International Standard ISO 3002/4

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Basic quantities in cutting and grinding — Part 4 : Forces, energy, power

Grandeurs de base en usinage et rectification — Partie 4 : Forces, énergie et puissance

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

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Basic quantities in cutting and grinding — Part 4: Forces, energy, power

0 Introduction

The forces considered in this part of ISO 3002 are those exerted by the tool upon the workpiece.

Forces can vary in time; in this part of ISO 3002 instantaneous forces, torques, and power are considered at an instant in time which, if necessary, should be specified.

Forces, torques, energy and power in this part of ISO 3002 may be considered in relation to a cutting part or to the tool as a whole. Whenever a clear distinction must be made the suffix "S" should be added to the symbols when related to the cutting part.

1 Scope and field of application

This International Standard defines a nomenclature for certain basic concepts concerning the machining and grinding of materials. This part of ISO 3002 establishes and defines those terms used for forces, energy and power in connection with cutting. It should be read in conjunction with ISO 3002/1 which is more general.

It is generally applicable to all machining operations, including grinding. However certain terms specifically for grinding are defined in ISO 3002/5.

The definitions[1] are divided into five main clauses: the first two deal with forces and torques exerted by a tool or by the cutting part on the workpiece, the next two are concerned with energy and power for a particular operation on a specific machine tool, and the last gives details of individual quantities where these may differ from the basic quantities.

NOTE — In addition to the terms given in the three official ISO languages (English, French, Russian), this part of ISO 3002 gives the equivalent terms in German, Italian and Dutch; these terms have been included at the request of Technical Committee ISO/TC 29, and are published under the responsibility of the committee members for Germany, F.R. (DIN), Italy (UNI) and the Netherlands (NNI). However, only the terms given in the official languages can be considered as ISO terms.

2 References

ISO 841, *Numerical control of machines — Axis and motion nomenclature.*

ISO 3002/1, *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.*

ISO 3002/2, *Basic quantities in cutting and grinding — Part 2: Geometry of the active part of cutting tools — General conversion formulae to relate tool and working angles.*

ISO 3002/3, *Basic quantities in cutting and grinding — Part 3: Geometric and kinematic quantities in cutting.*

ISO 3002/5, *Basic quantities in cutting and grinding — Part 5: Basic terminology concerning grinding by wheel.*[2]

3 Forces and torques exerted by the tool

3.1 total force exerted by the tool: The resultant of the *total force* F (see 4.1) exerted by all *cutting parts* engaged.

3.2 total torque exerted by the tool M: The entire torque produced by the cutting action of a tool around a specified axis.

3.3 cutting torque M_c: The torque exerted around the axis of rotation of the *primary motion.*

4 Forces exerted by a cutting part

Although it is realized that the *total 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*. Torques so caused are not considered here.

All planes and directions needed for the resolution of the *total force* are defined in the *cutting edge principal point*.

4.1 total force F exerted by a cutting part: The entire force produced by the action of a *cutting part* of the tool on the workpiece.

1) Definitions of all concepts mentioned or used in this part of ISO 3002 (printed in *italics*) can be found either in the body of this part or in the other parts, to which the reader is referred.

2) At present at the stage of draft.

NOTE — In grinding the *total force* may be considered at an individual grain in a similar way as a *cutting part* of a tool. More commonly, however, the *total force* exerted by all active grains is considered. For the purpose of resolution of the total force in grinding, the grinding principal point D is defined in ISO 3002/5.

4.2 General principles related to the resolution of the total force exerted by a cutting part

Different components of the *total force* can be considered:

a) geometrical components of the *total force* derived from the vector resolution of the *total force* along any chosen axes;

b) physical forces due to specific physical actions in certain directions, the simultaneous action of which results in the *total force*.

As an example, the geometrical *total force* in a certain direction relative to the *tool face* can physically be produced by one or more components such as a *friction force component*, a *thrust force component* (see 4.3.4.3), etc.

This part of ISO 3002 deals only with the *geometrical resolution of the total force* into components. Attention is drawn to the fact that a clear distinction must be made between the components of the total force exerted by a *cutting part* and those forces originating from a physical action at the *tool surfaces*, and contributing to the *total force*.

Geometrical resolution can be undertaken in many ways. This part of ISO 3002 recommends principles for terminology and symbols for the most common cases.

4.2.1 Geometrical resolution of the total force along directions of different motions and in directions perpendicular to these motions

Components of the *total force* can be resolved by perpendicular projection along the directions of the different motions and in directions perpendicular to these motions.

This will be the usual method whenever power is considered. In principle the component of *total force* will then be indicated with a suffix corresponding to the motion considered:

c for the *direction of primary motion;*

f for the *direction of feed motion;*

e for the *resultant cutting direction;*

N may be used as an additional suffix to indicate a direction normal to a line or direction, or a direction perpendicular to a plane. In the case of defining a direction normal to a line then the plane containing the normal direction should be specified.

p for the direction perpendicular to the *working plane* P_{fe}, i.e. the direction perpendicular to both the direction of *feed motion* and the *direction of primary motion.*

NOTE — A detailed study of these principles is given in 4.2.7 and 4.3.

4.2.2 Geometrical resolution of the total force along the line of intersection of planes and tool surfaces

The force component symbol shall be identified by two suffixes: the first to denote the plane and the second to denote the surface.

Example:

$F_{n\gamma}$ is the component of *total force* acting along the intersection of the *cutting edge normal plane* P_n and the *tool face* A_γ.

4.2.3 Geometrical resolution of the total force along machine reference axes (see ISO 841 and figure 1)

The component of the total force along a machine axis shall be identified by the characteristic suffix of this axis followed by the letter "m" (for machine).

Example:

$F_{Xm} - F_{Ym} - F_{Zm}$

4.2.4 Components of the total force related to characteristic directions of the workpiece or to an axis connected with the workpiece

In such cases, an additional suffix "w" shall be added to the appropriate directional suffix (or suffixes).

Example:

$F_{Xw} - F_{Yw} - F_{Zw}$

4.2.5 Components of the total force related to characteristic directions of the tool

In such cases, an additional suffix "s" shall be added to the appropriate directional suffix (or suffixes).

Example:

$F_{Xs} - F_{Ys} - F_{Zs}$

4.2.6 Components of the total force related to the assumed shear plane, assumed chip flow direction, etc.

In such cases, suffix "sh" shall be used for shear direction and suffix "ch" for chip flow direction.

A standard example in the particular case of orthogonal cutting is given in 4.4.

4.2.7 Components of total force perpendicular to a plane or tool surface

When the designation of a component of the *total force* in a direction perpendicular to a plane or tool surface is required and this direction cannot be defined in relation to other directions (see 4.2.1, 4.2.3 and 4.2.4) or by the intersection of previously defined planes (see 4.2.2) then the direction should be indicated by using two suffixes; the first to denote the plane or tool surface and "N" to indicate a direction perpendicular to the plane.

Thus the component of *total force* perpendicular to the *cutting edge normal plane* P_n would be designated by F_{nN} and the component of *total force* perpendicular to the *tool face* A_γ would be designated by $F_{\gamma N}$.

4.3 Geometrical resolution of the total force exerted by a cutting part, by perpendicular projection to the directions of motion and to their perpendiculars (see figures 2 and 3)

4.3.1 active force F_a (see figures 2, 3, 4 and 5) : The projection of the *total force* F in the *working plane* P_{fe}.

4.3.2 back force F_p (see figure 2) : The component of *total force* F perpendicular to the *working plane* P_{fe}.

NOTES

1 Because F_p is perpendicular to the directions both of *primary motion* and of *feed motion* it does not contribute to the cutting power (see 6.3).

2) $F^2 = F_a^2 + F_p^2$

4.3.3 Components of the total force F in the working plane related to the resultant cutting direction

4.3.3.1 working force F_e (see figures 2, 3, and 4) : The component of the *total force* F obtained by perpendicular projection on the *resultant cutting direction* (i.e. along vector $\vec{v}_e$). It is therefore defined in the *working plane* P_{fe}.

4.3.3.2 working perpendicular force F_{eN} (see figure 3) : In the *working plane* P_{fe}, the component of the *total force* perpendicular to the *resultant cutting direction*.

$$F_a^2 = F_e^2 + F_{eN}^2$$

4.3.4 Components of the total force in the working plane related to the direction of primary motion

4.3.4.1 cutting force F_c (see figures 2, 3 and 5) : The component of the *total force* obtained by perpendicular projection on the *direction of the primary motion* (i.e. along vector $\vec{v}_c$).

4.3.4.2 cutting perpendicular force F_{cN} (see figure 3) : The component of the *total force* perpendicular to the *direction of the primary motion* and in the *working plane* P_{fe}.

$$F_a^2 = F_c^2 + F_{cN}^2$$

4.3.5 Components of the total force in the working plane related to the direction of the feed motion

4.3.5.1 feed force F_f (see figures 2, 3, and 5) : The component of the *total force* obtained by perpendicular projection on the direction of the *feed motion* (i.e. along vector $\vec{v}_f$).

4.3.5.2 feed perpendicular force F_{fN} (see figure 3) : The component of the *total cutting force* perpendicular to the direction of the *feed motion* in the *working plane* P_{fe}.

$$F_a^2 = F_f^2 + F_{fN}^2$$

NOTE — When the *feed motion angle* $\varphi = 90°$ (for example turning, drilling), the *feed force* F_f is identical to the *cutting perpendicular force* F_{cN}, and the *cutting force* F_c is identical to the *feed perpendicular force* F_{fN} :

$$F_f = F_{cN}$$

$$F_c = F_{fN}$$

For such operations, only the terms *feed force* and *cutting force* shall be used. In these cases:

$$F_a^2 = F_f^2 + F_c^2$$

4.3.6 thrust force F_D (see figures 2 and 5) : The component of the *total force* obtained by perpendicular projection on the *cut dimension plane*.

NOTE — The other components of the *total force* in the *cut dimension plane* have already been defined, i.e.

a) *back force* F_p (see 4.3.2)

b) *cutting perpendicular force* F_{cN} (see 4.3.4.2)

The following relationships are valid:

$$F_D^2 = F_p^2 + F_{cN}^2$$

$$F^2 = F_c^2 + F_D^2$$

4.3.7 Angles between force components

The angles between force components shall be indicated explicitly.

Examples:

$\widehat{FF_a}$ is the angle between F and F_a (see figure 4);

$\widehat{F_aF_e}$ is the angle between F_a and F_e.

Similarly cos $\widehat{FF_a}$ or cos $\widehat{F_aF_e}$ are respectively the cosines of the angles between F, F_a and F_a, F_e.

NOTE — It is mathematically correct to derive further force components in a plane from the projection of the *total force* on this plane but projection on a direction should not be further resolved.

Therefore it is acceptable to compute the components of the *total force* in the *working plane* by computing the components of the *active force* in this plane since (see figure 4)

$$\cos \widehat{FF_e} = \cos \widehat{FF_a} \cos \widehat{F_aF_e}$$

Example:

$$F_e = F \cos \widehat{FF_e} = F_a \cos \widehat{F_aF_e} = F \cos \widehat{FF_a} \cos \widehat{F_aF_e}$$

4.4 Geometrical resolution of the total force in the simplified two dimensional model for orthogonal cutting (see figure 5)

Assuming that the *active cutting edge* is straight and sharp, that $\kappa_r = 90°$ and $\lambda_s = 0°$, neglecting all physical force components on the *flank*, and assuming that no lateral deformation of the material takes place, the *total cutting force* can be resolved according to a two dimensional model in the *working plane* P_{fe}.

In this case $F = F_a$.

4.4.1 shear plane P_{sh} (see figure 6): An idealized plane along which the shear deformation of the material is assumed to take place.

4.4.2 shear plane angle Φ (capital)[1] (see figure 6): The angle between the *direction of primary motion* and the intersection of the *shear plane* P_{sh} with the *working plane* P_{fe}.

In the idealized case considered here the shear plane angle can be computed as follows:

$$\operatorname{tg} \Phi = \frac{\cos \gamma_n}{\Lambda_h - \sin \gamma_n}$$

where Λ_h is the chip thickness compression ratio defined as the ratio of the idealized chip thickness h_{ch} to the *nominal thickness of the cut* h_D (see figure 6).

$$\Lambda_h = \frac{h_{ch}}{h_D}$$

The average chip thickness h_{ch} is measured in the *working plane* P_{fe} perpendicular to the tool face A_γ.

4.4.3 shear plane tangential force F_{sh} (see figure 5): The component of the *total force* obtained by perpendicular projection on the *shear plane* P_{sh}.

4.4.4 shear plane perpendicular force F_{shN} (see figure 5): The component of the *total force* perpendicular to the *shear plane* P_{sh}.

$$F^2 = F^2_{sh} + F^2_{shN}$$

4.4.5 tool face tangential force F_γ (see figure 5): The component of the *total force* obtained by perpendicular projection on the *tool face* A_γ in the *working plane* P_{fe}.

4.4.6 tool face perpendicular force $F_{\gamma N}$ (see figure 5): The component of the *total force* perpendicular to the *tool face* A_γ.

$$F^2 = F^2_\gamma + F^2_{\gamma N}$$

5 Energy

Energy is considered for a particular operation on a particular machine tool during a specified interval of time and with specified cutting conditions.

5.1 cutting energy E_c: The energy required to cause *primary motion* in order to remove a certain quantity of material.

$$E_c = \int_0^t F_c v_c \, dt$$

5.2 feed energy E_f: The energy required to cause *feed motion* in order to remove a certain quantity of material.

$$E_f = \int_0^t F_f v_f \, dt$$

5.3 working energy E_e: The energy required to remove a certain quantity of material; it is therefore the sum of the *cutting and feed energies*.

$$E_e = E_c + E_f$$

6 Power

6.1 power P: The scalar product of force and velocity vectors taken at the same point and at the same instant in time for a particular operation with specified cutting conditions.

Unless otherwise specified, these quantities should be taken at the *cutting edge principal point*. In the case of a multitoothed cutting tool, the working power of the tool is the sum of the powers of all engaged *cutting parts* taken at the same instant in time.

6.2 working power P_e: The product of the *working force* F_e and the *resultant cutting speed* v_e, both taken at the *cutting edge principal point* at the same instant in time.

$$P_e = F_e v_e = P$$

6.3 cutting power P_c: The product of the *working force* F_c and the *cutting speed* v_c, both taken at the *cutting edge principal point* at the same instant in time.

$$P_c = F_c v_c$$

6.4 feed power P_f: The product of the *feed force* F_f and the *feed speed* v_f both taken at the *cutting edge principal point* at the same instant in time.

$$P_f = F_f v_f$$

NOTE

$$P = (\vec{F}_c + \vec{F}_f) \times (\vec{v}_c + \vec{v}_f)$$

$$P = F_c v_c + F_f v_f + \vec{F}_c \vec{v}_f + \vec{F}_f \vec{v}_c$$

$$P = P_c + P_f + \vec{F}_c \vec{v}_f + \vec{F}_f \vec{v}_c$$

only when $\varphi = 90°$, $\vec{F}_c \vec{v}_f + \vec{F}_f \vec{v}_c = 0$

in which case $P = P_c + P_f$

1) The distinction is made between the *shear plane angle* Φ defined above and the shear angle related to the rotational deformation of the material as defined in plasticity theory.

7 Related quantities

All related quantities should be referred to a particular operation on a particular machine tool under specified cutting conditions.

7.1 cutting force per unit area of cut k_c: The ratio of the *cutting force* F_c exerted by a *cutting part* and the *nominal cross-sectional area of the cut* A_D.

$$k_c = \frac{F_c}{A_D}$$

In SI units, k_c is expressed in newtons per square metre, usually in newtons per square millimetre.

7.2 cutting force per unit of width of cut F'_c: The ratio of the *cutting force* F_c exerted by a *cutting part* and the *nominal width of cut* b_D

$$F'_c = \frac{F_c}{b_D}$$

In SI units, F'_c is expressed in newtons per metre, usually in newtons per millimetre.

NOTE — Similarly, other force components per unit area of cut or per unit width of cut may be defined, for example:

k_p is the back force per unit area of cut;

F'_D is the thrust force per unit width of cut.

7.3 cutting energy per unit material volume e_c: The energy required to remove a unit volume of workpiece material.

In SI units e_c is expressed in joules per cubic metre, usually in joules per cubic centimetre.

7.4 cutting power per unit material removal rate p_c: The *cutting power* required to remove a unit of material per unit of time.

In SI units, p_c is expressed in watts per cubic metre second, usually in watts per cubic centimetre second.

Table

Action	Symbol	Unit
Cutting force	F_c	N
Cutting energy	E_c	N·m = J = W·s
Cutting power	P_c	$\frac{\text{N·m}}{\text{s}}$ = W
Cutting force per unit area of cut	k_c	N·m^{-2} or N·mm^{-2}
Cutting energy per unit material volume	e_c	J·m^{-3} = N·m^{-2} or J·cm^{-3} = N·mm^{-2}
Cutting power per unit material rate	p_c	W·m^{-3}·s = N·m^{-2} or W·cm^{-3}·s = N·mm^{-2}

NOTE — When the *cutting force per unit area of cut* k_c, the *cutting energy per unit material volume* e_c and the *cutting power per unit material rate* p_c are considered for the same *cutting part* and at the same instant in time and if each is expressed in the SI units given, then the same numerical values are obtained.

The values for the *cutting force* k_c usually given in newtons millimetres to the power minus two will be unchanged if the *cutting energy* e_c is given in joules centimetres to the power minus three and the *cutting power* p_c in watts centimetres to the power minus three second.

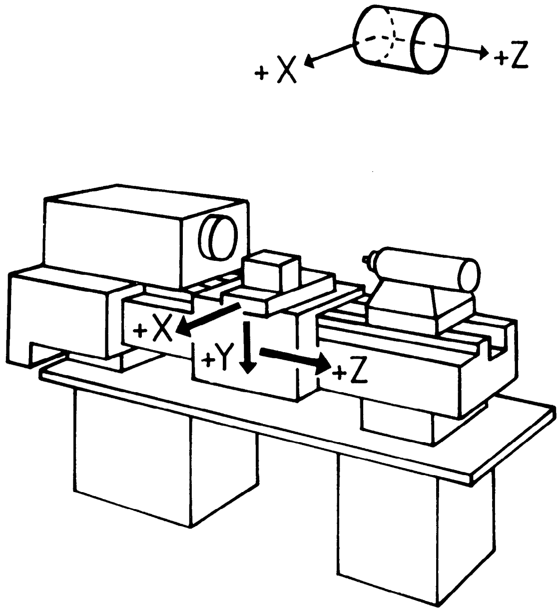


Figure 1 — Machine reference system for a lathe (taken from ISO 841)

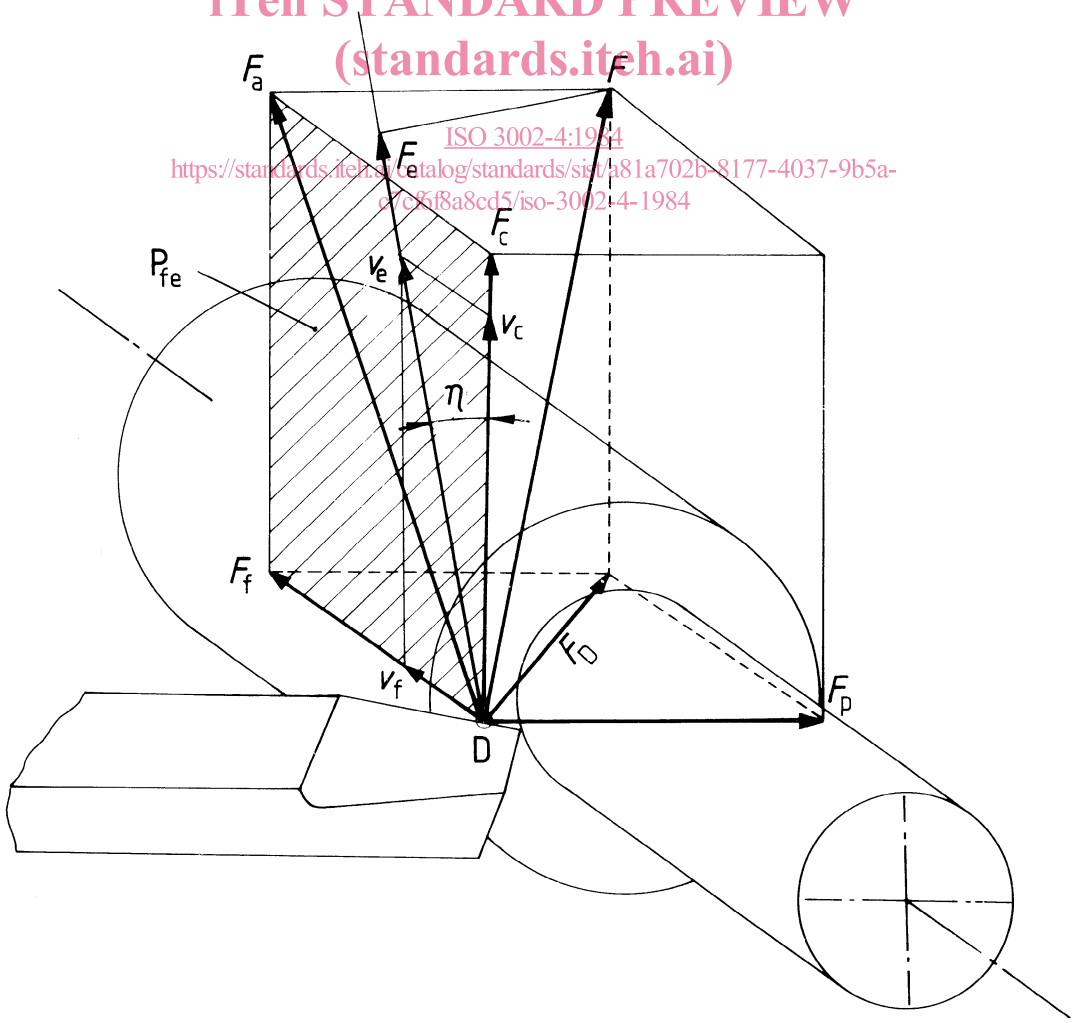
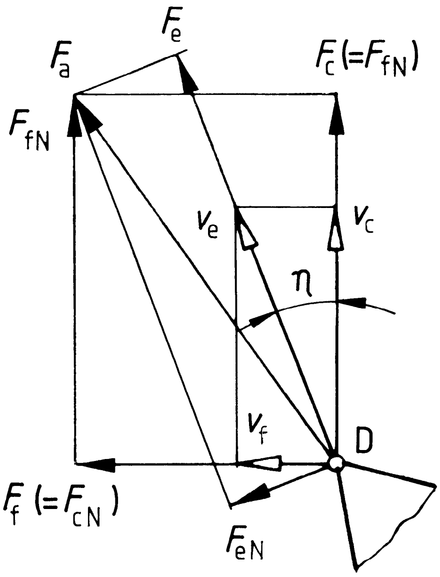
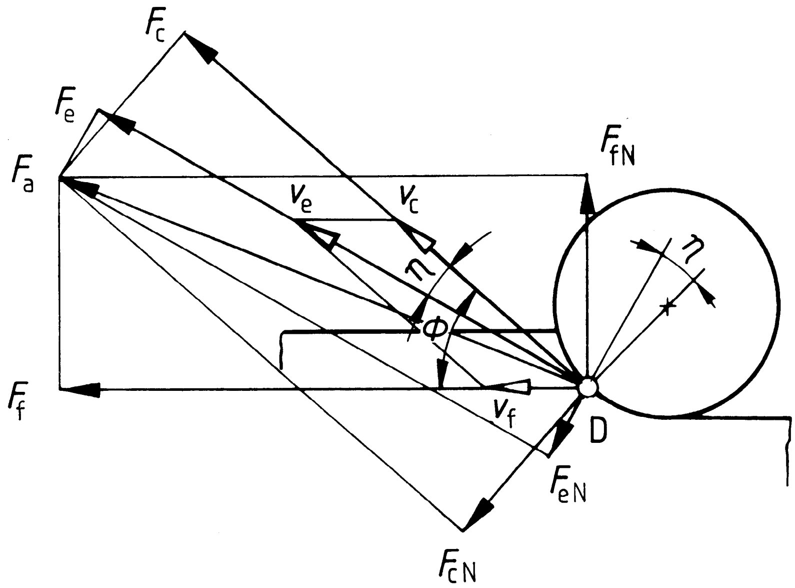


Figure 2 — Resolution of forces in cylindrical turning



a) turning (φ = 90°)



b) slab milling (φ < 90°)

Figure 3 — Resolution of forces in the working plane P_{fe}

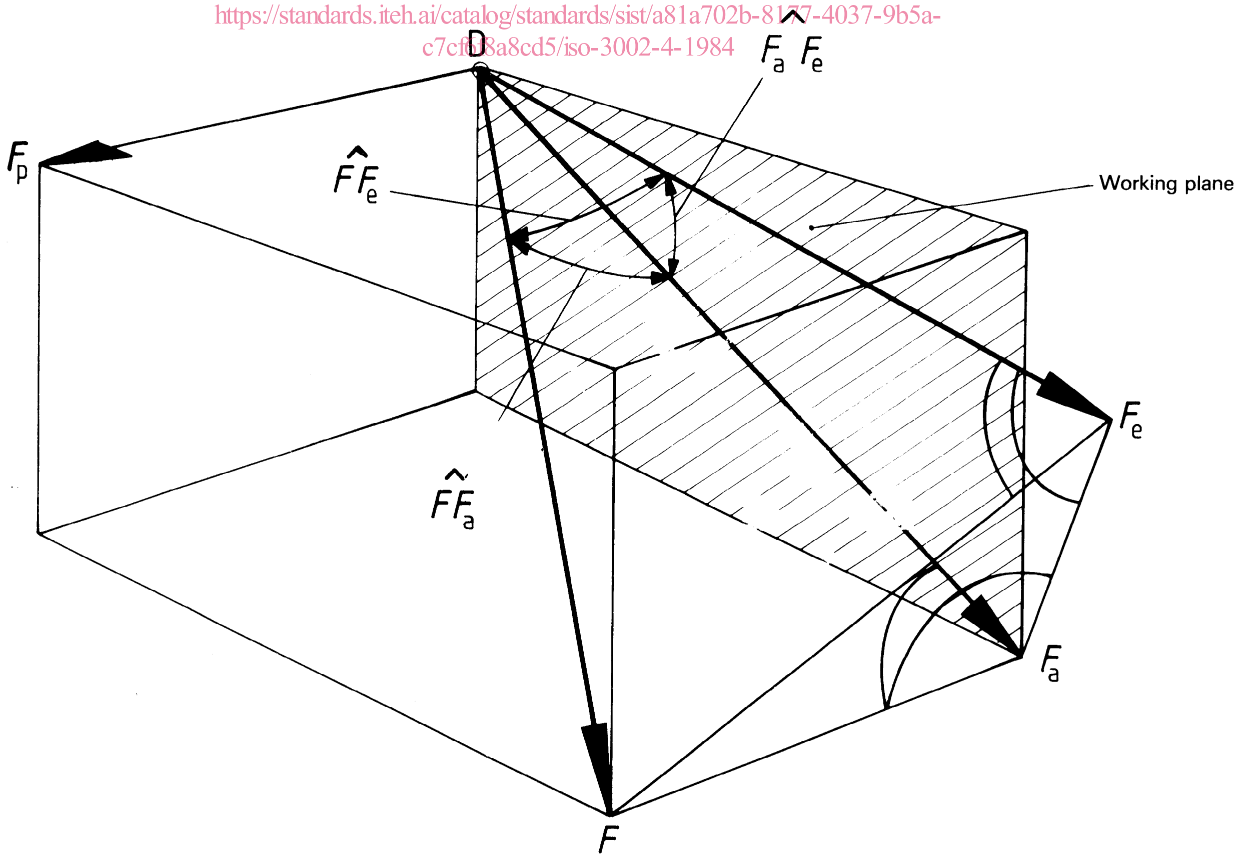


Figure 4 — Angles between force components