Chapter 1

Introductory Chapter: Extrusion - From Gear Manufacturing to Production of Cereals

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Additional information is available at the end of the chapter

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1. Introduction

Extrusion is a manufacturing process that generates profiles having a fixed cross-sectional area by pushing the billet material through a die. It is a bulk-forming process, where the stock material is deformed into the final shape under pressure (and temperature), without any melting and solidification or material removal. Its various major advantages over other manufacturing processes include huge shape versatility (from simple to extremely complex profiles); ability to handle brittle materials, as only compressive and shear stresses are employed during deformation; and very good surface finish of the extrudate (almost no postprocessing finishing operations required). By adding a mandrel to the die set, complex hollow shapes can also be extruded. The process is suitable for both hot and cold working. Metals and alloys, polymers and plastics, ceramics, concrete, and food products are the materials that are generally extruded. Extrusion of aluminum alloys finds extensive applications in construction, automobile, aerospace, and other sectors [1–3, 5].

2. Metal extrusion

The first patent for extrusion (called "squirting" at that time) was filed in 1797 by Joseph Bramah for the production of pipes from metals of low hardness. Preheated metal was forced through a die using a hand-worked plunger. Thomas Burr modified the process in 1820 to produce lead pipes, using a hydraulic press (which was also invented by Bramah). The method was expanded in 1894 by Alexander Dick to manufacture products made of copper and brass alloys [4].

Metals that are commonly extruded include aluminum, brass, copper, lead and tin, magnesium, zinc, steel, and titanium. In the case of steels, extrusion is generally restricted to plain-carbon steels; alloy steels and stainless steels are not suitable for this process. Some of the common extruded products are tracks, frames, rails, rods, bars, pipes and pipe fittings, wire and cable, tubes, hardware components and fittings, automobile parts, aircraft components, parts for nuclear industry, and a variety of general engineering and structural parts [4].

In commercial extrusion, billet and die set are preheated and then loaded into the container, which is also held at a suitable temperature. A dummy block is placed behind the billet, and the ram pressure forces the material through the die set. The whole equipment is called the extrusion press. After extrusion, the product is stretched (to straighten it out) and cooled (to reduce the warm softness), cut into required length, and stacked. Heat treatment (age hardening), anodizing and/or painting are done if required [5, 6]. Major components of the extrusion press are shown in **Figure 1**, while the sequence of operations in a typical commercial extrusion plant is shown schematically in **Figure 2**.

2.1. Extrusion of spur gears

Manufacturing of gears depends on the machinery available, customer requirements (design specifications), cost of production, and type of material from which the gear is to be made. There are many methods for manufacturing gears, including metal removal (machining), casting, tamping and fine blanking, cold drawing and extrusion, powder metallurgy, injection molding, gear rolling, and forging. Most of these processes are suited for gears with low wear requirements, low power transmission, and relatively low accuracy of transmitted motion. When the application involves higher values of one or more of these characteristics, forged or machined gears are used [7, 8].

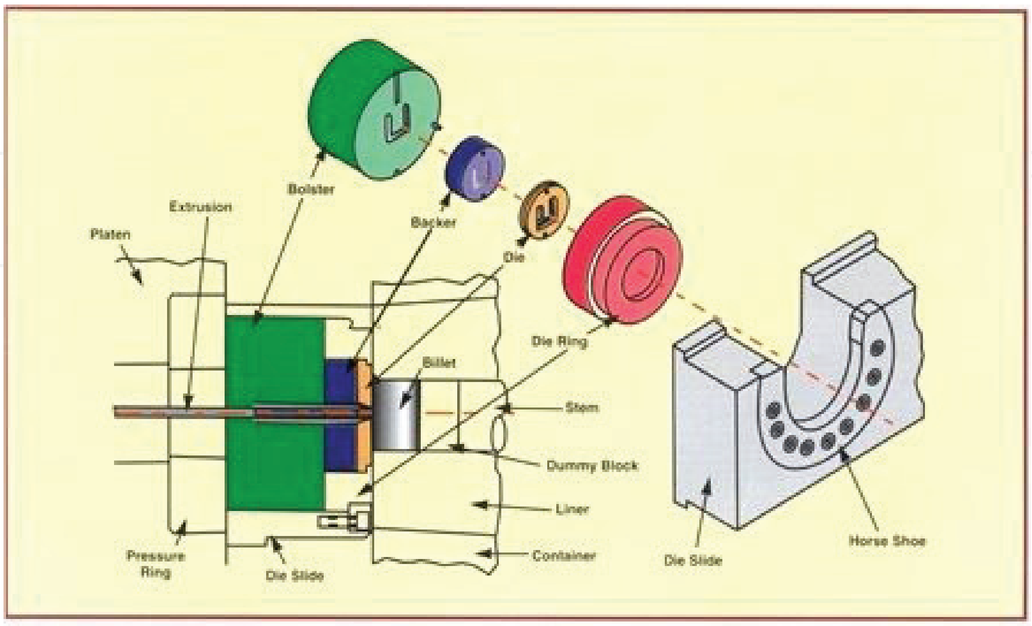

Figure 1. Major components of the metal extrusion press.

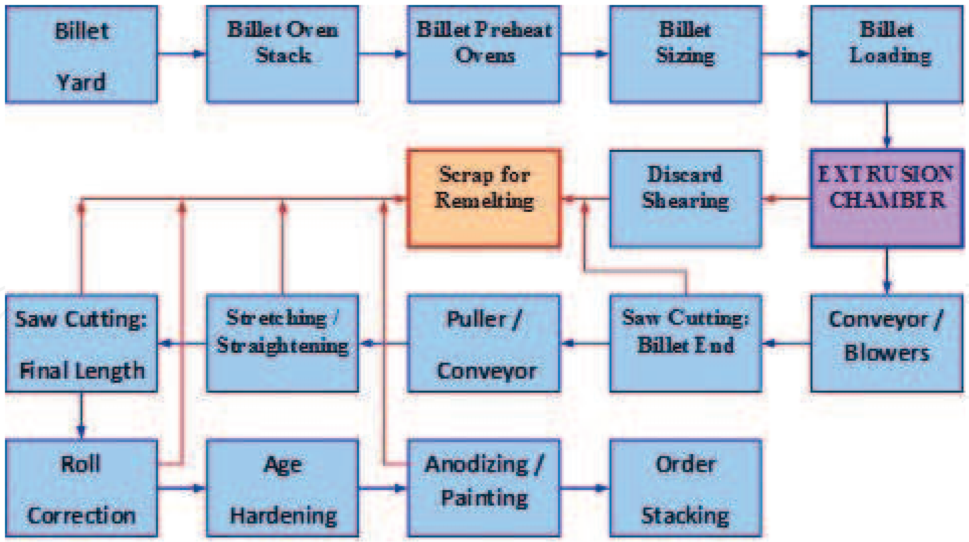

Figure 2. Plant layout (or process flow) in a typical commercial extrusion facility.

The process of cold drawing and extrusion requires the least tool expenditure for mass production of spur gear-toothed gear elements. It is extremely versatile, and almost any desired tooth form can be produced. A bar/billet is pulled (drawn) or pushed (extruded) through a series of several dies, the last having the final shape of the desired tooth form. Since the material is displaced by pressure, the outside surface is work-hardened and quite smooth. After passing through the dies, the bars (or blanks) are known as pinion rods. They are often put into screw machines that finish the individual gears. Any material that has good drawing properties, such as high-carbon steels, brass, bronze, aluminum, and stainless steel, may be used for the drawn pinion rod [9, 10].

Gears and pinions manufactured by this process have a large variety of applications and have been used on watches, electric clocks, spring-wound clocks, typewriters, carburettors, magnetos, small motors, switch apparatus, taximeters, cameras, slot machines, all types of mechanical toys, and many other parts for machinery of all kinds [11, 12].

2.2. Solid tubular expansion

In “direct extrusion,” the ram pushes the billet material through the die cavity in such a way that the ram and the product move in the same direction. During “indirect extrusion,” the die remains stationary, while the billet and the container move together, and the movement of the ram and the billet is in opposite directions. One novel adaptation of indirect extrusion is the process of tube expansion [13]. In solid expandable tubular (SET) technology, a metal tube (or pipe) is expanded by pushing (or pulling) a conical mandrel (die) through it [14]. Unlike commercial direct extrusion carried at higher temperatures, tube expansion is a type of cold (room temperature) extrusion process. In-situ expansion of petroleum tubulars has recently found many applications in the oil and gas drilling and development industry [15], especially for enhanced oil recovery (EOR). SET-based techniques such as water shutoff, zonal isolation, slim well design, etc. make production possible from old and depleted wells, and result in huge savings in material, time, and cost.

2.3. Stiff vacuum extrusion/extrusion briquettes

Extrusion can be efficiently utilized as a compaction/agglomeration process. One major application is the production of fuel briquettes. Initial attempts at extrusion-based agglomeration of steel were rather unsuccessful. Bethlehem Steel incorporated an agglomeration unit in their blast furnace in 1994. It was based on the stiff vacuum extrusion technology that was earlier developed by JC Steele & Sons and was generally used before for brickmaking. However, the company and its briquette unit closed down soon thereafter. The group consisting of Bizhanov, Kurunov, et al. is credited with serious studies and technology revival in the field, during 2009–2013. Their metallurgical process was verified through actual-scale industrial experiments and later converted into commercial production. They also coined the term "brex" to differentiate the product from traditional briquettes [16].

There is a growing interest now in agglomeration technology based on stiff extrusion. New factories have been built for briquetting in very large steel and ferrous alloy companies. This extrusion-based technology is used for agglomeration of steel mill wastes (blast furnace dust, blast furnace sludge, and lime plant sludge). The low-cost brex is a good substitute for expensive iron ore feedstock in blast furnaces used for pig iron production. Agglomeration of process dust is also done for recovery of nickel ore through the rotary kiln electric furnace process. Other uses of this technology include compaction of fuel briquettes from coal fines, pelletizing of synthetic gypsum to make fertilizer filler, conversion of low energy lignite coal into a higher energy fuel, pelletizing of bauxite to make high-grade alumina feedstocks for refractory products, production of synthetic gypsum rock using cement kiln dust, etc. [17].

3. Polymer extrusion

A very large number of different types of polymers can be extruded into products such as plastic tubes and pipes, rods, rails, fencing, seals, window frames, deck railings, sheets and films, coatings, wire insulation, etc. In 1820, Thomas Hancock invented a rubber "masticator" designed to reclaim processed rubber scraps. In 1836, Edwin Chaffee developed a two-roller machine to mix additives into rubber [18]. Thermoplastic extrusion was carried out for the first time in 1935 by Paul Troester and Ashley Gershoff in Hamburg, Germany. Shortly after, Roberto Colombo developed the first twin screw extruders in Italy [19]. Though thermoplastics are the main product, elastomers and thermosetting plastics can also be produced through extrusion. Cross-linking required for these polymers is formed as the material is heated and melted in the extruder. Further thermoforming of the extruded thermoplastic may be needed in some cases.

Schematic diagram of typical polymer extrusion is shown in **Figure 3**. The basic components of a plastic extruder are screw, drive, barrel, hopper, and die, the most critical part being the helical screw. It helps in transporting, heating and melting, and mixing of the polymer. The starting material can be in the form of chips, pellets, granules, flakes or powders. These are first dried in a top-mounted hopper to remove the moisture and are then gravity-fed into the extruder barrel containing the feed screw. If needed, additives (colorants, ultraviolet inhibitors, etc.) can be mixed into the resin before reaching the feed hopper in liquid or pellet form. Plastic extruders also find

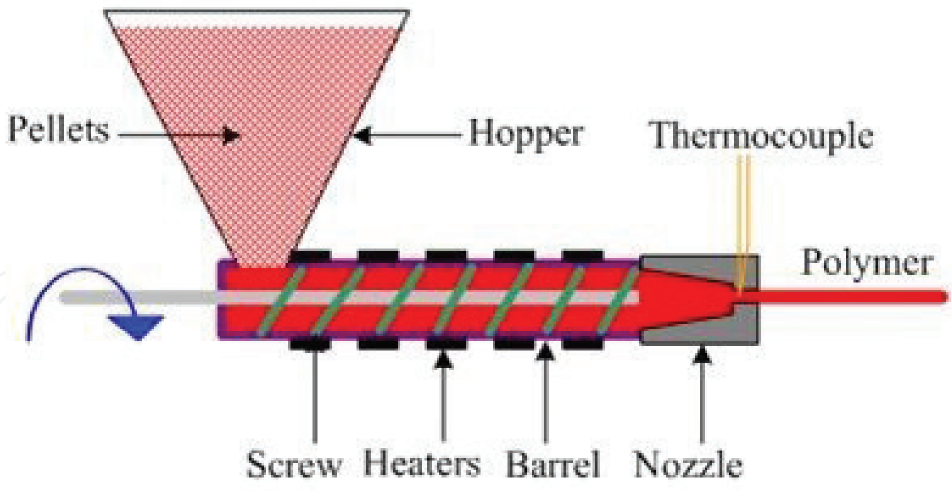

Figure 3. A schematic process diagram of typical polymer extrusion.

extensive use in recycling of plastic waste. This of course needs cleaning and sorting, and blending into the pellet-type resin stock before being used for extrusion [20].

The polymer resin is converted and melted through a combination of heating elements (positioned on the barrel) and shear energy coming from the rotating screw. The melting temperature is maintained with the help of thermocouples. Before entering the die, the resin goes through a reinforced screen (breaker plate) for removal of any contaminants. Screw motion forces the hot resin through the die, generating a continuous polymer product of the desired profile. The puller or "caterpillar haul-off" pulls (or stretches) the extruded material, while also cooling and solidifying it, with the help of blowers or a water bath. This tension is necessary for good quality and can also be applied by a pelletizer, which pulls the strands for later cutting [21].

4. Food extrusion

When extrusion is used for food processing, it is known as food extrusion. Different die shapes are used for different types of food. Extruded food product is cut to the desired length by blades. The extruder consists of a large, rotating screw that fits snugly inside a stationary barrel, fitted with a die set at its outward end [22].

Mass production of food is possible through the continuous and efficient system of extrusion, ensuring a consistent and uniform product. Extrusion has enabled the production of newly processed food products and revolutionized many conventional snack manufacturing processes [23]. Extruded food is usually high in starch content and includes products such as pasta (spaghetti, noodles, macaroni, etc.), breads (croutons, bread sticks and flat breads), breakfast cereals, ready-made snacks, confectionery, etc. [24].

The first food extruder was designed to manufacture sausages in 1870s [25]. Packaged dry pasta and breakfast cereals have been produced via extrusion since 1930s [26]. The method was applied to pet food production in 1950s. It has also been incorporated into kitchen appliances, such as meat grinders, herb grinders, coffee grinders and some types of pasta makers [27]. Extrusion of pet food is shown schematically in **Figure 4**.

4.1. Extrusion cooking

As a food product is processed through extrusion, it is also "cooked." During extrusion cooking, the food product is heated under a high degree of pressure and then slowly forced through a series of pores into another cooking chamber. As this process takes place, the moisture content of the food is reduced significantly, leaving behind a product that is thoroughly cooked and dried. The remaining extruded product is then ready for inclusion in dry mixes or further processing to produce various many of the packaged products that many consumers rely upon today [26]. This wide range of packaged foods includes salty snacks, breakfast bars, cereal-based health foods, etc. Even nongrainy foods such as soybeans are prepared using extrusion cooking, forming the basis for a number of vegetarian products [27].

4.2. Functional food

A functional food is a food that also performs an additional function beyond basic nutrition, generally related to improvement of health or prevention of disease. This is achieved by adding new ingredients or a different proportion of existing ingredients [28]. A familiar example of a functional food is oatmeal because it contains soluble fiber that can help lower the cholesterol levels. An example of a food "modified" to have health benefits is orange juice that has been fortified with calcium for bone health [29].

4.3. Nixtamalization

The process used for the preparation of maize (corn) or similar grain is known as nixtamalization. The grain is soaked and cooked in an alkaline solution (usually limewater), and hulled.

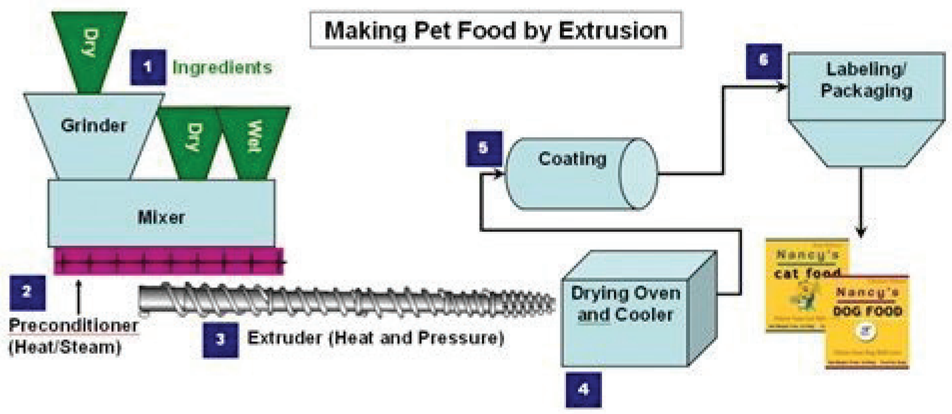

Figure 4. Schematic illustration of the process of pet-food extrusion.

Removal of the pericarp from other grains such as sorghum, using an alkali process, can also be termed as nixtamalization. Maize prepared in this way has several benefits over unprocessed grain: its grinding becomes easier, its nutritional value is increased, its taste and aroma are improved and the amount of mycotoxins is reduced [30].

The high alkalinity of lime and ash helps the dissolution of hemicellulose, the major glue-like component of the maize cell walls, and loosens the hulls from the kernels and softens the maize. Some of the corn oil is broken down into emulsifying agents (monoglycerides and diglycerides), while bonding of the maize proteins to each other is also facilitated. It is difficult to form dough by addition of water using cornmeal made from untreated ground maize. However, the above chemical changes allow easier dough formation. These benefits make nixtamalization a crucial preliminary step for further processing of maize into food products. The process is used together with both traditional and industrial methods used for the production of tortillas and tortilla chips (but not corn chips), tamales, hominy, and many other items [31].

4.4. Aquafeed/fish feed

Production of aquafeed (fish feed) is another application of food extrusion. Aquaculture (rearing/farming of aquatic animals or cultivation of aquatic plants for food) is one of the fastest developing sectors in the world. This growth directly translates into an increasing demand for aquafeed. One major type of aquafeed processing technology is extrusion. The nutrient components in fish feed mainly consist of protein, starch, crude fat, raw fiber, crude ash, vitamin and minerals. Protein provides energy and builds muscles. Vitamins and minerals can enhance natural resistance and feed conversion rate [32].

Extruded aquafeed pellet-making process consists of grinding, mixing, extrusion, drying, coating and cooling. As extrusion is a high-temperature short-time (HTST) heating process, it minimizes the degradation of food nutrients while improving the digestibility of protein and starches. Fish feed extruder is an efficient machine designed for processing floating or sinking aquatic feed just by adjusting the formula. Fish feed extrusion consists of wet extrusion and dry extrusion. The high temperature in dry extrusion is acquired through dissipation of mechanical energy from heated surfaces such as barrel and screw surface, or generated by shear forces between wall and material and screw and material. For wet extrusion, the temperature is achieved through preconditioning and steam injection [33].

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