

# TRIBOLOGY OF METAL CUTTING

TRIBOLOGY AND INTERFACE ENGINEERING SERIES

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- friction; contact damage;
- lubrication; and
- wear at all length scales.

TRIBOLOGY AND INTERFACE ENGINEERING SERIES, 50  
EDITOR: B.J. BRISCOE

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# TRIBOLOGY OF METAL CUTTING

VIKTOR P. ASTAKHOV



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## PREFACE

This book is about a subject that has been lurking in the underbrush of the manufacturing world for many years and is finally coming to the forefront. Tribology of metal cutting is, in some ways, the ugly beast that content providers – metal cutting researchers, tool and machine tool companies, market researchers and sales personnel, major manufacturing corporations and others – have wanted to keep in the closet. Global competition has forced the closet door open; really, it has eliminated the door itself. What used to be relatively simple and written as a set of postulates in texts on the subject is now uncomfortably complex.

### Historical Background

The term tribology comes from the Greek word *tribos*, meaning friction, and *logos*, meaning law. Tribology is therefore defined as “*the science and technology of interactive surfaces moving in relation to each other.*” The science of *Tribology* concentrates on contact physics and the mechanics of moving interfaces that generally involve energy dissipation. Its findings are primarily applicable in mechanical engineering and design where tribological interfaces are used to transmit, distribute and/or convert energy. The contact between two materials, and the friction that one exercises on the other, causes an inevitable process of wear. What those contact conditions are, how to strengthen the resistance of contact surfaces to the resulting wear, as well as optimizing the power transmitted by mechanical systems and complex lubrication they require, have become a specialized applied science and technical discipline which has seen major growth in recent decades. Bearing the rather colorful name “Applied tribology,” this field of research and application encompasses the scientific fields of contact mechanics, kinematics, applied physics, surface topology, hydro- and thermodynamics, and many other engineering fields under a common umbrella, related to a great variety of physical and chemical processes and reactions that occur at tribological interfaces.

When it comes to metal cutting, tribology is thought of as *something* that has to be studied in order to reduce the tool wear (and thus increase tool life). Although this is true

in general, it does not exhaust the application of tribological knowledge in metal cutting. Unfortunately, the published books and articles on the subject do not treat the subject in a systematic way. Rather, the collection of non-correlated facts on tool materials, cutting regimes, tool life and its assessment, cutting fluids, tool coatings, etc., is considered as the tribology of metal cutting. Having read the known works and related materials, one does not feel thoroughly equipped to analyze and improve the tribological conditions in various metal cutting operations. This is because of the commonly understood meaning of “metal cutting tribology,” which is something related to reduction of tool wear, its assessment and reduction. Although it is true that cutting tool wear and its proper assessment is a part of metal cutting tribology, the assessment and reduction of tool wear are only “natural by-products” of this field of study.

To proceed further and to comprehend the content of this book properly, one should clearly realize that the ultimate objective of metal cutting tribology is the reduction in the energy spent in metal cutting. Increased tool life, improved integrity of the machined surface, higher process efficiency and stability are the results of achieving this goal. This book attempts to provide specialists in the field of metal cutting with information on how to apply the major ideas of metal cutting tribology, or, in other words, how to make metal cutting tribology useful at various levels (starting with tool design, developing and/or selecting proper tool materials including coating, development and/or selecting proper cutting fluids and ending with cutting process optimization on the shop floor).

### **The Importance of the Subject**

Although in the practice of mechanical engineering, the waste of resources (energy) due to ignorance of tribological effects hardly exceeds a single digit, this waste is estimated to be approximately one-third of the world’s energy consumption, so the study and optimization of tribological process are considered to be of great importance. Enormous sums of money are spent on research in tribology. The objective of this research is understandably the minimization and elimination of losses resulting from friction and wear at all levels of technology where rubbing of surfaces is involved. It is claimed, research in tribology leads to greater plant efficiency, better performance, fewer breakdowns and significant savings.

In metal cutting, only 30–50% of the energy required by the cutting system is spent for the useful work, i.e. for the separation of the layer from the workpiece, as is conclusively proven in this book. This means that 25–60% of the energy consumed by the cutting system is simply wasted. Most of this wasted energy is spent at the tool–chip and tool–workpiece interfaces due to unoptimized tribological processes. This fact can be easily appreciated if one realizes that nearly all the energy spent in the cutting process is converted into thermal energy. Therefore, the temperature of a certain zone in the cutting system is a relevant indicator of the energy spent in this zone. This is because the energy spent generates heat, thus the higher temperature of a particular zone indicates greater energy spent in this zone. If we compare the temperature in the deformation zone and that at the discussed interfaces, we can come to a surprising yet well-known conclusion that the temperature in the deformation zone, where the major work of plastic deformation

and separation of the layer being removed from the rest of the workpiece takes place, is relatively low (normally in the range of 80–250°C), while the maximum temperatures at the tool–chip interface exceeded 1000°C. Therefore, most of the energy required by the cutting system is spent at the tool–chip and tool–workpiece interfaces. Unfortunately, this simple fact has been overlooked for years, so the deformation zone attracts much more attention from researchers in the field with less attention to the tribological aspects of metal cutting.

Naturally, this energy spent at the discussed interfaces lowers tool life, affects the shape of the produced chip, and leads to the necessity of using different cooling media that, in turn, lowers the efficiency of the machining system as more energy is needed for cooling medium delivery and maintenance.

The situation in metal cutting is entirely different from that in the design of tribological joints in modern machinery. In the latter, a designer is rather limited by the shape of the contacting surfaces, materials used, working conditions set by the outside operating requirements, use of cooling and lubricating media, etc. In metal cutting, practically any parameters of the cutting system can be varied in a wide range. Modern machine tools do not limit a process designer in his selection of cutting speeds, feeds or depth of cut. The nomenclatures of tool materials, geometries of cutting inserts and tool holders available at his disposal are very wide. The selection of cooling and lubrication media, and their application techniques are practically unlimited. Although the chemical composition of the work material is normally given as set by the designer, the properties of this material can be altered over a wide range by heat treatment, forging and casting conditions. The only problem in the selection of optimal tribological cutting parameters is the lack of knowledge on the metal cutting tribology. Therefore, study and optimization of the tribological conditions at these interfaces have a great potential in terms of reduction of the energy spent in cutting, increased tool life, reduction and elimination of coolants, etc.

The optimization of tribological processes in metal cutting results in the following:

- *Reduction of the energy spent in cutting.* Because the efficiency of the cutting system is very low (in machining of most steels it does not exceed 50%) due to energy losses during tribological interactions, the optimization of the tribological processes improves the efficiency of the cutting system by reducing the energy spent by the cutting system.
- *Proper selection of application-specific tool material (coating).* Considering the energy transmitted through the tribological interfaces in metal cutting, one can select a tool material for a given application to assure the chosen performance criterion such as tool life, quality of the machined surface, efficiency, etc.
- *Proper selection of tool geometry.* Because the tool geometry largely defines the state of stress in the deformation zone, stresses, temperatures and relative velocities at the tool–chip and tool–workpiece interfaces, the optimized tribological parameters can be directly used in the selection of proper tool geometry.
- *Control of machining residual stresses imposed (induced) in the machined surfaces.* The machining residual stresses are determined by the tribological process taking

place at both the tool–chip and tool–workpiece interfaces. Therefore, one can control both the superficial and in-depth machining residual stresses over a wide range in terms of their sign, magnitude and distribution by controlling the tribological processes at the mentioned interfaces.

- *Proper selection of cooling and lubricating media as well as the method of its delivery and application technique.* The proper selection and application of a particular medium is only possible when true tribological mechanism of its action is known. The composition and chemistry of cutting fluids can be designed based on the Rebinder effect rather than on other properties (cooling and lubricating as considered today) of a particular cutting fluid.

### **Uniqueness of this Publication**

There is a concern that some of the present cutting tool and process designers, manufacturing engineers and engineering students may not be learning enough about metal cutting tribology. Although containing some vitally important information, books to date do not provide methodological information on the subject that can be helpful in making critical decisions in process design, the design and selection of cutting tools, and the implementation of proper machine tool. The most important information is scattered over a great number of research and application papers and articles. Commonly, isolated experimental findings for particular test conditions are reported instead of methodology. As a result, the question: “What would happen if one test parameter is altered?” remains unanswered. Therefore, a broad-based book is needed.

The purpose of this book is twofold:

First, it aims to summarize the available information on metal cutting tribology with a critical review of work done in the past and thus help specialists and practitioners to separate facts from myths. As shown, the major problem in metal cutting studies is the physically incorrect model used today. Other known problems are just consequences of the implementation of this model. In other words, one fundamental misconception has caused a chain reaction of implementation issues. If a finding or result does not fit the concept of this model then the result is either “silenced,” or bent and twisted to make it fit.

Second, it intends to present, explain and exemplify a number of novel concepts and principles in the tribology of metal cutting such as the energy partition in the cutting system, physical efficiency of the cutting system and its practical assessment, versatile metrics of cutting tool wear, optimal cutting temperature and its use in the optimization of the cutting process, the physical concept of cutting tool resource, and embrittlement action of the cutting fluids.

The major distinguishing feature of this book is that the practical ways of modeling and optimization of the cutting process are considered using two simple in- and post-process parameters, namely, the cutting temperature and chip compression ratio that can be measured with sufficient accuracy not only at a research lab but also in the shop floor.

This makes this book not just another book on the subject, but a practical guide for a wide variety of readers from machining shop practitioners to scientists in the field of metal cutting. For the first time, it attempts to present metal cutting tribology as a science that really works.

The book is based on the author's wide experience in research, practical application and teaching in the area of metal cutting tribology, applied physics, mathematics and mechanics, materials science and engineering systems theory for more than thirty years. Emphasis is placed on the practical application of the results in everyday practice of machining, cutting tool and machining process design. The application of these recommendations will increase the competitive position of the users through machining economy and productivity. It will help them to design better cutting tools and processes, enhance technical expertise and levels of technical services.

### **Intended Audience**

The book is intended for four types of readers: (1) metal cutting tool, cutting insert and process designers, (2) manufacturing engineers involved in continuous process improvement *via* selection of better cutting tools, machines, coolants, optimization of cutting processes and improvement of machining quality, (3) research workers who are active or intend to become active in the field, (4) senior undergraduate and graduate students of manufacturing.

### **How this Book is Organized**

The chapters that follow and their contents are listed below:

#### *Chapter 1 Generalized model of chip formation*

This chapter covers the history, merits and major drawbacks of the single-shear plane model. It is argued that the single-shear plane model is inadequate to explain the real cutting process. It lists and discusses the following principle drawbacks of the single-shear plane model: infinite strain rate; unrealistically high shear strain; unrealistic behavior of the work material; improper accounting of the resistance of the work material to cutting; unrealistic representation of the tool-workpiece contact; inapplicability for cutting brittle work materials; incorrect velocity diagram; incorrect force diagram; inability to explain chip curling.

The chapter concludes that any progress in the tribology of metal cutting and in the prediction ability of metal cutting theory cannot be achieved if the single-shear plane model is still at the very core of this theory.

Based on the introduced definition of the metal cutting process as a purposeful fracture of the layer being removed, it presents the realistic generalized model of chip formation

suitable to analyze the tribological processes in metal cutting. The chapter reveals the influence of various factors on the chip structure and thus the tribological conditions. It is argued that the cutting process takes place in the cutting system, so any component of this system and/or any tribological process (taking place in this system) cannot be considered/optimized separately without accounting for the system properties.

### *Chapter 2 Energy partition in the cutting system*

This chapter clarifies the energy aspects of metal cutting tribology. It is argued that although many tribological (physical, chemical, etc.) processes can take place at the interfaces in metal cutting, the occurrence of any of these processes is decided by the form and amount of energy available. It considers for the first time the complete model of energy partition and flows in the metal cutting system.

The chapter introduces the concept of physical efficiency of the cutting system as the ratio of energies spent on the separation of the layer being removed from the rest of the workpiece and the total energy required by the cutting system to exist. It demonstrates that physical efficiency can be determined knowing the stress–strain curve of the work material, cutting regime and by measuring the cutting force. In a simple and physically grounded manner, the work of plastic deformation done in cutting is correlated with a measurable, post-process characteristic of the cutting process such as the chip compression ratio. The significance of chip compression ratio in the study and optimization of the cutting processes is revealed. Using these results, a practical analysis of the physical efficiency of particular cutting systems is presented and the influence of various parameters and properties on this efficiency is discussed. For a wide range of commonly machined steels, it is demonstrated that the physical efficiency is in the range of 25–60%, so a great margin exists for improving of metal cutting efficiency through optimizing tribological conditions.

Two distinctive ways of increasing the physical efficiency of the cutting system are proposed. The first is based on the energy theory of failure and utilizes the interference of the coherent deformation and thermal waves to reduce the required mechanical energy. The second is based on the correlation between the state of stress imposed by the cutting tool in the layer being removed and the fracture strain of the work material.

### *Chapter 3 Tribology of the tool–chip and tool–workpiece interfaces*

This chapter argues that because 30–50% of the energy required by the cutting system is spent in useful work, i.e. for the separation of the layer being removed from the workpiece, the rest is spent at the tool–chip and tool–workpiece interfaces. A systemic and systematic approach to the analysis of the tribological conditions at the tool–chip and tool–workpiece interfaces based on the generalized model of chip formation is presented, with the definition and determinations of basic tribological characteristics at these interfaces. The contact stresses, velocities and temperatures are considered. It explains why the similarity method, as compared to numerical methods, is much less sensitive to the particular model used in the thermal analysis of metal cutting.

The influence of various properties and parameters of the metal cutting process on its tribological characteristics is revealed. The stable and measurable tribological characteristics of metal cutting to be used in the meaningful selection of the parameters and characteristics of the cutting process are identified.

#### *Chapter 4 Cutting tool wear, tool life and physical resource*

This chapter argues that the existing measures and metrics of tool life and cutting tool evaluation suffer from severe drawbacks. The proper metrics for the assessment of cutting tool wear are presented and evaluated. It offers new effective characteristics of tool wear like the dimension wear rate and the relative surface wear rate.

It introduces and explains the concept, physical background and significance of the optimal cutting temperature (the first metal cutting law and its consequences) as the temperature at which the combination of minimum tool wear rate, minimum stabilized cutting force and highest quality of the machined surface is achieved. The validity of the formulated law is illustrated for a vast variety of cutting conditions, work materials and cutting operations. Practical methods for the determination of optimal cutting temperature are offered.

The influence of various parameters and characteristics of the cutting process such as the cutting speed, feed, depth of cut, parameters of cutting tool geometry, workpiece material and its diameter on tool life are quantified. Finally, it presents, explains and exemplifies a breakthrough concept of physical resource of the cutting tool in terms of the limiting energy passed through the cutting wedge.

#### *Chapter 5 Design of experiments in metal cutting tests*

This chapter challenges the existing standards, procedures and policies in metal cutting tests, particularly in the tool-life testing often conducted in tribological studies of the metal cutting process. It explores the methods of design of experiments (DOEs) in metal cutting. Particular attention is paid to the preprocess stage as the most important yet least formalized stage of DOE, where the most crucial decisions affecting the test outcome are made. It explains the basic terminology and requirements to the input and output parameters in DOE particularly to metal cutting.

The complete system of metal cutting tests starting from the screening of the DOE is presented, which is implemented at the first stage of testing where the essential parameters are to be identified to the group method of data handling, where the problem of optimization of essential parameters is dealt with. A new sieve DOE is introduced, based upon the Plackett–Burman design ideas, an oversaturated design matrix and the method of random balance. The proposed sieve DOE allows the experimentalist to include at the first phase of the experimental study as many factors as needed and then to sieve out nonessential factors and their interactions by conducting relatively small number of tests.

It is argued that the Group Method of Data Handling (GMDH), which is applied in a great variety of areas for data mining and knowledge discovery, and, accounting for its basic properties and qualities, seems to be the best option for metal cutting experimental studies as it fully utilizes the system approach. The basic properties and qualities of GMDH are discussed and practical example of its application in tool life testing is presented. A detailed example of the introduced DOEs using deep-hole machining testing is provided.

#### *Chapter 6 Improvement of tribological conditions*

This chapter classifies the existing methods of improvement into components and the system methods. It focuses on the cutting fluid (coolant) as it accounts for up to 15% of the shop production cost compared to the cutting tool costs, which accounts for up to 7%. The whole process of selection of the proper cutting fluid is discussed. It is argued that the existing methods of cutting fluid tests are inadequate. A new vision of the cutting fluid action is presented, arguing that the cooling and lubricating action are secondary compared to the embrittlement action (the Rebinder effect). It underlines the basic properties of various types of cutting fluids. The basic application aspects of cutting tool coatings are emphasized.

It explains that the metallurgical properties of the work material in terms of their influence on the machinability are neglected in research and industry practices, and elaborates on the influence of these properties on tool wear.

#### *Appendix A Basics definitions and cutting tool geometry*

It presents proper definitions of the parameters of the cutting tool geometry. The most general way of determining the uncut chip thickness as the most important input tribological parameter is provided.

#### *Appendix B Experimental determination of the chip compression ratio (CCR)*

It describes simple methods of experimental determination of CCR for basic machining operations.

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*Viktor P. Astakhov  
Rochester Hills, Michigan  
February, 2006*

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## NOMENCLATURE

$A_w = t_1 d_w$	Cross-sectional area of the uncut chip (m <sup>2</sup> )
$A_c$	Cross-sectional area of the chip (m <sup>2</sup> )
$Br$	Briks criterion
$(C_p \rho)_w$	The volume specific heat of work material (J/(m <sup>3</sup> °C))
$d_{cw}$	Depth of cold working (mm)
$d_w$	Cutting width (orthogonal cutting) or the depth of cut (mm)
$d_{w1}$	Width of chip (mm)
$d_{w-r}$	Depth of re-cutting (mm)
$D$	Similarity criterion that accounts on the parameters of the uncut chip thickness
$D_w$	Diameter of the workpiece (diameter of the hole being bored or drilled) (m)
$E$	Young's modulus or the modulus of elasticity (MPa)
$E_p$	Relative sharpness similarity criterion
$e_x, e_y$ and $e_z$	Direct strains
$e_i$	Equivalent strain
$erf(z)$	"Error function" encountered in integrating the normal distribution
$F$	Friction force at the tool–chip interface (N)
$F_{fF}$	Friction force at the tool–workpiece interface (N)
$F_{fN}$	Normal force at the tool–chip interface (N)
$F_n$	Normal force on the plane which approximates the surface of the maximum combined stress at its final inclination (shear plane) (N)
$F_s$	$F_s$ Shear force on the plane which approximates the surface of the maximum combined stress at its final inclination (shear plane) (N)
$F_x, F_y$ and $F_z$	Components of the cutting force in the tool coordinate system (N)
$F_\theta$	Similarity criterion that accounts for the thermal properties of the tool and work materials as well as for the tool geometry
$f$	Cutting feed (mm/rev)

$g$	Acceleration due to gravity ( $\text{m/s}^2$ )
$h_r$	Radial tool wear (mm)
$h_s$	Relative surface wear rate ( $\mu\text{m}/10^3 \text{sm}^2$ )
$h_{s-opt}$	Optimal relative surface wear ( $\mu\text{m}/10^3 \text{sm}^2$ )
$k_w$	Thermal conductivity of work material ( $\text{J}/(\text{m} \cdot \text{s} \cdot \text{C})$ )
$k_t$	Thermal conductivity of tool material ( $\text{J}/(\text{m} \cdot \text{s} \cdot \text{C})$ )
$k_{wf}$	Thermal conductivity of the working fluid ( $\text{J}/(\text{m} \cdot \text{s} \cdot \text{C})$ )
$K_h$	Cooling intensity
$l_c$	Contact length (natural) – the length of the tool–chip contact interface (mm)
$l_{c-p}$	Plastic part of the contact length (mm)
$l_{c-e}$	Elastic part of the contact length (mm)
$L_w$	Length of the workpiece (m)
$m_d$	Drill point offset (mm)
$n_w$	Workpiece rotational speed (rpm)
$N$	Normal force at the tool–chip interface (N)
$Nu$	Nusselt number
$P_c$	Cutting power (W)
$Pe$	Peclet criterion (number)
$Po$	Poletica criterion, $Po$ -criterion
$Pr$	Prandtl Number
$R$	Resultant cutting force (N)
$Re$	Reynolds Number
$r_{ct}$	Physical resource of the cutting tool (W)
$r_n$	Cutting tool nose radius (m)
$t_1$	Uncut chip thickness (m)
$t_2$	Chip having thickness (m)
$T$	Tool life (min)
$T_D$	Dimension tool life ( $\text{sm}^2$ )
$T_{UD}$	Specific dimension tool life ( $10^3 \text{sm}^2/\mu\text{m}$ )
$T_m$	Melting temperature of the work material ( $^\circ\text{C}$ )
$U_{cs}$	Total energy entering the cutting system (Ws)
$U_f$	Energy to fracture the layer being removed (Ws)
$v$	Cutting speed (velocity) (m/min)
$v_f$	Feed velocity (m/min)
$v_{cf}$	Velocity of the cutting fluid (m/min)
$v_h$	Dimension wear rate ( $\mu\text{m}/\text{min}$ )
$v_{opt}$	Optimal cutting speed (m/min)
$v_S$	Shear velocity (m/min)
$v_1$	Velocity of the chip relative to the tool rake face (m/min)
$w_w$	Thermal diffusivity of the work material ( $\text{m}^2/\text{s}$ )
$W_{cs}$	Power required by the cutting system (W)
$\alpha$	Tool flank angle ( $^\circ$ )
$\alpha_n$	Tool normal flank angle ( $^\circ$ )
$\alpha_{cf}$	Thermal diffusivity of the cutting fluid ( $\text{m}^2/\text{s}$ )
$\beta_n$	Cutting wedge angle in the normal plane ( $^\circ$ )
$\varepsilon$	Final shear strain
$\varepsilon_x, \varepsilon_y$ and $\varepsilon_z$	True strains along the main axes

$\varepsilon_f$	Strain at fracture of the work material
$\dot{\varepsilon}$	Strain rate (1/s)
$\varphi$	Shear angle (°)
$\varphi_1$	Approach angle of the gundrill's outer cutting edge (°)
$\varphi_2$	Approach angle of the gundrill's inner cutting edge (°)
$\gamma$	Tool rake angle (°)
$\gamma_n$	Tool normal rake angle (°)
$\gamma_{xy}, \gamma_{yz}$ and $\gamma_{zx}$	Engineering shear strains
$\eta_{cs}$	Physical efficiency of the cutting system
$\kappa_r$	Tool cutting edge angle, major cutting edge (°)
$\kappa_{r1}$	Tool cutting edge angle, minor cutting edge (°)
$\lambda_s$	Cutting edge inclination angle (°)
$\mu$	Mean friction angle at the tool–chip interface (°)
$\mu_f$	Friction coefficient
$\nu_s$	Poisson's ratio
$\theta_{r-av}$	Mean contact temperature at the tool–chip interface (°C)
$\theta_{fl-av}$	Mean contact temperature at the tool–workpiece interface (°C)
$\theta_{fl-max}$	Maximum temperature at the tool flank (°C)
$\theta_{ct}$	Cutting temperature (°C)
$\theta_{opt}$	Optimal cutting temperature (°C)
$\rho_{ce}$	Radius of the cutting edge (m)
$\rho_w$	Density of the work material (kg/m <sup>3</sup> )
$\rho_{ct}$	Density of the tool material (kg/m <sup>3</sup> )
$\rho_{cf}$	Density of the cutting fluid (kg/m <sup>3</sup> )
$\sigma_{UTS}$	Ultimate tensile strength of the work material (MPa)
$\sigma_{YT}$	Yield tensile strength of the work material (MPa)
$\sigma_c$	Mean normal stress at the tool–chip interface (MPa)
$\sigma_{c-f}$	Mean normal stress at the tool–workpiece interface (MPa)
$\sigma_f$	Fracture stress (MPa)
$\sigma_i$	von-Mises' stress
$\tau_y$	Yield shear stress of the work material (MPa)
$\tau_c$	Specific frictional force which is the mean shear stress at the tool–chip interface (MPa)
$\tau_{c-f}$	Specific frictional force which is the mean shear stress at the tool–workpiece interface (MPa)
$\tau_{in}$	Strength of adhesion bonds at the tool–workpiece interface (MPa)
$\zeta$	Chip compression ratio
$\zeta_t$	Normalized chip compression ration
$\omega_{ac}$	Angle of action

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