

SUSTAINABLE HARD MACHINING

IMPLEMENTATION AND ASSESSMENT



**ASHOK KUMAR SAHOO, RAMANUJ KUMAR
AND AMLANA PANDA**



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Sustainable Hard Machining

Sustainable Hard Machining: Implementation and Assessment analyzes the various methodologies of cooling and lubrication employed during hard machining operations, along with their potential contributions towards achieving sustainable machining. It includes the needs, challenges and trends towards sustainable hard machining of difficult-to-cut materials through the application of dry, minimum quantity lubrication (MQL), cryogenic and nanofluid assisted MQL for environmental, economic, ecological and societal benefits, leading to environmentally cleaner sustainable machining.

Features:

- Provides an introduction to hard machining, sustainability and environmentally conscious machining
- Discusses dry and minimum quantity lubrication (MQL) based hard machining
- Includes computational methods and optimization in hard machining
- Reviews nano-cutting fluids in hard machining
- Explores cryogenic cooling in hard machining

This book is aimed at graduate students and researchers in mechanical engineering, manufacturing and materials science.



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Sustainable Hard Machining

Implementation and Assessment

Ashok Kumar Sahoo, Ramanuj Kumar
and Amlana Panda



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Preface

In recent years, hard machining has evolved as an emerging manufacturing process for the benefit of many industries, including reduction of manufacturing cycles, manufacturing costs and setup times, minimization of machine tool usage, elimination of part distortion, minimization of harmful coolant usage due to dry cutting environment, minimization of investment costs and reduction of power consumption as compared to grinding in various applications. It has successively replaced the traditional grinding process and produces comparable surface finish. Sustainable manufacturing has become an important and strategic priority in order to achieve overall production efficiency considering economic, environmental and societal aspects simultaneously. The application of sustainable hard machining has been increasing in various areas of science and technology for use in the aircraft, automotive, defence, aerospace and other advanced industries. Therefore, research is essentially worthwhile to develop its application in industrial sectors. This book provides an overview of hard machining and sustainable manufacturing through machining of various hardened steels and difficult-to-cut materials. *Sustainable Hard Machining* is an indispensable reference/source book for sustainable manufacturing, process design and tool and process optimization, as well as production engineering on shop floors. The book also focuses on various cooling and lubrication strategies for sustainable machining, such as dry, MQL, nanofluid assisted MQL, cryogenic, etc. It will also benefit final-year undergraduate and postgraduate students, as it provides comprehensive information on the hard machining of difficult-to-cut materials to produce high-quality final components. *Sustainable Hard Machining* will also serve as a valuable work of reference for academics, manufacturing and materials researchers, manufacturing and mechanical engineers, and professionals in machining and machine tool technology and related industries.



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1 Introduction to Hard Machining and Sustainability

1.1 INTRODUCTION

Manufacturing can be simply defined as a value addition process by which raw materials of low utility and value are converted into high utility and valued products with definite dimensions, forms and finish, imparting desired functional ability. Solid state manufacturing processes can be broadly classified into metal forming and metal machining. During metal forming the volume is conserved and shape is achieved through deforming the material plastically in processes like forging, rolling, drawing etc. However, these mostly serve as primary or basic operations for typical products. In around 80% of components produced through metal forming, machining is essentially required to achieve dimensional accuracy, form accuracy and good surface finish in order to achieve the functional requirements.

Hard machining is the machining of materials with hardness of 45–68 HRC using different types of cutting inserts, preferably cubic boron nitride (CBN) and ceramics or similar superhard tool materials. It produces a comparably good surface finish with higher material removal rate as compared to traditional grinding. It is revealed that machining time has been reduced by as much as 60% for conventional hard turning due to the use of lower feed rate and depth of cut [1, 2]. With appropriate selection of geometrical parameters, machining parameters and environmental parameters, a better surface quality can be produced through hard machining than grinding operation. Multiple hard turning operations can be performed in a single setup rather than multiple grinding setups, which yields high accuracy. Typical benefits of hard turning include the reduction of manufacturing cycles and manufacturing costs, reduction of set up time, minimal usage of machine tools, achievable and comparable surface quality, elimination of part distortion, minimization of harmful coolant due to dry environment, minimal investment cost and less power consumption as compared to grinding in various applications [3, 4]. The application of hard machining in industrial applications is shown in Figure 1.1, and qualitative comparison between hard turning and grinding is shown in Figure 1.2 respectively [5].

These days, the combination of hard turning and grinding is performed on a single machine, to great effect, to reduce cycle times. Moreover, the process combination (hard turning and grinding) allows greater flexibility and improved component quality. A typical example of combination machining is the machining of gearwheels

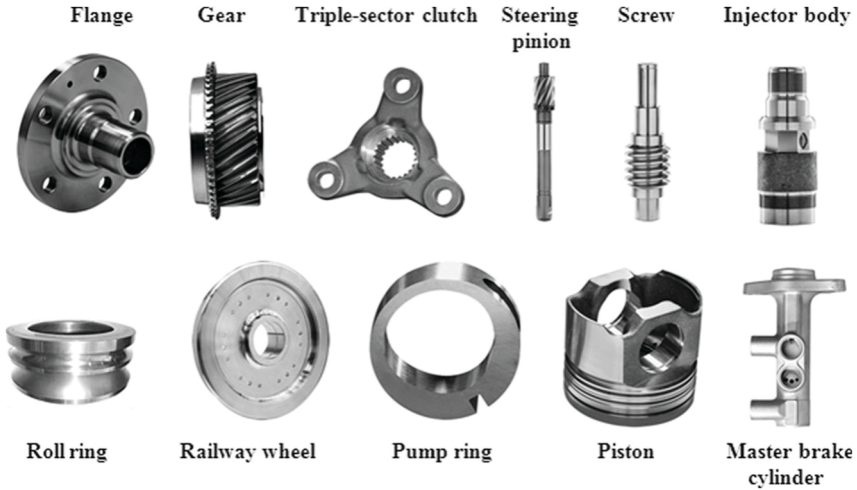


FIGURE 1.1 Industrial applications of hard-part machining. (From Ref. [5].)

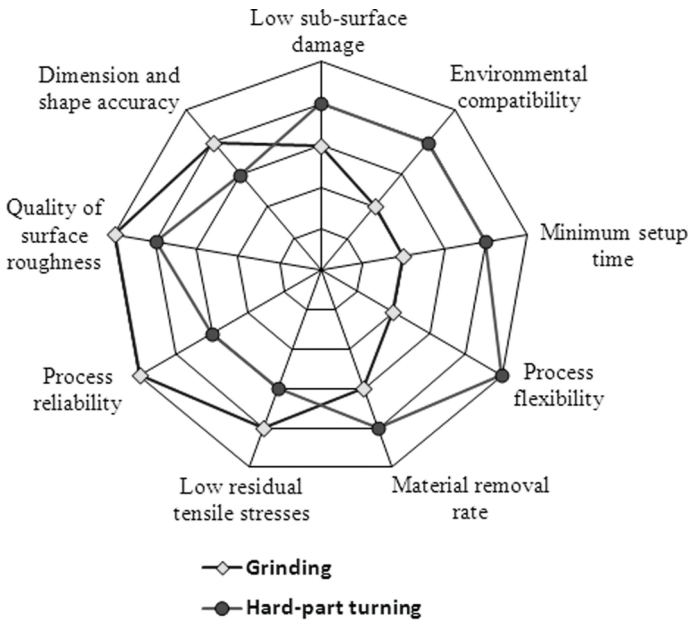


FIGURE 1.2 Qualitative comparison of hard-part turning with grinding. (From Ref. [5].)

as shown in Figure 1.3 (a). The shoulders are finish hard turned and the bore and cone are pre-turned and finish-ground because of the high demands made on their quality [5]. The scroll-free turning process is a process wherein a turning tool carries out a rolling motion which offers new opportunities in the machining of precision components. The cutting edge of an inclined CBN wheel moves over the rotating

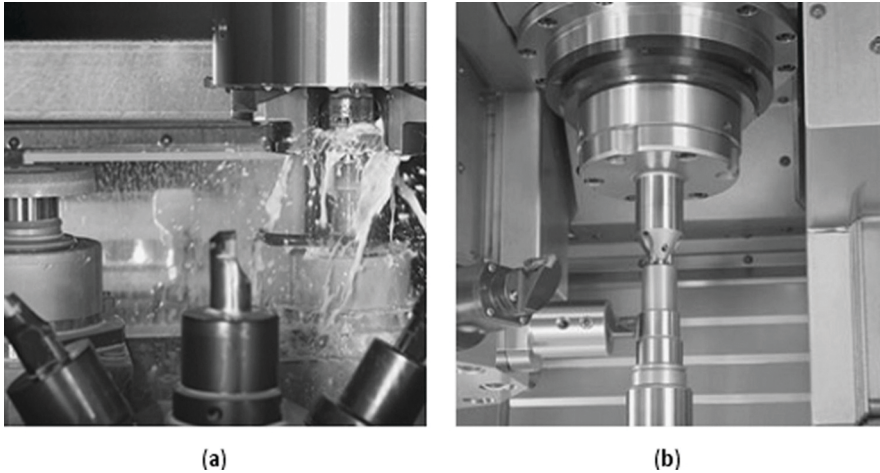


FIGURE 1.3 (a) A combination of hard turning and grinding and (b) scroll-free turning. (From Ref. [5].)

workpiece and the cutting speed is generated by the workpiece rotation, as shown in Figure 1.3 (b) [5].

The desirable properties of cutting tool materials for machining hardened steels are high hardness, high hardness-to-modulus ratio, high abrasive resistance, high thermal conductivity and high thermal and chemical stability. Hard turning is usually performed by a different range of tipped or solid inserts like CBN, polycrystalline cubic boron nitride (PCBN), ceramic tools, cermets and coated carbide [6, 7]. Carbide tools are more popular for machining alloy steels and cast iron. However, these tools possess low hardness but high toughness compared to ceramic and CBN cutting tools. To enhance the surface properties and hardness, thin hard coatings (TiC , TiN , TiCN , Al_2O_3) in single layer, bilayer or multilayer form are deposited over the carbide substrate through physical vapour deposition or chemical vapour deposition techniques. The machining performance and tool life of coated carbide cutting tools are now improved due to the high hardness, wear resistance and chemical stability of coatings compared to conventional cutting tool materials, i.e. high-speed steels, uncoated carbide. Two types of PCBN are used in machining hardened steels, i.e. high CBN content and low CBN content tools. PCBN cutting tools have high hardness, are wear resistant and have high thermal stability but are brittle and thus prone to fracture. So, for implementation of such tools in hard machining, special cutting edge preparation with larger negative rake angle is thus required to improve the strength of the cutting edge.

The following conditions are essential for successful implementation of hard turning [8].

- (i) The machine tool should have high rigidity, high surface speed and high accuracy with good surface finish, as the cutting speed during hard turning normally goes as high as 250 m/min.

- (ii) Superhard cutting tool materials with high wear resistant properties are essential during hard turning of workpieces of hardness 45 HRC or more because of the generation of higher cutting force. Popular cutting tool materials used by researchers during hard turning are CBN, PCBN, coated CBN tool inserts and ceramics as well as WC coated with TiN or CBN–TiN [9–11].
- (iii) Hard turning generates higher cutting temperature as it is operated under dry environment in which reduction of the shear strength of the work material occurs through thermal softening and subsequently favours machining. Therefore, it is advantageous to perform hard machining at higher cutting speed under dry environment. It is economical as well under dry environment.
- (iv) The rise of cutting temperature under dry hard machining causes rapid tool wear due to thermal softening and thus deteriorates surface quality and tool life. Raised cutting temperature also causes instant boiling of coolant which reduces the tool life and degrades the surface quality. Application of flood cooling in hard machining also increases the thermal stress/thermal distortions and thus induces the catastrophic failure of cutting tool materials. It is sometimes favoured for the minimization of white layer thickness and so there is always a debate about the application of coolant in hard machining, because of which it is sometimes operated under dry conditions only. But complete absence of coolant drastically affects the tool life and surface quality to some extent [12, 13].

Because of these agreements and disagreements about the application of coolant in hard machining, there is an intermediate methodology of application of coolant called minimum quantity lubrication (MQL) in the cutting zone, or near-dry machining. This will also satisfy the requirement of sustainable hard machining towards achieving environmental, ecological and economic benefits. Hard turning yields white layer formation which affects component service life. Residual tensile stress exists in hard machining that brings the limitation of its application. Hard turning also induces thermal expansion of the cutting tool and workpiece. In spite of these limitations, it has several advantages with respect to time, cost and ecology, which brings attention to the shop floors for finishing of the hardened components such as ball and roller bearings, crank pins and other automotive components and replaces grinding operation. Despite the high potential of hard machining to increase productivity and offset environmental concerns by dry cutting, and its competitiveness with grinding processes, industrial application of this technology is still rather limited. Limitations of hard turning are uncertainties like part accuracy, surface integrity, tool wear pattern, prediction of tool life and economic feasibility. Various limitations of the hard turning process are as follows:

- Tooling cost per unit is notably higher in hard machining compared to grinding.
- Existence of residual tensile stress profiles at the surface.
- Formation of white layer accelerates substantial variations in component performance.
- Errors in dimension, surface roughness and geometric form occurring from tool wear.

Considering these challenges, research in the field of hard turning will definitely be worthwhile. This may lead towards establishing a competitive and economically more effective alternative to grinding.

Appropriate selection of cutting inserts with geometry and cutting parameters during hard machining is a challenge to the machining industries and is considered as a burning issue because of tremendous pressure to achieve good surface quality. Surface quality is greatly affected by the cutting tool wear and heat generation. Thus, there is a need for optimization of cutting parameters, geometrical parameters and environmental parameters to overcome the issues related to hard machining. Appropriate development of prediction modelling is also required in order to increase the machinability of hardened materials. Therefore, research is essential and worthwhile to develop its application in industrial sectors. The requirement of surface quality during hard machining is greatly affected by the amplitude of vibration signals as the radial force component is higher. It strongly affects the surface quality with dimensional tolerances and induces vibrations and chatter. Therefore, the correlation of machining parameters with vibration signals on tool wear and surface roughness during hard machining is worthy of investigation, and these are considered as burning issues nowadays in machining industries for the improvement of productivity.

Sahoo and Sahoo [14] investigated hard turning of AISI 4340 steel using different cutting inserts under dry environment to study the progression of tool wear. The

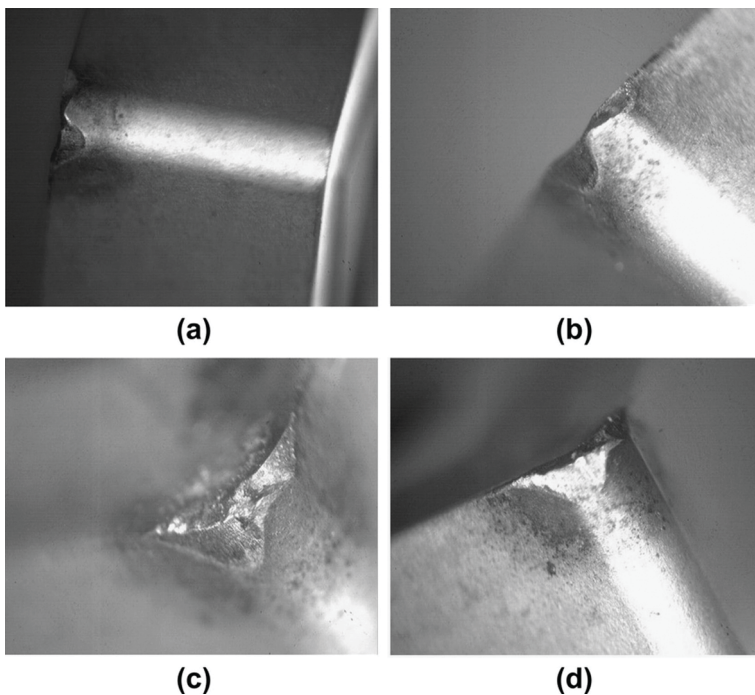


FIGURE 1.4 Tool tips of uncoated carbide insert after machining times (a) 0.46 min, (b) 0.66 min, (c) 0.9 min and (d) 1.77 min. (From Ref. [14].)

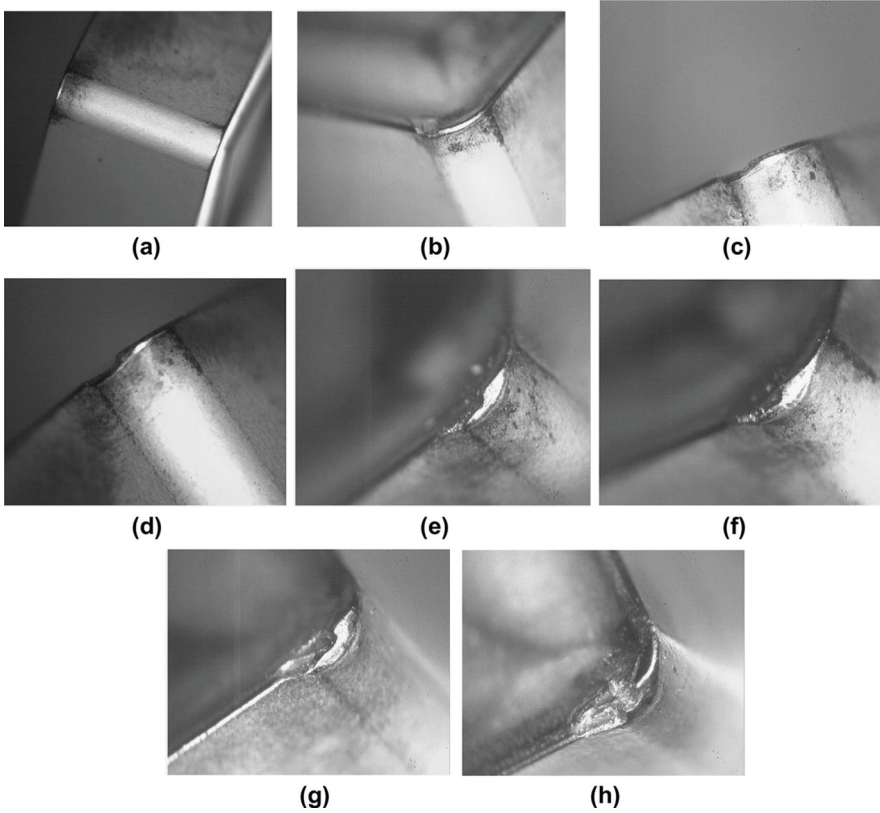


FIGURE 1.5 Tool tips of TiN coated carbide insert after machining times (a) 0.9 min, (b) 1.77 min, (c) 3.44 min, (d) 5.65 min, (e) 8 min, (f) 10.1 min, (g) 15.63 min and (h) 19.48 min. (From Ref. [14].)

results show that multilayer coated carbide inserts performed well as compared to uncoated carbide inserts in hard turning. The multilayer TiN/TiCN/Al₂O₃/TiN coated carbide insert outperformed the uncoated and TiN/TiCN/Al₂O₃/ZrCN coated carbide inserts, having steady growth of flank wear and surface roughness as shown in Figure 1.4, Figure 1.5 and Figure 1.6 respectively [14]. The tool life for TiN and ZrCN coated carbide inserts was found to be approximately 19 min and 8 min, respectively, under the extreme cutting conditions tested. The uncoated carbide insert used to cut hardened steel fractured prematurely. Abrasion, chipping and catastrophic failure are the principal wear mechanisms observed during machining.

Suresh et al. [15] studied the machinability characteristics of hardened AISI 4340 steel using coated carbide insert. Figure 1.7 (a) shows the grooves at the rake surface during machining at a cutting speed of 200 m/min, feed rate of 0.1 mm/rev, machining time of 2 min and 1 mm depth of cut. It may be attributed to the abrasive mechanism and adhesion of the material. Also, it is due to the higher stresses and thermal softening of the tool material at higher cutting temperature in this region. The

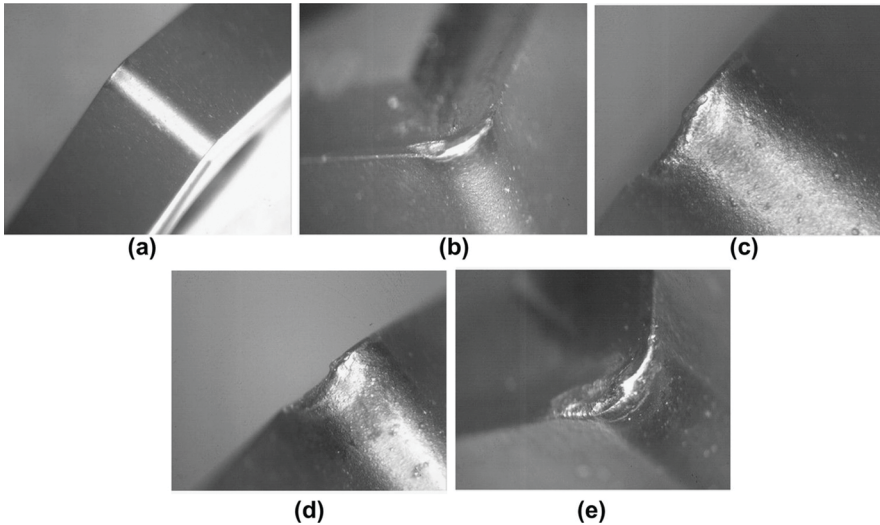


FIGURE 1.6 Tool tips of ZrCN coated carbide insert after machining times (a) 0.9 min, (b) 1.77 min, (c) 3.44 min, (d) 5.65 min and (e) 8 min. (From Ref. [14].)

tool wear mechanism of chipping at the cutting edge is clearly observed in Figure 1.7 (b) at higher parametric conditions such as a cutting speed of 260 m/min, feed rate of 0.26 mm/rev and 1.2 mm depth of cut. Better surface quality is observed at higher cutting speed with lower feed rate. At higher cutting speed with higher depth of cut, short saw-toothed loose arc thick chips were produced, as shown in Figure 1.8 [15].

1.2 SUSTAINABLE MANUFACTURING

1.2.1 NEED AND CONCEPT

The current advanced manufacturing industries are constantly focusing on alternative machining strategies to yield sustainable goals such as environment-conscious regulations without affecting the material removal rate/productivity [16]. Environmental complexities and economic development go side by side. Manufacturing industries should minimize adverse activities so as to be environmentally benign as per ISO 14000 standards. Therefore, emerging sustainability trends (e.g. the Horizon 2020 target to cut 20% of CO₂ emissions and natural resource consumption) are shifting the industry from non-degradable to biodegradable cutting oils by reducing tons of mineral based fluids (13,726 million tons in 2016 globally with 1% annual increment). Policies are set by the government to meet with requirements for product quality, productivity and environmental pollution. Therefore, there is a need to achieve sustainable manufacturing processes with minimum environmental damage, energy consumption, carbon emissions and machinability characteristics (tool wear, surface roughness and temperature) [17]. In particular, sustainability assessment plays a very crucial perspective before implementation in manufacturing

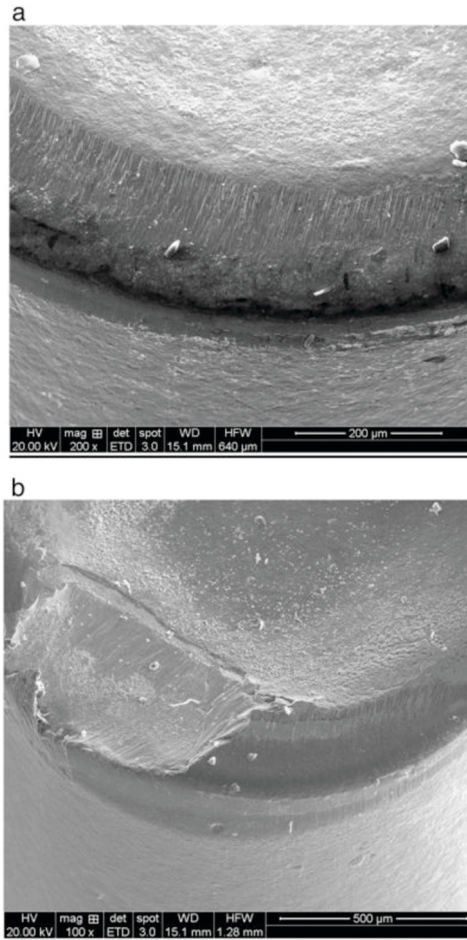


FIGURE 1.7 SEM images of the wear of the cutting tool: (a) $v = 200$ m/min, $f = 0.1$ mm/rev, $t = 2$ min and $d = 1$ mm; and (b) $v = 260$ m/min, $f = 0.26$ mm/rev, $t = 2$ min and $d = 1.2$ mm. (From Ref. [15].)

industries for cleaner machining. Sustainable manufacturing implies the manufacturing of quality products with minimum cost, i.e. economical, minimal energy/power consumption etc.

The major users of power and raw materials are the manufacturing industries. Therefore, manufacturing processes should be optimized for power and material requirements so as to have minimal ecological and economic effects. Finished components are produced with optimal usage of resources, using techniques that are economically viable, environmentally benign, ecologically and societally effective and technologically feasible. Energy efficiency with minimal CO_2 emission is the prime requirement of manufacturing industries due to strict government regulations. Therefore, sustainable manufacturing is the current requirement to manufacture

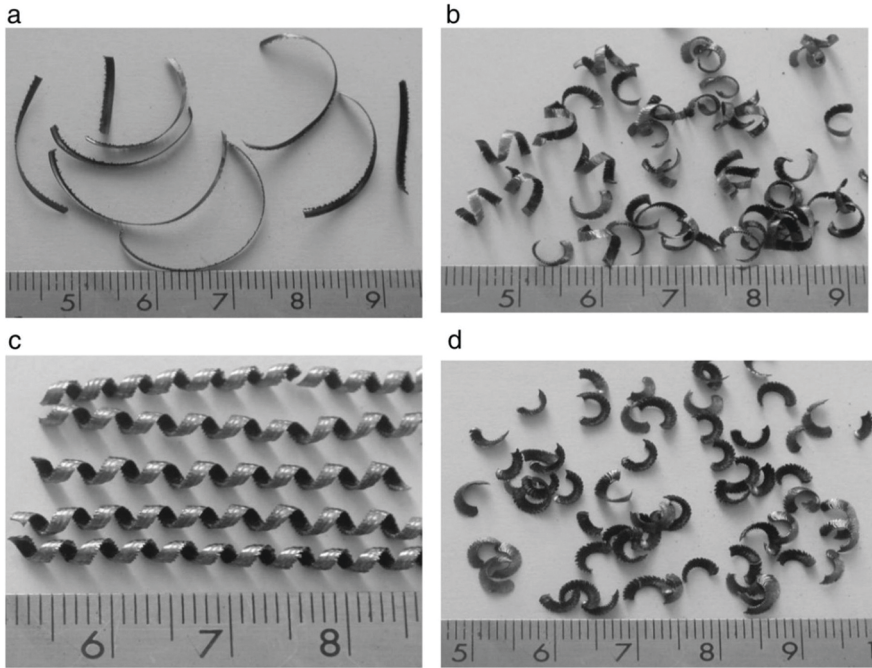


FIGURE 1.8 Aspects of chips obtained as a function of cutting conditions (30× magnification) (a) under cutting conditions $v = 140$ m/min, $f = 0.18$ mm/rev and $d = 0.8$ mm, (b) under cutting conditions $v = 260$ m/min, $f = 0.18$ mm/rev and $d = 0.8$ mm, (c) under cutting conditions $v = 200$ m/min, $f = 0.18$ mm/rev and $d = 1.2$ mm and (d) under cutting conditions $v = 260$ m/min, $f = 0.18$ mm/rev and $d = 1.2$ mm. (From Ref. [15].)

environmentally friendly products with minimal cost, a reduction of waste and maximum utilization of renewable energy sources [18–20]. Sustainability relates to the main three pillars named as i) Economic aspects, ii) Environmental aspects and iii) Social aspects.

There are three steps to achieving sustainable manufacturing: appropriate selection of the work material, sustainable manufacturing process selection and sustainable machining operation. Figure 1.9 shows the pillars of sustainable manufacturing and the steps towards sustainability [18]. Metal machining is considered as the vital industrial sector for producing desired products with accuracy and contributes to the improvement of world economies. Therefore, proper attention should be focused on various aspects such as power consumption, CO_2 emission, tool life, appropriate cutting environments, i.e. cooling/lubrication methods, and higher productivity achievements with profitability so as to be environmentally sustainable with healthy results for the operator. When these are considered, they are mapped with facets of sustainability, the green economy and the circular economy [21]. For technologically effective manufacturing, various factors need to be addressed, such as cost, manufacturing time, surface quality and adaptability. So, the economic,