

## Viktor P. Astakhov. Comments on STANDARD ISO 3002/4

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#### Basic quantities in cutting end grinding – Part 4: Forces, energy, power

##### General comments:

The objective of the standard is not clear. In other words, one may wonder what is the practical use of the quantities defined by this standard. It is assumed *priori* that the magnitude, direction and point of application of the total cutting force **are known** so that other parameters and characteristics of the cutting process can be derived using simple geometrical and physical formulae presented in the body of the standard.

In reality, however, this is not the case even in the simplest case of cutting known as orthogonal cutting. Let me explain this point in details:

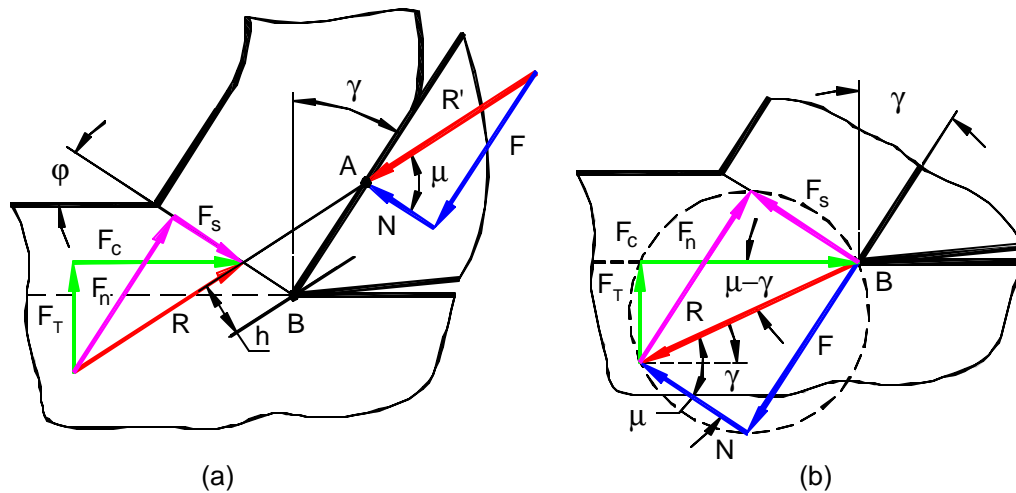
- **MAGNITUDE** of the cutting force. It can be calculated using one of three possible ways: (1) stocking a crystal ball, (2) using the existent theory of metal cutting, or (3) measured experimentally. The first two ways are practically equivalent in terms of accuracy and physical justifications while the third one is not much better. Let me explain this point in details. 'Theoretical' determination of the magnitude of the cutting force is based on the following. Originally the shear strength (M.E. Merchant, Mechanics of the metal cutting process, *Journal of Applied Physics*, vol. 16, pp. 267-275, 1945) and now the so-called flow shear stress is the only mechanical characteristic of the work material used to calculate the resistance of this material to cutting (and thus the cutting force and cutting power). However, everyday practice of machining shows that the machining of medium carbon steel AISI 1045 (hardness – HB179, tensile strength, ultimate – 625MPa, tensile strength, yield – 530 MPa) results in much lower cutting force and greater tool life than those obtained in the machining of stainless steel AISI 301 (HB 165, tensile strength, ultimate – 515MPa, tensile strength, yield – 205 MPa) (Zorev NN. Metal Cutting Mechanics, Pergamon Press, Oxford, 1966; Astakhov VP. Metal Cutting Mechanics, CRC Press, Boca Raton, 1999) even though the flow shear stress is much lower for steel AISI 301. This **OBVIOUS** fact **CANNOT** be explained using the existent theory of metal cutting. The experimental technique available today does not allow determining this value with reasonable accuracy because before measuring, one should clearly understand what he/she is going to measure. In the considered case, it may sound very 'simple' – THE **MAGNITUDE** of the cutting force. In reality, it is much more complicated because the cutting force is time dependent (Astakhov V.P. and Shvets S.V., "A system concept in metal cutting" *Journal of Materials Processing Technology* 79, pp.189-199, 1998), i.e. varies within each cycle of chip formation so its magnitude is variable. Moreover, the wave effects may play a significant role in metal cutting so the measurement of the magnitude of the cutting force should account for all these effects (Astakhov V.P., Shvets S.V., A Novel Approach to Operating Force Evaluation in High Strain Rate Metal-Deforming Technological Processes, *Journal of Materials Processing Technology*, Vol. 117, Nr. 1-2, pp. 226-237, 2001). When this is not the case then even under **PERFECTLY CONTROLLED CUTTING CONDITIONS** and with **EXTRAORDINARY CARE** taken while performing experiments, scatter in measuring the magnitude of the cutting force exceeds 50% (for example, Ivester R.W., Kennedy M., Davies M., Stevenson R., Thiele J., Furness R., "Assessment

- of Machining Models: Progress Report", National Institute of Standards and Technology, Gaithersburg, USA, 2000.).
- DIRECTION of the cutting force. Direction of the cutting force is determined in a simplest assumption that Coulomb friction with a constant friction coefficient is the case on the tool-chip interface (M.E. Merchant, Mechanics of the metal cutting process, *Journal of Applied Physics*, vol. 16, pp. 267-275, 1945).

It is true that, in general, the coefficient of friction for sliding surfaces remains constant within wide ranges of the relative velocity, apparent contact area, and normal load. In contrast, for metal cutting the coefficient of friction varies with respect to the normal load, the relative velocity, and the apparent contact area. The coefficient of friction in metal cutting was found to be so variable that Hahn (Hahn R.S., "On the Temperature Development at the Shear Plane in the Metal Cutting Process", Proceedings of the First U.S. Nat. Appl. Mech., ASME, New York, pp. 661-666, 1952; Chao B.T., Trigger, K.J., "Cutting temperatures and metal cutting phenomena", SME Journal of Engineering for Industry, Vol. A 73, pp. 777-793, 1951) doubted whether this term served any useful purpose. Moreover, Finnie and Shaw (Finnie I., Shaw M.C., "The Friction Process in Metal Cutting", Transactions of ASME, Vol. 77, pp. 1649-1657, 1956) have concluded that a coefficient of friction is inadequate to characterize the sliding between chip and tool and thus recommended to discontinue using the concept of the coefficient of friction in metal cutting. An extensive analysis of the inadequacy of the concept of the friction coefficient in metal cutting was presented by Kronenberg (pp.18-25 in Kronenberg M., Machining Science and Application. Theory and Practice for Operation and Development of Machining Processes, Pergamon Press, Oxford, 1966) who stated "I do not agree with the commonly accepted concept of coefficient of friction in metal cutting and I am using the term "apparent coefficient of friction" wherever feasible until this problem has been resolved."

Based on the experimental information available today, we may conclude that the assumed direction of the cutting force is incorrect. Moreover, as conclusively proven (for example in Astakhov V.P., Metal Cutting Mechanics, CRC Press, Boca Raton, 1999), the chip formation process is cyclic and the direction of the cutting force changes constantly within each cycle of chip formation.

- POINT OF APPLICATION of the cutting force (the cutting edge principal point according to the terminology defined by the standard). According to the standard "Although it is realized that the total cutting force on the cutting part does not act only on the cutting edge, it is assumed that the origin of the total force vector is located at the cutting edge principal point." Unfortunately, no ground for this assumption is provided by the standard. Rather, the authors of the standard just blindly followed the know Merchant's approximation made in 1945 (M.E. Merchant, Mechanics of the metal cutting process, *Journal of Applied Physics*, vol. 16, pp. 267-275, 1945) shown in Fig. 1.



**Figure 1. The single shear plane model (a), the velocity diagram (b), Ernst and Merchant free-body diagram (c), Merchant 'convenient' force diagram.**

Merchant, considering forces acting in metal cutting, arrived to the force system shown in Fig. 1a (Fig. 7 in M.E. Merchant, *Mechanics of the metal cutting process, Journal of Applied Physics*, vol. 16, pp. 267-275, 1945). In this figure, the total force is represented by two equal, opposite forces (action and reaction)  $R$  and  $R'$  which hold the chip in equilibrium. The force  $R'$  which tool exerts on the chip is resolved into the tool face-chip friction force  $F$  and normal force  $N$ . The angle  $\mu$  between  $F$  and  $N$  is thus the friction angle. The force  $R$  which the workpiece exerts on the chip is resolved along the shear plane into the shearing force,  $F_s$  which, in Merchant's opinion, is responsible for the work expended in shearing the metal, and into normal force  $F_n$ , which exerts a compressive stress on the shear plane. Force  $R$  is also resolved along the direction of tool motion into  $F_c$ , termed by Merchant as the cutting force, and into  $F_t$ , the thrust force. Although this diagram looks logical, there are a number of concerns about its physical justification. When one compares this figure with Fig. 5 in M.E. Merchant, *Mechanics of the metal cutting process, Journal of Applied Physics*, vol. 16, pp. 267-275, 1945, he might note that the shearing velocity  $V_s$  and the shearing force  $F_s$  have opposite directions so it may appear that the metal cutting process generates energy rather than consumes it. In other words, a microvolume of the work material is forced in one direction but it moves in the opposite direction. Having noticed this discrepancy, Merchant moved the whole force system to the cutting edge as shown in Fig. 1b (Fig. 8 in M.E. Merchant, *Mechanics of the metal cutting process, Journal of Applied Physics*, vol. 16, pp. 267-275, 1945) justifying this move by "convenience" (p. 272 in M.E. Merchant, *Mechanics of the metal cutting process, Journal of Applied Physics*, vol. 16, pp. 267-275, 1945) and changing (without any explanation) the direction of the shearing force. In doing so, Merchant shifted the cutting force,  $R$  parallel to itself. As such, the moment equal to this force times the shift distance,  $h$  (Fig. 1a) was overlooked. Unfortunately, this simple flaw was not noticed by the subsequent researchers who just copied these two pictures. Moreover, the force diagram shown in Fig. 1b became known as the classical Merchant force circle and is discussed today in any book on metal cutting. No wonder that the principle of minimum energy did not yield in any meaningful results when the force system, shown in Fig. 1d was used as the model.

One may wonder how significant is the overlooked moment. Astakhov proved theoretically and experimentally that this missed moment is the prime cause for chip formation and thus distinguishes the cutting process among other deforming processes (Astakhov V., Metal Cutting Mechanics, CRC Press, 1999)).

**Considering the body of the standard:**

1. Although it is stated in section 4.2 that “This part of ISO 3002 deals only with the *geometrical resolution of the total cutting force* into components”, the body of the standard contains determination of the shear plane forces (referred in Section 4.2.6, 4.4.3, 4.4.4 as shear plane tangential and perpendicular forces shown in Figures 5 and 6) which are physical forces. First of all, these arise due to the shearing process taking place only in cutting of **SOME WORK MATERIALS** (generally referred to as ductile materials). Second, it is assumed that the position of the shear plane is uniquely determined by the shear angle  $\bar{j}$ , which, according to the standard, is a constant of the cutting process.  
The same must be said about the tool face tangential force and tool face perpendicular force (Sections 4.4.5 and 4.4.6, respectively).
2. The definition of the shear plane (Section 4.4.1) is incorrect. There are a number of planes along which the shear deformation in the machining of ductile materials takes place. Which one is the shear plane?  
Another question arises about the cutting of brittle work materials, where a shear plane does not form in the sense shown in figure 6.
3. It does not follow from the body of the standard what is the use and significance of the related quantities (clause 7). These average parameters cannot be used to compare the cutting processes at different cutting conditions as it is clearly stated in the introduction to this clause. Therefore, it would be very practical to define the aim of these characteristics and to show some examples of their practical use.