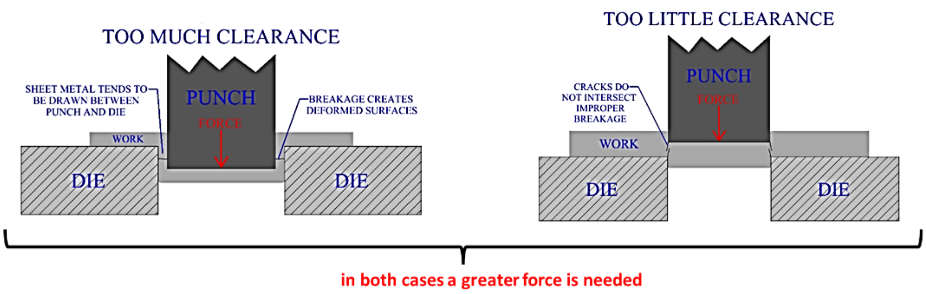


Figure 26. The effect of punch–die clearance on the quality and characteristics of the sheet metal cutting process [24].

Typical clearance values range from 3% to 8% of the sheet thickness, depending on the material:

- Aluminium alloys: ~4%
- Copper alloys: ~6%
- Steel: ~7.5%

There are three primary cutting operations used in sheet metal processing:

1. Shearing – A straight-line cut between two blades, used to divide large sheets into smaller sections. It is often a preliminary operation for further forming processes.

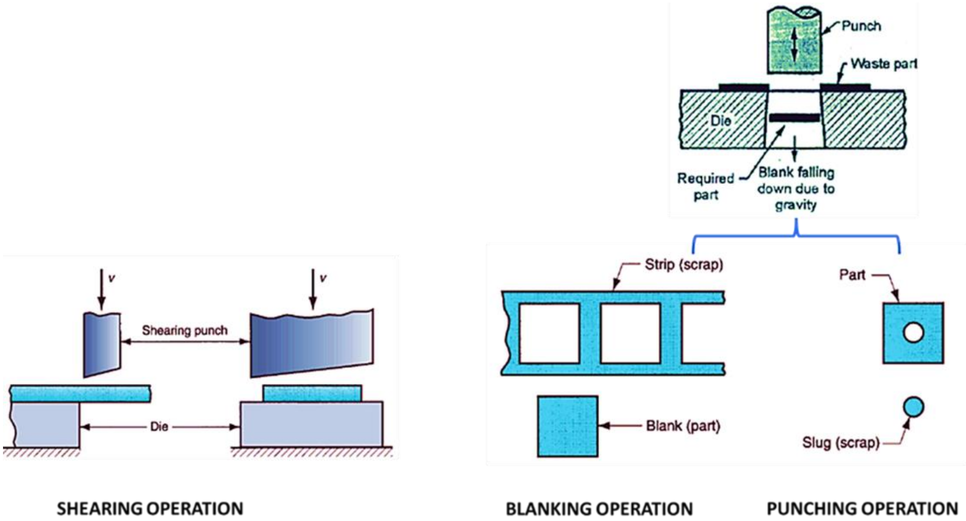


Figure 27. Schematic representation of shearing, blanking, and punching operations in sheet metal processing.

2. ***Blanking*** – Involves cutting out a closed shape from the sheet in a single stroke. The cut-out piece, called the blank, is the desired part. Blanking is widely used to produce parts that will be later formed or assembled.

3. ***Punching*** – Similar to blanking, but in this case, the hole is the desired feature, and the removed material, called the slug, is discarded. The remaining sheet becomes the final part.

These cutting operations form the basis for many industrial applications in sheet-metal manufacturing, from automotive components to household appliances.

3.6.2. Bending operations

Bending is a sheet metal forming process in which the workpiece undergoes plastic deformation around a straight axis, changing its shape without significantly altering its thickness. During bending, the inner side of the material is compressed, while the outer side is stretched. Once the external force is removed, the material retains its new, permanently deformed shape.

Bending operation is typically carried out using punch and die tooling. Two of the most commonly used bending techniques are V-bending and edge bending, each associated with specific types of dies.

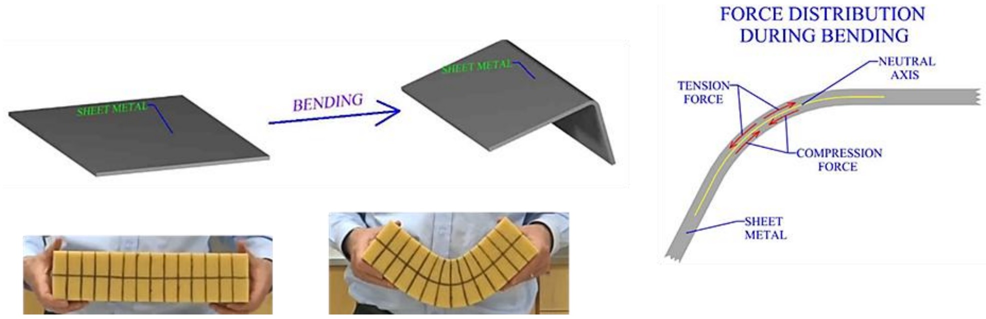


Figure 28. Illustration of sheet metal bending: (top left) initial flat sheet and final bent shape; (bottom) physical demonstration of compression on the inner side and tension on the outer side of the bend; (right) schematic of force distribution around the neutral axis.

In V-bending, the sheet is placed between a V-shaped die and punch. As the punch descends, it presses the sheet into the die cavity, creating a bend. This method can produce a wide range of bend angles, from very sharp to very broad. V-bending is simple and cost-effective, making it ideal for low-production volumes or prototype work. It is often performed using a press brake, and the tooling involved is relatively inexpensive and easy to change.

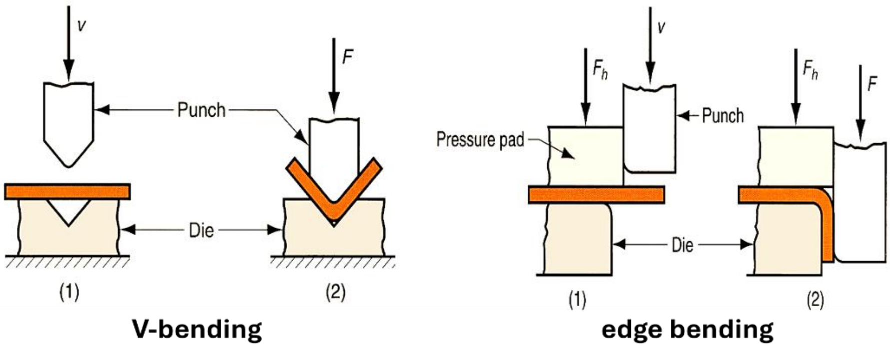


Figure 29. Bending techniques: V-bending and edge bending

Edge bending, also known as wiping, is used when more precise or repeatable bends are needed, typically in high-volume production. In this method, the sheet is held firmly against the die by a pressure pad, which prevents movement during bending. A punch then forces the unsupported section of the sheet to bend over the edge of the die. The use of a pressure pad ensures accuracy but also requires more complex and costly tooling compared to V-bending.

3.6.3. Deep drawing operation

Deep drawing is a sheet metal forming process used to produce cup-shaped, box-shaped, or other curved and concave parts. The operation begins by placing a flat metal blank over a die cavity. A punch then pushes the blank into the die, forcing the material to flow and take the shape of the cavity.

The most basic form of this process involves creating a cylindrical cup. A circular blank with diameter Db is drawn into the die using a punch of diameter Dp. To ensure smooth material flow and avoid tearing, both the punch and die must have rounded corners, denoted as Rp and Rd. If these radii were too sharp, the process would resemble poor-quality hole punching rather than controlled forming.

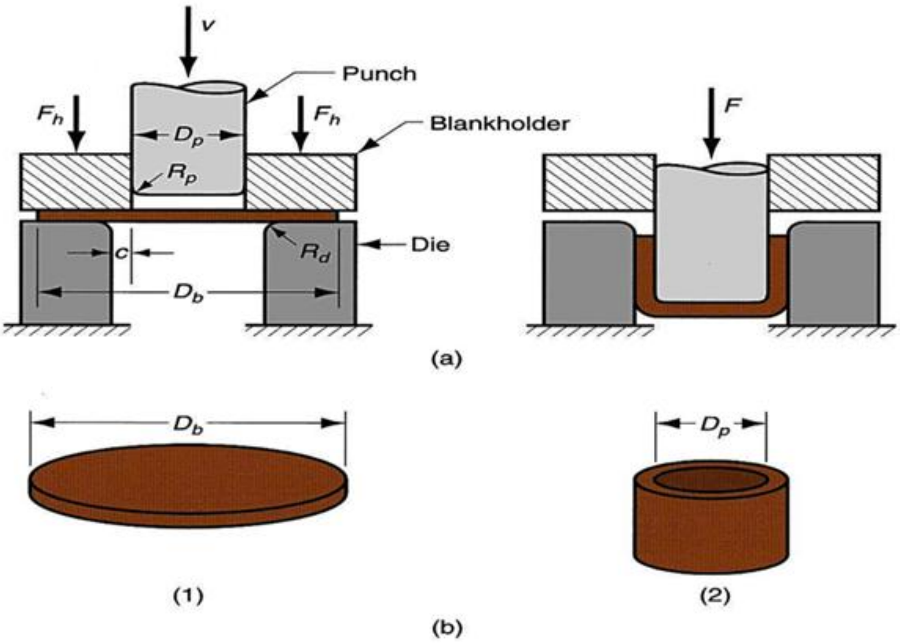


Figure 30. Drawing of a cup-shaped part: (a) stages of the drawing operation. (1) before punch contact and (2) near the end of stroke; (b) corresponding workpiece – (1) initial blank and (2) final drawn part. Symbols: c – clearance, Db – blank diameter, Dp – punch diameter, Rd – die corner radius, Rp – punch corner radius, F – drawing force, Fh – holding force [25].

A clearance (c) is maintained between the punch and die walls, typically about 10% larger than the sheet's thickness, to allow proper metal flow. During forming, a downward punch force (F) shapes the blank, while a blank holder applies a separate holding force (Fh) to control material movement and prevent wrinkling. As the punch descends, the sheet undergoes a complex combination of tensile, compressive, and bending stresses, gradually transforming the flat blank into the desired three-dimensional geometry.

Supplementary technical details

- **Clearance** = 10% of the blank thickness.
- **Drawing Ratio** = ratio of blank diameter Db to punch diameter Dp $DR = \frac{D_b}{D_p}$

$$DR \leq 2.0$$

- **reduction** r, $r = \frac{D_b - D_p}{D_b}$, r < 0.5

- **thickness-to-diameter ratio**, t/D_b = thickness of the starting blank t divided by the blank diameter Db.
- $t/D_b > 1\%$.
- **Drawing Force**, $F = \pi D_p t(TS)\left(\frac{D_b}{D_p} - 0.7\right)$

- **holding for**ce – 30 – 40% of the drawing force

Chapter IV

METAL CASTING PROCESSES

4.1. Introduction to casting processes

Casting is a manufacturing process in which molten metal is poured into a mold cavity, where it solidifies and takes the shape of the mold. The term casting also refers to the final part produced by this process. Casting is one of the oldest known methods of shaping metals, dating back over 6000 years. Although the basic principle seems simple: melt the metal, pour it, and let it cool, achieving a successful casting involves many variables and process controls.

The basic steps in the casting process are [26-27]:

1. Pattern creation

A pattern is made to replicate the desired final shape of the casting. It can be made from wood, plastic, or metal, and must include allowances for shrinkage and machining.

2. Mold preparation

A mold is formed around the pattern using materials such as sand, ceramic, or plaster, depending on the chosen casting process. The mold contains a cavity into which the molten metal will be poured.

3. Alloy selection

A suitable metallic alloy, either ferrous or non-ferrous, is selected based on the mechanical and physical requirements of the final product.

4. Melting

The selected metal or alloy is melted in a furnace, electric, gas-fired, or induction, until it reaches the appropriate pouring temperature.

5. Pouring

The molten metal is poured into the mold through a gating system designed to control metal flow and minimize impurities or turbulence.

6. Solidification

The molten metal cools and solidifies inside the mold, gradually taking the shape of the cavity.

7. Cooling and removal

Once solidified and sufficiently cooled, the mold is opened (or broken, in the case of expendable molds), and the casting is removed. Further cooling or heat treatment may be applied to enhance properties.

8. Finishing

The final casting undergoes cleaning, trimming, and machining to remove excess material (gates, risers) and achieve the desired surface finish and dimensional accuracy.

Advantages of casting

- Suitable for producing complex geometries, including internal cavities.
- Can produce net-shape or near-net-shape parts.
- Capable of manufacturing very large components (over 100 tons).
- Applicable to virtually all metals that can be melted.
- Some processes support mass production with high efficiency.

Disadvantages of casting

- Lower mechanical properties compared to forged or wrought parts.
- Risk of porosity and internal defects.
- Dimensional accuracy and surface finish may be poor in some processes.
- Handling molten metals poses safety risks.
- Certain casting processes have environmental concerns (e.g., emissions, waste sand).
- Casting is used to manufacture components ranging from a few grams to several tons. Examples include:
    - Small parts: jewelry, dental crowns, electronic housings
    - Medium parts: pump casings, engine blocks, frying pans
    - Large parts: machine frames, railway wheels, statues, and industrial machinery components

Types of casting processes

Casting methods are classified into two main categories based on mold type [28-29]:

1. ***Expendable mold casting*** - the mold is destroyed after each casting. Common expandable mold casting processes:
    - Sand casting
    - Shell molding
    - Investment casting
    - Expanded polystyrene (Lost foam) casting
2. ***Permanent mold casting*** - the mold is reusable and typically made of metal. Common permanent mold casting processes:

- Gravity die casting
- Low-pressure die casting
- High-pressure die casting
- Centrifugal casting

4.2. Expendable mold casting processes

4.2.1 Sand casting

Sand casting is the most widely used casting process in manufacturing due to its versatility, low cost, and ability to produce large and complex shapes. In this process, molten metal is poured into a sand mold, allowed to solidify, and then the mold is broken open to remove the finished casting. After removal, the casting usually requires cleaning, inspection, and sometimes heat treatment to improve its mechanical or metallurgical properties.

A typical sand mold consists of two main halves:

- the cope (top half)
- the drag (bottom half)

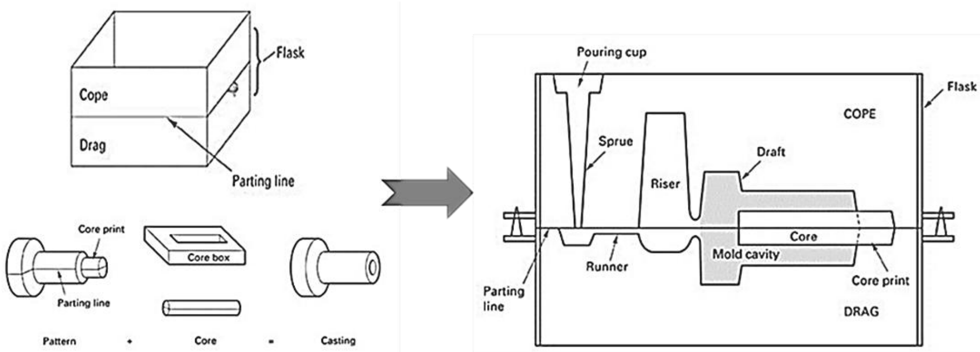


Figure 1. Schematic representation of a sand casting setup, showing the mold components, pattern placement and gating system.

These are held in a container called a flask, which is also split into two corresponding sections. The two halves meet at the parting line, which separates the cope from the drag.

The shape of the part is formed using a pattern, which is a replica of the final casting. The pattern is placed in the mold box, and sand is packed around it. Once the pattern is removed, the remaining cavity defines the external geometry of the cast part. To account for metal shrinkage during cooling, patterns are usually made slightly oversized.

The molding sand is typically a mixture of silica sand, clay, and water, providing the necessary strength and permeability. If the casting has internal cavities, these are created using cores, solid shapes inserted into the mold cavity. Cores are most often made of sand but may also be formed from metal, plaster, or ceramics, depending on the application.

A sand casting mold includes a gating system, which controls how the molten metal enters the cavity. The main components of the gating system are:

- Pouring cup – receives the metal from the ladle.
- Sprue – a vertical channel that directs metal downward.
- Runner – a horizontal passage that guides metal to the mold cavity.
- Riser – a reservoir that supplies additional molten metal during solidification to compensate for shrinkage.

The riser must remain liquid longer than the main casting in order to properly feed the part during cooling. As the molten metal flows in, air and gases within the cavity must escape. This is usually achieved through the natural porosity of the sand or small vents built into the mold. Ensuring proper venting is essential for achieving a complete and defect-free casting.

Advantages and disadvantages of the sand casting process, highlighting its key benefits as well as limitations are given bellow.

Advantages	Disadvantages
Cost-effective for small to medium production runs	Lower dimensional accuracy compared to other casting methods
Suitable for manufacturing very large or heavy components	Produces rough surface finish, often requiring additional machining
Compatible with a wide range of metals and alloys	Less suitable for thin-walled or complex precision parts
Flexible and simple tooling design	Risk of casting defects such as porosity, shrinkage cavities, or inclusions
Molds are recyclable and environmentally manageable	Lower mechanical properties due to slower cooling and coarse grain structure

4.2.2. Shell molding process

Shell molding is a casting process that uses a thin shell-shaped mold made of sand bonded with a thermosetting resin. The mold is typically around 9 mm thick and offers improved surface finish and dimensional accuracy compared to conventional sand molds. The thermosetting resin is a polymer that permanently hardens when heated, usually at temperatures above 200 °C.

Steps in the shell molding process

- A heated metal pattern plate is placed over a box containing a sand-resin mixture.
- The box is inverted, allowing the hot pattern to come into contact with the sand-resin mixture. The heat partially cures the mixture on the pattern surface, forming a thin, hard shell.
- The box is turned upright again, and the uncured loose material falls away.
- The partially cured shell is then fully hardened in an oven for a few minutes.
- Once cured, the shell is stripped from the pattern.
- Two shell halves are assembled and supported in a container filled with backing material such as sand or metal shot. The molten metal is poured into the cavity.
- After solidification, the casting is removed, and the sprue is cut off, resulting in the final part.

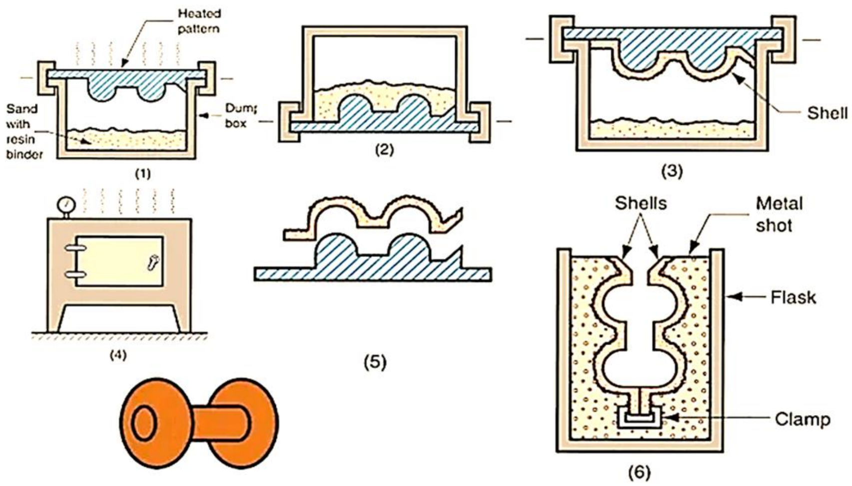


Figure 2. Steps in the shell molding process [adapted after 4].

Advantages of shell molding

- Excellent surface finish: The mold surface is smoother than in green-sand casting, allowing molten metal to flow more easily and resulting in surface roughness values as low as 2.5 µm.
- High dimensional accuracy: Typical tolerances are around ±0.25 mm, which often eliminates the need for machining.
- Suitable for automation: The process can be fully mechanized, making it ideal for mass production.
- Cost-effective at high volumes, especially for steel castings under 10 kg.

Disadvantages of shell molding

- Higher pattern cost: The metal patterns required for shell molding are more expensive than those used in green-sand casting, making the process less economical for small production runs.

4.2.3. Investment casting (Lost-wax process)

Investment casting, also known as the lost-wax process, is a precision casting technique used to produce components with high dimensional accuracy, fine surface finish, and complex geometries. The name comes from the fact that the wax pattern is "lost" (melted out) before pouring the metal.

Steps in the investment casting process

- Wax pattern creation: Wax patterns are made by injecting molten wax into a metal mold (master mold). These patterns are exact replicas of the final part.
- Assembly into pattern tree: Multiple wax patterns are attached to a central wax sprue, forming a pattern tree or casting tree, which allows for multiple parts to be cast simultaneously.
- Ceramic shell formation: The entire wax tree is repeatedly dipped into a ceramic slurry made of fine silica sand and a refractory binder. Initial coatings use fine-grained sand for high surface detail. Later layers use coarser sand to provide structural strength. After sufficient coating, the mold is air-dried for about 8 hours to allow the binder to harden.

- Wax removal and mold preheating: The mold is placed upside down and heated so that the wax melts and drains out. Any remaining wax is burned off during preheating, which also improves metal flow and reduces contamination.
- Pouring: Molten metal is poured into the preheated ceramic mold, filling the intricate cavities once occupied by the wax.
- Solidification and shell removal: After the metal solidifies, the ceramic mold is broken away, often by vibration or impact.
- Part separation: Individual parts are cut from the sprue, completing the process.

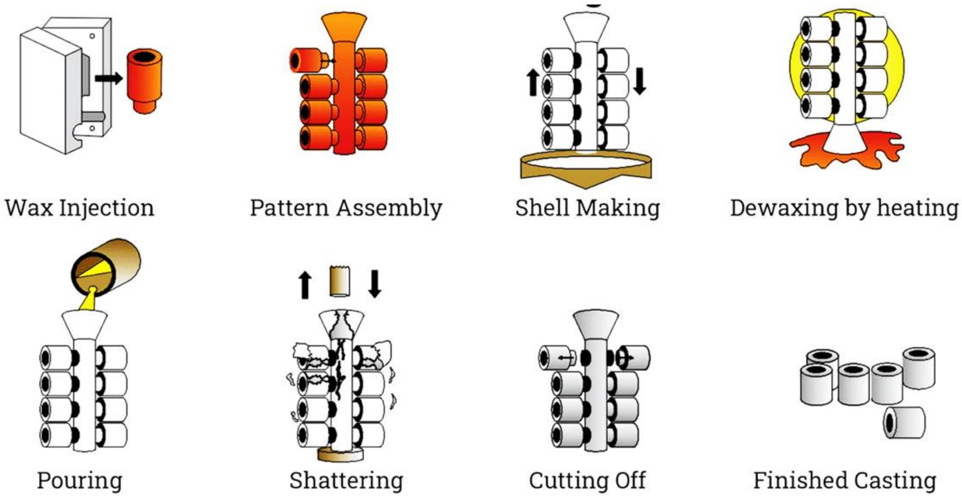


Figure 3. Main steps of the investment casting process: from wax pattern creation and ceramic shell building, to wax removal, metal pouring, mold breakup, and final part separation [30].

Advantages of investment casting

- Suitable for complex and detailed geometries
- Excellent dimensional accuracy (tolerances as tight as ±0.075 mm)
- Good surface finish, reducing or eliminating the need for machining
- Net-shape process – parts often require no additional processing
- Wax patterns can be reused, reducing material waste

Disadvantages of investment casting

- High mold and tooling costs (metal dies for wax patterns)
- Longer production cycles compared to other casting methods
- Labor-intensive, especially for shell building and assembly
- A new wax pattern is needed for each casting cycle

Applications

Investment casting is commonly used for steels, stainless steels, and high-temperature alloys. Typical parts include:

- Turbine blades and engine components
- Precision mechanical parts
- Jewelry and dental fixtures
- Complex geometries that cannot be easily machined or forged

4.2.4 Expanded polystyrene casting process (Lost-foam casting)

The expanded polystyrene casting process, also known as the lost-foam process, evaporative-foam casting, full-mold process, or lost-pattern process, uses a foam pattern made of polystyrene, which vaporizes when it comes into contact with molten metal. This method eliminates the need for pattern removal, parting lines, and separate cores in many cases, making the mold preparation significantly easier.

Key steps in the process

- Pattern fabrication and coating: A polystyrene foam pattern, including the sprue, risers, and gating system, is fabricated to replicate the final casting geometry. The pattern is then coated with a refractory slurry, which improves surface finish and protects the pattern from premature damage during pouring.
- Mold preparation: The coated foam pattern is placed inside a mold box, and sand, often mixed with a binder or compacted using vibration, is packed around it to provide support and shape the mold cavity.
- Metal pouring and pattern vaporization: Molten metal is poured directly into the foam sprue. As the metal flows into the mold, it vaporizes the foam pattern, replacing it and filling the entire cavity. The vapor escapes through the porous mold material.

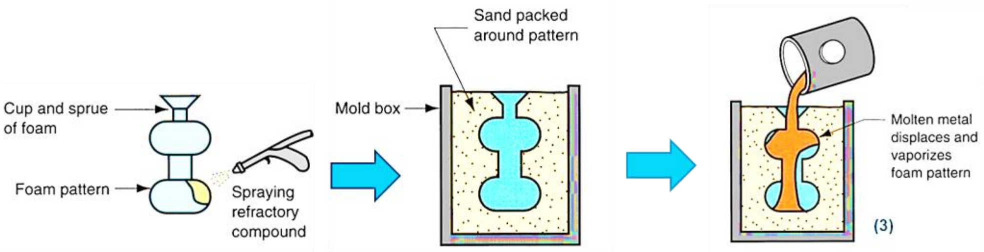


Figure 4. Key steps in the expanded polystyrene casting process: pattern fabrication and coating, mold packing with sand, and molten metal pouring with foam vaporization [4].

Advantages of expanded polystyrene casting

- No need to remove the pattern from the mold, simplifying the process
- No parting lines, draft angles, or separate cores required in many cases
- Reduced tooling complexity compared to traditional sand casting
- Excellent for producing complex parts in a single, seamless mold
- Efficient for mass production, especially in automotive applications.

Disadvantages of expanded polystyrene casting

- A new foam pattern is required for each casting
- Cost-effectiveness depends heavily on pattern production costs
- Not ideal for small batches unless patterns are inexpensive or easy to make.

Applications

The process is widely used for large, complex castings such as automotive engine blocks, internal flow components, and other structural components. It is particularly attractive for mass production where consistent pattern quality can be ensured.

4.3. Permanent mold casting processes

A key limitation of expendable mold casting is that a new mold is required for every part produced. In contrast, permanent mold casting uses reusable molds, typically made of steel or cast iron, which allows for multiple castings from the same mold. These molds withstand high temperatures and are especially suitable for non-ferrous alloys, including aluminum (Al), magnesium (Mg), and copper-based (Cu) alloys.

Advantages of permanent mold casting include:

- Improved surface finish
- Tighter dimensional tolerances
- Faster solidification due to the metal mold's thermal conductivity, resulting in fine grain structure and enhanced mechanical properties.

4.3.1 Gravity die casting

Gravity die casting is a process where molten metal is poured into a metal mold (die) under the force of gravity alone, without additional pressure. The mold is reusable and typically made from steel or cast iron.

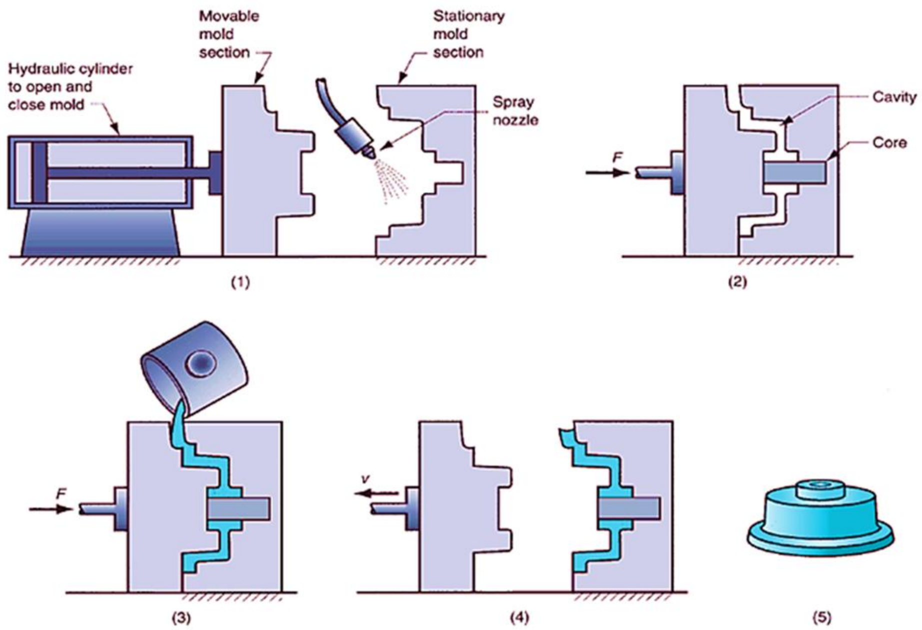


Figure 5. Steps in the gravity die casting process: mold preparation and preheating (1), core placement, mold closing (2), molten metal pouring and solidification (3), mold opening (4) and final part removal [4].

Steps in gravity die casting

- Mold preparation: The mold is opened, preheated to 200–400 °C, and coated with a refractory paint that improves heat transfer and facilitates part removal. Preheating also ensures better metal flow into the cavity.
- Core placement (if needed): If the casting requires internal cavities, metal or sand cores are inserted into the mold before closing.
- Mold closing: The mold halves are brought together, typically with the aid of a hydraulic system.
- Metal pouring and solidification: Molten metal is poured through a sprue and fills the mold by gravity. As the metal cools, it solidifies quickly due to the high thermal conductivity of the mold.
- Mold opening and part removal: After solidification, the mold is opened, and the finished part is removed. The cycle can then begin again.

Advantages of gravity die casting

- Good dimensional accuracy, often requiring minimal machining
- Fast cooling and high production rates
- Improved surface finish due to the smooth mold surfaces
- Superior mechanical properties from fine grain structure
- Minimal post-processing compared to sand casting.

Disadvantages of gravity die casting

- Higher tooling costs (due to durable metal molds)
- Limited design flexibility, complex geometries and thin walls (< 4.5 mm) are difficult to cast
- Casting weight limitations due to the manual or semi-automatic nature of the process
- Restricted to non-ferrous alloys, primarily aluminum, magnesium, and copper-based metals.

4.3.2 Low pressure casting

In contrast to traditional casting methods that rely on gravity to fill the mold, low pressure casting uses low gas pressure, typically around 0.1 MPa, to force molten metal upward into the mold cavity from beneath the surface of the melt.

The setup includes a metallic mold divided into two halves: a stationary half and a movable half. The molten metal is held in a sealed ladle located inside an airtight chamber. A refractory (ceramic) tube connects the molten metal to the base of the mold cavity (see Figure 6).

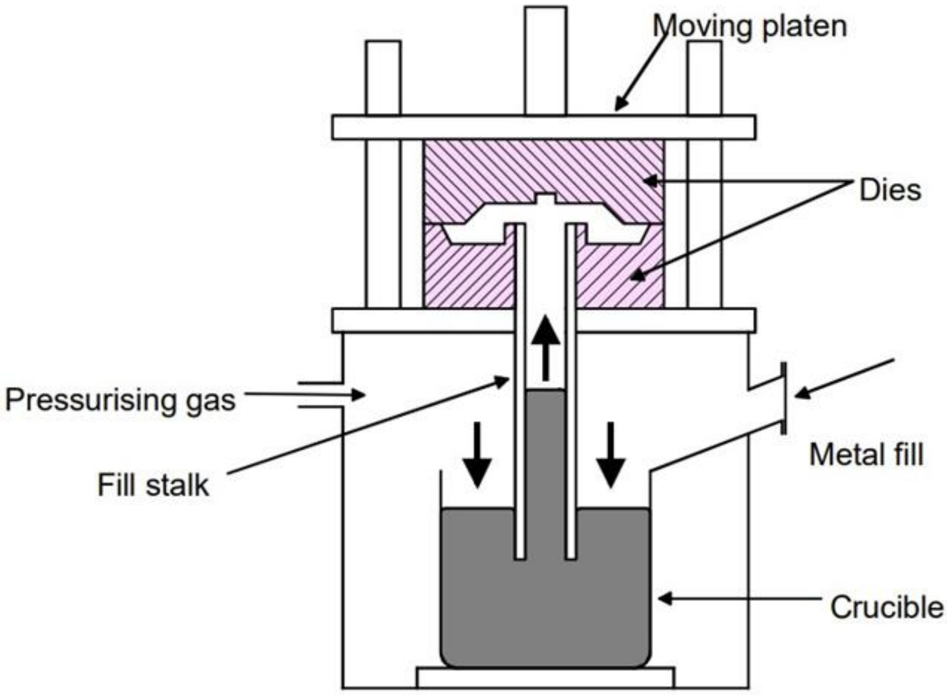


Figure 6. Schematic of the low pressure casting process [31].

To initiate casting:

- Pressurized gas (e.g., air, nitrogen, or argon) is introduced into the sealed chamber.
- This pressure forces the molten metal to rise through the refractory tube (fill stalk) and fill the mold from the bottom up.
- The pressure is maintained until the metal inside the mold cavity solidifies.
- Once solidification is complete, the pressure is released, and any remaining metal in the tube flows back into the ladle.

- The mold is then opened, and the finished part is removed by separating the movable mold half.

Advantages of low pressure casting

- Cleaner metal is introduced into the mold: the metal is drawn from beneath the surface of the ladle, avoiding oxidation and impurities found near the surface.
- Improved mechanical properties due to reduced gas porosity and fewer inclusion defects.
- Better filling control and mold filling dynamics than in gravity casting.
- Ideal for casting complex shapes with high-quality surfaces and internal soundness.
- Low pressure casting is commonly used for aluminum and magnesium alloy components, especially in the automotive and aerospace industries, where material quality and internal integrity are critical.

Disadvantages of low pressure casting

- High equipment and maintenance costs: Requires specialized equipment (sealed chamber, refractory tubes, gas systems) and regular maintenance of components exposed to heat and pressure.
- Slower production cycle: Longer processing times due to controlled pressurization, solidification, and cooling steps.
- Material limitations: Suitable mainly for non-ferrous alloys (e.g., aluminum, magnesium); not compatible with high-temperature ferrous metals.
- Process sensitivity and mold complexity: Requires precise gas pressure control and accurate mold design to avoid casting defects and ensure proper filling.

4.3.3 Die casting

What sets die casting apart from other casting methods is the use of high pressure to fill the mold cavity, allowing for fine detail, high dimensional accuracy, and rapid cycle times. Die casting is a permanent mold casting process in which molten metal is injected into a steel mold (die) under high pressure, typically ranging from 7 to 350 MPa. The pressure is maintained during solidification to ensure the casting retains its precise shape and quality. Once the metal has solidified, the mold is opened and the part is ejected.

There are two main types of die casting machines, classified by how the molten metal enters the mold:

Hot-chamber die casting

- The metal is melted in an integrated container attached to the machine.
- A piston injects the liquid metal directly into the die under high pressure.
- Suitable for low-melting-point alloys like zinc, tin, and lead.
- Offers faster cycle times due to the built-in melting system.

Cold-chamber die casting

- The molten metal is melted externally and ladled into an unheated injection chamber.
- A hydraulic piston then forces the metal into the die under high pressure (typically 14 to 140 MPa).
- Commonly used for aluminum, magnesium, and brass alloys.
- Slower cycle times compared to hot-chamber machines due to manual ladling.

Cold-chamber die casting cycle

- The die is closed, and molten metal is poured into the chamber.
- The piston (ram) injects the metal into the die cavity and holds pressure during solidification.
- The ram is withdrawn, the die is opened, and the casting is ejected using ejector pins.

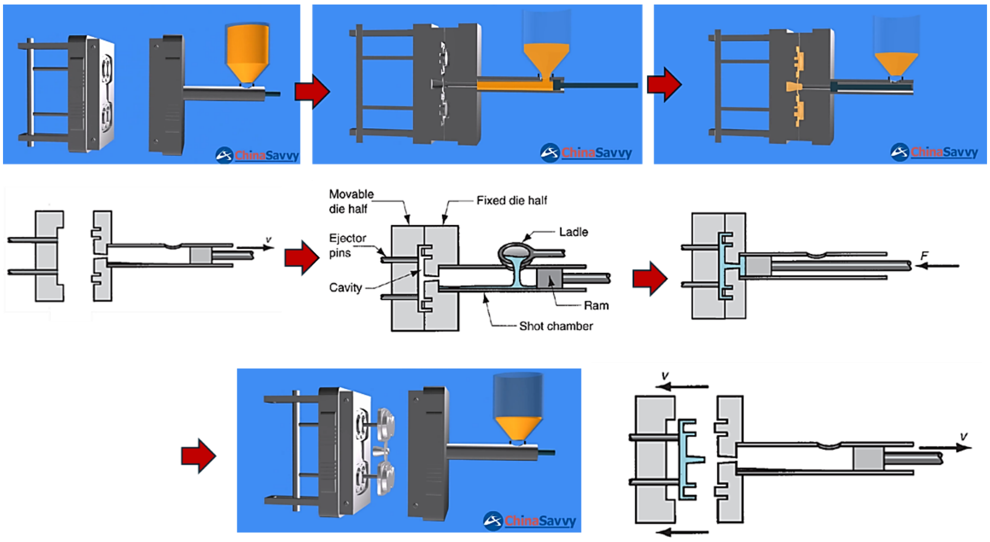


Figure 7. Cold-chamber die casting cycle

Dies are made from tool steel, mold steel, or maraging steel to withstand high pressure and thermal cycling. For high-temperature experiments (e.g., casting steel), tungsten or molybdenum may be used due to their refractory properties. Dies can be single-cavity (one part per cycle) or multi-cavity (multiple parts per cycle). Ejector pins are integrated to remove parts after solidification. Lubricants are sprayed into the mold before each cycle to prevent sticking and ensure smooth ejection.

Advantages of die casting

- High production rates – hundreds of parts per hour
- Excellent dimensional accuracy, with tolerances as tight as ±0.076 mm
- Ability to produce thin sections (as thin as 0.5 mm)
- Fine grain structure and good mechanical strength due to rapid cooling
- Minimal post-processing required

Disadvantages of die casting

- High tooling and equipment costs: Die casting requires expensive steel molds and high-pressure injection machines, making it cost-effective mainly for large production volumes.

- Limited to non-ferrous metals: The process is generally restricted to alloys with lower melting points, such as aluminum, zinc, and magnesium; ferrous metals (like steel or cast iron) cannot be used due to thermal stress on the die.
- Unsuitable for very large parts: Die casting is typically used for small to medium-sized components; producing large castings is difficult due to equipment limitations and challenges in filling large molds uniformly.
- Porosity and trapped gases: High-speed metal injection can trap air inside the mold, leading to gas porosity, which may weaken the part or require post-processing like impregnation or heat treatment.

4.3.4. Centrifugal casting

Centrifugal casting is a manufacturing process in which molten metal is poured into a rotating mold, and centrifugal force is used to distribute the metal along the outer walls of the mold cavity. The mold typically rotates at speeds between 500 and 3000 rpm, generating forces up to 100 times gravity (100 g). The rotation continues during solidification to ensure even metal distribution and high structural integrity.

Molten metal is poured into the rotating mold, usually made of steel or cast iron, from one end. The centrifugal force pushes the metal outward, where it forms a dense layer along the inner wall of the mold. This method is especially suited for producing hollow, cylindrical parts without the need for a core. The outer shape of the part depends on the shape of the mold cavity and can be round, hexagonal, or other polygonal forms, while the inner surface is typically cylindrical, since the molten metal forms a smooth, even surface against the rotation axis.

Types of centrifugal casting

- Horizontal centrifugal casting: The axis of rotation is horizontal. Used for long tubular parts such as pipes, tubes, and cylinders, where the length is much greater than the diameter.

- Vertical centrifugal casting: The axis of rotation is vertical. Suitable for parts with a larger diameter than height, such as bushings, rings, and bearing sleeves.

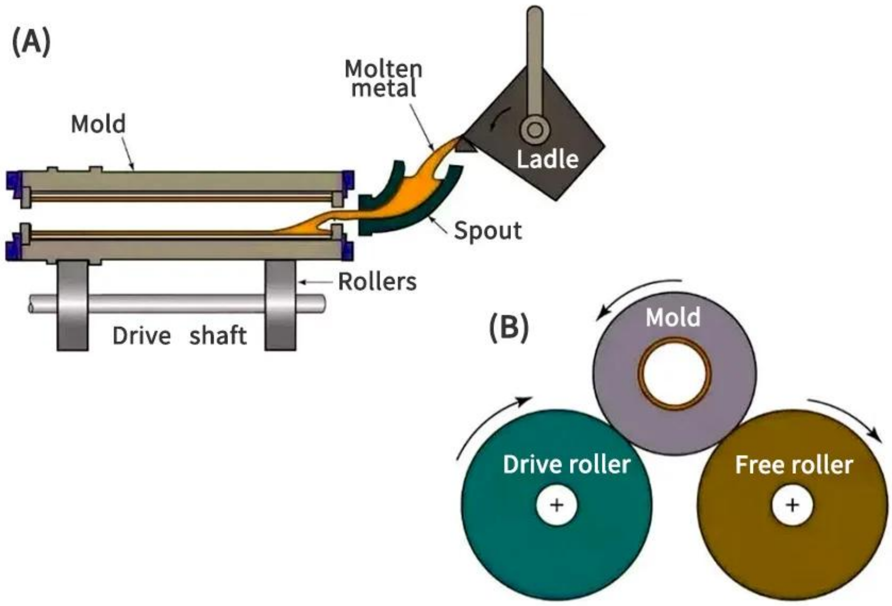


Figure 8. Schematic of the horizontal centrifugal casting process [32]

Typical applications

- Pipes and tubes (steel, iron, copper alloys)
- Bushings, rings, and sleeves
- Brake drums and cylinder liners
- Parts requiring high structural integrity, especially along the outer walls

Advantages of centrifugal casting

- High structural integrity: Centrifugal force removes impurities and gases toward the inner surface, resulting in a dense, defect-free outer wall.
- No need for cores: Hollow shapes can be formed without internal cores, simplifying the process and reducing tooling.

- Good mechanical properties: Rapid cooling and grain refinement at the outer regions produce parts with excellent strength and wear resistance.
- Versatile shapes: Can produce parts with varied external geometries (round, hexagonal, etc.) and relative precise inner cylindrical shapes.

Disadvantages of centrifugal casting

- Limited to rotationally symmetric parts: Only suitable for cylindrical or ring-like geometries; cannot be used for irregular or boxy shapes.
- High equipment cost: Requires specialized rotating molds and machinery, which can be costly for small production runs.
- Uneven inner surface: The inner layer may contain defects or inclusions and often needs machining or removal.
- Size and weight limitations: Mold design and rotation limits may restrict the size or wall thickness of cast components.

Chapter V

3D PRINTING

5.1. Introduction to 3D printing

3D printing, also called additive manufacturing, has transformed how we create and make things. This amazing technology lets us build three-dimensional objects from digital designs, adding material layer by layer. We can use different materials like plastics, metals, and even ceramics to print objects. From making medical devices to airplane parts, and from fashion items to building materials, 3D printing is changing many industries and opening up exciting new possibilities.

The 3D printing process involves four main steps [33-35]:

1. **Design**: First, you need to create a digital 3D model using a computer software CAD (Computer-Aided Design). You can either design something new or scan an existing object to create the model. The software helps you make detailed designs and test them to make sure they'll work properly.
2. **Slicing**: Next, special software cuts the 3D model into many thin horizontal layers. This step changes the model into instructions that the printer can follow. The software also figures out the best way for the printer to move, saving material and making sure the object will be strong.
3. **Printing**: The 3D printer then builds the object one layer at a time, following the sliced design. Different printers work in different ways, some melt plastic and squeeze it out, while others use lasers to harden liquid materials. How fast and precise the printing is depends on what kind of printer you're using.
4. **Post-Processing**: After printing, the object might need some extra work to make it perfect. This could mean cleaning it, hardening it, or making it look better. You might need to remove supporting parts, sand it smooth, paint it, or add special coatings. This final step is important to make sure the printed object looks and works exactly as it should.

5.2. 3D printing technologies

There are several different ways to do 3D printing, and each method has its own special features, materials, and uses. Let's look at the most common types:

5.2.1. Fused deposition modeling (FDM)

Fused deposition modeling, also called Fused filament fabrication (FFF), is the most common type of 3D printing, especially popular among hobbyists and for making prototypes.

FDM uses a spool of thermoplastic filament, which is heated and melted inside the printer's nozzle. The nozzle moves in precise patterns, depositing the molten plastic layer by layer onto a build platform. As the plastic cools, it solidifies, creating the object. Each layer bonds to the one below it, forming a durable structure.

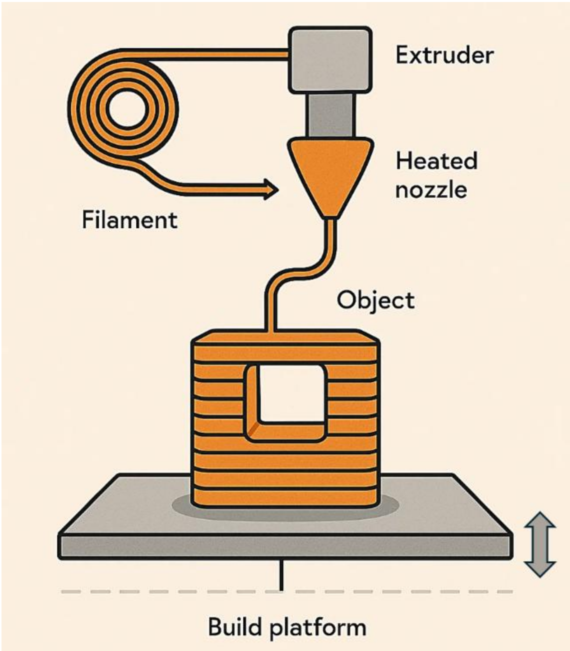


Figure 1. The principle fused deposition modeling (FDM)

Materials: Users can choose from several common materials in FDM printing. The most popular ones are PLA (Polylactic Acid), which is made from plant materials and is easy to use; ABS (Acrylonitrile Butadiene Styrene), which is the same material used in LEGO bricks; PETG

(Polyethylene Terephthalate Glycol), which is similar to water bottle material; and special mixed materials like filaments containing carbon fiber for extra strength.

- **Advantages**: FDM is great for beginners because it's affordable and easy to learn. There are many different materials to choose from, and it works well for making quick prototypes and useful parts.
- **Limitations**: The main drawbacks of FDM are that it can't make super detailed objects, and the finished surface shows visible lines where each layer was added. Also, printed objects might be stronger in some directions than others.

5.2.2 Stereolithography (SLA)

Stereolithography (SLA) is one of the first 3D printing methods ever invented and is famous for making very precise, smooth objects. SLA uses a container filled with liquid resin that hardens when exposed to ultraviolet (UV) light. A laser or projector moves across the resin surface, curing specific areas to create one layer of the object. Once a layer is completed, the build platform lowers slightly, and the next layer is formed. This process repeats until the object is finished.

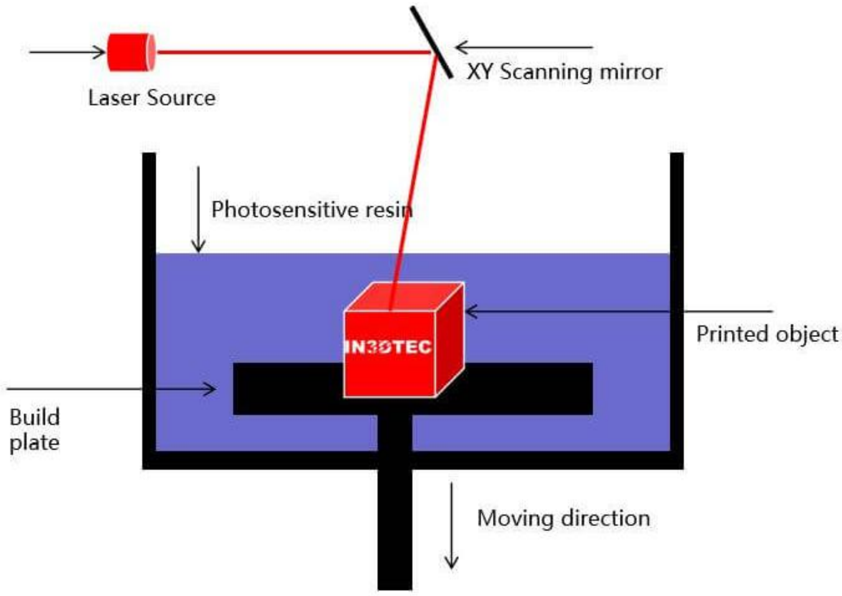


Figure 2. The principle of Stereolithography (SLA) [36].

Materials: SLA printers use photopolymer resins, which can be engineered for specific properties like flexibility, transparency, or heat resistance. Specialty resins are also available for dental and medical applications.

- **Advantages**: SLA creates very detailed objects with smooth surfaces. It's perfect for objects that need to be precise, like dental models, jewelry, and complex prototypes.
- **Limitations**: SLA printers and their materials cost more than FDM. The printed objects often need extra time under UV light to become fully hard, and the liquid materials must be stored carefully to protect them from light and moisture.

5.2.3. Selective laser sintering (SLS)

Selective Laser Sintering (SLS) is a powerful 3D printing method used to make strong and complex objects. SLS employs a high-powered laser to fuse powdered materials into solid structures. A thin layer of powder is spread over a build platform, and the laser selectively melts specific areas according to the design. After each layer, a new layer of powder is spread, and the process repeats until the object is complete. Excess powder supports the object during printing, eliminating the need for additional support structures.

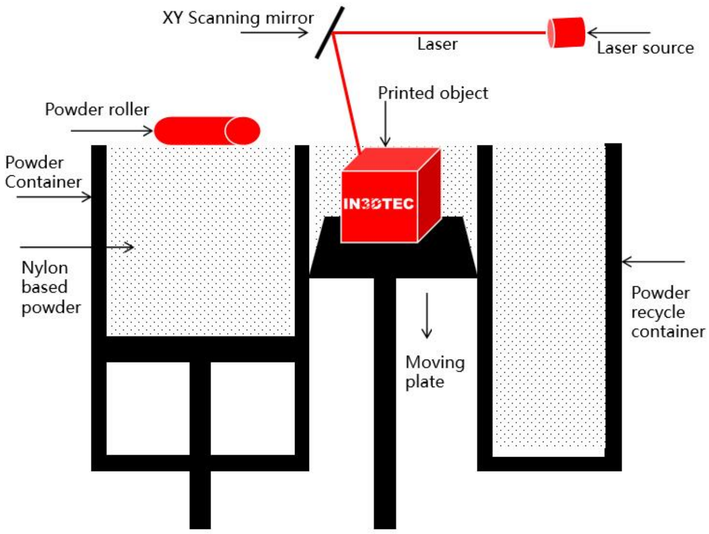


Figure 3. Schematic illustration of Selective Laser Sintering (SLS) [36].

Materials: Common materials include nylon, polyamides, glass-filled composites, and metals like aluminum or steel. The versatility of materials allows for creating strong and durable parts.

- **Advantages**: One of the best things about SLS is that it can create complex shapes with excellent strength without needing extra supports. This makes it perfect for making working prototypes and actual parts used in important industries like airplane manufacturing, car production, and medical equipment.
- **Limitations**: The main challenges with SLS are the high cost of the machines and the relatively slow printing speed. Also, objects might come out with a somewhat rough surface that needs extra finishing work.

5.2.4. Digital light processing (DLP)

Digital Light Processing (DLP) is an additive manufacturing technique that utilizes a digital projector to cure an entire layer of photopolymer resin at once. Unlike Stereolithography (SLA), which traces the shape of each layer using a laser, DLP hardens each cross-section simultaneously, significantly reducing the build time.

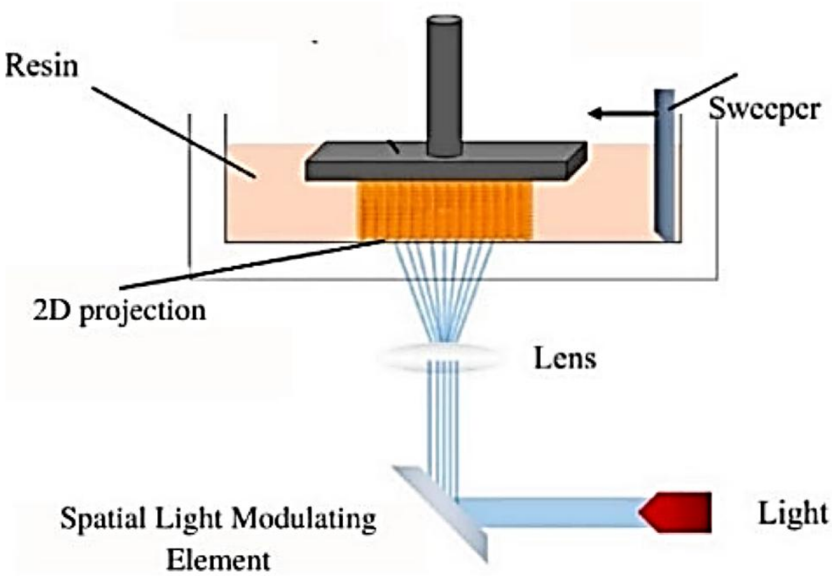


Figure 4. The working principle of Digital Light Processing (DLP) [37]

Materials: DLP employs liquid photopolymer resins, similar to those used in SLA. These resins can be formulated to achieve a variety of mechanical and physical properties, depending on the application.

- **Advantages:** This method is particularly effective for producing parts with high resolution and fine surface details. DLP is commonly used in fields that require precision, such as dental and medical applications, jewelry design, and small-batch manufacturing.
- **Limitations:** As with SLA, both the equipment and the consumables used in DLP can be relatively costly. Printed parts typically require post-curing under ultraviolet (UV) light to achieve full mechanical strength. Additionally, the resins must be handled and stored with care due to their sensitivity to light and environmental conditions.

5.2.5. Multi jet fusion (MJF)

Multi Jet Fusion (MJF) is an advanced powder bed fusion technology developed by HP that integrates inkjet printing techniques with thermal energy to build parts layer by layer. Unlike laser-based methods, MJF uses arrays of inkjet nozzles to deposit functional agents onto a thin layer of polymer powder, typically nylon. Once the agents are applied, infrared energy is used to fuse the selected regions of the powder bed.

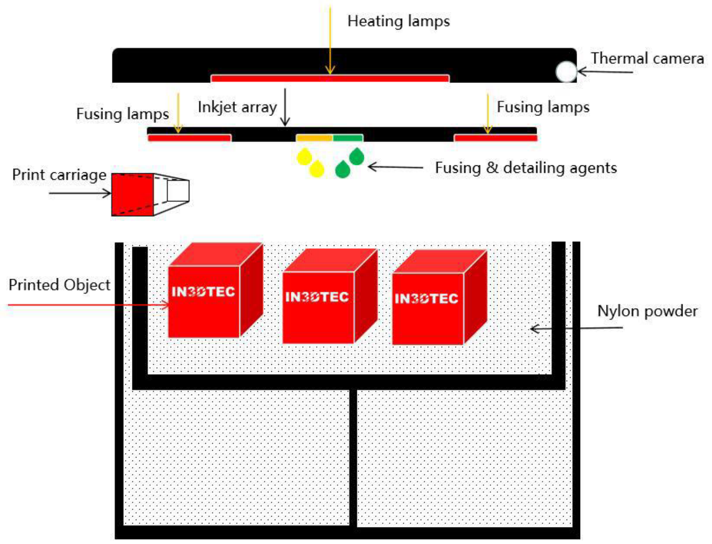


Figure 5. Diagram showing the working principle of Multi Jet Fusion (MJF) [36]

Materials: The process primarily utilizes polyamide powders such as PA12 (nylon 12), known for their durability and versatility. Research and development continue to expand the material portfolio to include other polymers and composite blends.

- **Advantages**: MJF produces components with excellent mechanical properties, uniform strength in all directions, and high resolution. It is capable of fabricating functional parts with fine features, smooth surfaces, and minimal need for supports, making it suitable for both rapid prototyping and series production.
- **Limitations**: The equipment and materials involved in MJF are relatively expensive. Additionally, although parts typically emerge with good surface finish, post-processing (such as dyeing, smoothing, or sealing) may still be necessary to meet specific aesthetic or functional requirements.

5.2.6. Electron beam melting (EBM)

Electron Beam Melting (EBM) is an advanced metal 3D printing process that uses a high-energy electron beam to selectively melt metal powder inside a vacuum chamber, building parts layer by layer. It is particularly well-suited for producing strong, high-performance components in industries like aerospace and medicine. In EBM, a focused electron beam scans across a bed of metal powder, fusing particles together based on a digital model. The process occurs in a vacuum, which helps maintain material purity and reduces oxidation. Each layer of the object is built from bottom to top by repeating this scanning and melting sequence.

Materials: EBM typically works with metal powders, especially titanium alloys (widely used in aerospace and medical implants), cobalt-chrome (for dental and orthopedic applications), and Inconel (a nickel-based alloy ideal for high-temperature environments).

- **Advantages**: This method produces dense, high-strength parts with excellent structural integrity. Because the printing occurs in a vacuum, the risk of contamination is minimal. EBM is ideal for manufacturing critical components, such as jet engine parts, orthopedic implants, and high-load mechanical structures.

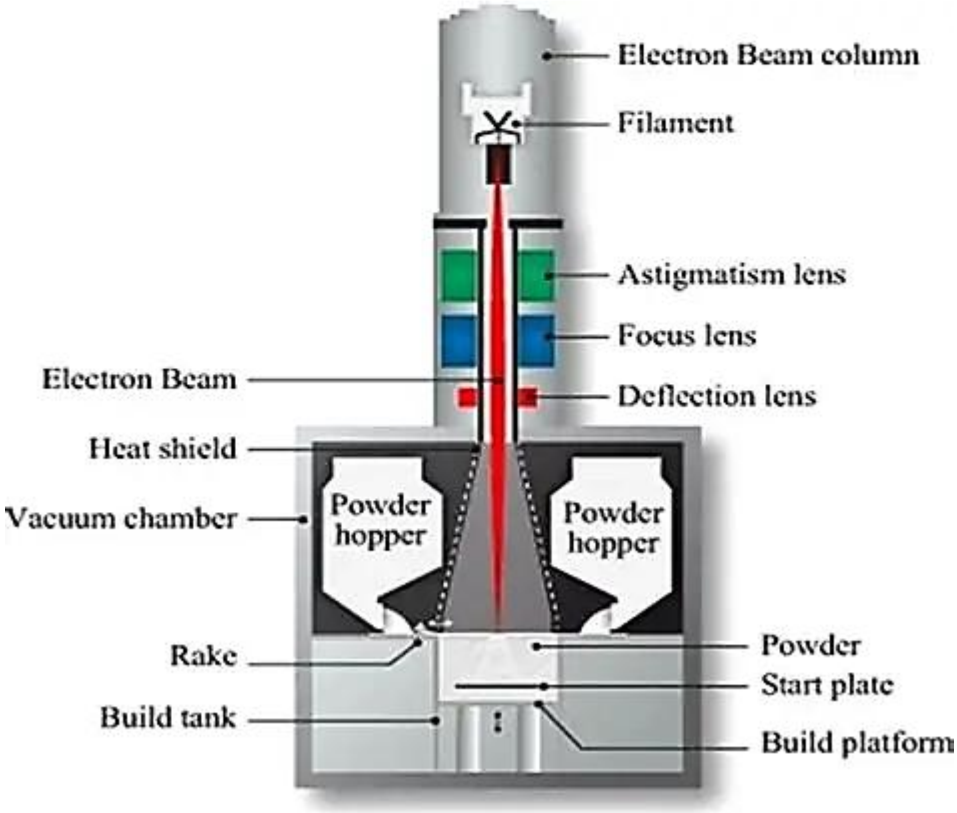


Figure 6. The principle of Electron Beam Melting (EBM) [38]

- **Limitations**: Despite its strengths, EBM has some downsides. The machines are expensive, and the build process is relatively slow compared to other metal printing technologies. Additionally, printed parts often require post-processing (such as machining or polishing) to improve their surface finish.

5.3. The future of 3D printing

3D printing offers a number of clear benefits that make it a valuable tool in modern manufacturing, design, and education. However, like any technology, it also presents a set of challenges that must be addressed as it continues to evolve.

Advantages of 3D printing technologies

- High customization: One of the greatest strengths of 3D printing is the ability to create products tailored to specific needs. Whether it's a custom medical implant, a personalized tool, or a student-designed model, this technology makes it easy to produce one-of-a-kind items without additional cost or effort.
- Fast prototyping: Designers, engineers, and students can quickly turn their ideas into physical models. This allows rapid testing and improvements, accelerating product development and reducing time-to-market for new innovations.
- Cost efficiency for Small Batches: Traditional manufacturing methods require expensive molds and tooling. In contrast, 3D printing eliminates these setup costs, making it ideal for small production runs or complex geometries that would otherwise be costly to produce.
- Reduced waste and storage: Additive manufacturing builds objects using only the material needed, which minimizes scrap. In addition, on-demand printing reduces the need for large inventories and storage space.

Drawbacks of 3D printing

- Limited material selection: Although the range of printable materials is expanding, it still lags behind traditional manufacturing. Many high-performance metals, composites, and specialized plastics are not yet widely available or compatible with common 3D printers.
- Consistency and quality control: Achieving uniform quality can be difficult. Print settings, machine calibration, and environmental factors can all influence the final outcome, making process control and testing crucial.

5.4. Unconventional applications of 3D printing

While 3D printing is widely used for prototyping and product development, its real potential shines in unexpected places. From helping astronauts in orbit, to creating entire bridges here on Earth, this technology is transforming industries and challenging the limits of traditional manufacturing.

One of the most striking uses of 3D printing is in aerospace. SpaceX uses metal 3D printing to produce components of its SuperDraco rocket engines and simplify the design of Raptor rocket engines. These engines are designed to be compact, powerful, and reliable, making them ideal for launch escape systems. Printing complex metal parts allows for fewer welds, better performance, and faster development times that are key advantages in space exploration.

Figure 7. Design simplification of the Raptor rocket engine enabled by 3D printing [39]

In civil engineering, 3D printing is being used to construct pedestrian bridges. These structures are printed using concrete or metal, directly layer by layer, with robotic arms or gantry systems. Notable examples include a steel bridge in Amsterdam, created by MX3D, and concrete footbridges in China and Spain. This method allows for organic shapes, reduced material waste, and faster installation in urban settings.

Construction-scale 3D printers are now building full-sized houses using special cement-based materials. Entire homes have been printed in under 48 hours. This technology is gaining traction for low-cost housing in developing regions, post-disaster rebuilding, and even future Martian habitats. By automating construction, it reduces labor costs and shortens timelines.

Figure 8. The first ever 3D-printed steel bridge (Amsterdam) [40]

Figure 9. Full-size house realized via 3D printing [41].

3D printing isn't just for structures, it's being used to print living tissues. With bioprinting, scientists can layer living cells to form skin, cartilage, and even small organ models. While printing a full organ for transplant remains a long-term goal, great progress has been made in personalized implants, dental models, and prosthetics, some even tailored for animals.

3D printing can now shape eatable materials like chocolate, cheese, or dough into artistic or custom-designed foods. In the fashion world, designers use it to create complex patterns for shoes, jewelry, or even entire garments. These industries benefit from the design freedom and on-demand production that additive manufacturing offers.

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