J. Paulo Davim (Ed.)

Metal Cutting Technologies

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Metal Cutting Technologies

Progress and Current Trends

edited by
J. Paulo Davim

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Editor
Prof. Dr. J. Paulo Davim
University of Aveiro
Dept. of Mechanical Engineering
Campus Santiago
3810-193 Aveiro
Portugal
pdavim@ua.pt

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Preface

Metal cutting technologies have great interest for many important industries such as automotive, aeronautics, biomedical, molds, and dies. Metal cutting is a manufacturing process in which parts are formed by removal of unwanted material. The interest for this topic increased over in the 21st century, with rapid progresses in materials science, automation and control, and computers technology. This volume aims to provide research progresses in metal cutting for modern industry, namely, traditional machining processes (turning, milling, drilling), high-speed cutting, high efficiency cutting, sustainable machining, and nontraditional machining processes (electrical discharge machining, EDM).

The current volume aims to provide recent information on metal cutting technologies – progress and current trends – in seven chapters. Chapter 1 of the book provides information on the principle of minimum strain energy to fracture of the work material and its application in modern cutting technologies. Chapter 2 is dedicated to energy consumption optimization in machining processes. Chapter 3 described machining with high-pressure cooling. Chapter 4 contains information on effect of machining on the fatigue life of steels. Chapter 5 describes finite element method analysis and artificial neural network modeling for optimizing machinability indicators during dry longitudinal turning of Ti–6Al–4V extra low interstitial alloy. Chapter 6 contains information on double-tool turning. Finally, Chapter 7 is dedicated to the effect of electrical resistivity on the electrical discharge machining process.

The current volume can be used as a research book for final undergraduate engineering course or as a topic on metal cutting technologies at the postgraduate level. Also, this book can serve as a useful reference for academics, researchers, manufacturing, mechanical and industrial engineers, professionals in metal cutting technologies, and related industries. The interest of scientific in this book is evident for many important centers of the research, such as laboratories, universities, as well as industry. Therefore, it is hoped that this book will inspire and enthuse others to undertake research in this field of metal cutting technologies.

The editor acknowledges De Gruyter for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the chapter authors for their availability for this work.

J. Paulo Davim
Aveiro, Portugal
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About the editor

J. Paulo Davim received his PhD in Mechanical Engineering from the University of Porto in 1997, the Aggregate title from the University of Coimbra in 2005 and a DSc from London Metropolitan University in 2013. Currently, he is Professor at the Department of Mechanical Engineering of the University of Aveiro. He has more 30 years of teaching and research experience in Manufacturing, Materials and Mechanical Engineering with special emphasis in Machining & Tribology. Recently, he has also interest in Management/Industrial Engineering and Higher Education for Sustainability. He has worked as an evaluator of projects for international research agencies as well as an examiner of PhD thesis for many universities. He is the Editor in Chief of eight international journals, Guest Editor of journals, books Editor, book Series Editor and Scientific Advisory for many international journals and conferences. Presently, he is an Editorial Board member of 30 international journals and acts as reviewer for than 80 prestigious Web of Science journals. In addition, he has also published as author and co-author more than 10 books, 60 book chapters and 350 articles in journals and conferences (more 200 articles in journals indexed in Web of Science/h-index 35+ and SCOPUS/h-index 43+).

Contents

List of contributing authors

L.L. Alves,
IPFN,
Instituto Superior Técnico,
Universidade de Lisboa,
Av. Rovisco Pais,
1049-001 Lisboa,
Portugal
Chapter 7

Viktor P. Astakhov,
General Motors unit of Production
Service Management Inc. (PSMi),
Saline, MI, USA
Saline, MI,
Chapter 1

A. Basak,
Adelaide Microscopy,
The University of Adelaide,
Adelaide, SA, Australia
Chapter 4

I.M.F. Bragança,
ISEL,
Instituto Superior de Engenharia
de Lisboa,
Instituto Politécnico de Lisboa,
Rua Conselheiro Emídio Navarro,
1959-007 Lisboa,
Portugal
Chapter 7

U.S. Dixit,
Department of Mechanical
Engineering,
Indian Institute of Technology
Guwahati,
Guwahati 781 039,
Assam, India
Chapter 6

J. Fonseca,
Faculdade de Engenharia,
Universidade do Porto,
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal
Chapter 7

N.A. Fountas,
Laboratory of Manufacturing Processes and
Machine Tools (LMProMaT),
Department of Mechanical Engineering
Educators,
School of Pedagogical and Technological
Education (ASPETE),
GR 141 21,
N. Heraklion,
Athens, Greece
Chapter 5

Wit Grzesik,
Opole University of Technology,
Opole, Poland
Chapter 2

Witold F. Habrat,
Department of Manufacturing Techniques
and Automation,
The Faculty of Mechanical Engineering and
Aeronautics,
Rzeszów University of Technology,
12 Powstańców Warszawy Str.,
35–959 Rzeszów, Poland
Chapter 3

F. Hakami,
Department of Mechanical Engineering,
Curtin University,
Bentley, Perth,
Australia
Chapter 4

R. Kalidasan,
Department of Mechanical Engineering,
Indian Institute of Technology
Guwahati,
Guwahati 781 039,
Assam, India
Chapter 6

J.D. Kechagias,
Department of Mechanical Engineering,
Technological Educational Institute of
Thessaly, 41110 Greece
Chapter 5

Piotr Laskowski,
Research and Development Laboratory
for Aerospace Materials,
Rzeszów University of Technology,
12 Powstańców Warszawy Str.,
35–959 Rzeszów,
Poland
Chapter 3

D.E. Manolakos,
Department of Mechanical Engineering,
National Technical University of Athens,
Athens, Greece
Chapter 5

J.D. Marafona,
Faculdade de Engenharia,
Universidade do Porto,
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal
Chapter 7

Angelos P. Markopoulos,
Section of Manufacturing Technology,
School of Mechanical Engineering,
National Technical University of Athens,
Heroon Polytechniou 9,
15780 Athens, Greece
Chapter 3

A. Pramanik,
Department of Mechanical Engineering,
Curtin University,
Bentley, Perth,
Australia
Chapter 4

P.A.R. Rosa,
IDMEC,
Instituto Superior Técnico,
Universidade de Lisboa,
Av. Rovisco Pais,
1049-001 Lisboa,
Portugal
Chapter 7

S. Senthilvelan,
Department of Mechanical Engineering,
Indian Institute of Technology
Guwahati,
Guwahati 781 039,
Assam,
India
Chapter 6

N.M. Vaxevanidis,
Laboratory of Manufacturing Processes
and Machine Tools (LMProMaT),
Department of Mechanical Engineering
Educators,
School of Pedagogical and
Technological Education (ASPETE),
GR 141 21,
N. Heraklion
Athens, Greece
Chapter 5

Xinran Xiao,
Department of Mechanical Engineering,
Michigan State University,
East Lansing, MI,
USA
Chapter 1

Viktor P. Astakhov and Xinran Xiao

1 The Principle of Minimum Strain Energy to Fracture of the Work Material and Its Application in Modern Cutting Technologies

Abstract: This chapter introduces, explains, and exemplifies a physics-based "flagship" concept called the principle of minimum strain energy to fracture (PMSEF) to be used in metal cutting research, design of practical machining operations and cutting tools, as well as assessment of composition and properties of work materials in terms of their machinability. The concept is based on the definition of metal cutting as purposeful fracture of the work material and on the fact that the energy of plastic deformation (EPD) of the layer being removed in its transformation into the chip constitutes up to 75% of the total energy supplied to the cutting system. According to PMSEF, EPD can be reduced by altering stress triaxiality in the deformation zone. The application of PMSEF leads to greater tool life, lower temperatures in the machining zone and cutting force, and higher accuracy of machining.

The correlation of the rake angle and shape of the tool rake face with EPD was revealed using the established influence of stress triaxiality in the deformation on the total strain at fracture of the work material. It is demonstrated both numerically and experimentally that this triaxiality has significant effect on the total strain and thus on EPD. It is also discussed that feasible methods of improving machinability of the work material should include PMSEF in their foundation.

1.1 Introduction

Machining is one of the oldest, yet still most common, manufacturing operations with a wide range of techniques such as turning, milling, drilling, grinding, etc. Unfortunately, machining also appears to be one of the least understood manufacturing processes. Many of today's machining operations are carried out under suboptimal conditions. A recent survey about the machining efficiency in automotive and mold-making industries [1] reveals the following five major issues: 1. The correct cutting tool geometry is selected less than 30% of the time; 2. The tool is used at the rated cutting regime only 48% of the time; 3. Only 57% of the tools are used up to their full tool-life capability; 4. The correct tool material is selected less than 30% of the time; and 5. The correct cutting fluid (coolant) parameters are used 42% of the time.

The low machining efficiency is a major obstacle in advanced manufacturing. In the last decade, with the advance of computer control, sensing, metrological techniques, and multiaxis Computer Numerical Control (CNC) machines, fully automated manufacturing cells and production lines became commonplace. For example, in a state-of-the-art power train plant, one operator is responsible for two production cells, each consisting of six CNC machines. These CNC machines are priced at over \$1,000,000 each. In these production environments, the manufacturing cost is measured by \$/minute. In such a manufacturing environment, the cost of cutting tools hardly exceeds 6% of the direct manufacturing cost. This small percentage alienates many managers with pure business backgrounds, causing reduced funding for metal cutting and cutting tool development efforts.

In the authors' opinion, however, such a direct-tooling-cost consideration is simply misleading and thus wrong. Although a business case can be made for any industry where machining efficiency is of concern, let's consider two important issues related to the automotive industry:

1. For CNC machining centers and manufacturing cells, operating cost is approximately \$1.20/min (the commonly used benchmark); for 2,200 operating hours per year, \$1.20 minute means an operating cost of \$158,400 per year for just one machine (cell). Even factoring in 80% efficiency for loading/unloading, changing tools, and setup, an increase in the penetration rate by 50% amounts to a potential yearly savings of \$63,360 per CNC machining center per year. Often, doubling machining productivity can be accomplished with the use of an advanced tool (drills, milling tool, reamers, etc.) capable of high penetration rate (HP tools).
2. The downtime caused by cutting tool premature failures has rapidly become the most costly factor in automated machining operations. Sporadic cutting tool failure is the major hurdle in the application of the fully automated unattended manufacturing cells and production lines. Unfortunately, the issue of machine tool downtime continues to plague the industry.

The saving of the operating cost is self-obvious, whereas an issue with downtime is not clear for many specialists in the field. Downtime can be considered as any duration of time during which no machining operation is being performed. This downtime can be thought of as consisting of two major parts. The first part, which can be referred as the scheduled downtime, is included in the cycle time and thus in efficiency analysis (termed as the unavoidable downtime). It includes the loading–unloading time, time needed for transportation between stations/machines, tool change and inspection time, spindle speed ramp-up time, and maintenance time. The second part of the downtime, which can be referred as the uncontrolled downtime, is caused by tool failures.

The scheduled downtime with old machining and manufacturing technology (manual loading–unloading, part and tool setting on the machine, part gaging in the machine, etc.) was so significant that the reduction of machining time did not affect the machining efficiency. As a result, a reduction of the machining operating time due to the use of advanced (and thus more expensive) cutting tools and optimization of machining processes was not requested, and, therefore, discouraged as manufacturing professionals did not see any benefits of such activities.

This has been rapidly changing since the beginning of the 21st century as global competition forced many manufacturing companies, first of all car manufacturers, to increase efficiency and quality of machining operations. To address these issues, leading tool and machine manufacturers have developed a number of new products – new tool materials and coatings, new cutting inserts and tool designs, new tool holders, powerful precision machines, part fixtures, advanced controllers that provide a wide spectrum of information on cutting processes, and so on. These increase the efficiency of machining operations in industry by increasing working speeds, feed rates, tool life, and reliability. These changes can be called the "silent" machining revolution as they happened in rather short period of time. Implementation of the listed developments led to a stunning result: for the first time in the manufacturing history, the machining operating time became a bottleneck in the part machining cycle time. Therefore, the implementation of high-penetration rate tools and well-designed machining operations became a necessity.

The uncontrolled downtime due to tool failures was not in the center of interest of researchers and engineers for years because (1) it was insignificant compared to the scheduled downtime; (2) speed and cutting feed were relatively low so that cutting tool failed by wear, which was periodically controlled; and (3) the costs of tool failure was low as cutting tools were relatively inexpensive and their failures did not bring much damage to the machining system (machine, part fixture, and workpiece). However, times have changed so that the uncontrolled downtime has gradually become significant. Tool failure today is a major cause of unscheduled stoppage in a machining environment and is costly not only in terms of time lost, but also in terms of capital destroyed [2]. Some estimates state that the amount of downtime due to tool breakage on an average machine tool is on the order of 6.8%, while when tool failures are considered, the figure is closer to 20% [3]. Even if the tool does not fail during machining, the use of excessively worn or damaged tools can put extra strain on the machine tool system and cause a loss of quality of the finished part.

Another important, but routinely ignored, aspect of cutting tool failure is the failure's effect. For example, a failure of a small, $100 carbide drill can result in a significant downtime in a high production rate automotive plant. This downtime ranges from a half-hour downtime (for the removal of scrap parts and resetting the manufacturing line/cell to its normal operating condition) to weeks when a special drill is used (common in the automotive industry) and when all drills from the inventory were damaged (broken) due to drilling-system-related issues. This is because the lead time for such a drill can be significant (up to 8 weeks).

Other issues directly correlated with a tool failure are the amount of scrap and cost of part (or sometimes, units) containment, including their part-by-part manual inspection and sometimes dissembling the units with potentially defected parts. When a tool breaks, the following losses are involved: (1) the cost of the broken tool; (2) the cost of the scrap parts (part material and previous handling/manufacturing); (3) downtime for removing scrap parts, removing the broken tool and installing a new one, and resetting a manufacturing cell/production line. Provided that the cutting tool broke due to extensive wear (the most common case), and owing to the fact that the machined parts are gaged only periodically (e.g., each 50th or 70th part), the common quality procedure in the automotive industry requires that all parts machined since the last inspection (gauging) prior to tool breakage or failure should be recalled from a buffer/assembly and checked manually.

The foregoing discussion suggests an imminent need for advanced tools and machining operations/technologies designed using the cutting theory (modeling and verification) and thus for greater quality and reliability [4]. In the authors' opinion, a sound metal cutting theory is of prime importance for the development of modern machining technologies and cutting tools.

As quaint as it sounds in retrospect, a realistic cutting theory can, and thus should, be of a great assistance in the design of practical machining operations. "There is nothing more practical than a good theory," wrote Lewin [5]. Lewin's message was twofold: theorists should try to provide new ideas for understanding or conceptualizing a (problematic) situation – ideas that may suggest potentially fruitful new avenues of dealing with that situation. Conversely, applied researchers should provide theorists with key information and facts relevant to solving a practical problem – facts that need to be conceptualized in a detailed and coherent manner. More generally, theorists should strive to create theories that can be used to solve practical problems, and practitioners and researchers in applied metal cutting should make use of available scientific theory.

This chapter aims to introduce and explain a physics-based "flagship" concept called the principle of minimum strain energy at fracture (PMSEF) to be used in metal cutting research, design of practical machining operations and cutting tools, as well as assessment composition and properties of work materials in terms of their machinability.

1.2 General structure of the proposed approach

The structure of the proposed approach is represented by a flow chart shown in Fig. 1.1. As can be seen, it includes four major blocks and two subblocks. The essence of each shown block and the logical relationships between the blocks are discussed below.

1.2.1 Block 1: Definition of the metal cutting process

The proper definition of any physical process not only constitutes the physical essence of this process, but also provides essential means for process control and thus optimization. It has to be specific to capture the major distinctive features of the process that distinguish the defined process from other closely related processes.

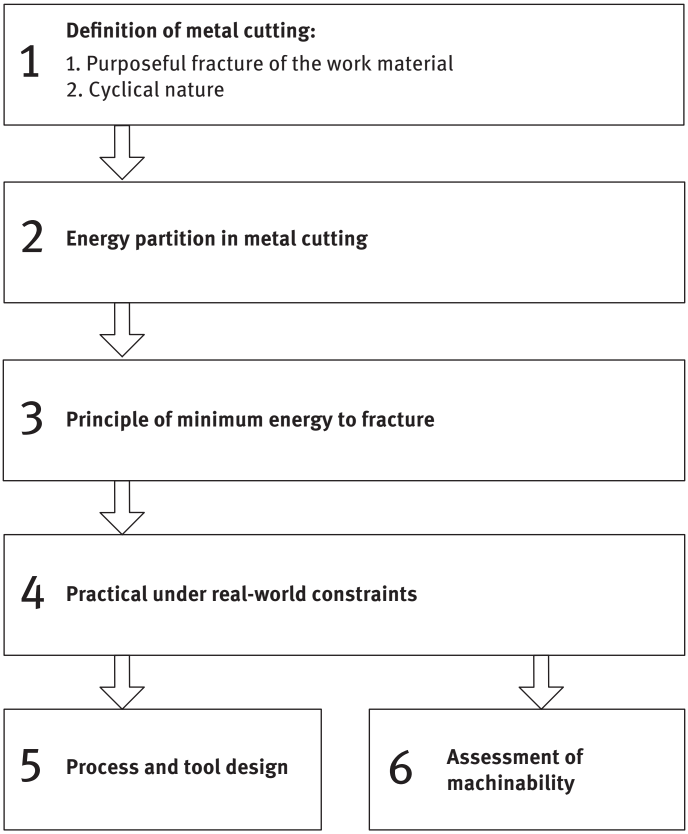

Fig. 1.1: Structure of the proposed approach.

Further considerations are based on the metal cutting process definition formulated by Astakhov [6] as:

> *The process of metal cutting is defined as a forming process, which takes place in the components of the cutting system (the tool, workpiece, and partially formed chip) that are so arranged that the external energy applied to the cutting system causes the purposeful fracture of the layer being removed. This fracture occurs due to the combined stress, including the continuously changing bending stress, causing a cyclical nature of this process.*

Distinguishing the metal cutting from other closely related manufacturing process/operations (e.g., stamping, punching, drawing, and rolling), this definition implies the following distinctive features of the metal cutting process:

1. *Bending moment*. The bending moment forms the combined stress in the deformation zone that significantly reduces the resistance of the work material to cutting. As a result, metal cutting is the most energy-efficient material removal process (energy per removed volume accounting for the achieved accuracy) compared

to other closely related processes. It is interesting to note that the presence and importance of the bending moment as a distinguishing feature of metal cutting was pointed out and explained in detail by Taylor in his famous classical paper published in 1907 [7].

2. *Purposeful (micro)fracture of the layer being removed under combined stress*. The fracture occurs in each successive cycle of chip formation.
3. *Cyclical nature*. Metal cutting is inherently a cyclical process. As such, a single chip fragment is formed in each chip formation cycle. As a result, considered at the appropriate magnification, the chip structure is not uniform. Rather, it consists of chip fragments and connectors [8]. The frequency of the chip formation process (known also as the chip segmentation frequency) primarily depends on the cutting speed and on the work material. The cutting feed and the depth of cut (>1 mm) have very small influence on this frequency [8].

1.2.2 Block 2: Energy partition in the cutting system

1.2.2.1 Model

Any technical system exists if and only if the amount of energy required by its functioning is supplied to this system. The energy flows within the components of a system in their dynamic interactions. The distribution of this energy over the system's components is known as energy partition. Such interactions can occur in any physical, chemical, etc., process if the amount of energy for a particular process is sufficient in a particular interaction. Therefore, an analysis of energy partition in any technical system is of prime concern in the design and optimization of this system.

The major objective of the cutting system is to remove a certain volume of the work material from the rest of the workpiece so that the energy required for this removal, E_{rm}, should be a starting point in the analysis of energy partition in this system. The determination of this energy is the most important step in the analysis, as the known approaches to the modeling of metal cutting mainly differ in this respect. Therefore, the determination of this energy and its optimization is in major focus of the foregoing consideration and thus will be discussed in further detail.

Once energy E_{rm} is determined, the further analysis of energy flow in the cutting system can be carried out. Ideally, if there are no energy losses in the cutting system, the energy supplied to the cutting system, E_{cs}, is transmitted through the cutting tool having the cutting tool energy E_{ct} to the partially formed chip with the chip energy E_{ch}, which is equal to the energy needed for the separation of the layer being removed, E_{sp}, i.e., $E_{cs} = E_{ct} = E_{ch} = E_{rm}$. In real cutting systems, however, energy losses occur due to elastic and plastic deformations of their components as well as friction losses during various interactions of these components. These energy losses are converted into thermal energy, which in turn flows as heat, affecting these losses even further. Therefore, energy flows in the components of the cutting system and losses occurring in

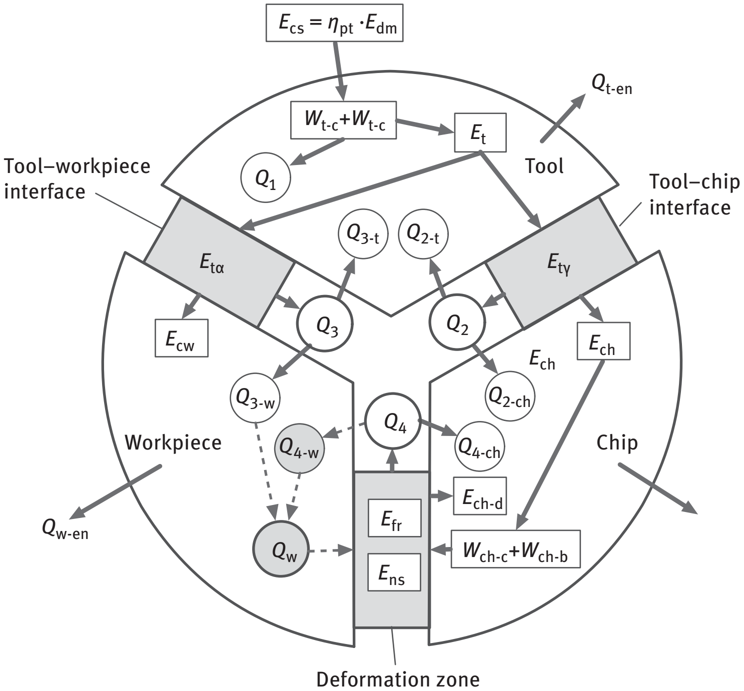

Fig. 1.2: Graphical representation of energy flows in the metal cutting system.

such flows should be considered in the design and optimization of the cutting system parameters and regimes.

Figure 1.2 shows a schematic model of the cutting system. As energy flows from the source, this model schematically represents the energy partition in the components of the cutting system starting with the total energy supplied to this system, E_{cs}. This energy is a part of the energy produced by the drive motor, E_{dm}. Obviously

$$E_{cs} = \eta_{pt} \cdot E_{dm}, \tag{1.1}$$

where η_{pt} is the efficiency of the power train system of the machine tool. Note that for modern machine tools with motor-spindle units, this efficiency is high (almost 99.5%, i.e., $\eta_{pt} = 0.995$), whereas for older machines with gearboxes it can be as low as 85%, i.e., $\eta_{pt} = 0.85$.

1.2.2.2 Cutting tool

The first component of the cutting system is the cutting tool. According to the energy conservation law, the work done over compression ($W_{t\text{-}c}$) and bending ($W_{t\text{-}b}$) of the cutting tool transforms into its potential energy (E_t) and is also partially spent on internal friction during deformations, which results in heat generation (Q_1). Normally,