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Geometry of Single-point Turning Tools and Drills

Fundamentals and Practical Applications

Springer

Viktor P. Astakhov, PhD
Michigan State University
Department of Mechanical Engineering
2453, Engineering Building
East Lansing
MI 48824-1226
USA
astvik@gmail.com

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Preface

Although almost any book and/or text on metal cutting, cutting tool design, and manufacturing process discusses to a certain extent the tool geometry, the body of knowledge on the subject is scattered and confusing. Moreover, there is no clear objective(s) set in the selection of the tool geometry parameters so that an answer to a simple question about optimal tool geometry cannot be found in the literature on the subject. This is because a criterion (criteria) of optimization is not clear, on one hand, and because the role of cutting tool geometry in machining process optimization has never been studied systematically, on the other. As a result, many practical tool/process designers are forced to use extremely vague ranges of tool geometry parameters provided by handbooks. Being at least 20+ years outdated, these data do not account for any particularities of a machining operation including a particular grade of tool material, the condition of the machine used, the cutting fluid, properties and metallurgical condition of the work material, requirements to the integrity of the machined surface, etc.

Unfortunately, while today's professionals, practitioners, and students are interested in cutting tool geometry, they are doomed to struggle with the confusing terminology. When one does not know what the words (terms) mean, it is easy to slip into thinking that the matter is difficult, when actually the ideas are simple, easy to grasp, and fun to consider. It is the terms that get in the way, that stand as a wall between many practitioners and science. This books attempts to turn those walls into windows, so that readers can peer in and join in the fun of proper tool design.

So, why am I writing this book? There are a few reasons, but first and foremost, because I am a true believer in what we call technical literacy. I believe that everyone involved in the metal cutting business should understand the essence and importance of cutting tool geometry. In my opinion, this understanding is key to improving efficiency of practically all machining operations. For the first time, this book presents and explains the direct correlations between tool geometry and tool performance. The second reason is that I felt that there is no comprehensive book on the subject so professionals, practitioners, and students do not have a text from which to learn more on the subject and thus appreciate the real value of tool geometry. Finally, I wanted to share the key elements of tool geometry that I felt were not broadly understood and thus used in the tool design practice and in optimization of machining operations in industry. Moreover, being directly involved in the launch of many modern manufacturing facilities equipped with state-of-the-art high-precision machines, I found that the cutting tool industry is not ready to meet the challenge of modern metal cutting applications. One of the key issues is the definite lack of understanding of the basics of tool geometry of standard and application-specific tools.

The lack of information on cutting tool geometry and its influence on the outcome of machining operations can be explained as follows. Many great findings on tool geometry were published a long time ago when neither CNC grinding machines capable of reproducing any kind of tool geometry were available nor were computers to calculate parameters of such geometry (using numerical methods) common. Manual grinding using standard 2- and 3-axis simple grinding features was common so the major requirement for tool geometry was the simpler the better. Moreover, old, insufficiently rigid machines, aged tool holders and part fixtures, and poor metal working fluid (MWF) selection and maintenance levered any advancement in tool geometry as its influence could not be distinguished under these conditions. Besides, a great scatter in the properties of tool materials in the past did not allow distinguishing of the true influence of tool geometry. As a result, studies on tool geometry were reduced to theoretical considerations of features of twist drills and some gear manufacturing tools such as hobs, shaving cutters, shapers, etc.

Gradually, once mighty chapters on tool geometry in metal cutting and tool design books were reduced to sections of few pages where no correlation between tool geometry and tool performance is normally considered. What is left is a general perception that the so-called “positive geometry” is somehow better than “negative geometry.” As such, there is no quantitative translation of the word “better” into the language of technical data although a great number of articles written in many professional magazines discuss the qualitative advantages of “positive geometry.” For example, one popular manufacturing magazine article read “Negative rake tools have a much stronger leading edge and tend to push against the workpiece in the direction of the cutter feed. This geometry is less free cutting than positive rakes and so consumes more horsepower to cut.” Reading these articles one may wonder why cutting tool manufacturers did not switch their tool designs completely to this mysterious “positive geometry” or why some of them still investigate and promote negative geometry.

During recent decades, the metalworking industry underwent several important changes that should bring cutting tool geometry into the forefront of tool design and implementation:

1. For decades, the measurement of the actual tool geometry of real cutting tools was a cumbersome and time consuming process as no special equipment besides toolmakers microscopes was available. Today, automated tool geometry inspection systems such as ZOLLER "Genius 3", Helicheck® & Heli-Toolcheck®, etc. are available on the market. The common problem, however, is that tool manufactures do not really understand what they measure.
2. Today's tool grinder is typically a CNC machine tool, usually of 4, 5, or 6 axes. Extremely hard and exotic materials are generally no problem for today's grinding systems and multi-axis machines are capable of generating complex geometries.
3. Advanced cutting insert manufacturing companies perfected the technology of inserts pressing (for example, spray drying) so practically any desirable shape of cutting insert can be produced with a very close tolerance. The introduction of micro- and sub-micrograin carbide grades, characterized by great fracture toughness, strength, and hardness, allows lifting of the last possible limitation on tool geometry, namely the sufficient strength of the cutting wedge. Earlier, the implementation of "exotic" geometries was restricted by the properties of the tool materials.
4. Many manufacturing companies updated their machines, fixtures, and tool holders. Modern machines used today have rigid high-speed spindles. Hydraulic and shrink-fit tool holders, pre-setting machines, and non-contact automatic control of tool geometry features find widespread use in many manufacturing facilities. In other words, many traditional "excuses" for poor tool performance and known scatter in tool life are eliminated so that tool design and geometry can be directly correlated with tool performance. Unfortunately, many tool manufacturers are not ready to meet this new challenge as the basic designs and geometries of their cutting tools did not change although new tool materials with superior properties as well as new opportunities of applying advanced tool geometries were developed.
5. Many manufacturing companies established tight controls and maintenance of their MWF units. Tight control of the MWF (coolant) concentration, temperature, chemical composition, pH, particle count, contaminations as tramp oil, bacteria, etc. is becoming common. Many production line and manufacturing cells are equipped with high-pressure and micron-filtration units with digital readouts of the MWF pressure and temperature (in and out). All of these impose even higher requirements of the tool geometry and design (location) of the coolant outlet nozzles.

All this pushed tool design including primarily the selection of tool materials and geometry to the forefront as no more traditional excuses for poor tool performance could be accepted. One might think that this happy marriage of CNC grinders and advanced tool materials should result in the wide introduction of advanced tool geometries. However, this is not the case in reality as many tool designers do not possess proper knowledge on the subject and the available literature provides little help on the matter. Co-existence of two basic standards, namely *ASME B94.50 -*

1975 Basic Nomenclature and Definitions for Single-Point Cutting Tools and *ISO 3002-1:1982, Basic quantities in cutting and grinding - Part 1: Geometry of the active part of cutting tools - General terms, reference systems, tool and working angles, chip breakers*, which use non-interchangeable terminology and definitions, adds a great deal to the confusion in understanding the basic parameters of the cutting tool geometry.

Why One Needs to Know Cutting Tool Geometry

Although any book and textbook on metal cutting, cutting tool, or manufacturing processes discuss to a certain extent the subject matter, no one known to the author provides any explanation of the necessity of knowing tool geometry. At best, the influence of the components of tool geometry on tool performance is considered in quantitative terms (better, higher, longer, greater, etc.) with no quantifications to make any intelligent choice of tool geometry parameters.

It is a natural perception that tool geometry affects tool life. However, in accordance with ANSI/ASME Tool life testing with single-point turning tools (B94.55M-1985), standard tool-life testing and representation includes Taylor's tool life formula

$$vT^n = C_T$$

where T is tool life in minutes, and C_T is a constant into which all cutting conditions affecting tool life must be absorbed. Although Taylor's tool life formula is still in wide use today and is the very core of many studies on metal cutting including the level of National and International standards, this formula does not suggest that tool geometry affects tool life. The reason for this is simple as one should always remember that it was introduced in 1907 as a generalization of many-year experimental studies conducted in the nineteenth century using work and tool materials and experimental technique available at that time. Since then, each of these three components underwent dramatic changes. Unfortunately, the validity of the formula has never been verified for these new conditions. Nobody proved so far that it is still valid for any other cutting tool materials than carbon steels and HSS.

Analysis of the standard methodology of tool life testing, available criteria of tool wear, and tool life assessment clearly indicates that these assessments are insufficient, and very subjective. They do not account for cutting tool geometry (flank, rake, cutting edge angles, for example) so they are not suitable to compare cutting tools having different geometries. Moreover, they do not account for the cutting regime and thus do not reflect the real amount of work material removed by the tool during the time over which the measured rake or flank wear is achieved. As a result, they can hardly been used for optimization of the cutting tool geometry, any process improvements and optimization, as well as the process adaptive intelligent control.

Understanding tool geometry is a key to improving efficiency of practically all machining operations. This general statement should be extensively elaborated with clear specific details as no one known to the author book, paper, manual or any other technical publication/material provides the answer to an array of simple yet practical questions: "why does one need to know the cutting tool geometry?", "what are those parameters of tool geometry one needs to use in a particular case of machining?", "to what extent does the tool geometry affect tool life, cutting force, tool wear, integrity of the machined surface?", "what is effect of the tool geometry on the accuracy and efficiency of machining operations?" Therefore, a need is felt to clarify the issues and thus provide practical help to the practitioners (tool designers, manufacturing/process engineers) and methodological help to the researchers. This is the main objective of this book. It argues that one needs to know the tool geometry because it allows determination of:

1. *Uncut chip thickness*. Only when one knows and understands tool geometry he can properly determine the uncut chip thickness for each and every cutting element (wedge) involved. Knowing this probably the most important parameter, one can:

   - *Maximize productivity of machining.* Productivity of machining can be thought of as the tool penetration rate defined as the product of the rotation speed (r.p.m.) and cutting feed per revolution. The cutting speed is normally limited by the properties of the tool material (red hardness) while feed per revolution is considered as the major resource in increasing productivity. This is because it can be significantly increased though tool design and geometry. Any cutting insert (solid, brazed, or mechanically clamped) is characterized by the so-called breaking uncut chip thickness known in industry as the maximum chip load. As such, an increase in the number of cutting inserts working simultaneously, the feed rate can be proportionally increased. For example, if a two-flute reamer is replaced by a four-flute reamer then the penetration rate can be increase twofold. Another method of feed rate increasing that can be used concurrently with the first is adjusting the so-called lead angle of the cutting edge. Increasing the lead angle of a cutting insert leads to so-called "chip thinning" (decreasing the uncut chip thickness under a given feed per revolution). As a result, the feed per revolution can be increased with increasing lead angle to keep the maximum allowable uncut chip thickness for the inserts. For example, the most common use of this feature in milling where the lead angle is increased to 45° is that it allows increasing the feed rate by 1.4-fold. As such, a wiper insert is introduced to reduce the feed marks left on the machined surface due to the increased feed.
   - *Prevent burnishing and galling instead of cutting.* In simple terms, the cutting edge is not a perfect line of intersection of the rake and flank surfaces. Rather, it is characterized by the radius of the cutting edge. This radius is common and applied (at the insert sintering or by special edge preparation techniques) to prevent chipping of the cutting edge. The problem arises when this radius becomes less then five uncut chip

thicknesses. In this case, the cutting becomes rather difficult, and significant burnishing or even galling takes place causing a significant increase of the cutting temperature and reduction of tool life. Moreover, the quality including surface integrity of the machined surface deteriorates rapidly. Knowing the uncut chip thickness, however, one can select the proper radius of cutting edge to prevent this from happening.

- *Calculate the chip compression ratio*. Measuring the chip thickness and dividing it by the uncut chip thickness, one can determine the uncut chip thickness. Knowing this fundamental of metal cutting theory and practice parameter, one can calculate practically all other process parameters and characteristics such as the power spent in plastic deformation of the layer being removed in its transformation into the chip, the tool-chip contact length, contact stresses (both normal and shear) at the tool-chip and tool-workpiece interfaces, and can calculate tool-chip contact temperature, etc. All this allows selecting the proper tool materials and machining regime. This facilitates the only practical way to optimize the cutting process. This method can be use at different levels – from the research laboratory to the shop floor.

2. *Direction of the chip flow*. The simplest yet very practical aspect of tool geometry is that this geometry defines the direction of chip flow. This direction is important to control chip breakage and evacuation. Although knowledge of chip control was available a long time ago, it is can be properly utilized only at the present stage when advancements in the technology of insert manufacturing and properties of the tool materials allow one to make virtually any intricate shape of cutting inserts. The so-called "helical tool geometry" that allows preventing chip re-cutting, reduction in cutting forces, improving quality of machining surface, etc., becomes the key design and marketing feature of some tool manufacturers.
3. *Cutting force on each cutting element as well as the total cutting force*. The cutting force is primarily determined by the mechanical properties of the work material, machining regime, and uncut chip thickness. Together with four other components of cutting tool geometry, namely, the rake angle, tool cutting edge angle, tool minor cutting edge angle, and inclination angle, the uncut chip thickness defines the magnitudes of the orthogonal components of the cutting force. Knowing the correlation among the mentioned angles and force components, one can design efficient cutting tools with inserts where no force acts on the locating pins, insert tilting under the action of the cutting force is eliminated, inserts are self-locked in the pockets of the holder for an efficient process where the cutting force does not cause excessive bending, buckling and deformations of long and non-rigid workpieces. This knowledge allows designing effective clamping mechanisms and insert pockets, and locating and clamping fixtures for the workpiece to assure the required accuracy of machining at minimum cost.

4. *Quality (surface integrity and machining residual stress) of machined surfaces*. Quality of the machined surface increasingly becomes one of the important parameters of the machined parts. Although only recently the only specified parameter on part drawings was surface finish, the direction of surface roughness and the shape of valleys and peaks, superficial and in-depth machining residual stresses as well as other parameters of the integrity of the machined surface became common requirements on part drawings. The geometry and the cutting tool together with machining regime define the mentioned surface integrity. First of all, tool geometry defines surface finish (surface topography). The influence of cutting geometry on machining residual stress is easily realized if one recalls that this geometry defines to a great extent the state of stress in the deformation zone, i.e., around the tool. This state of stresses combined with the thermal energy released due to plastic deformation and fracture of the layer being removed, as well as due to friction on the tool flank, presents the background of the formation of the machining residual stress both superficial and in-depth.
5. *Tool life*. The geometry of the cutting tool affects tool life directly as this geometry defines the magnitude and direction of the cutting force and its components, sliding velocity at the tool-chip interface, the distribution of the thermal energy released in machining, the temperature distribution in the cutting wedge, etc.

Uniqueness of this Publication

This book is intended to be the first comprehensive book on cutting tool geometry of single point cutting tools and drills although the methodologies presented are valid for the geometry of any cutting tool.

The book subject mater is covered in a systemic and systematic way that covers the most of the common and special single-point cutting tools and drills as most common tools used in various industries. The uniqueness of the book is in its manner of coverage of key items as they are covered from the very simple basic geometry level, slowly adding layers of complexity up to the advanced vector geometry level. It explains with multiple examples how to select the proper geometry for a given particular case, how to design, adjust (set), and re-sharpen cutting tools. Bridging the gap between theory and practice, the book goes to the most advanced level of kinematic tool geometry as the summation of several simultaneously-occurring motions to achieve the desired shape of the machined part while maintaining optimal tool geometry. In practical terms, it means that the book clearly shows what seems to be "rocket science" as differential topology or vectorial analysis can do to solve real-life problems on the shop floor and/or in the design of standard and application-specific cutting tools. It provides valuable help in utilizing the ability of modern CNC tool sharpening machines (for example ANKA and Walter CNC grinding systems). It provides methodological guidance for properly using automated tool geometry inspection systems such as ZOLLER "Genius 3", Helicheck® & Heli-Toolcheck®, etc., because the major obstacles in the wide implementation of these tool geometry measuring systems are:

(a) convincing new potential customers on the potential benefits of knowing real tool geometry, (b) proper machine setting with respect to the tool-in-had coordinate system, and (c) interpretation of the output in terms of its correlation with the geometry parameters assigned by the tool drawing.

The key features and advantages of the book that sets it apart from all known subject matter can be summarized as follows:

- For the first time, clear objectives of cutting tool geometry section/optimization are formulated and explained with multiple examples.
- Individual and combined influences of the parameters of cutting tool geometry on cutting tool performance and outcomes of a machining operation are revealed through establishing clear bridges between cutting theory, tool geometry, and shop practice.
- The three basic systems of consideration of the tool geometry, namely, tool-in-hand, tool-in-machine (holder), and tool-in-use are considered and the transformations between these systems are established.
- For the first time, the book discusses the system outlook of common problems and solutions in cutting tools implementation practice in the setting of automotive powertrain plant. It addresses several urgent problems that many present-day tool manufacturers, tool application specialists, and tool users in the automotive industry are facing. First, the book is meant to be a source of instant solutions, including pieces of useful practical suggestions that one can just implement into one's own applications, providing the solutions of common problems. Second, it is meant to be a useful reference to the most important aspects of the cutting tool design, application and troubleshooting practices. Finally, it covers emerging trends in the cutting tool geometry, machining regimes, and optimization of machining operations.
- For the first time, the book provides a comprehensive analysis of the design and geometry of deep-hole machining tools. The book provides practical recommendations for the proper selection of the components of deep-hole machining system to assure system coherency.

After reading the book and reviewing the many practical examples included, a potential reader should gain solid knowledge and understanding of tool geometry, namely, the shapes, angles, and other geometric aspects of single-point and multi-point cutting tools. He should be well equipped for all the facets of geometry related tool business management starting with design and/or selection of the proper geometry and finishing with troubleshooting of failed tools.

How this Book is Organized

The chapters that follow and their contents are listed here:

Chapter 1: What Does It Mean "Metal Cutting"?
To design a cutting tool and thus to assign its proper geometry, select the proper tool material and machining regime, one needs to know the physical essence of the

metal cutting process starting with its definition and finishing with the easiest way to accomplish the objective of this process. This chapter provides guidelines to distinguish the metal cutting process commonly referred to as metal cutting among other closely related manufacturing processes and operations. It presents the known results and compares them with those used in other forming processes/operations. It argues that if the usual notions are used, the metal cutting process does not have any distinguising feature. Analyzing what and when went wrong with the existing notions in metal cutting, this chapter provides a physically-based definition of the metal cutting process. Using the introduced definition, this chapter for the first time describes explicitly the role of cutting tool geometry in the metal cutting process that sets the stage for a better understanding of other chapters in this book. Because in the development and implementation of any cutting tool the experiment remains essential, the complete hierarchical system of tool testing is also discussed and the most useful similarity numbers used in testing are introduced and explained.

Chapter 2: Basic Definitions and Cutting Tool Geometry, Single Point Cutting Tools
This chapter presents the basic terms and their definitions related to cutting tool geometry according to ISO and AISI standards. It considers tool geometry and inter-correlation of geometry parameters in three basic systems: tool-in-hand, tool-in-machine, and tool-in-use. It also reveals and resolves the common issues in the selection of geometry parameters including those related to indexable inserts and tool holders. The chapter introduces the concept and basics of advanced representation of cutting tool geometry using vector analysis. A step-by-step approach with self-sufficient coverage of terms, definitions, and rules (in Appendixes) makes this complicated subject simple as considerations begin with the simplest geometry of a single-point cutting tool and finish with summation of several motions. Extensive exemplification using practical cases enhances understanding of the covered material.

Chapter 3: Fundamentals of the Selection of Cutting Tool Geometry Parameters
This chapter presents a general methodology for the selection of optimal tool geometry based upon minimization of the work of plastic deformation in metal cutting. It argues that the chip compression ratio is the most objective yet simple ‘gage’ that should be used for the assessment of this work and thus to optimize tool geometry. Individual and system influences of the major parameters of the cutting tool geometry are discussed. The tool cutting edge, rake, flank and inclination angles, as well as edge preparation are included in considerations because these parameters have a multi-faced influence on practically all aspects of the metal cutting process and greatly affects the outcomes of a machining operation. The chapter offers explanations and rationales for many common perceptions and experimental knowledge concerning the listed parameters.

Chapter 4: Straight Flute and Twist Drills
This chapter discusses classification, geometry, and design of straight flute and twist drills. It argues that the design, manufacturing, and implementation practices of drills are lagging behind the achievements in tool materials, powerful, high-

speed-spindles rigid machines, and high-pressure MWF (coolant) supply. Although the wide availability of CAD design tools and CNC precision grinding machines make it possible to reproduce any drill geometry, there are not many new drill designs becoming available recently. The chapter points out that the prime objective of the drilling system is an increase in the drill penetration rate, i.e., in drilling productivity as the prime source for potential cost savings. As the major problem is in understanding particularities of drill geometry and its components, this chapter walks the reader from simple concepts starting from the basic terminology in drill design and geometry to the most complicated concepts in the field, keeping the context to the simplest possible fashion and providing practical examples. It provides an overview of important results concerning drill geometry and synthesizes the most relevant findings in the field with the practice of tool design.

Chapter 5: Deep-hole Tools
This chapter discusses classification, geometry, and design of deep-hole drills. The concept of self-piloting is explained. The system approach to deep-hole machining is introduced and common system issues are discussed with examples. The major emphasis is placed on gundrills. A number of simple design rules are proposed and explained with examples. The conditions of free penetration of the drill into the hole being drilled are explained. The geometry consideration systemically related to MWF flow and thus the concept of the optimum MWF flow rate are explained. A number of novel design concepts are revealed. This chapter also discusses system consideration in experimental study of gundrill parameters. It is demonstrated that tool life is a complex function of not only geometry parameters and machining regime alone but also of their combination. Tool geometry optimization using the Hooke and Jeeves method is also discussed.

Appendix A: Basic Kinematics of Turning and Drilling
This appendix discusses basic turning and drilling operation and presets the definitions of the basic terms used in kinematics of turning, boring, and drilling. The cutting speed, cutting feed, feed rate, depth of cut and material removal rate are considered with practical examples of calculations. Based on the chip compression ratio (CCR) discussed in Chap. 1, a simple practical methodology to calculate the cutting power (force) and its partition in the cutting system is considered with examples. It is shown that the greatest part of the energy needed for cutting is spent in plastic deformation of the layer being removed.

Appendix B: ANSI and ISO Turning Indexable Inserts and Holders
This appendix aims to help specialists in tool design and end users to make proper selection of the standard cutting inserts, and tool holders. It walks a potential reader through particularities of ISO and ANSI standards explaining differences between these standards and clarifying specific issues. It points out important discrepancies between these standards and their interpretations found in the catalogs of tool manufacturers. Examples provided in this appendix help to understand the selection process and its results clearly.

Appendix C: Basics of Vector Analysis
This appendix presents the basics of vector analysis to help readers to comprehend the analysis of the tool geometry as made in the book. The concepts of vector and scalar quantities are explained. Starting with trivial vector operations as vector summation and subtraction, the text walks a potential reader to the dot and cross and scalar triple products of vectors as the fundamental operations used in the analysis of tool geometry. Suitable exemplifications are provided for each of these vector operations.

Appendix D: Hydraulic Losses: Basics and Gundrill Specifics
This appendix discusses MWF pressure losses in the hydraulic circuit of the gundrilling system. An electrical analogy of this hydraulic system is used to explain the essence of these losses. To fulfil *Design Rule No. 3* introduced in Chap. 5, namely, to maximize the MWF pressure in the bottom clearance space, all hydraulic losses are distinguish as 'bad' (reduce the pressure) and 'good' (increase the pressure in the bottom clearance space) losses. The concept and significance of the critical and optimal MWF velocity and flow rate as applicable to chip transportation in the V-flute are introduced and explained with an example.

Appendix E: Requirements and Examples of Cutting Tool Drawings
This appendix argues that probably the most important stage in the implementation of the optimized tool geometry is its assigning on the tool drawings. To assign this tool geometry properly, a tool designer should be a well-seasoned specialist with an advanced degree having a broad knowledge of the design, manufacturing, implementation, failure analysis and many other surrounding subjects. As this is not the case today, the common flaws with exemplification of some common tool drawings are discussed. The appendix sets the basic requirements to tool drawings with examples of proper tool drawings.

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Okemos, Michigan, USA *Viktor P. Astakhov*
March, 2010

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