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Finite-element analysis and simulation of machining: a bibliography (1976–1996)

Jaroslav Mackerle *

Linköping Institute of Technology, Department of Mechanical Engineering, S-581 83 Linköping, Sweden

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Abstract

This paper gives a bibliographical review of the finite-element methods (FEMs) applied to the analysis and simulation of machining. The bibliography at the end of the paper contains references to papers, conference proceedings and theses/dissertations on the subject that were published in 1976–1996. The following topics are included: material removal and cutting processes in general, computational models for specific machining processes, effects of geometric and process parameters, thermal aspects in machining, residual stresses in machining, dynamic analysis and control of machine tools, tool wear and failure, chip formation mechanism, and optimization and other topics, respectively.

Keywords: Finite-element method; Machining; Bibliography

1. Introduction

Machining is a term covering a large collection of manufacturing processes designed to remove material from a workpiece. The primary machining processes are: turning, shaping, milling, drilling, sawing, abrasive machining, and broaching. Some advanced machining methods used today are: electric discharge machining (EDMs), laser cutting, chemical milling, high-pressure water cutting, electrochemical machining, etc.

Turning is the machining process used to generate external, cylindrical forms by removing material by a cutting tool. Boring is internal turning to generate internal shapes. Shaping processes remove material from surfaces through the use of a single-point tool supported by a ram that reciprocates the tool in a linear motion against the workpiece. Milling is a process for generating surfaces by removing a predetermined amount of material from the workpiece. It employs motion between the workpiece and the rotating cutting tool. Drilling is an operation for producing round holes in materials. Sawing is a process of cutting a workpiece with power saws of various geometry. The grinding process is an abrasive machining process where material is removed from a workpiece in small chips/particles by the mechanical action of abrasive particles. Finally, broaching is a process where a cutting tool that has multiple transverse cutting edges is pushed/pulled through a hole or over a surface to remove material by axial cutting. The terminology and detailed explanation of machining and metalworking operations can be found in [1,2].

The direct experimental approach to study machining processes is expensive and time consuming, especially when a wide range of parameters is included: tool geometry, materials, cutting conditions, etc. The alternative approaches are mathematical simulations where numerical methods are applied. Amongst the numerical procedures, the finite-element methods (FEMs) are the most frequently used. To study machining is a quite complicated task where complex disciplines such as metallurgy, elasticity, plasticity, heat transfer, contact problems, fracture mechanics, and lubrication are involved. The goal of finite-element analysis is to derive a computational model predicting the deformations, stresses and strains in the workpiece, as well as the loads on the tool working under specific cutting parameters.

Several finite-element techniques are available today for accurate and efficient modelling of the machining

* Tel.: +46 13 281111; fax: +46 13 282717.

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process: material and geometrical non-linear analysis, mesh rezoning techniques, element-separation for chip formation modelling, element separation criteria, tool-wear modelling, residual stress prediction, etc. In many cases the FEM simulations have also been validated by comparisons with the results of experimental investigations.

This paper gives a review of published papers dealing with FEMs applied in the area of machining processes. The subject is too large to be covered extensively in a single paper, therefore only a synoptic view will be given. For a more efficient information retrieval, the lists of references of papers published between 1976 and 1996 are divided into the following topics: (i) material removal and cutting processes in general; (ii) computational models for specific machining processes; (iii) the effects of geometric and process parameters; (iv) thermal aspects in machining; (v) residual stresses in machining; (vi) dynamic analysis and control of machine tools; (vii) tool wear and failure; (viii) the chip formation mechanism; and (iv) optimization and other topics.

This paper is organised into two parts. In the first part each topic is handled and current trends in the application of finite-element techniques are mentioned. In the second part, an appendix, papers published in the open literature for the period 1976–1996 on the subjects presented above are listed. References have been retrieved from the author's database, MAKEBASE [3,4]. Readers interested in finite-element literature in general are referred to [5] or to the author's Internet Finite Element Book Bibliography (http://ohio.ikp.liu.se/fe/index.html).

2. Material removal and cutting processes in general

This section deals with the investigation of metal cutting processes in general. These processes are dependent on the workpiece parameters (material type, crystallography, temperature, pre-deformation), cutting tool parameters (tool design geometry, material), and cutting parameters (speed, feed, depth of cut, environment). Some studies have been done that include the influence of only a few specific topics, other, more advanced studies, have been conducted to understand the complex physical behavior underlying the specific machining process.

Two basic models are in focus: orthogonal (two-force) models, and oblique (three-force) models. Most machining processes are oblique but the orthogonal model studies are easier to simulate and they can be useful/adequate for understanding the basic mechanics of machining processes.

The topics included in this section on numerical simulations of material removal are: the material-removal process; surface development; orthogonal cutting; oblique cutting; sheet cutting; intermittent/interrupted cutting; conception of machine tools; cutting tool performance; metal flow studies; shear-band phenomena; strain localization; workability issues; contact stresses and friction in machining; tool–work interactions; the workpiece in a machining fixture; high-speed machining; machining additives.

The types of analysis are: 2-D and 3-D; material and geometrical non-linearity; thermomechanical; thermoelastic–plastic; thermo–viscoplastic; elasto–plastic; viscoplastic; rigid–plastic; large deformation; ALE thermomechanical; Eulerian; adaptive remeshing.

The types of material are: metal; steel; aluminium; titanium alloy; nickel-base superalloy; ceramic; composite; polymer; ceramic tools; carbide tools; tungsten carbide tools; diamond tools.

3. Computational models for specific machining processes

Listed references are sorted into the following categories: turning, milling, drilling, sawing, grinding, broaching, and advanced machining; in the last category subjects such as EDM, laser cutting, electrochemical machining, flame cutting, high-pressure water cutting, ultrasonic machining, nanoscale cutting etc. are included.

The machining of composites, especially of metal matrix composites, causes particular problems such as greater tool wear; also the hardness of the ceramic fibres and particles is too high. Usually polycrystalline diamond-tipped tools are necessary for the successful machining of metal–matrix composite.

Physical understanding of microcutting is necessary for developing and improving the process of ultraprecision metal cutting technology. FEMs have also been used to simulate nanoscale cutting. The purpose of these studies was to clarify the chip removal of nanoscale cutting and to reexamine the cutting process in general.

The topics included in this section are: *turning*—turning and tool fracture; tool wear in turning; dynamic response in turning; machining accuracy in turning; thermal behavior of a tool during turning; cutting and clamping forces in turning; design of legs for a lathe; single point diamond turning; interrupted turning and tool chipping; finish turning; *milling*—modal analysis of a milling machine; dynamic response in milling; tool and tool beds design; machine-tool modelling; wear of tools in milling; analysis of cutting forces; thermal problems in milling; design of a mill spindle; face milling; plain milling cutter; helical milling cutter; end milling; hot strip milling; milling of thin-walled sections; *drilling*—dynamic response in drilling; thermal problems in drilling; design of drills; drill wear; torsional strength for twist drill; drills under bending; residual stresses in drilling; hole-drilling method of residual stress measurements; composites during drilling; burr formation in drilling; twist drills; multifacet drills; thick web drills; radial drilling machines; high speed precision drilling; *sawing*—modal analysis of a band system; dynamic response in sawing; sawtooth interface simulations; sawing of composites; band saw blades; circular saw rolls; *grinding*—thermal problems in grinding; machine–tool interaction; grinding and phase transformation; residual stresses in grinding; design of grinding wheels; fracture of grinding wheels; bonded grinding wheels; abrasive and superabrasive grinding wheels; grinding burrs; creep-feed grinding; high-speed grinding; ultrahigh-speed grinding; cylindrical transverse grinding; plunge grinding; surface grinding; wet grinding; crankpin grinder; microgrinding; *broaching*—tool–workpiece in broaching; forces, power, stress and displacement in broaching; *advanced machining*—laser machining; ultrasonic machining; electrochemical machining; surface micromachining; nanoscale cutting; superprecision machining; EDM; plasma and flame cutting; high-pressure water jet cutting; *applications in*—electronics, acoustics, precision engineering, machining of composites, machining of ceramics.

4. Effects of geometric and process parameters

For every machining operation it is necessary to select a cutting speed, a feed, and depth of cut. New cutting tool materials and tool geometries are improving product quality and manufacturing productivity. Papers presented in this section try to study the connections between these input variables and process behavior. A large number of the input variables makes it almost impossible to deal with a such complex situation. Available mathematical models try to predict the direction of the shearing process of metal cutting, cutting forces, tool wear, etc. The main objective of research is to apply the FEM to study the effects of geometric and process parameters in the process of machining.

Some of the topics included are: tool geometry effects on the cutting of hardened/quenched steels; the effects of tool geometry on chip flow and wear; tool life owing to engagement angle; rake-angle effects on orthogonal cutting; the effects of tool geometry on punching; the effects of tool geometry on dynamic vibrations; the modelling of machining under various cutting conditions; metal cutting parameters and manufacturing accuracy.

5. Thermal aspects in machining

High temperatures in machining are the cause of unsatisfactory tool life and limitations on cutting speed. Various numerical and experimental techniques are available to study the flow of cutting heat and the temperature distribution within both the workpiece and the tool. The role of temperature becomes more important with increasing cutting speed and the usage of more advanced ceramic materials. The thermal model of a machine tool should account for the following heat-transfer situations: heat conduction, heat conduction across contact zones, radiation, forced convection along rotated element surfaces, free convection along external surfaces, and convection along the body surfaces that is caused by rotating parts. The finite-element model should preferably be in 3D.

A note on the grinding process: grinding requires an extremely high energy input per unit volume of material removal compared with other machining processes. Almost all of the energy is converted to heat in the grinding zone. An elevated temperature occurs in the grinding wheel as well as in the workpiece.

The topics included in this section: temperature distribution in machining; the effect of contact pressure on heat transfer in machining; the influence of process variables on the temperature distribution; heat flow through a cutting tool; tool–work interface temperature; thermal cracking of cutting tools; control of thermal deformations; cooling in machining; effect of thermal load on the residual stress; thermal phenomena in—orthogonal machining, orthogonal micromachining, high-speed machining, milling, drilling, boring, grinding, interrupted turning, grinding, honing, laser cutting; cutting temperature in ceramic tools; thermal phenomena in bonded carbide tipped tools.

Type of analysis: 2D and 3D analysis; thermomechanical coupling; thermoelastoplastic large deformation analysis; thermoviscoplastic analysis; ALE thermomechanical analysis; rigid-plastic FEM; simulation of moving heat sources; adaptive remeshing techniques; thermal error modelling; improved thermal simulation by help of experimental data.

6. Residual stresses in machining

The machining process evokes a residual stress in the surface layer. The main cause of a residual stress is the phase transformation of the surface material. Distortions and residual stresses are unwanted results from abusive machining conditions. The residual stresses on the machining surface is an important factor in determining the performance and fatigue strength of components.

Some of the topics included are: analysis and measurement of residual stresses in machining; plasticity effects on residual stress measurement; effect of thermal and mechanical loads on residual stresses; residual stresses due to a moving heat source; the effect of cutting on the redistribution of residual stresses; the effect of tool condition on residual stresses; hole-drilling technique for measuring residual stresses; residual stresses in orthogonal metal cutting; residual stresses in metal grinding; residual stresses in the grinding of metal–matrix composites.

7. Dynamic analysis and control of machine tools

The whole cutting system includes a spindle, bearings and a cutter. The design of the spindle system dynamic characteristics is based on the variation of parameters such as the bearing preload, the bearing spacing, mass inserts on the spindle and damping. The dynamic characteristics of the spindle assembly affects the cutting ability of the whole machine.

In turning, which is a widely used machining process, self-excited or chatter vibration is a serious problem that effects the deterioration of the surface finish, affects the dimensional accuracy of the workpiece, and reduces the tool/machine lifetime. Also, forced vibrations can be induced in machine tools by component defects, unbalanced parts, poor assembly, etc. To study dynamics in turning and to reduce/suppress chatter vibration is a very important task. Fundamental studies of this complex process are still needed.

Vibration from a milling cutter occurs during machining due to slenderness and long overhang, and generates waviness on the machined surface and hence deterioration in machining accuracy/quality. There are two different approaches to study the dynamic response during machining: one is a cutting force model that does not contain many cutting parameters; the second approach is a structural dynamic model of the whole cutting system.

The topics included in this section are: cutting process dynamics; studies of dynamics phenomena in milling, grinding, turning, drilling; machine tool bed dynamics; parameter identification of machine tools; damping treatment; vibrations of machine tools; dynamic analysis of lathe spindle assembly; dynamic analysis of a high-speed spindle-bearing assembly; dynamic analysis of high-speed drilling; the dynamics of a machining robot; dynamic analysis of a saw blade; the suppression of a chatter vibration; boring bar chatter control; vibration control of cutting processes; vibration control of boring; vibration control of ultrasonic tooling.

8. Tool wear and failure

The failure of mechanical components is caused primarily by fatigue. In machining, mechanical and thermal loads, and phase transformation, are main factors that affect the surface integrity of a machined part. Plastic deformation and friction in the contact between the tool and the workpiece generate heat, which raises the temperature of both components. The elevated temperature of the tool reduces its wear resistance and changes both the geometry and the size. This can result in increased cutting forces with larger deflections in the workpiece and may create a chatter condition.

Cutting tools are changing constantly with new types of materials, special tool coatings and new types of cutters, mills, drills, etc. High-speed steel, cast non-ferrous alloys and cemented carbides are the most frequently used turning, milling and boring tool materials. Other advanced materials include: coated/uncoated tungsten carbides, cermets, ceramics and polycrystallines.

The following subjects are included: tool fracture; thermal cracking; crack initiation and growth; failure and damage in cutting tools; tool wear; fatigue fracture; tool flank wear; diffusion wear; cracks in brittle materials; fracture probability; delamination of composites during machining; shear localization and ductile fracture.

The cutting tool materials analysed are: steel; ceramic tools; cemented-carbide tools; boride-cement tools; diamond; ceramics resin concrete; sintered carbide; aluminium oxide tools.

9. Chip formation mechanism

Metal cutting is a chip-formation process. The problem of chip formation and its control has been studied by trying to define the mechanism of chip formation, chip flow and chip breaking. The parameters involved are the tool and workpiece materials (type, strength, hardness, shape), the cutting data (feed, cutting depth and speed), the tool geometry, the cutting geometry, etc. The character of the movement of the chip along the contact length with the tool is another important factor. Most of the heat generated in machining is removed from the cutting zone by the chip. Chip control is necessary, especially in turning and drilling. Milling creates a natural chip length due to the limited length of cutting edge engagement.

To numerically simulate the chip formation mechanism during the machining process is not an easy task. There are too many complicated factors to be taken into account: contact and work material deformation with large plastic strains and friction, high temperature effects, strain-rate and strain hardening effects.

The topics in chip-formation processes include: chip formation in orthogonal machining; chip formation in high-speed machining; chip formation in microcutting; chip formation in interrupted turning; chip formation in oblique cutting; 3D continuous chip formation; segmental chip formation; serrated chip formation; chip separation; chip breaking; shear localization in chip formation; chip flow and tool wear; chip–tool interface contact problems.

10. Optimization and other topics

In this last section, optimization problems arising in machining are handled. Specifically: tool-shape optimization; machine-shape foundation optimization; optimization of a milling cutter; lathe bed optimization; optimum fixture design; optimum design of an abrasive disk; optimum design of a radial drilling machine; optimum drill geometry; optimum design of a lathe spindle; optimization of the functional properties of machines; and optimization problems in electrochemical machining.

Other topics where the finite-element technique has been implemented include: CAD and machining; computer graphics and machining; virtual engineering in machine tool design; error compensation in machine tools; validation of finite-element codes; and cutting-force measurement.

Acknowledgements

The bibliography presented in the Appendix is by no means complete but it gives a comprehensive representation of different finite-element applications on the subjects. The author wishes to apologise for the unintentional exclusions of missing references and would appreciate receiving comments and pointers to other relevant literature for a future update.

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Appendix A. A bibliography (1976–1996)

This bibliography provides a list of literature references on finite-element applications in machining. The presented listings contain papers published in scientific journals, conference proceedings, and theses/dissertations, retrospectively to 1976. References have been retrieved from the author's database, MAKEBASE. The COMPENDEX database, Metals abstracts and Applied Mechanics Review have also been checked. The references presented are grouped into the same sections as listed in the first part of this paper.

The emphasis of this bibliography is to list, first of all, papers published in various international journals. There have been numerous national and international conferences and symposia held worldwide, but conference proceedings are a source of never-ending bibliographical confusion. No review on conference proceedings can ever be comprehensive. The main criticism of conferences is that the material presented is often a repetition of what is published elsewhere in the literature, and also the complaint of uneven quality of papers is often heard. Surveys have shown low usage of published conference proceedings in practice. Also, many important conference papers are published afterwards in an edited version in international journals.

References are not arranged chronologically but sorted in each category alphabetically according to the first author's name. If a specific paper is relevant for several subject categories, the same reference can be listed under respective section headings.

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