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Introduction

1.1 Stainless Steels and Super Alloys as Difficult-to-Cut Materials

In recent decades, engineering materials have greatly developed. At the same time, the cutting speed and the material removal rate (MRR) in machining such materials using traditional methods such as turning, milling, drilling, grinding, and so on, has been going down. In many cases, it has been challenging to machine these materials such as stainless steels, refractory metals and alloys, Ti-alloys, super alloys, carbides, ceramics, composites, and even diamond, using traditional methods. It is no longer possible to find tool materials that are sufficiently hard to cut such materials.

To meet these challenges, new processes with advanced methodology and tooling have needed to be developed. These are the nontraditional processes, which are capable of machining a wide spectrum of these difficult-to-cut materials irrespective of their hardness. The increasing use of ceramics, high strength polymers, and composites will also necessitate the use of nontraditional methods of machining. In addition, grinding will be applied to a greater extent than in the past, with greater attention to creep feed grinding (CFG), and the use of polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) [1].

The question now is why both stainless steels and super alloys, as difficult-to-cut materials, have both been selected in regard to their machinability in this book? The reasons are as follows:

1. There are diverse and important industrial applications necessitating the use of special materials and alloys, characterized by high strength, high temperature strength, and high corrosion, and oxidation resistance.
2. There is difficulty associated with machining both materials, especially as they comprise dozens of grades of different machining characteristics.

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3. Both materials are characterized by low thermal conductivity, high coefficient of thermal expansion, high ductility, and high work-hardening rate, making their machining a tedious task. Their low thermal conductivity leads to an increase in tool temperature, and consequently reduces the tool life. The high work-hardening rate and low thermal conductivity affect chip formation leading to segmented chips. Also, the high coefficient of thermal expansion of these alloys leads to serious difficulties in maintaining machining tolerances.
4. The high ductility favors development of built-up edge (BUE) on the tool, thus destroying surface finish, and promoting vibration and chatter.

The basic issue in achieving optimum machining of stainless steels and super alloys is to select adequate cutting speed and correct tool for each work material. In order to realize this objective, a good understanding of the effect of cutting speed on mechanical and thermal properties of the work material and cutting tool should be considered. Some other techniques which are used to enhance the machinability of stainless steels and super alloys will be presented in relevant chapters of this book.

1.1.1 Historical Background of Stainless Steels and Super Alloys

1.1.1.1 Stainless Steels

Stainless steels (SSs) were introduced at the beginning of the twentieth century as a result of pioneering work in England, Germany, and France. However, the development had started several decades before. In 1821, the French Berthier found that iron-chromium alloy was resistant to some acids. Others studied the effects of Cr in an iron matrix, but using a low percentage of Cr. In 1875, another Frenchman, Brustline recognized the importance of carbon levels in addition to Cr.

In 1904, Leon Guilet published a research on martensitic and ferritic SS-alloys with composition that today would be known as 410, 442, 446, and 440 C. In 1906, he also published a detailed study of an Fe-Ni-Cr austenitic alloy; that was equivalent to the 300 series of SS. In Germany, in 1908, Monnartz and Borchers found evidence of the relationship between a minimum level of Cr (10.5%) on corrosion resistance as well as the importance of low carbon content and the role of Mo in increasing corrosion resistance to chlorides.

Harry Brearley of Sheffield was generally accredited as the initiator of the industrial era of SS. He was trying to develop a new material for barrels for heavy guns that would be resistant to abrasive wear. He noted that materials with high Cr-contents did not take an etch. This discovery had led to the patent of a steel with 9–16% Cr and less than 0.7% C; the first stainless steel had been born. Most of his work was on stainless 430, patented in 1919. The first product was the table cutlery that is still used today.

Parallel with the work in England and Germany, F.M. Becket was working in Niagara Falls, to find a cheap and scaling-resistant material for furnaces that run up to 1000 °C. He found that at least 20% Cr was necessary to achieve resistance to oxidation or scaling. That was the first development of heat-resistant steels.

The world's first free-machining stainless, invented by Frank Pahlmer (1928) [2], was a straight-grade with sulfur (0.15%S). It was the forerunner of today's martensitic 416 stainless. Sulfur and phosphorous were both added to make the austenitic 303 stainless which is the first free-machining Cr-Ni grade in the early 1930s. Selenium (Se) additions instead of sulfur have been favored in the States.

1.1.1.2 Super Alloys

Stainless steels served as a starting point for the satisfaction of high temperature engineering requirements. Moreover, they were soon found to be limited in their strength capabilities. The metallurgists responded to the increased needs by making what might be termed *super alloys (SAs)* of stainless varieties. Of course, it was long before the *hyphen* was dropped and the improved iron-base materials became known as one type of super alloy.

The term super alloy was first coined shortly after the second World War to describe a group of alloys developed for use in turbo-superchargers and aircraft turbine engines that required high performance at elevated temperatures. For more than six decades now, super alloys have provided the most reliable and cost-effective means of achieving high operating temperatures and stress conditions in aircraft, and also land gas turbines. As we move towards the third decade of the twenty-first century, super alloys seem to be extending their useful temperature range along with their excellent inherent characteristics. The development of these materials continues to this day with optimization of chemical composition and production methods. This will lead to the development of a new class of material tailored to meet the need for better mechanical properties at elevated temperatures.

Although patents for Al- and Ti-additions to Nichrome type alloys were issued in the 1920s, the super alloy industry emerged with the adoption of Co-base super alloys (Haynes, Stellite 31) to satisfy the increasing demands of higher temperature strength of aircraft engines. Some Ni-Cr-alloys (Inconels and Nimonics), based more or less on toaster wire and developed in the first decade of the twentieth century, were also available for engineering applications. So the race was on to make superior metal alloys available for the insatiable thirst of the designer for higher temperature strength capability. The race still continues.

1.1.2 Industrial Applications of Stainless Steels and Super Alloys

1.1.2.1 Stainless Steels

The average person has no idea what stainless steel is, but it is all around us. Most of us use stainless steel table ware and wear a wristwatch with a stainless steel case. There are stainless steel racks in refrigerators and ovens and there are stainless steel toasters, tea kettles, and even kitchen sinks. Cars have stainless steel exhaust systems that last for ten years instead of the three years that would be expected if they had been ordinary steel. The industrial applications of specific types of stainless steel alloys will be presented afterwards in the relevant locations of the book.

Stainless steels are defined as steel alloys characterized primarily by their corrosion resistance, high strength and ductility and high chromium content. They are called stainless because in the presence of O_2 (air), they develop a colorless thin, hard, adherent film of chromium oxide, and remain lustrous. This film builds up again in the event the surface is scratched (i.e., self-healing). For passivation to occur, a minimum chromium content of about 10.5% by mass should be present. Several other alloying elements such as carbon, nickel, manganese, silicon, titanium, molybdenum, aluminum, sulfur, phosphorous, nitrogen, and so on, can be added to the Cr-Fe matrix to form well over 150 different compositions of SSs, of which about 15 are most commonly used.

These alloys are milled into coils, sheets, plates, bars, wire, and tubing to be used in cookware, cutlery, surgical instruments, major appliances, industrial equipment (e.g., in sugar refineries), and as an automotive and aerospace structural alloy and construction material in large buildings. Storage tanks and tankers used to transport orange juice and other foods are often made of SS, due to its corrosion resistance and antibacterial properties. This also influences its use in commercial kitchens and food processing plants, as it can be steam-cleaned, sterilized, and does not need painting or application of other surface finishes.

1.1.2.2 Super Alloys

Super alloys or heat resistant super alloys (HRSA) constitute a category that straddles the ferrous and nonferrous metals. Some of them are based on iron, whereas others are based on nickel and cobalt. In fact, many super alloys contain substantial amounts of three or more metals, rather than consisting of one base metal plus alloying elements. Although the tonnage of these alloys is not significant compared with most of the other metals, they are nevertheless commercially important because they are very expensive; and they are technologically important because of what they can do.

Super alloys are a group of high-performance alloys designed to meet very demanding requirements for strength and resistance to surface degradation (corrosion and oxidation) at high service temperatures. Conventional room temperature strength is usually not the important criterion for these metals, and most of them possess room temperature strength properties that are good but not outstanding. Their high temperature performance is what distinguishes them; tensile strength, hot hardness, creep resistance, and corrosion resistance at very elevated temperatures are the mechanical properties of interest. Operating temperatures are often in the vicinity of 1100 °C, without a damaging reduction in strength and hardness [3].

The main fields of application of super alloys generally embrace aircraft gas turbines, space vehicles, steam turbine power plants, reciprocating engines, heat-treatment equipment, metal processing forming and casting dies, nuclear power systems, medical applications, chemical and petrochemical industries, pollution control equipment, coal gasification, and liquefaction systems. Super alloys (also some types of SSs, classified as super alloys) are frequently used in advanced aero-engine components such as turbine blades, turbine vanes, turbine vane rings, turbine nozzles, engine, and turbine casings.

1.2 Traditional and Nontraditional Machining Processes

1.2.1 Importance of Machining in Manufacturing Technology

While technological advancements continue to take place throughout the developed manufacturing industry, machining still remains the most important process used to shape metals and alloys. Compared to other manufacturing processes, machining is characterized by its versatility and capability of achieving the highest accuracy and surface integrity in the most economical way [4]. Most materials and alloys, hard or soft, cast or wrought, ductile or brittle, are machined. Most engineering products, in terms of size from watch parts to aircraft wing spares (over 30 m long), or ship propellers, are produced by machining. Such versatility of machining processes can be attributed to many factors, including the following:

- Machining does not require elaborate tooling.
- It can be employed to most engineering materials.
- Tool wear is kept within limits, and tools are not costly.
- The large number of machining parameters can be suitably controlled to overcome techno-economical difficulties.

The development of new tool materials opened a new era for the machining industry in which a parallel development in machine tools took place. In the last century, nontraditional machining techniques offered alternative methods for machining parts of complex shapes in extra-hard and tougher exotic materials that were difficult-to-machine by traditional methods.

In highly developed industrial countries, the yearly cost associated with metal removal has been estimated at about 10% of the gross national production. Metal cutting machine tools form about 70% of the operating production machines, and are characterized by their high accuracy and productivity. For these reasons, rational approach and minor improvements in productivity of material removal processes are of major importance in high volume production. It is also known that about 10% of the materials produced by machining industry goes into waste. This is not an exclusive feature of the machining process as it is also present in all other methods related to manufacturing. Therefore, machining should not be identified, in most cases, as a method yielding a high loss of material [5].

Machining is generally used as a final finishing operation for parts produced by casting and forming before they are ready for use. However, there are a number of reasons that makes machining processes an obligatory solution as compared with other manufacturing techniques. These are:

- If closer dimensional control and tight tolerances may be required than are available by casting and forming.
- If special surface quality may be required for proper functioning of a part.
- If the part has external and internal geometric features that cannot be produced by other manufacturing operations.
- If it is more economical to machine the part rather than to produce it by other manufacturing operations.

On the other hand, machining has the following limitations:

- It generally necessitates a longer time to remove material than to shape the part by forming and casting.
- Unless carried out properly, machining can have adverse effects on the properties of the surface quality of the product.
- Machining is generally energy-, capital-, and labor-intensive.
- Machining necessitates highly qualified operators and specialized personnel. A wrong decision causes high production cost and less machining quality.
- Machining necessitates sophisticated measuring tools.

1.2.2 Classification of Machining Processes

Engineering materials have been recently developed whose hardness and strength are considerably increased, such that the cutting speed and the MRR tend to fall when machining such materials using traditional methods like turning, milling, grinding, and so on. In many cases, it is impossible to machine hard materials to certain shapes using these traditional methods. Sometimes it is necessary to machine alloy steel components of high strength in a hardened condition. It is no longer possible to find tool materials that are sufficiently hard to cut at economical speeds, such as hardened steels, austenitic steels, Nimonics, carbides, ceramics, and fiber-reinforced composite materials. The traditional methods are unsuitable to machine such materials economically, and there is no possibility that they can be further developed to do so because most of these materials are harder than the materials available for use as cutting tools.

By utilizing the results of relevant applied research, it is now possible to process many of the engineering materials that were formerly considered to be nonmachinable using traditional methods. The newly developed machining processes are often called nonconventional or nontraditional machining processes (NTMPs). These are nontraditional in the sense that traditional cutting tools are not employed; instead, energy in its direct form is utilized. These processes cover recent research and development in techniques that focus on achieving high accuracies and good surface finishes of parts machined without burrs or residual stresses, especially with hard-to-cut materials that cannot be machined by traditional means.

Therefore, the machining processes are classified into traditional machining processes (TMPs) and NTMPs [1] (Figure 1.1).

1. TMPs, in which chips are formed by the interaction of a cutting tool with the material being machined. These processes employ traditional tools of a basic wedge form to penetrate into the workpiece. These tools must be harder than the material to be machined. TMPs comprises two categories:
    a. Cutting: (chipping processes) that use tools of definite geometry such as turning, planing, drilling, milling, broaching, and so on.
    b. Abrasion processes that use tools of nondefinite geometry such as grinding, honing, lapping, and so on.
2. NTMPs, in which the machining energy is utilized in its direct form. These processes are less familiar, and are desired to meet the increasingly difficult demands for which TMPs cannot be used.

NTMPs also comprise two categories (Figure 1.2):

- Abrasion processes, where the mechanical energy is used for machining of the work materials; these processes include ultrasonic machining (USM), water jet machining (WJM), abrasive jet machining (AJM), abrasive water jet machining (AWJM), and so on.
- Erosion processes using chemical and electrochemical energy such as chemical machining (CHM), electrochemical machining (ECM), and so on, or using thermal energy such as electric discharge machining (EDM), laser beam machining (LBM), electron beam machining (EBM), plasma beam machining (PBM), and so on (Figure 1.1). EDM has firmly established its use in the production of forming tools, dies, molds and effectively machining of advanced materials such as SAs, and SSs.

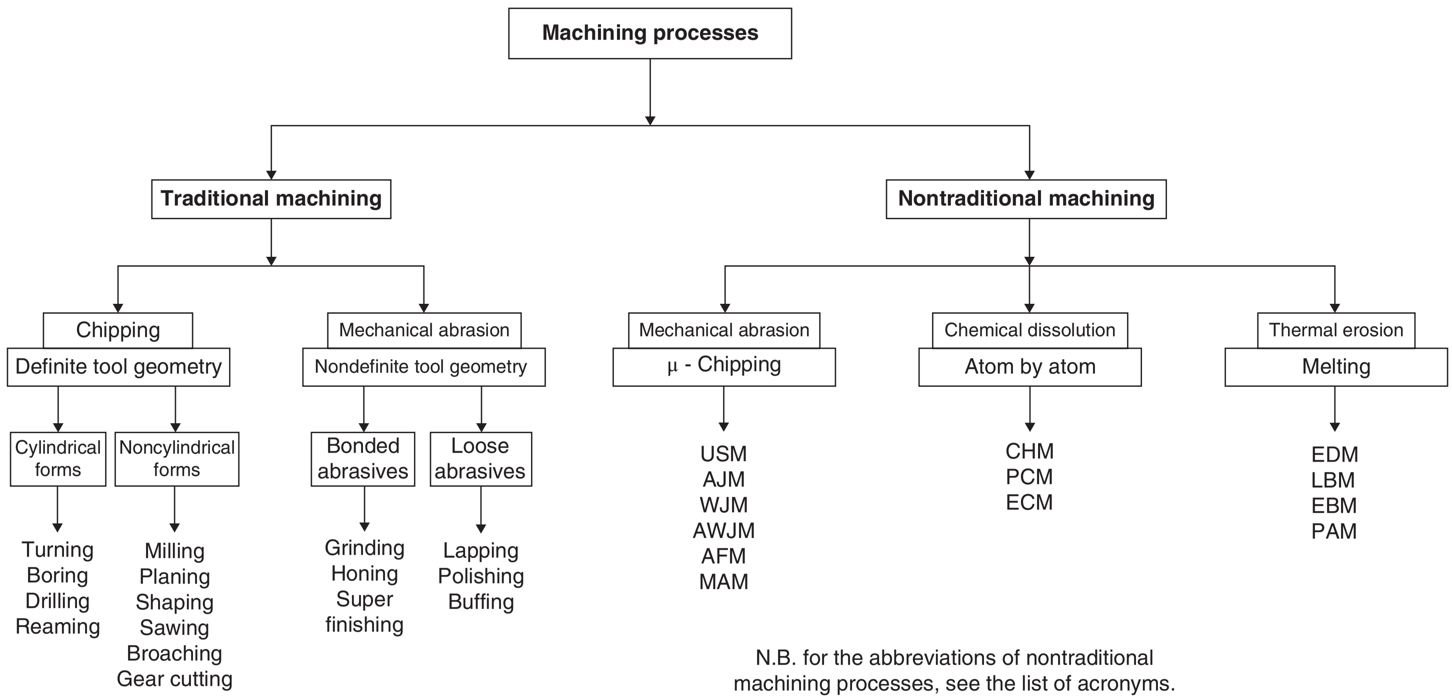

Figure 1.1 Classification of machining processes.

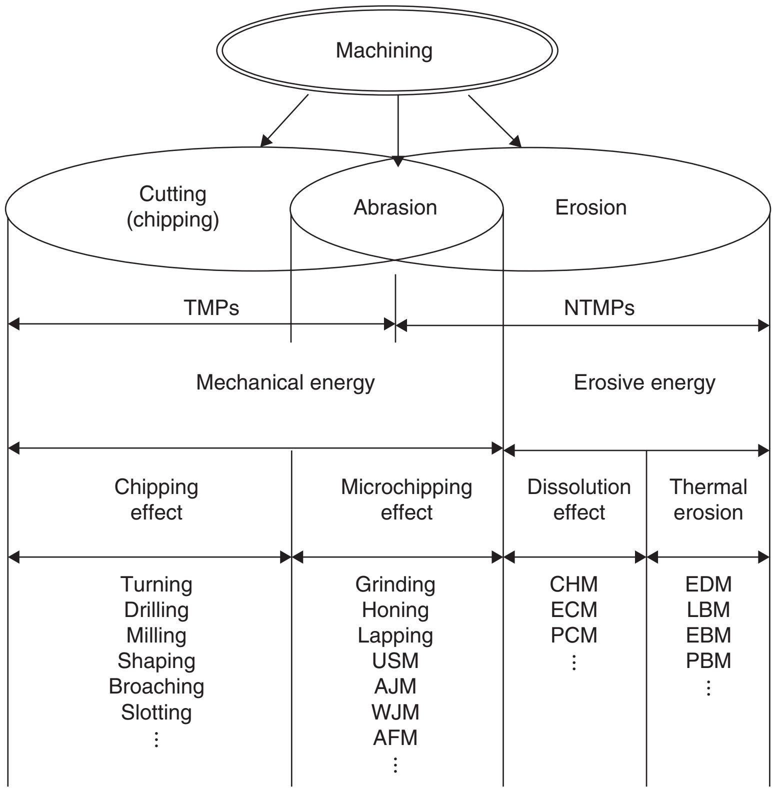

Figure 1.2 Traditional and nontraditional machining processes (From: Youssef *et al.* [1]. Reproduced with permission).

NTMPs are mostly restricted to small-scale removal of materials. They have specifically the following characteristics as compared to traditional processes:

- They are capable of machining a wide spectrum of metallic and nonmetallic materials irrespective of their hardness or strength.
- Complex and intricate shapes, in hard and extra-hard materials, can be readily produced with high accuracy and surface quality and commonly without burrs.
- The hardness of cutting tools is of no relevance, especially in many NTMPs, where there is no physical contact between the work and the tool.
- Simple kinematic movements are needed in the NTM equipment, which simplifies the machine design.
- Micro and miniature holes and cavities can be readily produced by NTM.

However, it should be emphasized that:

1. NTMPs cannot replace TMPs. They can be used only when they are economically justified or it is impossible to use TMPs.

2. A particular NTMP found suitable under given conditions may not be equally efficient under other conditions. A careful selection of the NTMP for a given machining job is therefore essential. The following aspects must be considered in that selection:
    a. Properties of the work material and the form geometry to be machined
    b. Process parameters
    c. Process capabilities
    d. Economic and environmental considerations.

1.2.3 Variables of Machining Processes

Any machining process has two types of interrelated variables. These are input (independent) and output (dependent) variables (Figure 1.3) [4]:

1.2.3.1 Input (Independent) Variables

- Workpiece material, like composition and metallurgical features
- Starting geometry of the workpiece, including preceding processes
- Selection of process, which may be TMP or NTMP
- Tool material and tool geometry
- Cutting parameters
- Work-holding devices ranging from general purpose vise to specially designed jigs and fixtures
- Cutting fluids.

1.2.3.2 Output (Dependent) Variables

- Cutting force and power. Cutting force influences deflection and chattering; both affect part size and accuracy. The power influences heat generation and consequently tool wear.
- Geometry of finished product, thus obtaining a machined surface of desired shape, tolerance, and mechanical properties.

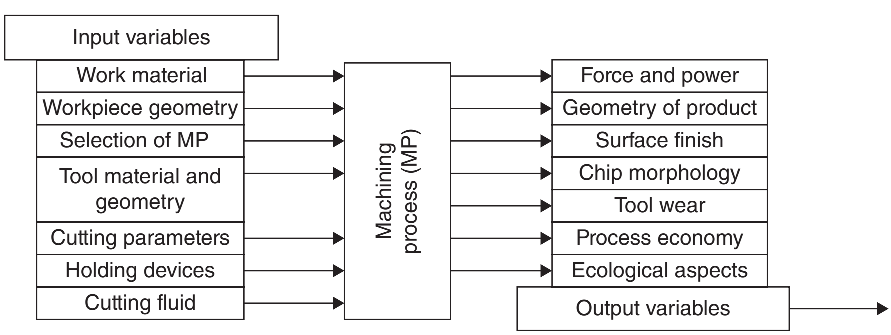

Figure 1.3 Input and output variables of a machining process.

- Surface finish: it may be necessary to specify multiple cuts to achieve a desired surface finish.
- Tool failure due to the increased power consumption.
- Economy of the machining process is governed by cutting speed, and other variables, as well as cost and economical factors. Machining economy represents an important aspect.
- Ecological aspects and health hazards must be considered and eliminated by undertaking necessary measures.

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